Development of NbTiN-Al MKID camera for the Nobeyama 45-m telescope

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- Microwave Kinetic Inductance Detector (MKID)
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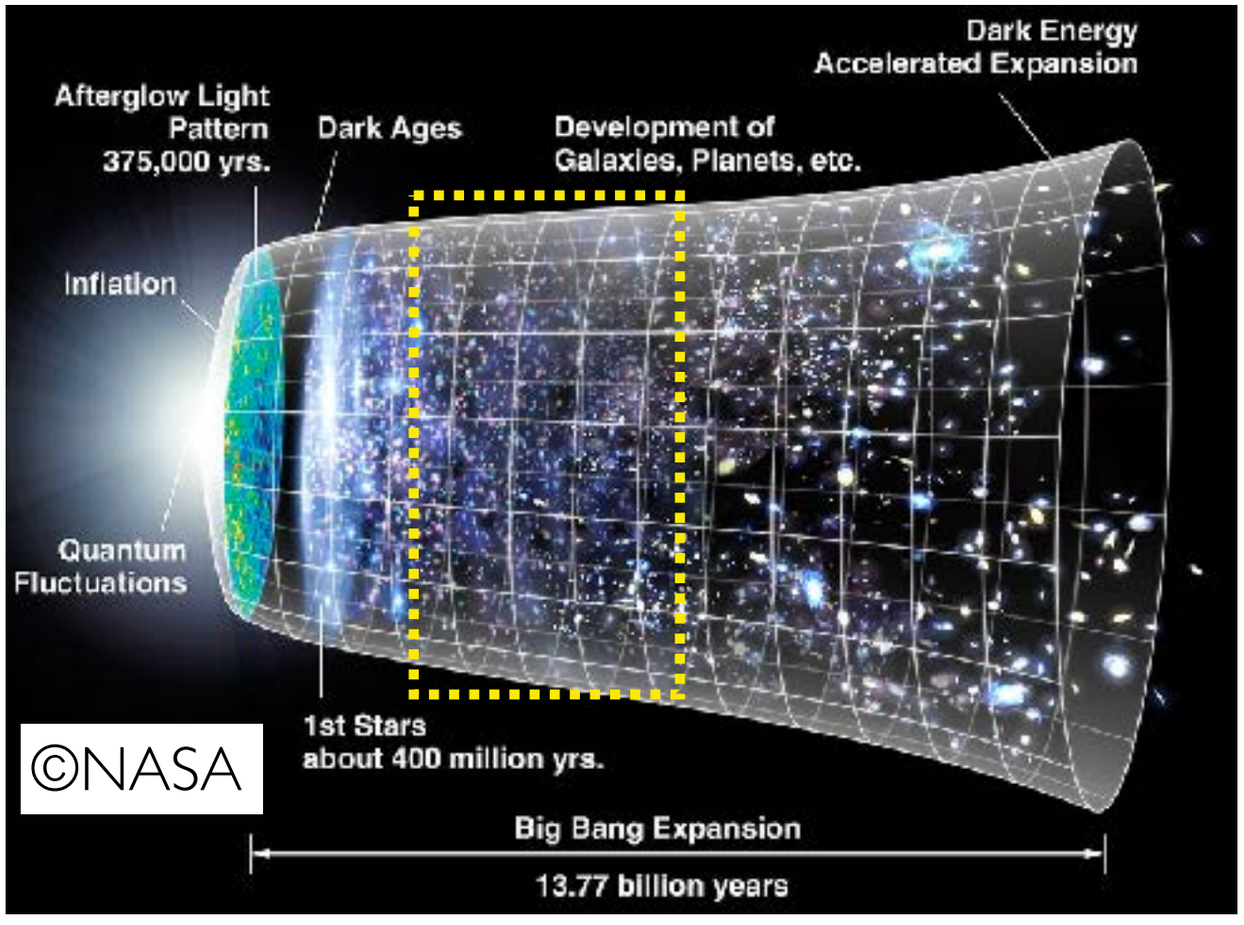
Survey of Distant Galaxies

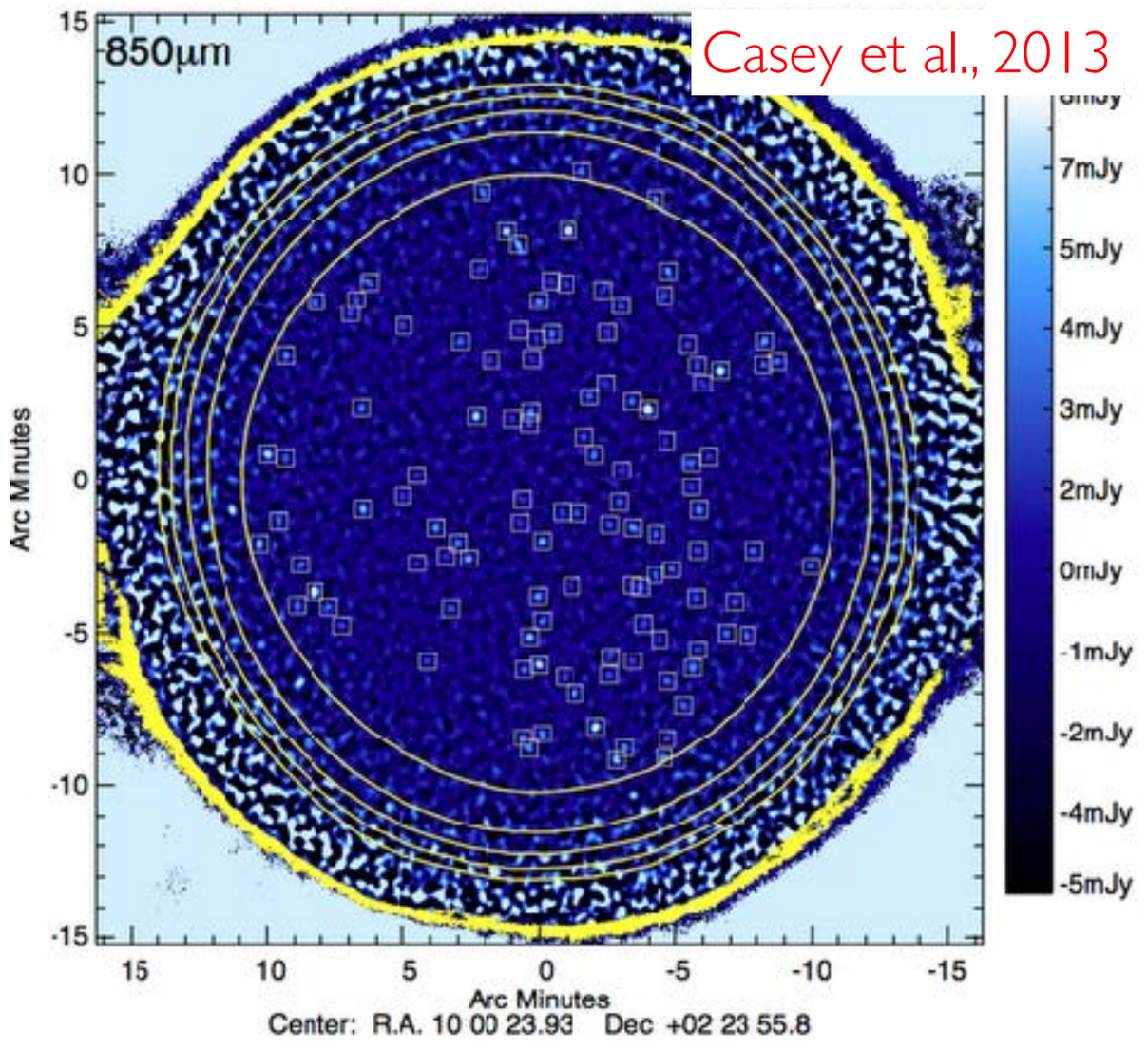
✶ Distant Galaxy Survey

- distant galaxy is important source to understand the galaxy evolution
  - Optical : absorbed by dust
  - mm-wave to THz : dust emission
- multi-band observation
  - redshift can be determined from SED



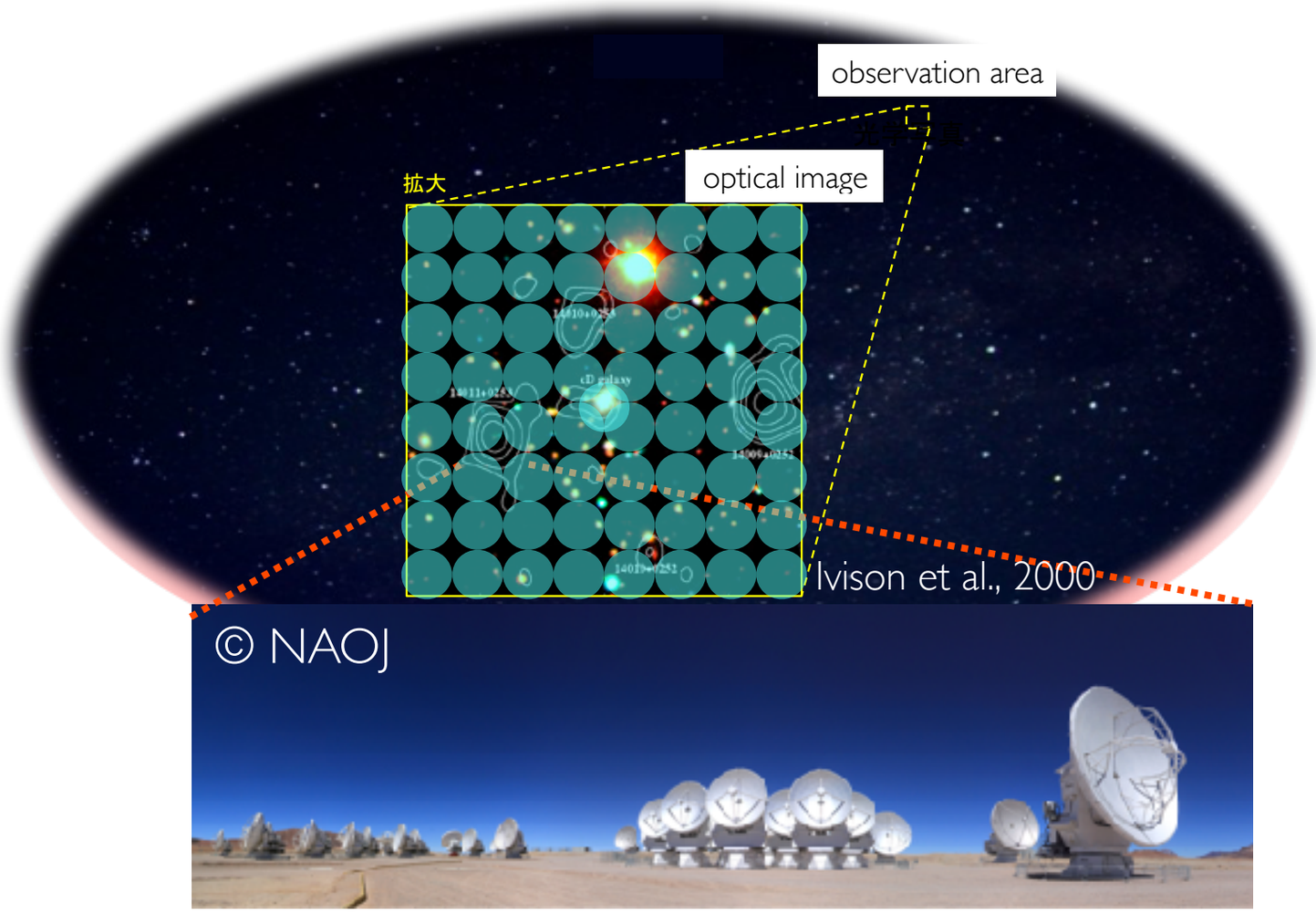
✶ Star Formation History

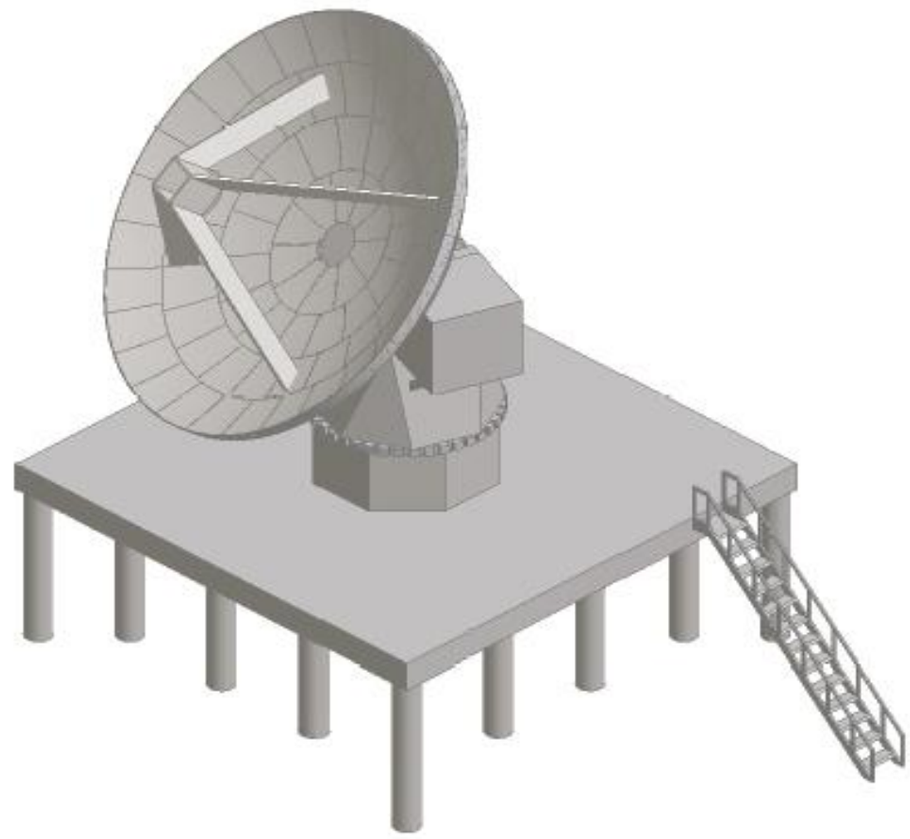
- distant galaxy is obscured by dust
- wide-filed mm & submm continuum camera is important to survey galaxies



Wide-Field Observations

✳ Multi-pixel camera for wide-field observations





ALMA : high-angular resolution interferometer
→ follow-up observations of galaxies detected by the camera

To observe a lot of distant galaxies,
- camera development for wide-field observation
- good observation site for astronomical observations

are important

Camera Development

✳ 100-GHz band Camera

- Camera will be installed on the Nobeyama 45m telescope
- Collaboration with National Astronomical Observatory of Japan
- free-free emission is dominant at the 100-GHz continuum
  - good tracer of the massive star forming region (HII region)

Observation Frequency	100-GHz band (90 – 110 GHz)
Field-of-view	~ 3 arcmin
Detector	Microwave Kinetic Inductance Detector
No. of pixels	109 pixels
Bath temperature	< 200 mK

✳ THz band Camera (Future Plan)

- Our group is planning to construct the 1deg. FoV 10 m telescope at the Antarctica plateau.
- Target bands : 400 / 850 / 1300 GHz

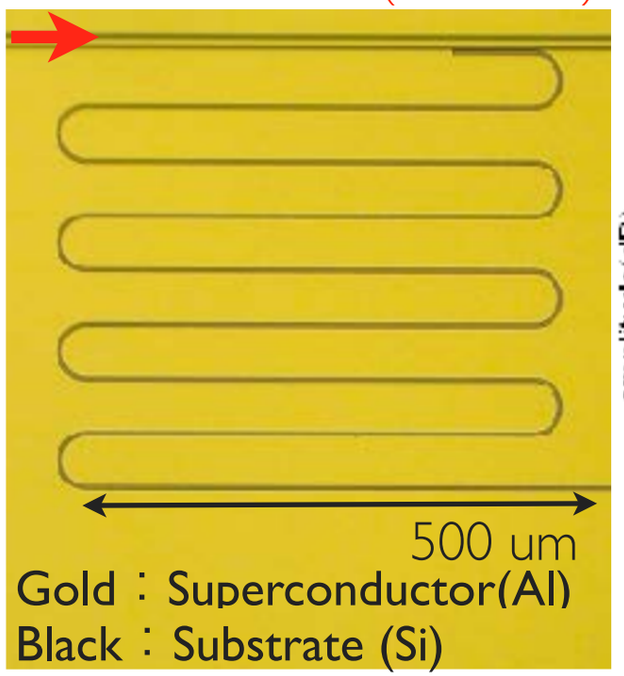
MKID is one of the important technology for realizing wide-field camera

Microwave Kinetic Inductance Detector (MKID)

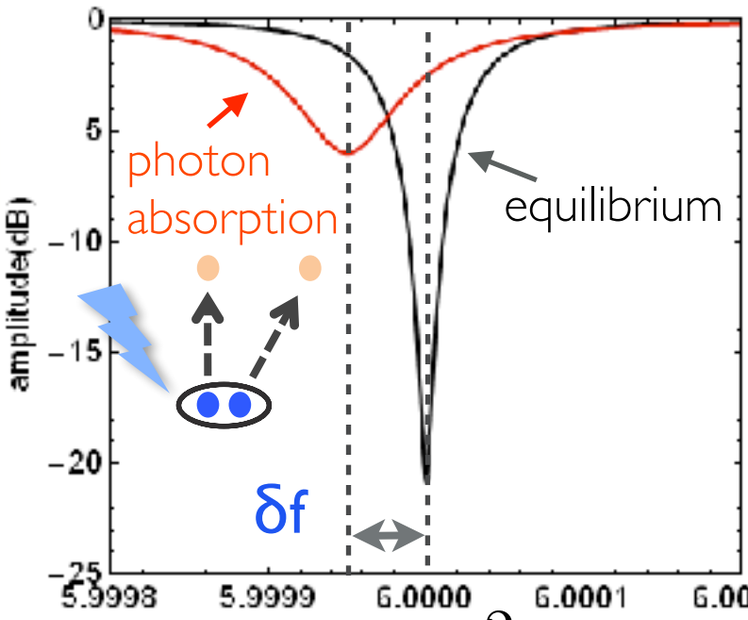
✳ Operation Principle

- Superconducting resonators operated in the microwave range
- Incident photons break Cooper-pair
  - → Kinetic Inductance is changed
  - → Resonance frequency of MKID is also changed

ex) Al MKID : > 85 GHz photons can be observed



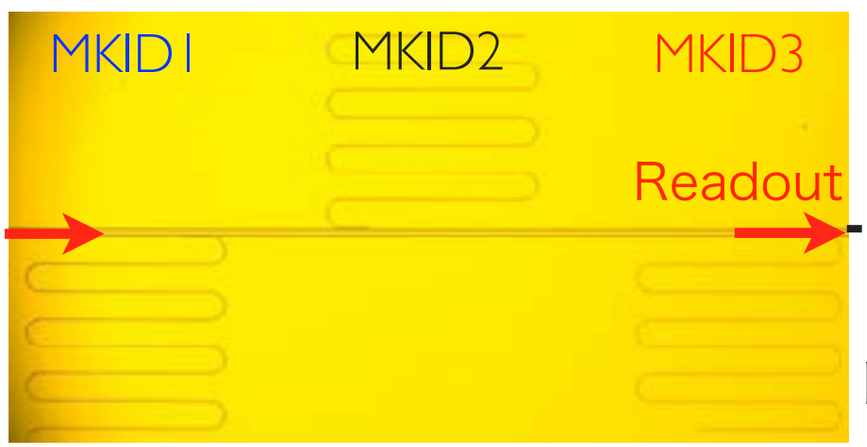
Day et al., Nature, 2003



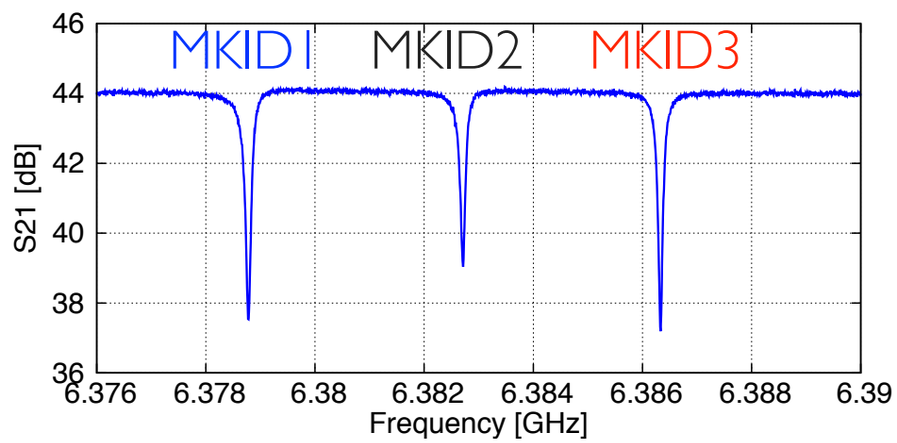
$$\omega_0 = \frac{2\pi}{4l\sqrt{(L_g + L_k)C}}$$

✳ Advantage of MKID

- High-detector yield is expected because the MKID fabrication process is relatively simple
- Intrinsic frequency multiplexing capability → ~1000 pixels can be measured with one LNA



Low-noise amplifier



Test Observations

✳ Commissioning in 2018 season

○ ・Optics, detector yield and stability satisfy a requirement

× ・Measured sensitivity was one order lower than the target sensitivity.

✳ Improvement of camera sensitivity

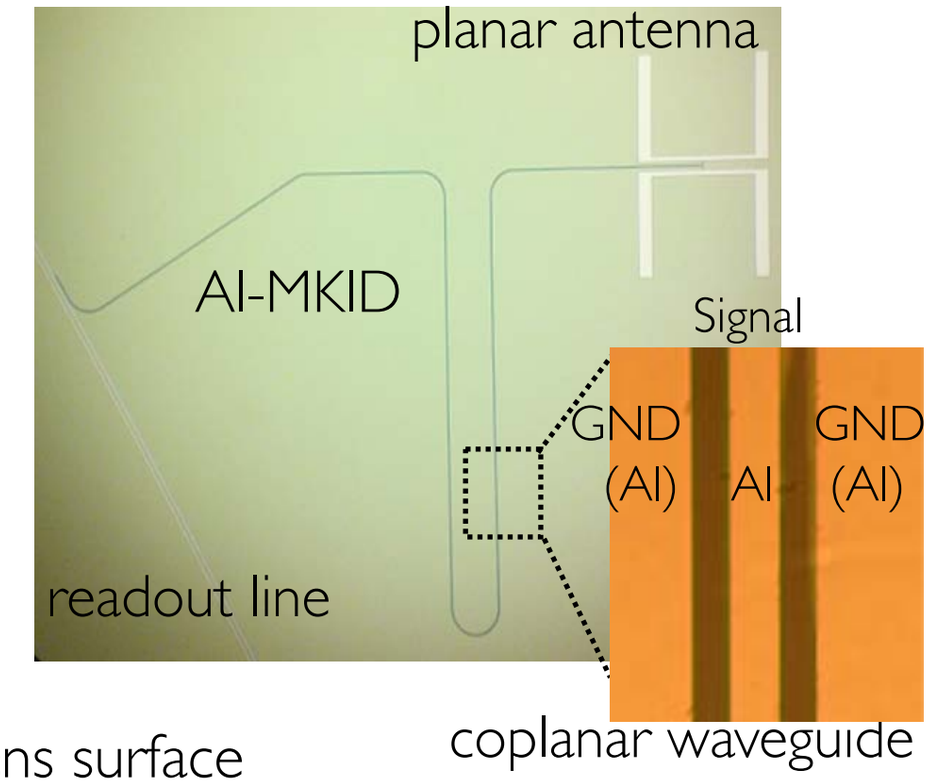
1. Low optical efficiency of MKID array

・All Al MKID (gap E of Al : ~85 GHz)

- Loss at GND & antenna (= low efficiency)

・NbTiN-Al MKID (gap E of NbTiN : ~1.1 THz)

- NbTiN GND and Al signal line **Yates et al., 2011**

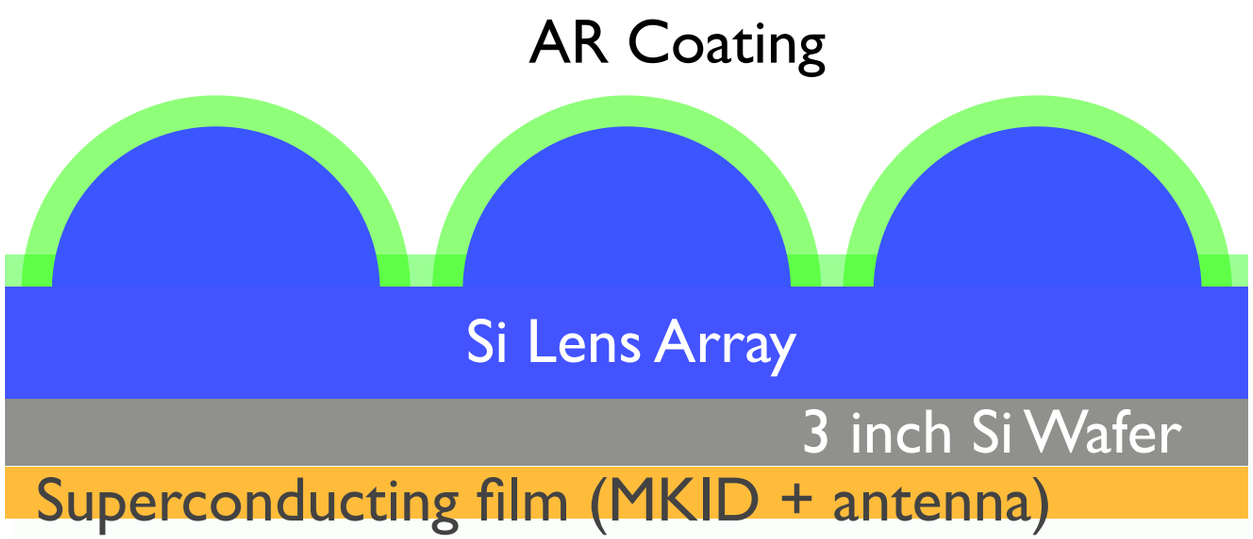


2. Surface reflection of Si lenses

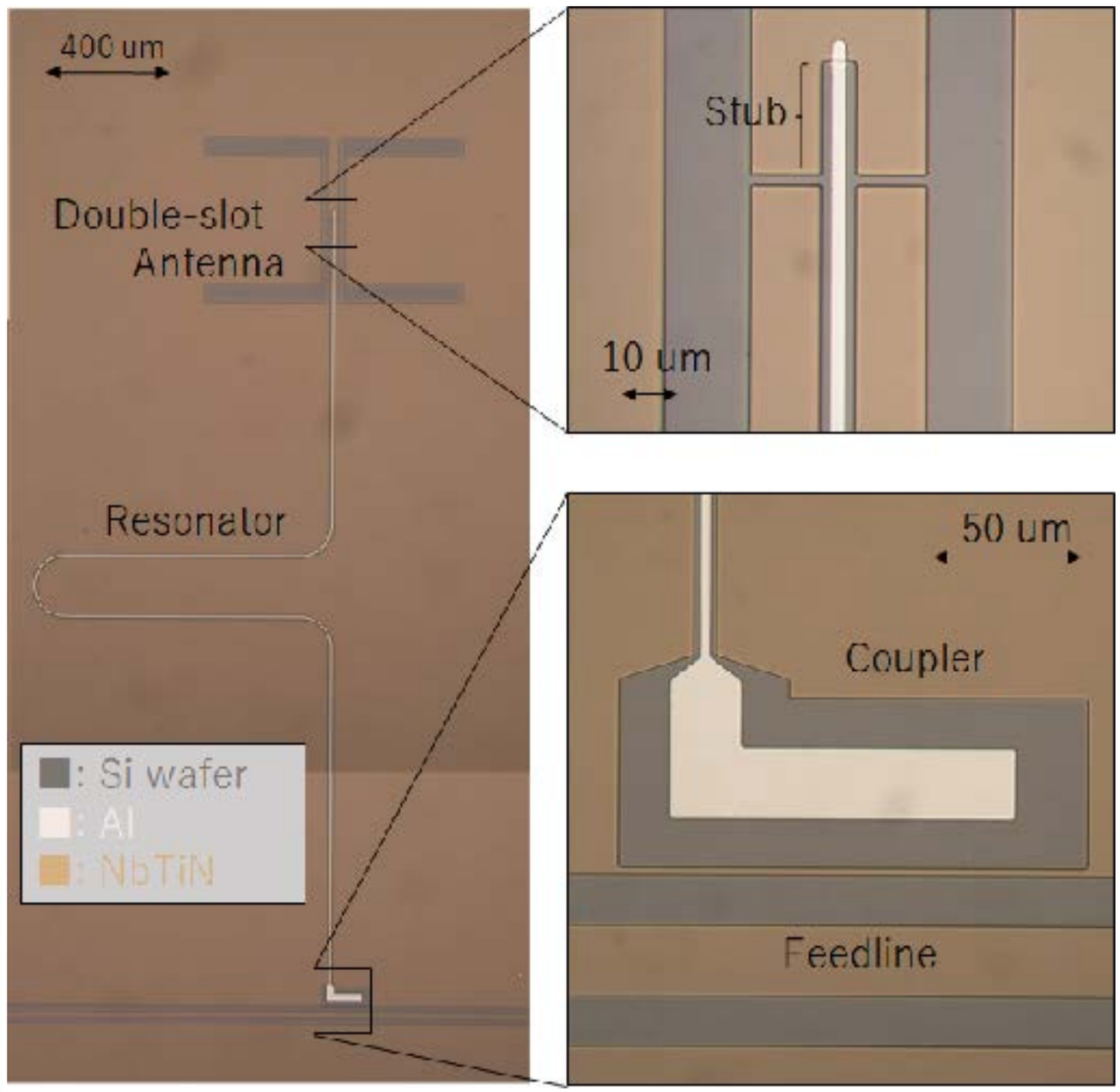
・high refractive index causes reflections of ~30% at lens surface

Focal Plane Array

- 100-GHz band MKID Camera
  - Double-slot antenna & Si lens array
  - Glass beads AR coating
- 109 pixel NbTiN-Al MKID Array
  - 200 nm NbTiN & 50 nm Al
  - MKIDs are distributed over the entire 3-inch Si wafer



< NbTiN-Al MKID >



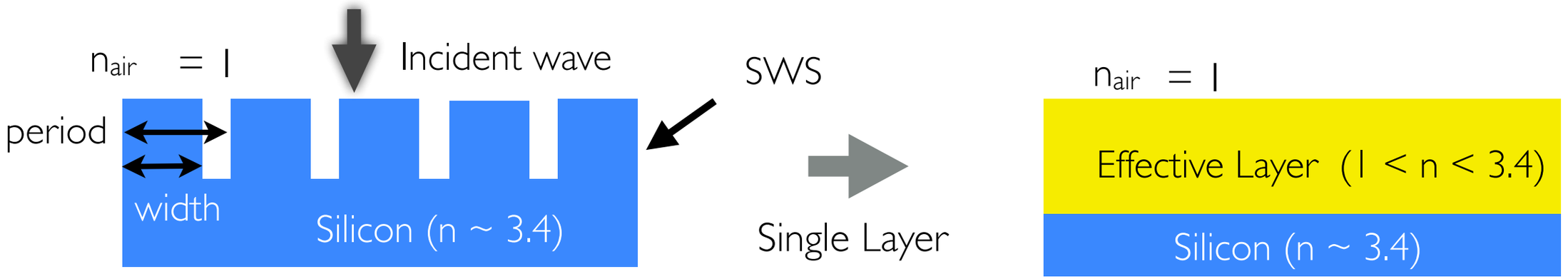
fabricated by Y. Murayama

Anti-Reflective Structures

✳ Subwavelength Structure (SWS)

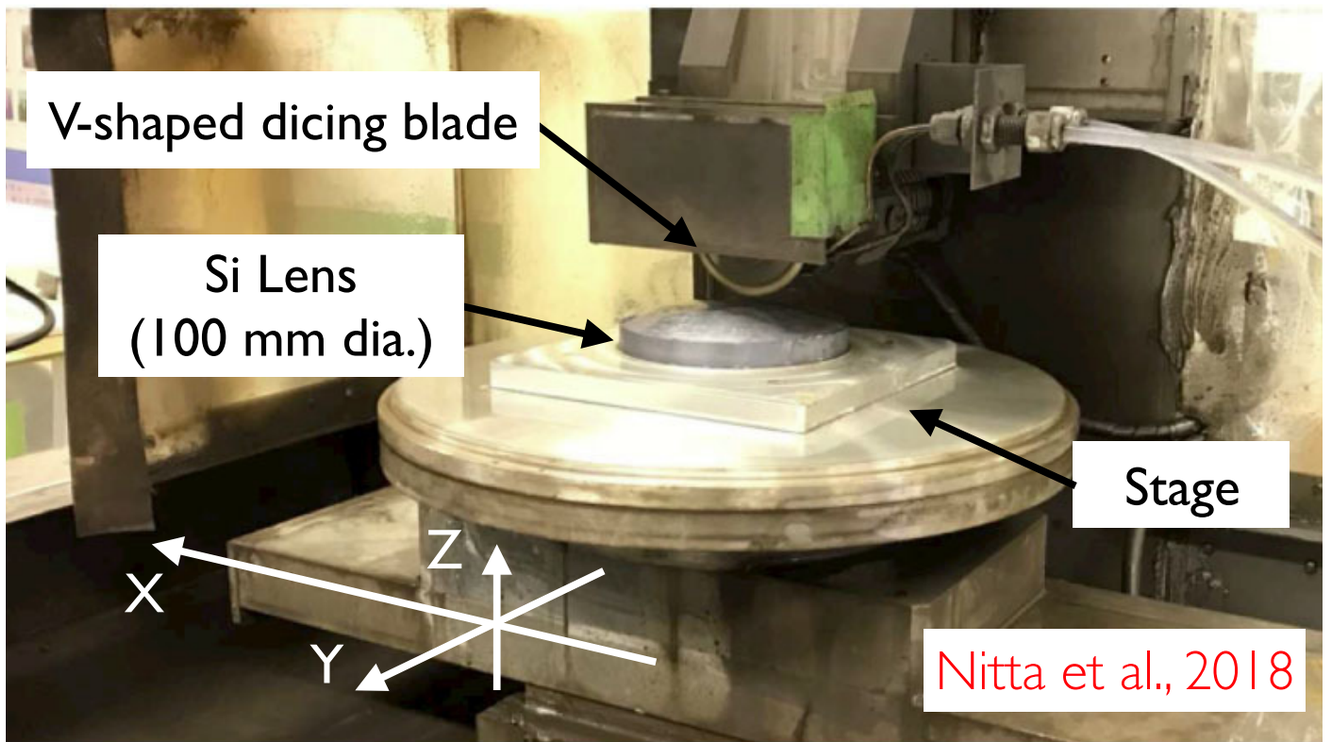
- Periodic structures in subwavelength scale
- The structures act as antireflective (AR) layers

  → ex) optimized for Si : n = 1.84



✳ Fabrication Method

- Development of a dedicated three-axis dicing machine
  (Oshima Prototype Engineering Co.)
  →Lens surface can be machined
- Various (Rectangular and V-shape) types of dicing blades were used



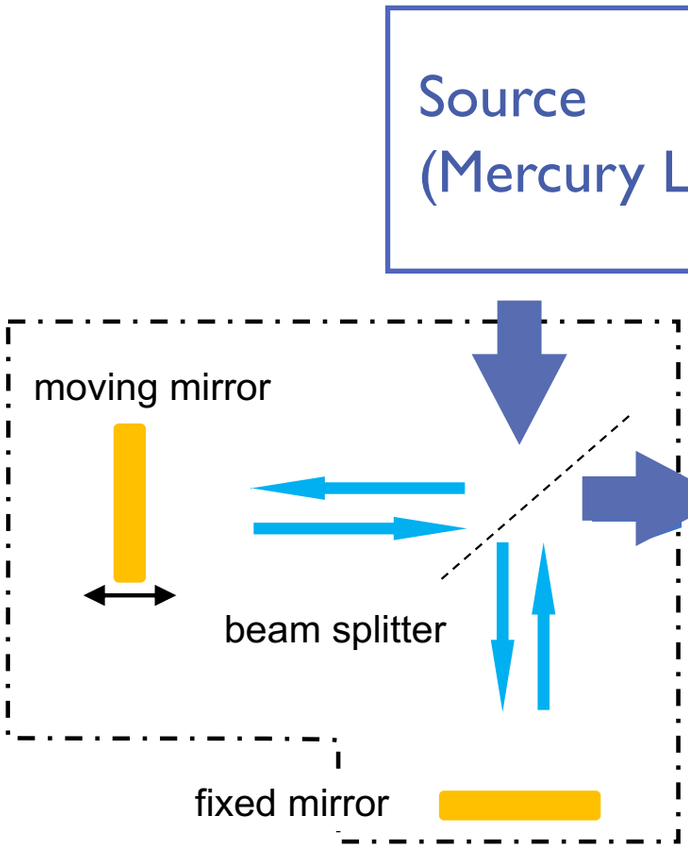
Lab Measurement

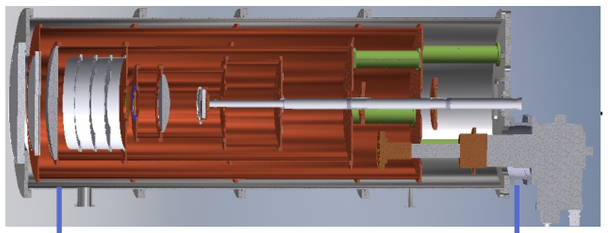
- Optical Measurement
  - Detector Yield
  - Frequency Response
  - Beam Patterns
- Camera Sensitivity
  - Optical Efficiency
  - Noise Equivalent Power

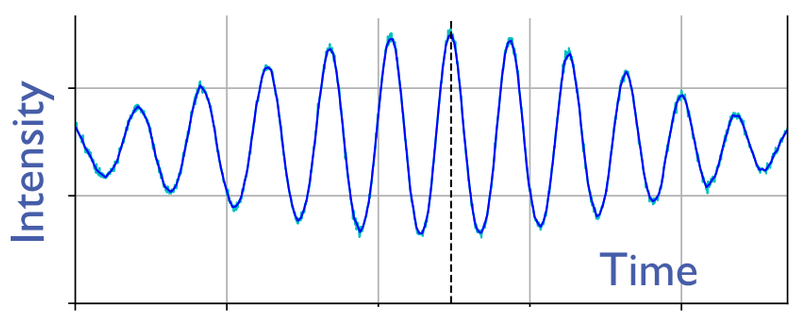
Measured with
Makoto Nagai (NAOJ), Yosuke Murayama (D3), Ryuji Suzuki,
Ryotaro Hikawa, Rikako Suzuki (M2) and many collaborators

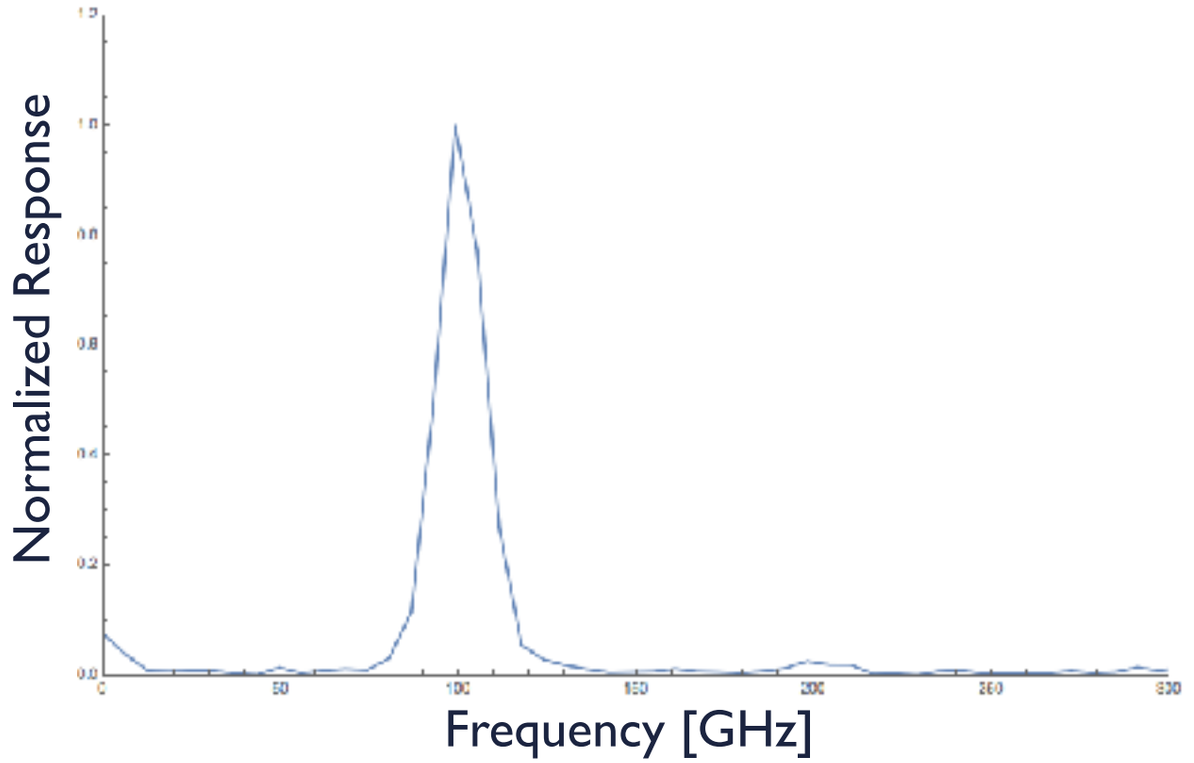
Frequency Band Characteristic

✳ Fourier Transform Spectrometer







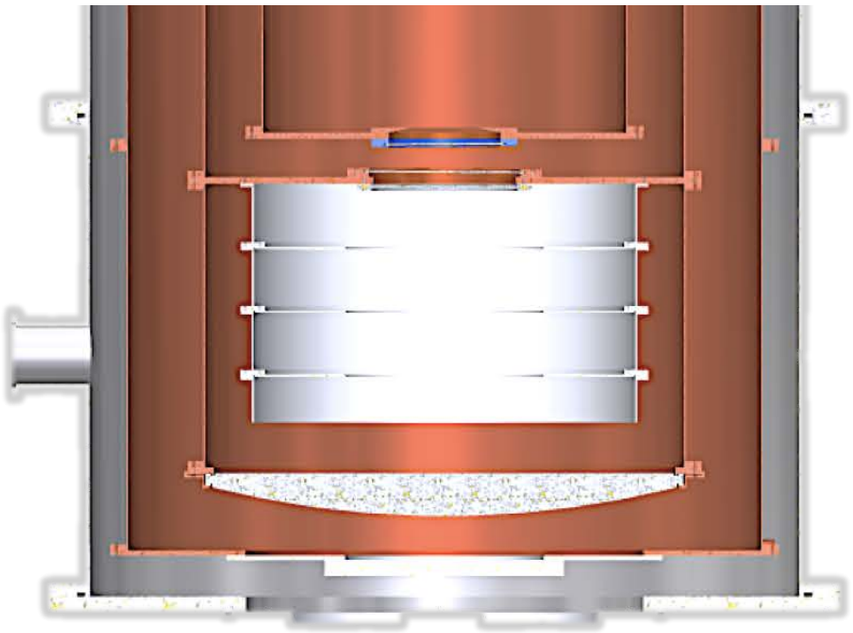


- The measured center frequency and bandwidth are 95 GHz and 16 GHz, respectively.
- This result is in good agreement with the expected response which is determined by the Al superconducting gap and the 120-GHz low-pass filter used in the cold optics.

Beam Characteristic

✳ Knife-Edge Measurement

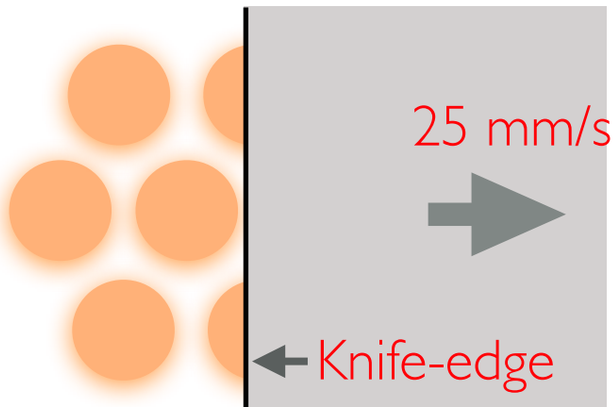
Arnaud et al., 1971



cross section

thin BB source (300 K)

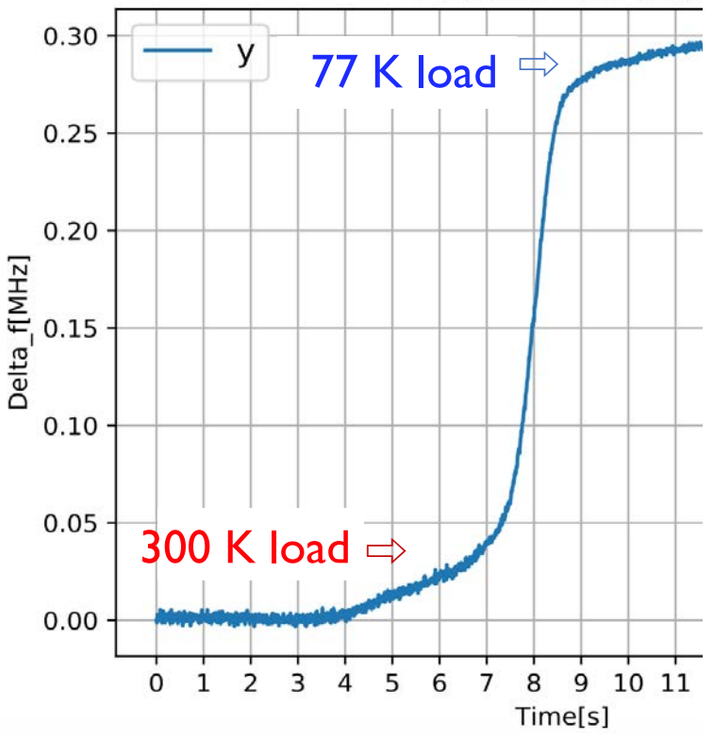
BB in Li-N_2 (77K)



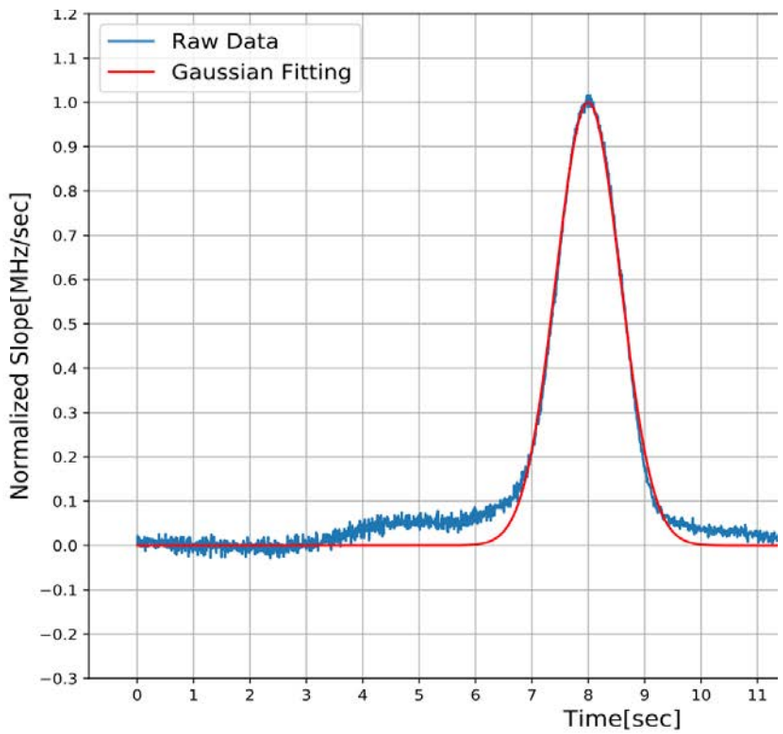
Top View

- Scan thin blackbody (BB) source at a constant speed
  - 300 K and Li-N_2 (77 K) BB sources were used to obtain the optical response
- Differential responses correspond to the beam shapes
  - Beam map (shape and position) can be obtained

< Raw Data >



< Differential Response>



- Beam waist size at the camera focal plane is almost the same as the simulation.

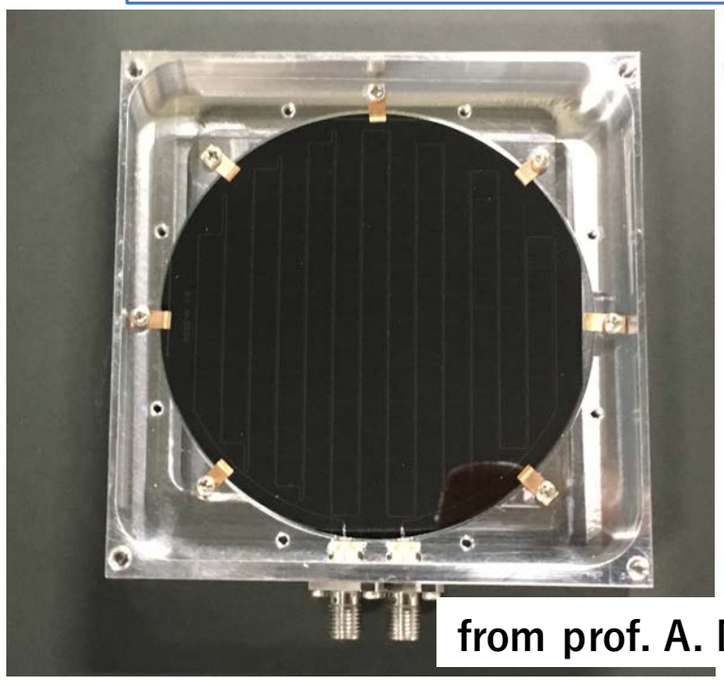
Future Plan

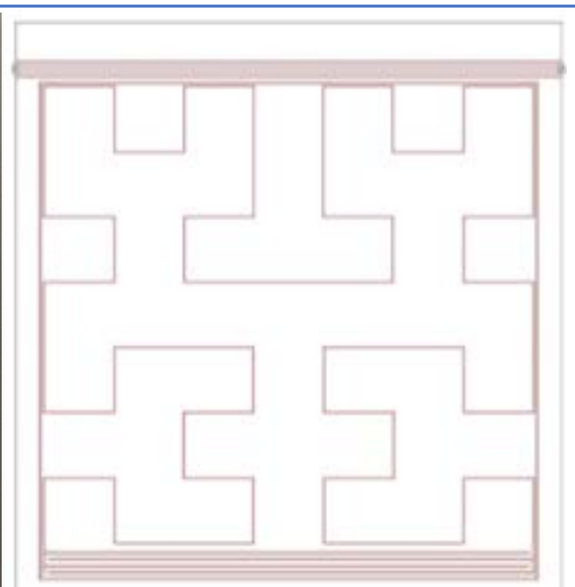
LeKID Array

✳ Lumped Element Kinetic Inductance Detector (LeKID)

- Collaboration with Université Grenoble Alpes

LeKID（developed by French NIKA2 group）





from prof. A. Monfordini and prof. J. Macias-Perez

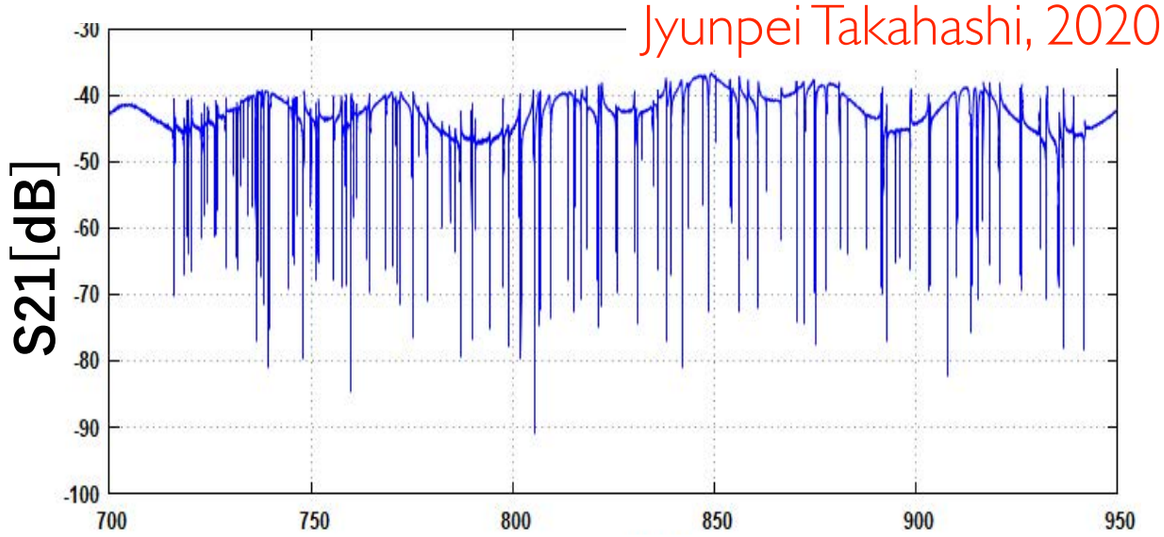
❖ This array was developed by NIKA2 camera group

NIKA2 : Adam et al., A&A 609, A115, 2018

❖ 144 pixel array

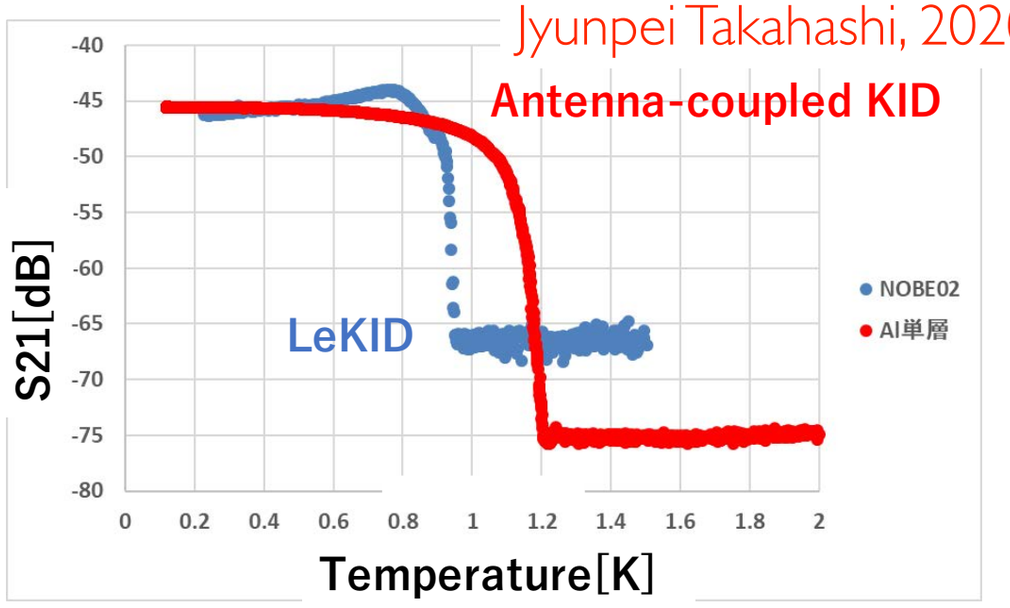
❖ bi-layer (Ti and Al) for changing Tc and tuning the observation band

Jyunpei Takahashi, 2020



- 138 / 144 pixels : high yield

Jyunpei Takahashi, 2020



Summary

✳ Scientific Motivation

- distant galaxy survey
  - wide-field survey is important to detect the unknown galaxies

✳ MKID Camera for the Nobeyama 45-m Telescope

- MKID is the superconducting resonator operated in the microwave range
- Camera development
  - 109 pixel array using lens-antenna coupled NbTiN-Al MKIDs
  - Results of beam pattern, yield and frequency response are as expected.
  - This camera will be installed on the Nobeyama 45-m telescope in this Oct.
    - improvement of the multi-pixel readout system is needed

✳ Future Development

- Collaboration with Université Grenoble Alpes (LeKID development)
- ~ 20000 pixel camera is designed for the Antarctica 10 m telescope