Development of 109-pixel NbTiN/Al Hybrid MKID for 100-GHz band continuum observations

University of Tsukuba / NAOJ

Yosuke Murayama

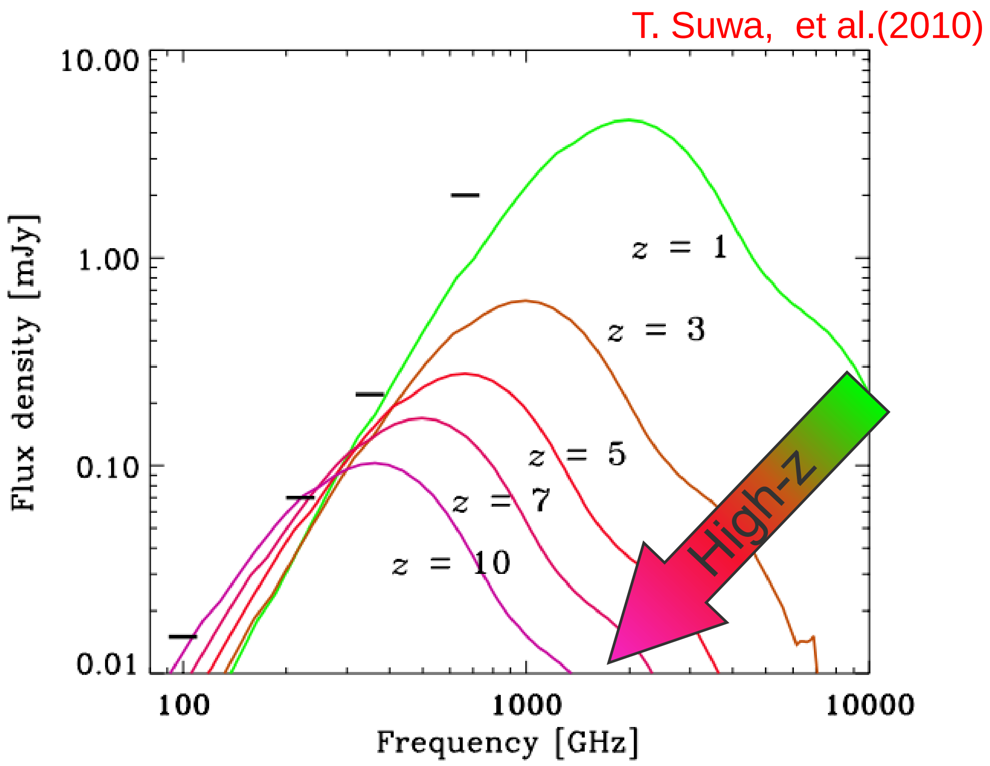
on behalf of the MKID Camera Team

3th June, 2019

Outline

1. Background, Scientific motivation
2. 100-GHz band MKID camera
3. Commissioning with the Nobeyama 45-m telescope
4. Development NbTiN/Al Hybrid MKID

1.1 Survey of Distant Galaxies



SED model of dusty galaxy: Dust temperature 42K, “Arp220-like” infrared galaxy (*Color:* difference of the redshift z)

Motivation

- To understand the star-formation history and the evolution of galaxies

Dust emission from distant galaxies

- Dust (particle size <1um) in distant galaxies radiates luminous in the infrared band.
- We could observe the emission in mm/submm/THz band as the results of **redshift**.

Multiband observation (100 GHz + submm, IR)

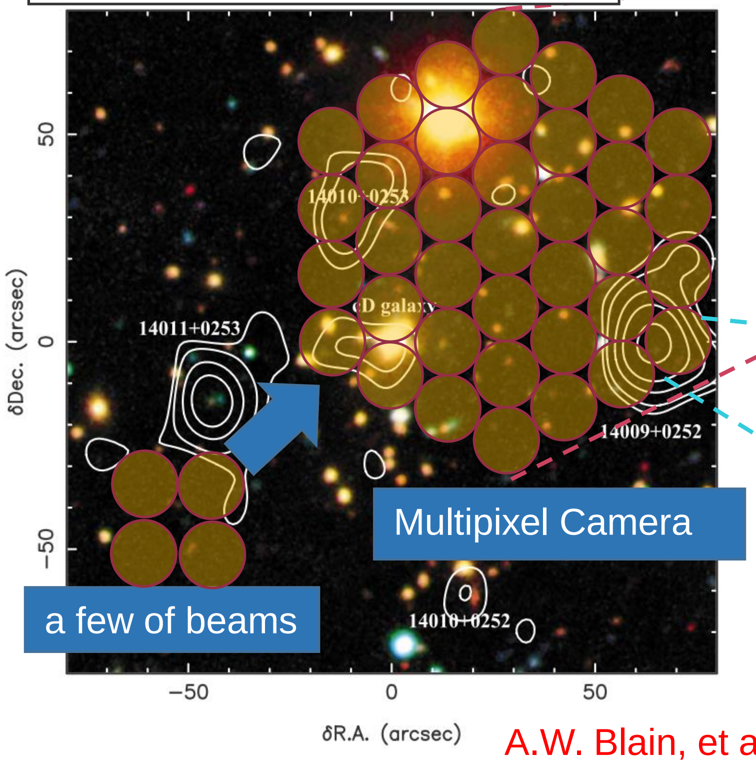
- We can obtain the photometric redshift (photo-z), luminosity, temperature and star-formation rate (SFR) of the distant galaxies.

1.2 Survey with single dish telescope + radio camera

Single dish telescope + radio camera

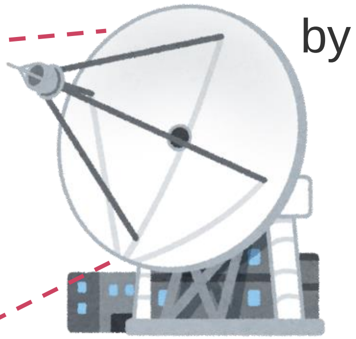
- Wide Field-of-View (FoV) single dish telescope and radio camera (hundreds ~ thousand pixels) are important to make distant galaxies survey efficiently.

color: optical
contour: submm (ν=350GHz)



A.W. Blain, et al.(2002)

Survey of distant galaxies by single dish + camera



High angular resolution observation by radio interferometer

1.3 Follow-up high-resolution observation

Follow-up observation by radio interferometer

- Radio interferometers, like ALMA, have ultra-high angular resolution.

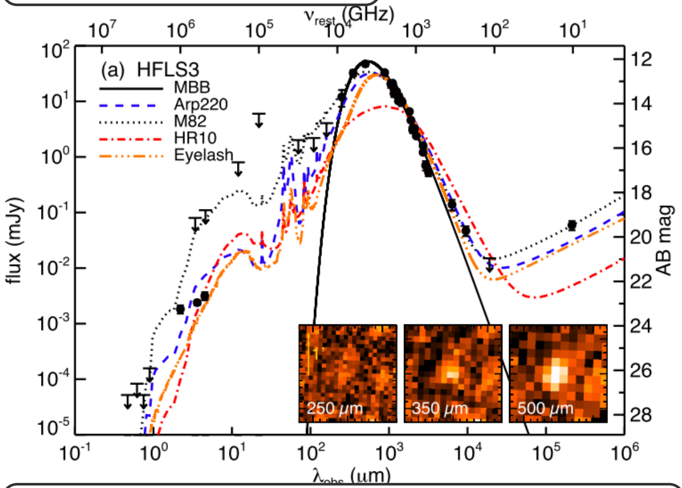
Increase the number of high-z objects detection with single dish + camera (=> determine photo-z)

High-resolution molecular line observation by ALMA (=> More accurate determination of redshift z than photo-z)

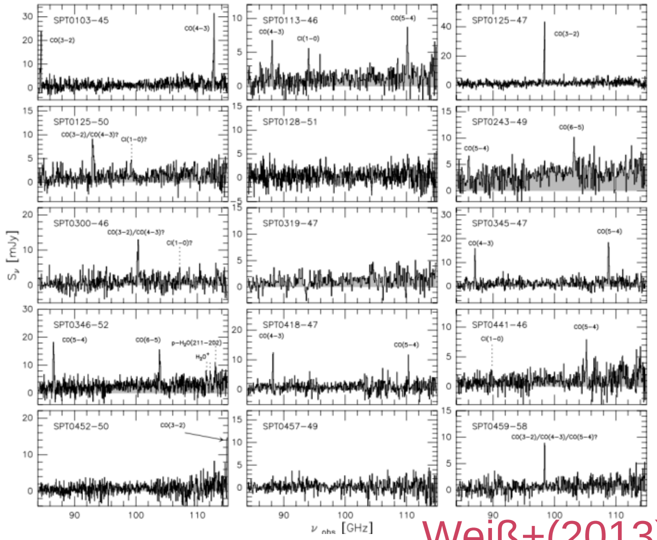
Statistically understand distribution, distance, SFR of galaxies

Identify photo-z

Riechers+(2013)

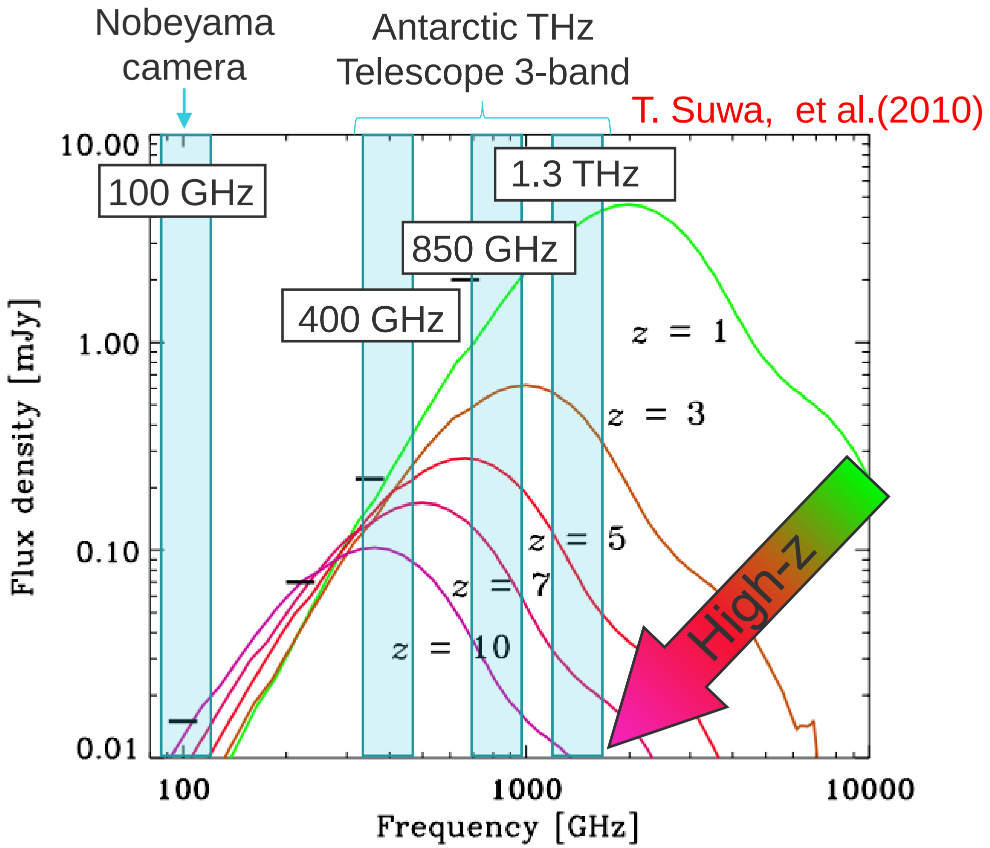


ALMA 100-GHz spectroscopy



Weiß+(2013)

1.4 mm/sub-mm/THz wavelength Camera Projects

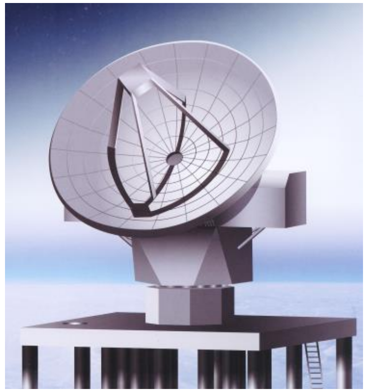


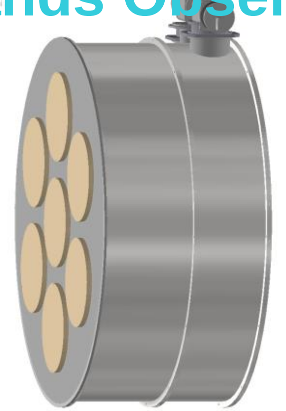
SED model of dusty galaxy: Dust temperature 42K, “Arp220-like” infrared galaxy (*Color:* difference of the redshift z)

100-GHz band Observation

- Nobeyama 45-m radio telescope
- 100-GHz band camera

400-GHz/850-Ghz/1.3-THz bands Observation





- Antarctic THz Telescope (10-m)
- 3-bands camera

2.1 100-GHz band MKID Camera

Nobeyama 45-m telescope + 100-GHz band MKID camera

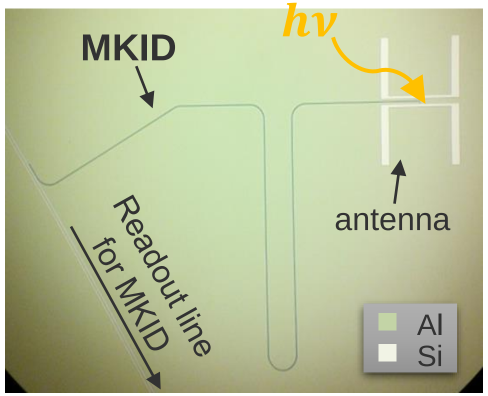
- Field-of-View (FoV) 3 arcmin. antenna & radio camera help us survey 100-GHz band

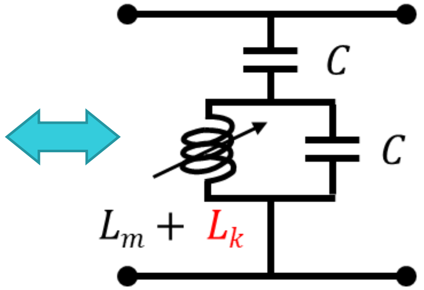
Specification of our camera

Continuum observation frequency	100-GHz band (85-120 GHz)
FoV	~ 3 arcmin.
Polarization	Linear & Single polarization
Detector	Microwave Kinetic Inductance Detector (**MKID**)
Cold optics	Refractive optics using Si lenses
Number of pixel	109 pixel
Operation temperature	< 200 mK

2.3 Microwave Kinetic Inductance Detector

Microwave Kinetic Inductance Detector (MKID) is one of the superconducting resonator (Day, et al.(2003))





Resonant frequency in microwave f_0:

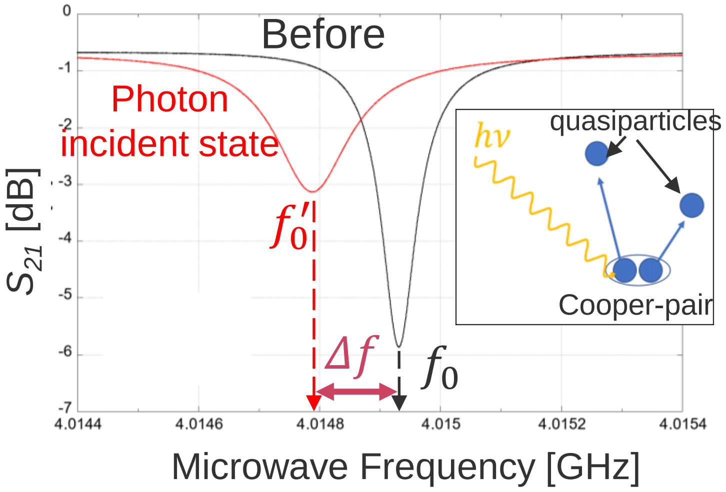
$$f_0 = \frac{1}{4l}\frac{1}{\sqrt{LC}} = \frac{1}{4l}\frac{1}{\sqrt{(L_m+L_k)C}}$$

l: Length of resonator, C: Capacitance, L_m: Magnetic inductance,
L_k: Kinetic inductance (depends on the density of Cooper-pairs)

Incident photons ($h\nu > 2\Delta$; Higher than superconducting gap energy) break the Cooper-pairs in the MKID

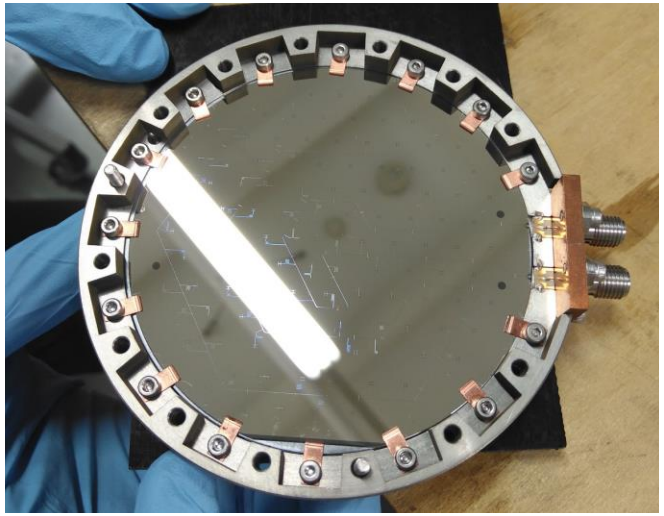
$\Rightarrow$ Change in kinetic inductance L_k

$\Rightarrow$ Change in resonance frequency shift Δf

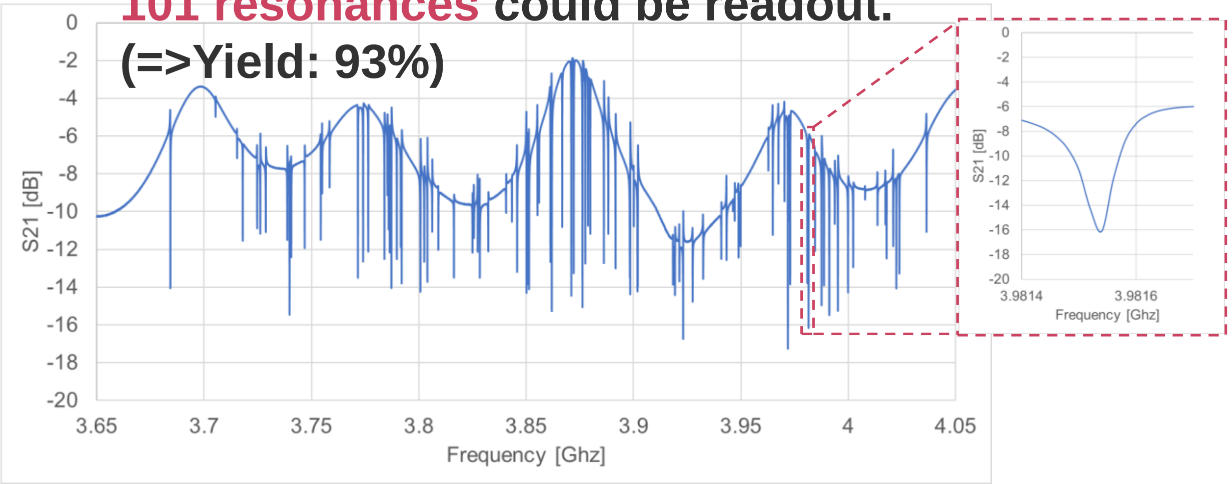


2.4 Status of 109-pixel MKIDs device in dark

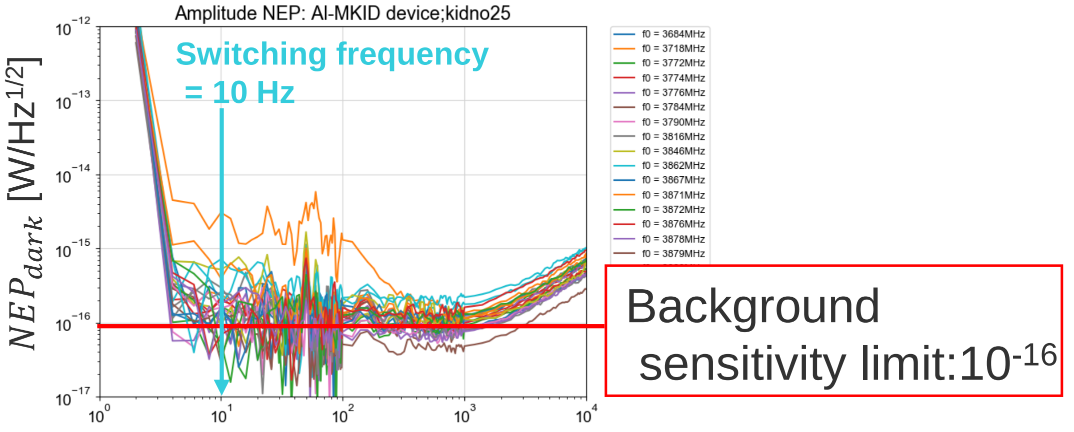
Item Name	Device data
Superconducting film (thickness) / deposition	Al (~150 nm) / e-beam evaporator
3-inch wafer	Si wafer (>10 kΩ·cm)
Quality factor	6×10^4 (median of 82-MKIDs)
Quasiparticle lifetime [μs]	120 (averaged 5-MKIDs)
Amplitude NEP_{dark} @10Hz [W / Hz$^{1/2}$]	3.2×10^{-16} (averaged 25-MKIDs)
Phase NEP_{dark} @10Hz [W / Hz$^{1/2}$]	1.8×10^{-16} (averaged 25-MKIDs)



101 resonances could be readout. (=>Yield: 93%)

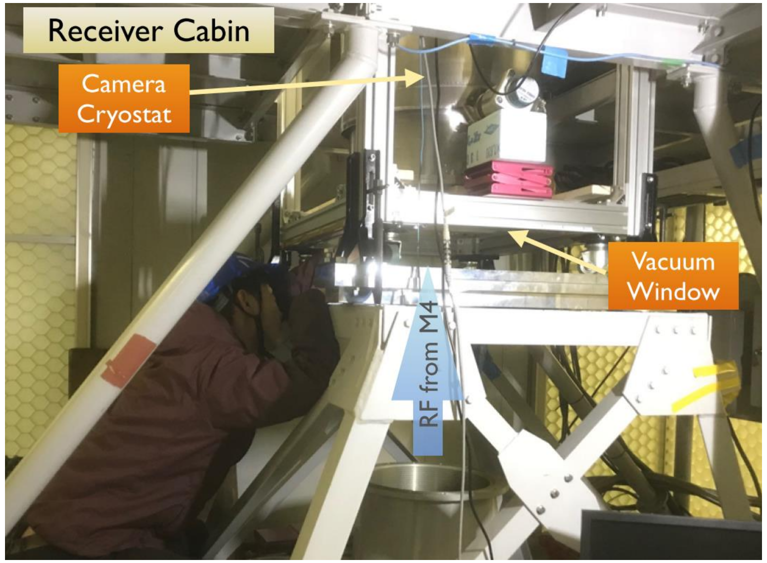


Sensitivity: Noise Equivalent Power *NEP* [W/Hz$^{1/2}$]



3.1 Camera Installation to the telescope

Carry in Nobeyama 45-m telescope



Inside the telescope (Receiver cabin)

On-sky observations: 18th May 2018 ~ 1st June 2018

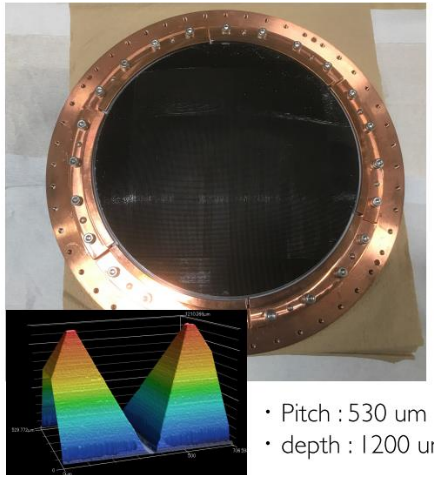
- Scan type: raster-scan observation (2x2 ,3x3,4x4 arcmin^2)
- Objects: the planets (Jupiter, Venus and Mars), galaxy, QSO

=> We obtained the beam pattern, sensitivity and efficiency measurements

Current Problems

- **[Optics] Low transmittance: τ ~ 34%**
  - The reflection loss is about 30% on the surface of silicon
    => Anti-reflection coating/structure is needed
- **[Detector] Higher NEP_{dark}**
  - NEP_{dark} (Goal): $10^{-17}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$
  - $NEP_{dark,\ Amp}$@10Hz: $3.2 \times 10^{-16}\mathrm{W}/\sqrt{\mathrm{Hz}}$
- **[Detector] Low optical efficiency: η_{opt} ~ 3%**
  - NEP_{opt}(Goal): $< 10^{-16}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$: limited by the atmosphere
  - NEP_{opt}@10Hz: $\sim 10^{-15}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$
  - $\boldsymbol{NEP_{opt} = \sqrt{\underbrace{NEP^2_{det}}_{\propto NEP^2_{dark}} + \left(NEP^2_{photon} + NEP^2_{g-r}\right)/(\tau\eta_{opt})}}$

Subwavelength structure on silicon lens



・Pitch : 530 um
・depth : 1200 um

4.1 NEP_{dark} Calculation

	Requirement	Measurement (device installed NRO45m)
Dark NEP [$\mathrm{W\,Hz^{-1/2}}$]	$\sim 10^{-17}$	3.2×10^{-16} (Averaged 25 kids)@10 Hz
Optical NEP [$\mathrm{W\,Hz^{-1/2}}$]	$\leq 10^{-16}$	$\sim 10^{-15}$

$$NEP^2_{dark,\,A} = S_A(\omega)\left[\frac{\eta\tau_{qp}}{\Delta}\frac{\delta A}{\delta N_{qp}}\right]^{-2}(1+\omega^2\tau_{qp}^2)(1+\omega^2\tau_r^2)$$

Baselmans+2008

η: efficiency of quasiparticle creation ~ 0.57, Δ: superconducting gap energy, ω: noise frequency, τ_r: resonator ring time

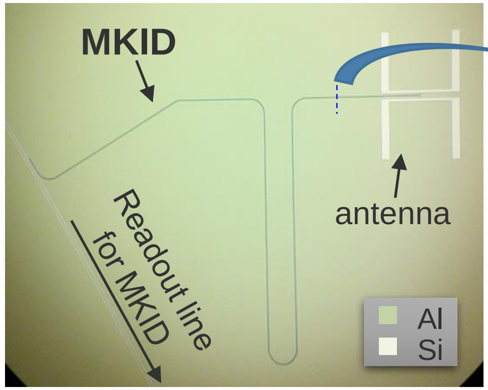
Important Parameters

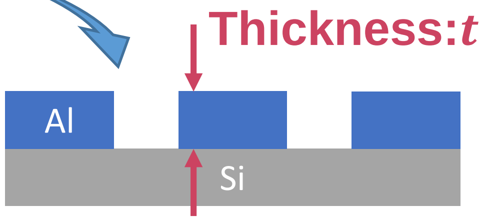
- S_A [1/Hz]: Noise spectrum density in Amplitude readout
- $\frac{\delta A}{\delta N_{qp}} \propto \frac{Q}{V}$: **Responsivity** of MKID in Amplitude readout
  (Q: Q-factor, V: Volume of the resonator)
- τ_{qp} [sec.]: Lifetime of quasiparticles

4.2 Improvement of Responsivity

- **Reduce resonator volume V**

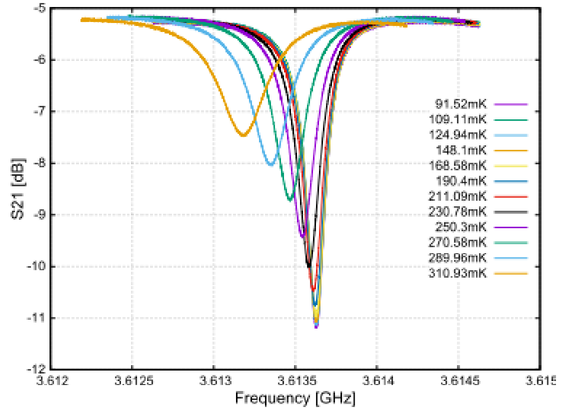
$$\frac{\delta A}{\delta N_{qp}} \propto \frac{\delta f}{\delta N_{qp}} \propto \frac{Q}{V}:$$ **Responsivity** of MKID

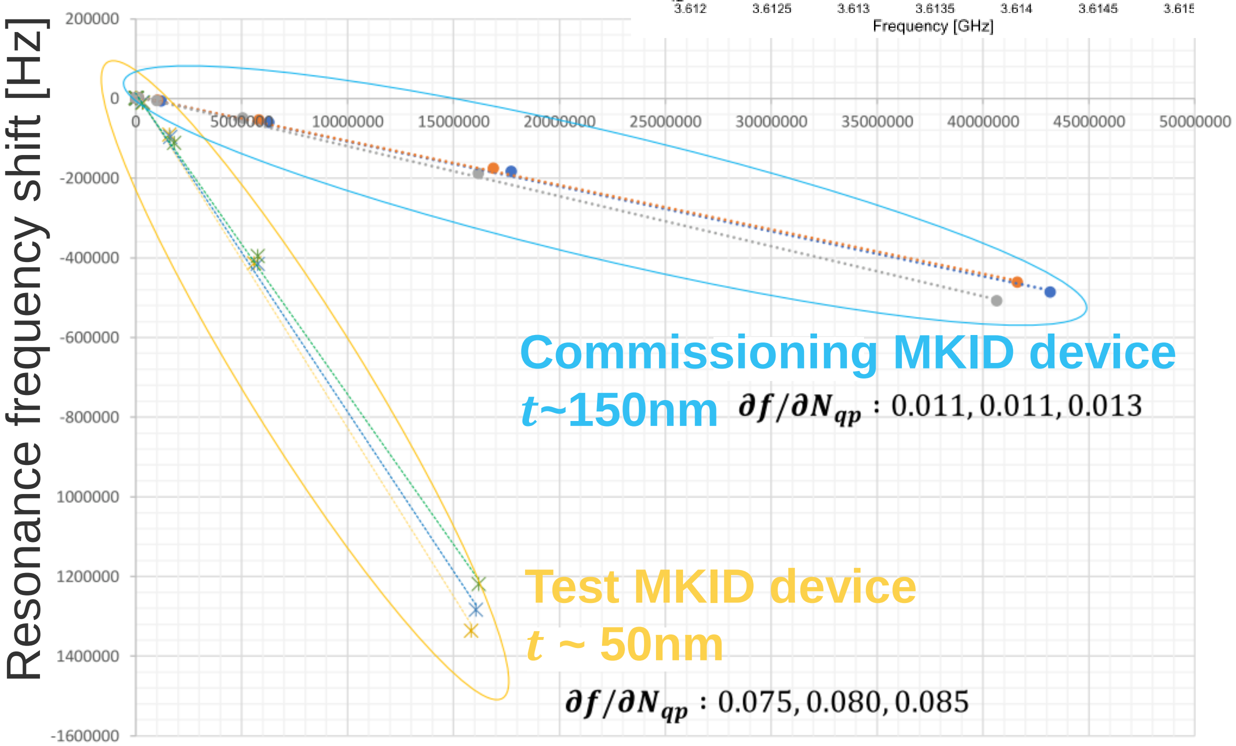




Cross-section of a MKID

MKID Device	Al thickness [nm]	Responsivity $\delta f/\delta N_{qp}$ [Hz]
Commissioning device	150	~ 0.011
Test thinner Al device	50	~ 0.080





Nqp []: Number of quasiparticle

4.3 NbTiN/Al Hybrid MKID

Quasi-particles are created around the antenna because the both CPW central line and GND plane are made of Al.

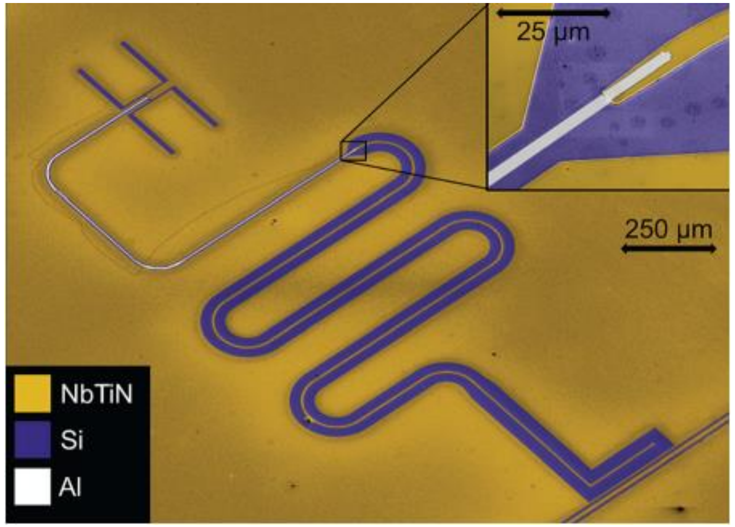
But by using NbTiN/Al hybrid MKID, the radiation (90 GHz < f < 120 GHz) will be absorbed ***only*** in the Al central line.

S. J. C. Yates+2011,
R. M. J. Janssen+2013

- NbTiN (for GND plane) gap energy: ~1.1 THz
- Al (for resonators' CPW center line): ~90 GHz

R. M. J. Janssen+2013

NbTiN/Al hybrid can improve optical efficiency η_{opt}.



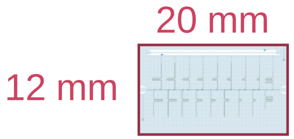
4.4 Development NbTiN/Al MKID

[Step 1] **Test hybrid MKID device (chip size 20cm x 12cm)**

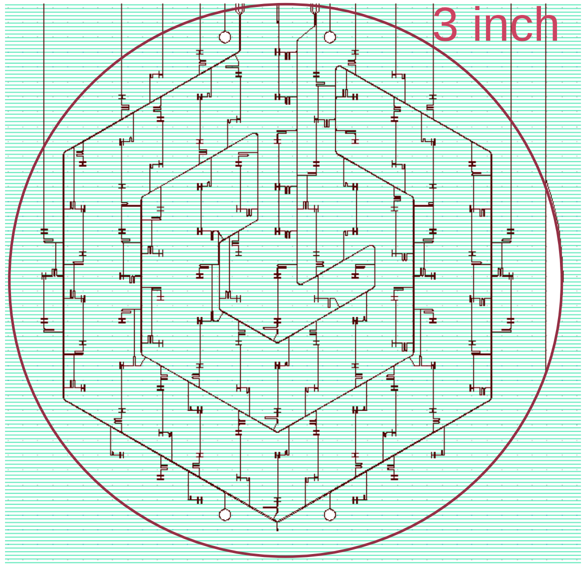
* Check fabrication parameters and the NbTiN/Al contact region

[Step 2] **109-pixel hybrid MKID device (3-inch wafer)**

*For Nobeyama 45-m radio telescope camera



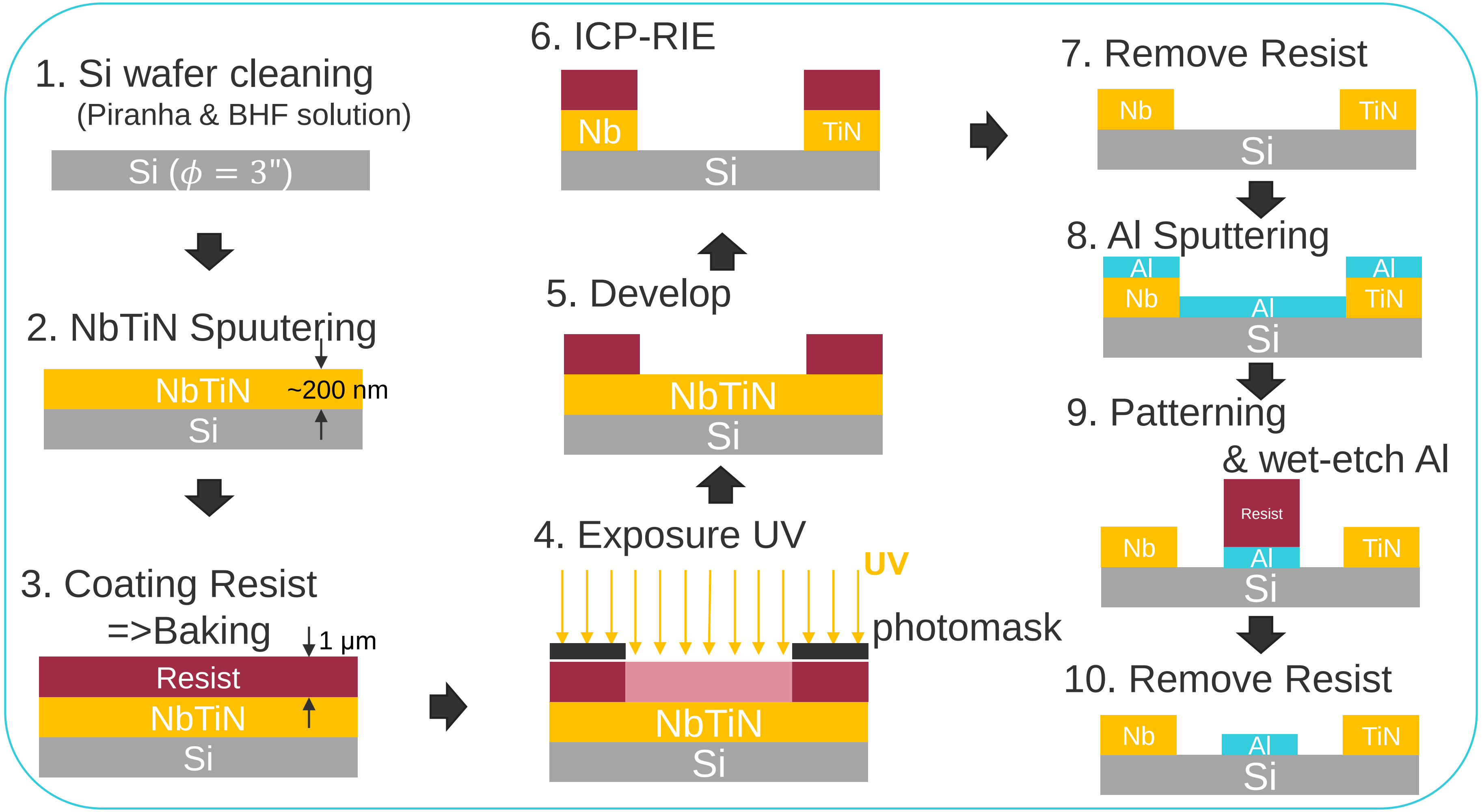
Test hybrid device
18-kids

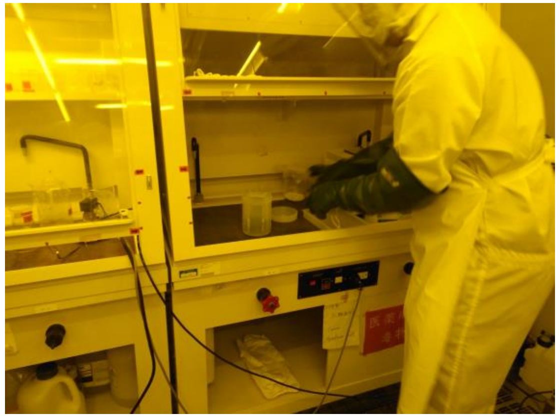


109-pixel hybrid device

4.5 Fabrication Flow

Our MKID have been developing in the Advanced Technology Center, National Astronomical Observatory in Japan, Mitaka.



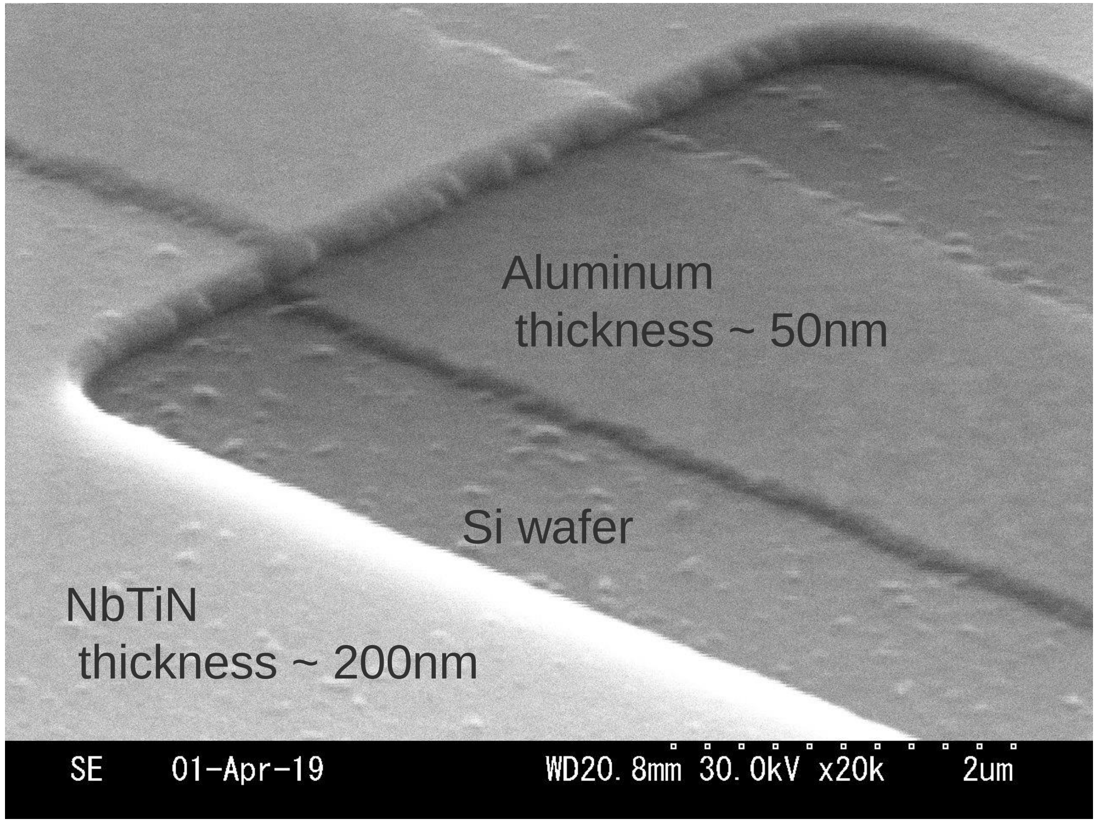


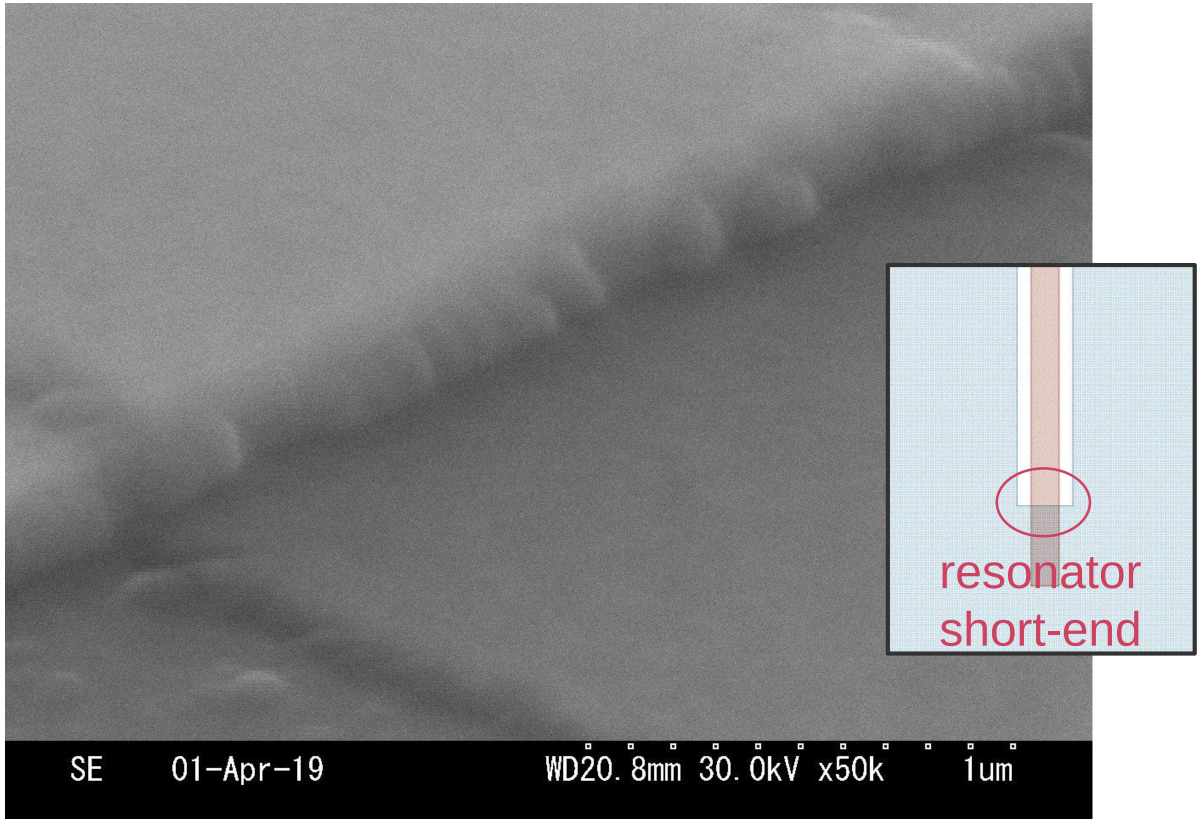
- Wafer: 3-inch Si, 10 kΩcm, FZ, non-doped
- Al film: AJA
- NbTiN film: CS-200ET (Tc~13K, ρ~160 $\mu\Omega$cm)

- Exposure: Aligner
- Etching: Wet etch for Al
  ICP-RIE for NbTiN

4.7 SEM image: NbTiN/Al contact region

- Taper: Good
- Al short-end seems to connect NbTiN GND plane.





Summary

Summary

- To understand the evolution process of the galaxies,
  we have been developing 100-GHz band camera for the NRO45m telescope.
- In the commissioning during 2018.05 - 2018.06, we observed the planets, galaxy, QSO.

Future development

- Measurement optical efficiency of Hybrid MKID
- Improvement of the pattering process to increase detector yield of Hybrid MKIDs

Acknowledgement

We would like to thank the Nobeyama Radio Observatory staff for their support.