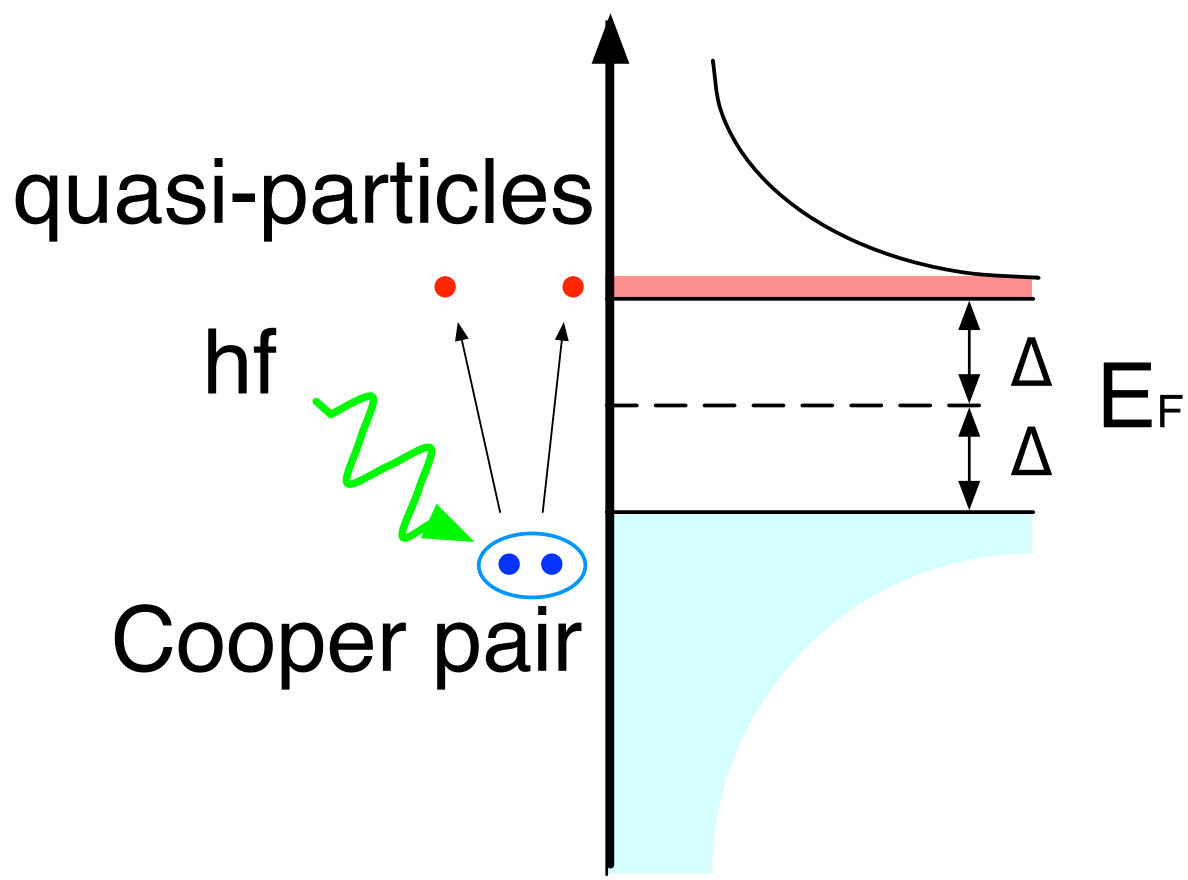
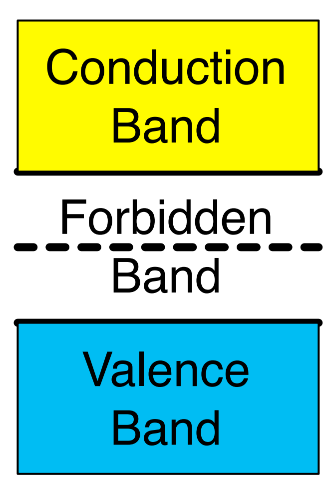
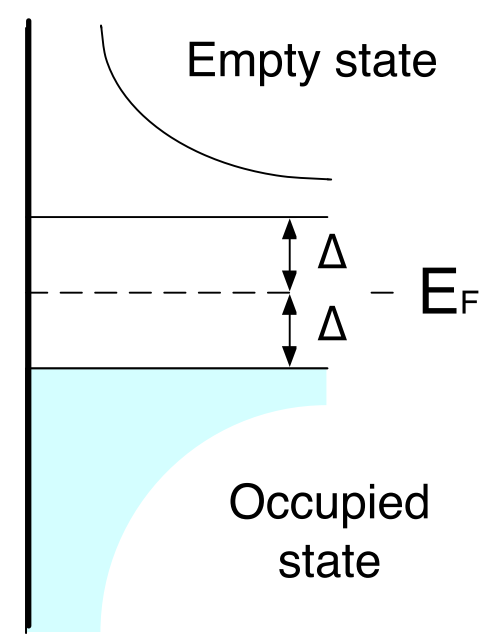
可視赤外線の超伝導検出器の紹介



国立天文台
先端技術センター
関本裕太郎

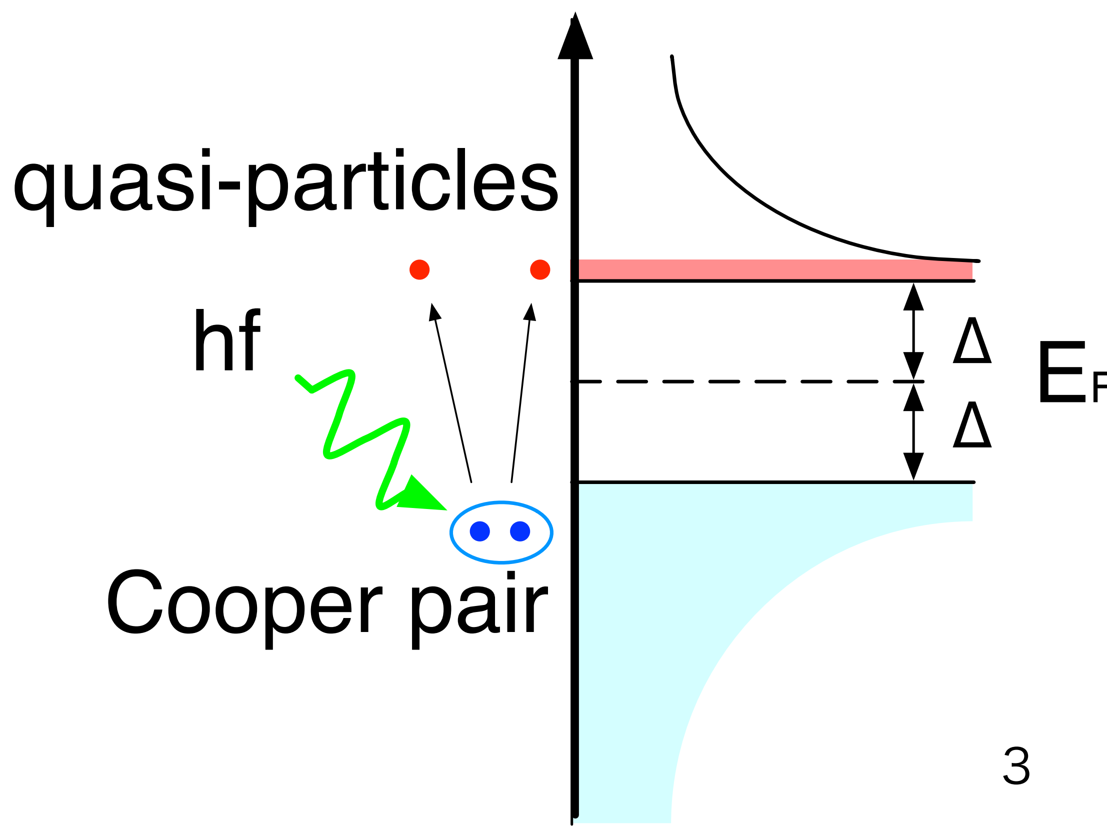
	半導体	超伝導
Bandgap	~ eV	~ meV
運用温度	20 ~ 100 K	100 mK ~ 4 K
時間分解能	~ msec	~ μsec





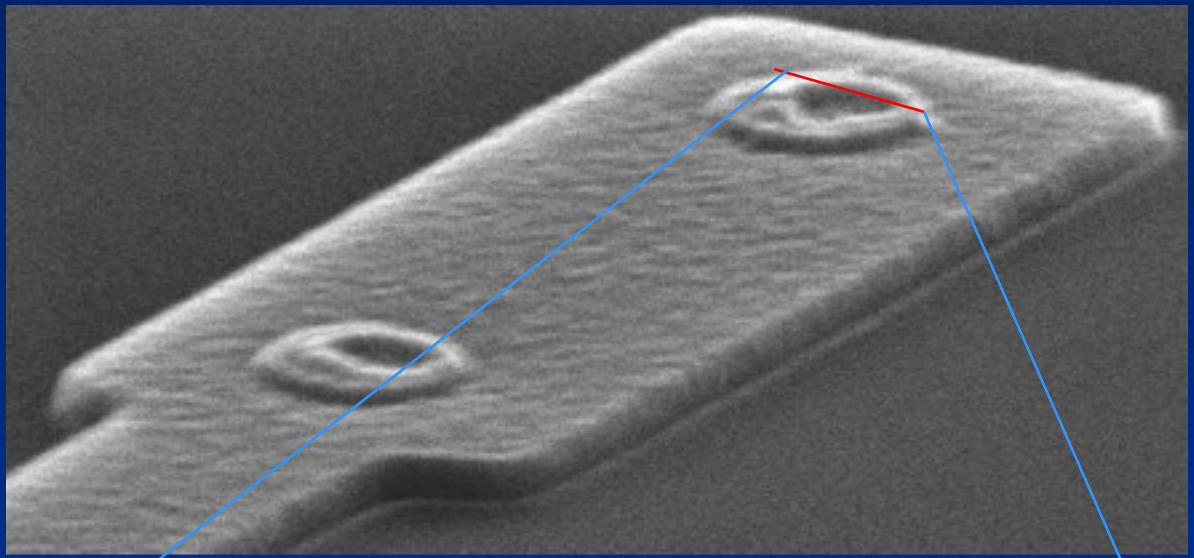
超伝導Cooper pair-breaking検出器

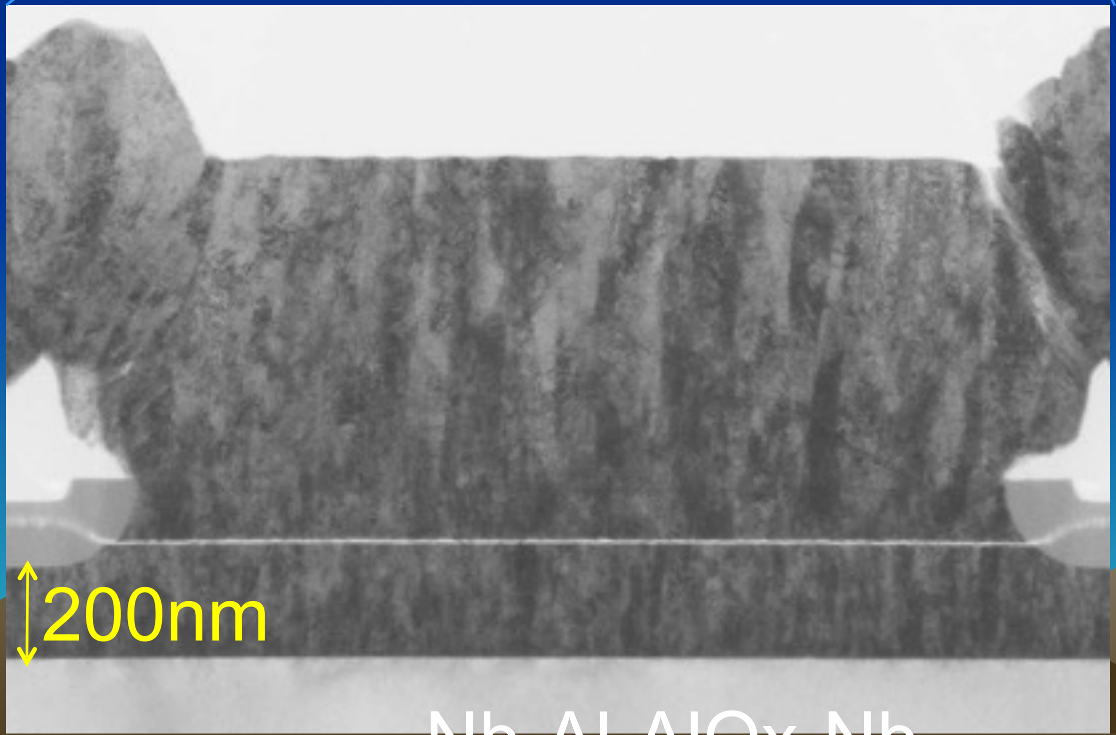
- SIS : Superconductor - Insulator - Superconductor
- STJ : Superconductive Tunnelling Junction
    - SIS = STJ 準粒子生成によって生じる電流を読み出す。
- MKID : Microwave Kinetic Inductance Detector
    - 準粒子生成によって生じるインダクタンスの変化を読み出す。
- TES : Transition Edge Sensorは、温度を計測するbolometer



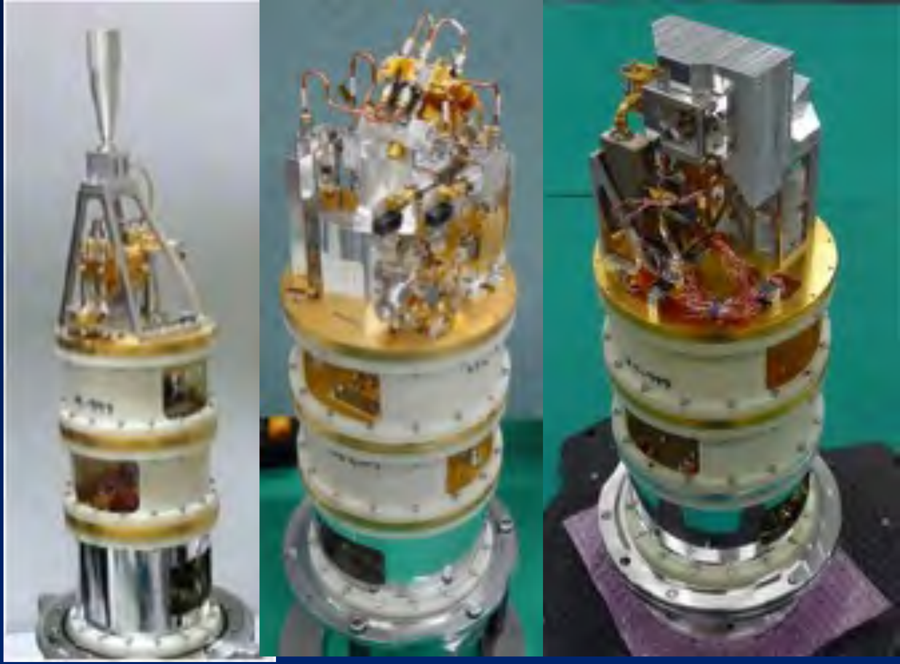
SIS mixer

T. Tamura et al. 2014 IEEE AS

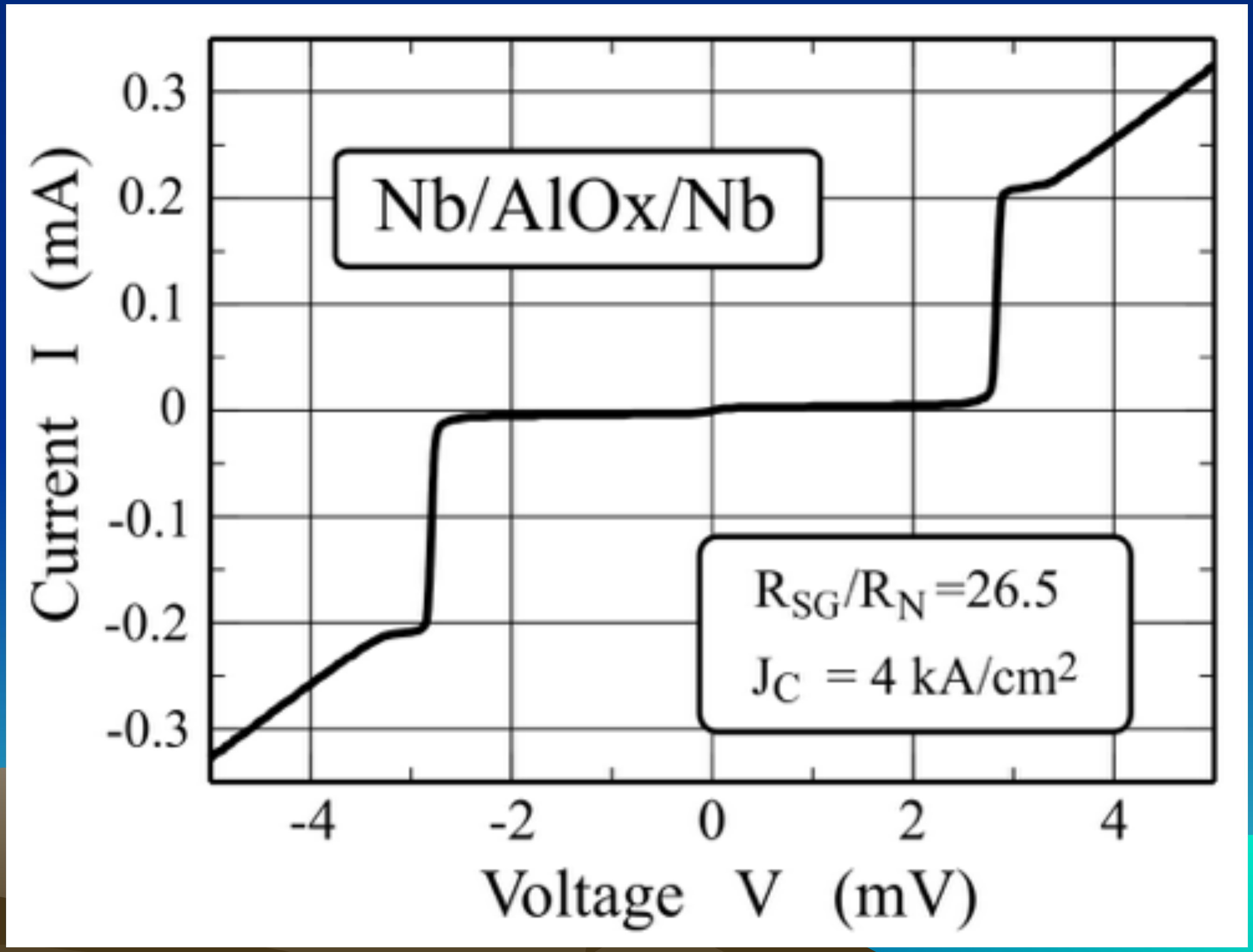




Nb-Al-AlOx-Nb



ALMA Band 4 (125 – 163 GHz)
ALMA Band 8 (385 – 500 GHz)
ALMA Band 10 (787 – 950 GHz)

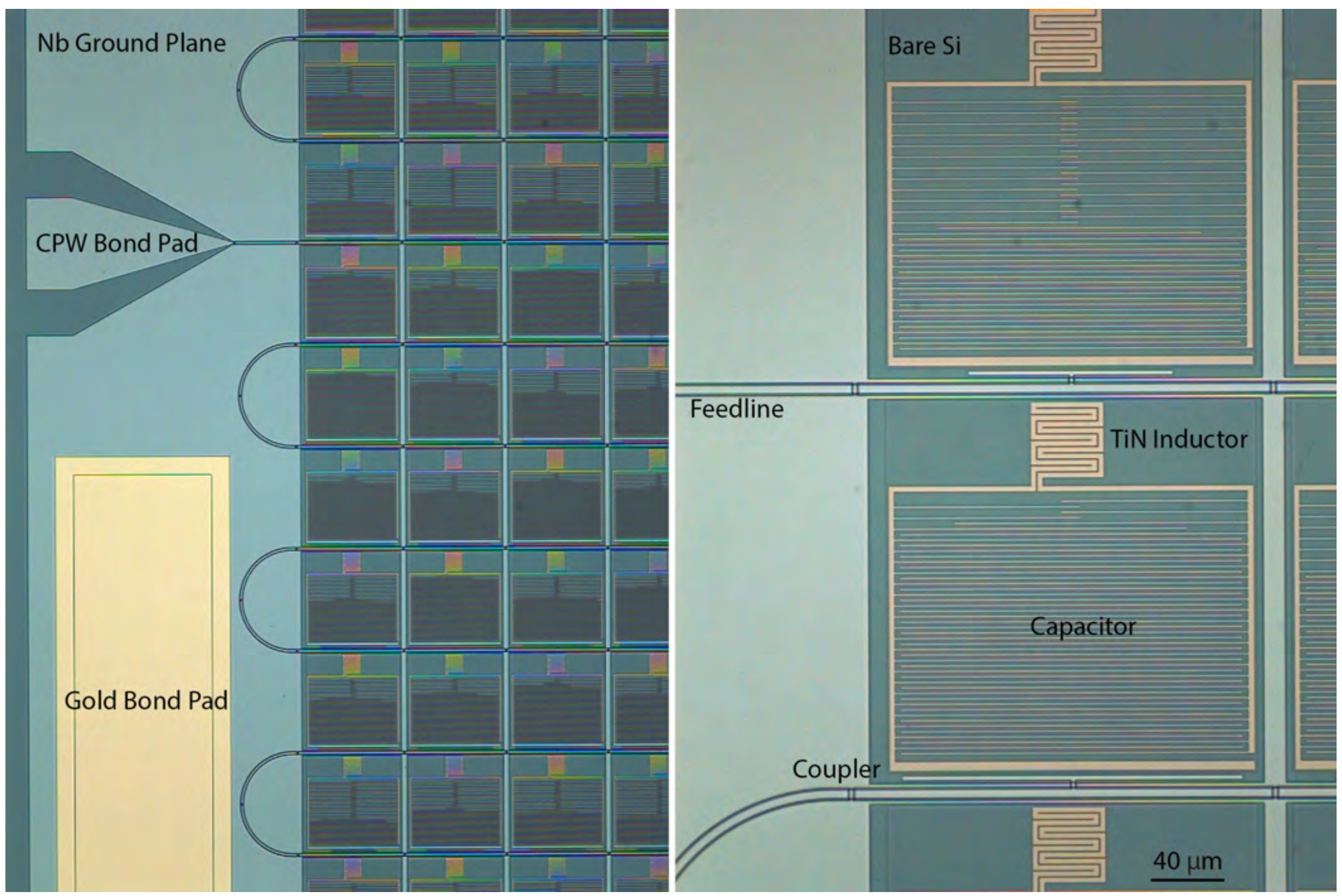


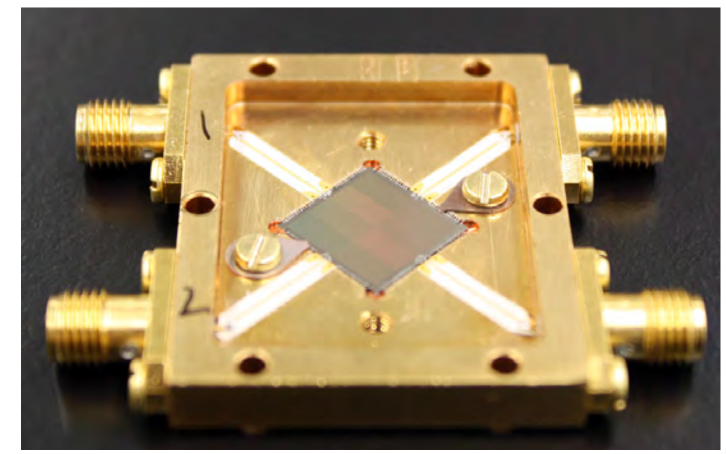
近赤外線超伝導検出器

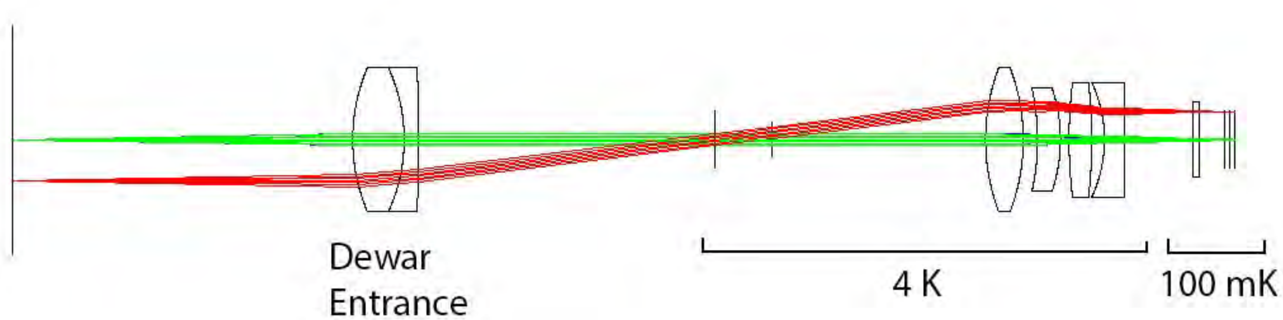
- Band gapが小さい 2Δ ~ 1 meV
    - 分光が可能
- 配線層 = 超伝導線路
    - 量子効率を高くできる
- 大面積・多ピクセルは難しい

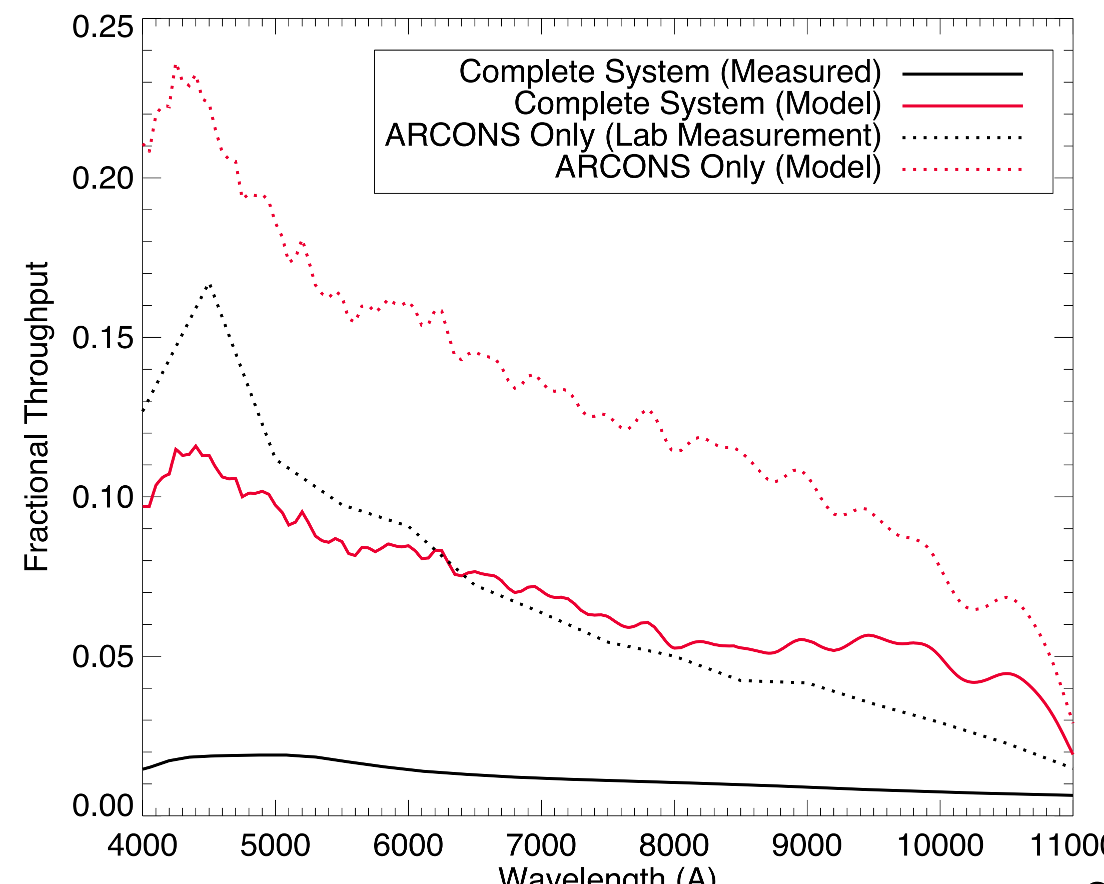
ARCONS: B. Mazin + 2013 PASP 125, 12

A microlens focuses the light on to the 40×40 µm inductor. The MKIDs in ARCONS absorb light directly in theTiN film that comprises the inductor. This TiN has an intrinsic absorption of roughly 70% at 400 nm, and 30% at 1 μm. 2024 (44×46) pixel array. Tc is about 800 mK. The surface inductance is a high 25 pH/square. 222×222 μm square. The quasiparticle lifetime in our TiN films is 50–100 μs. a maximum count rate of approximately 2500 cts/pixel/second.

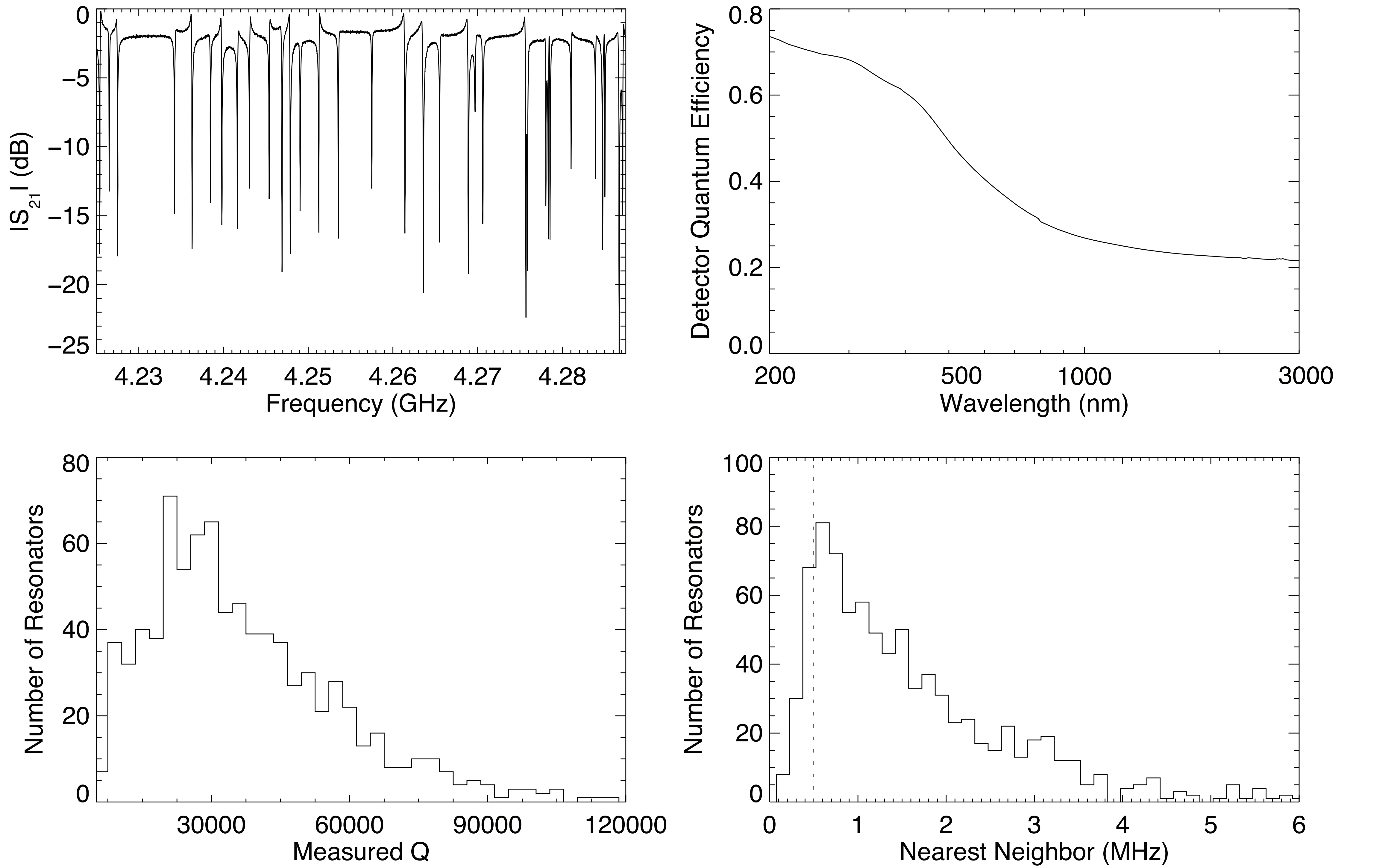




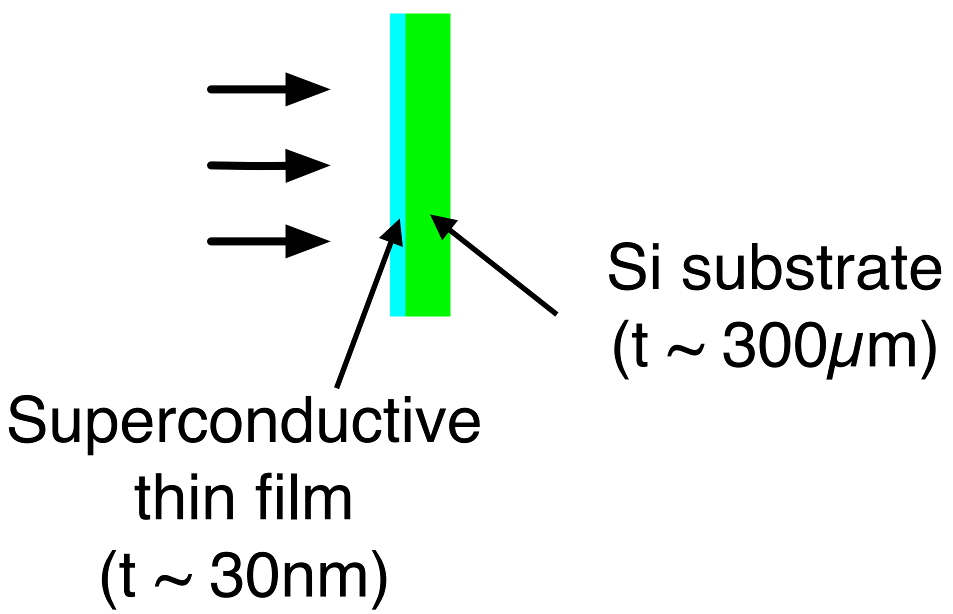


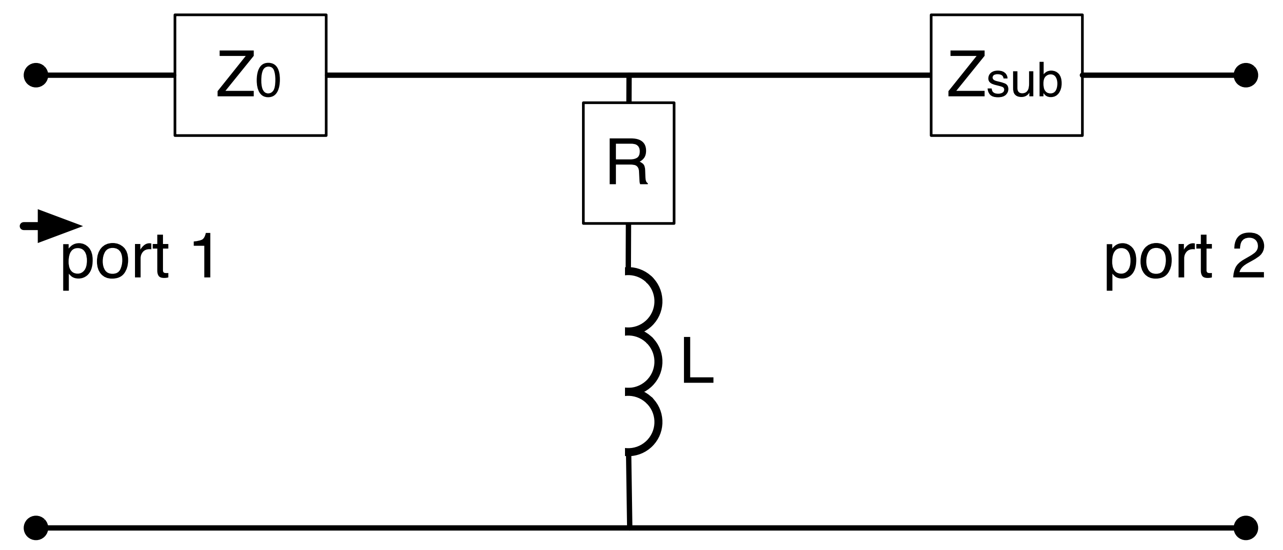


B. Mazin + 2012 Optics Express

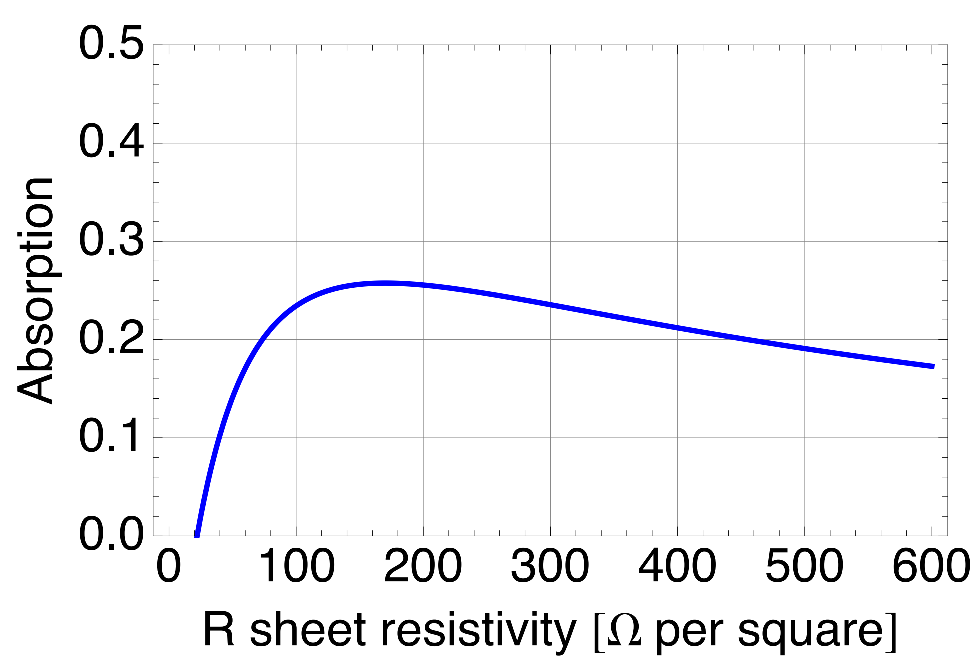


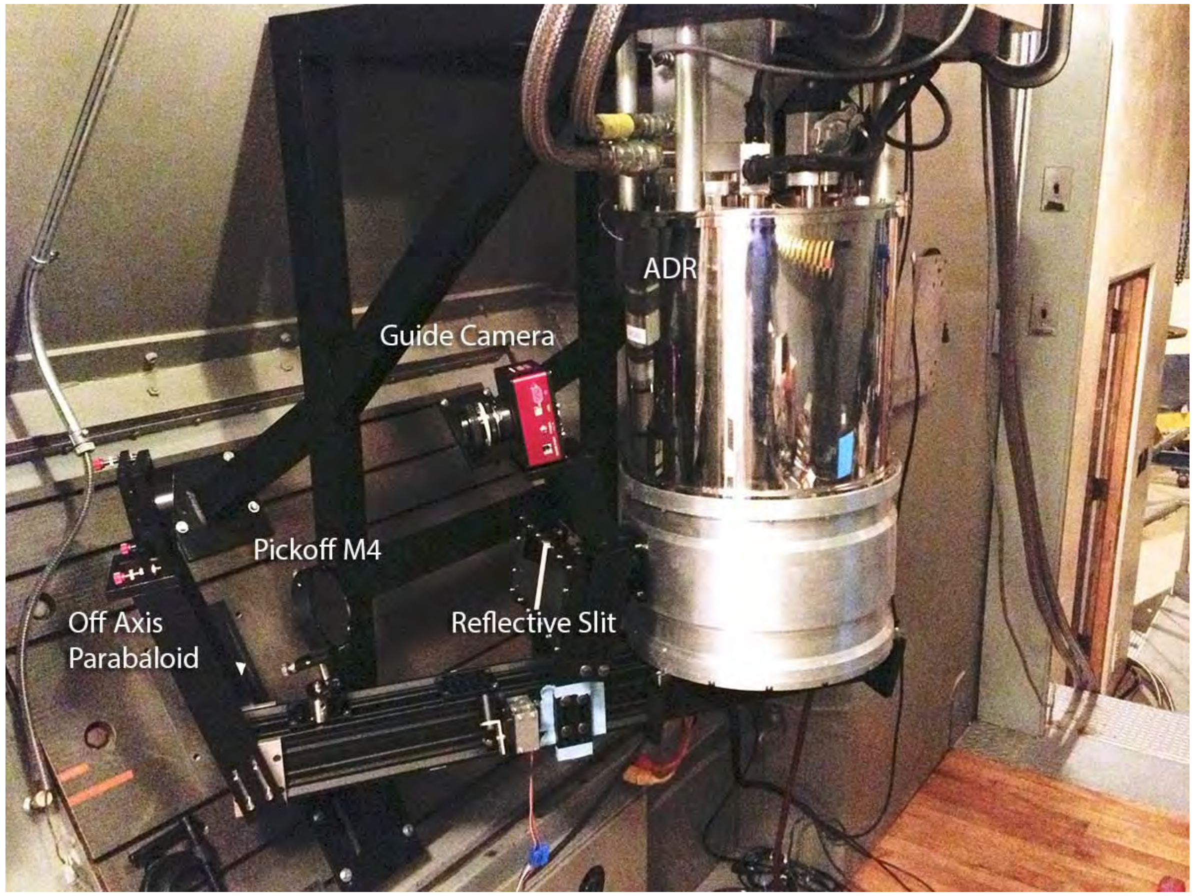
Optical Coupling



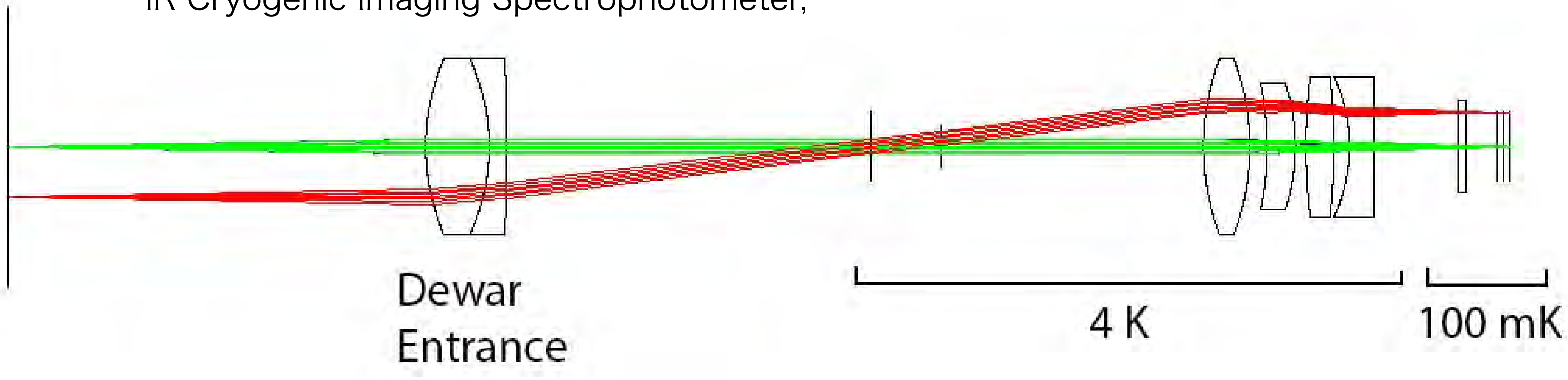


λ = 1.5 μm



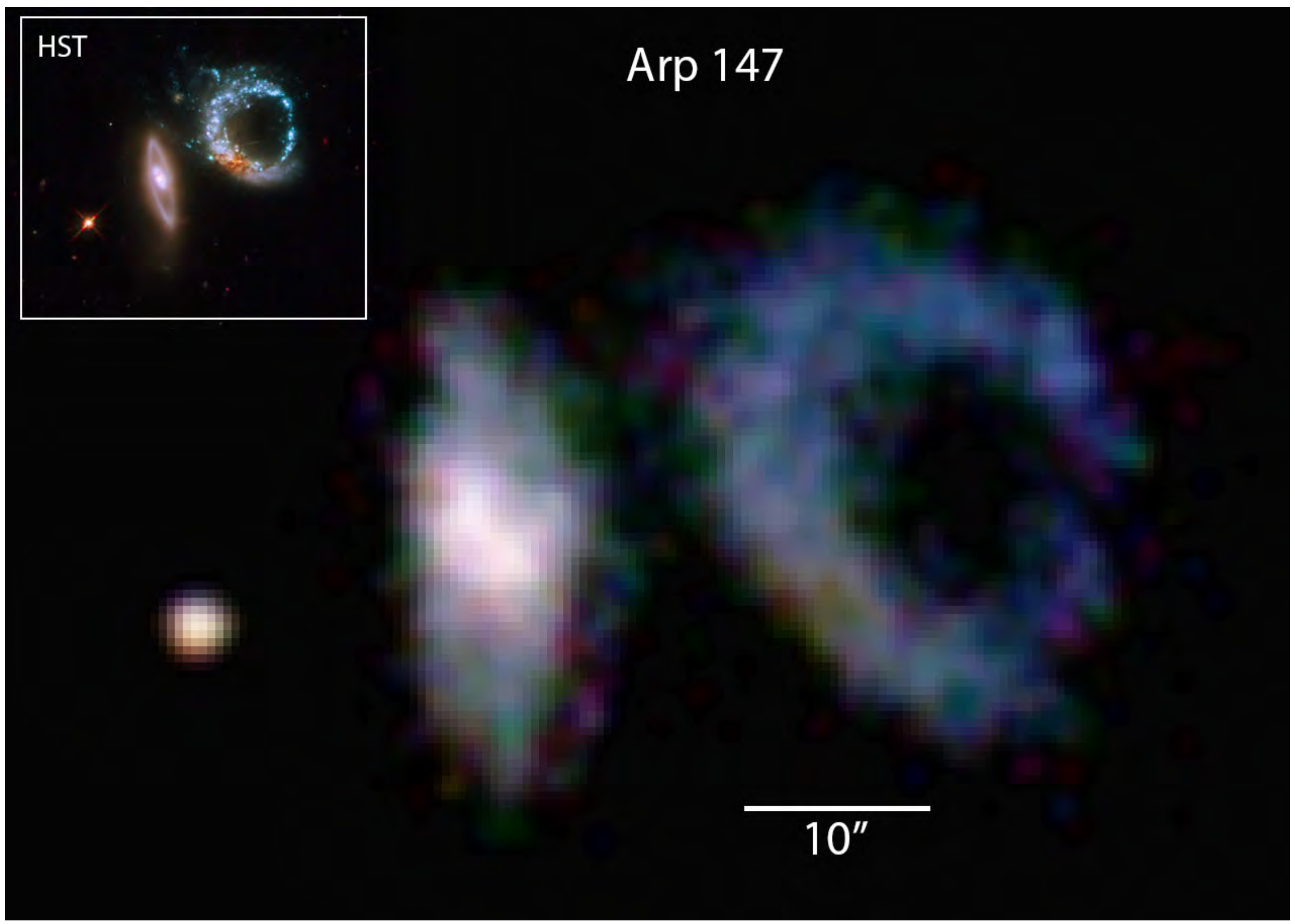


B. A. Mazin,et al. 2013, PASP 125, 1348
“ARCONS: A 2024 Pixel Optical through Near-IR Cryogenic Imaging Spectrophotometer,”



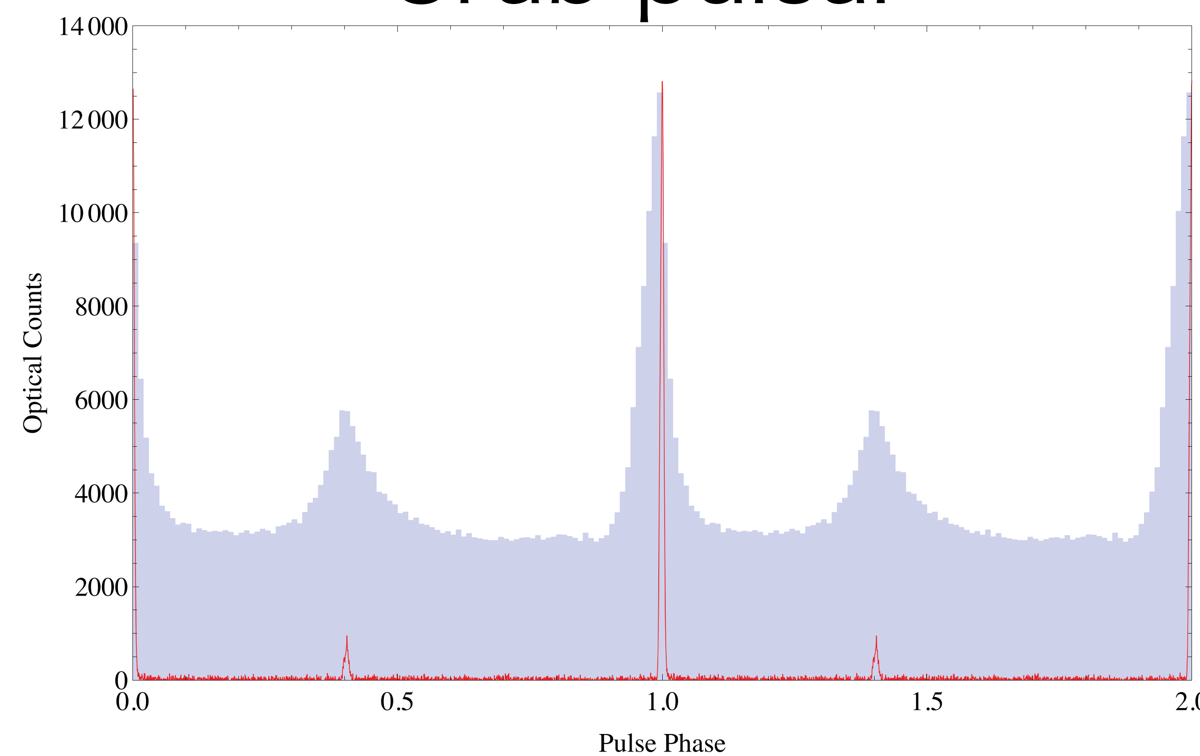
ARCONS: B. Mazin, et al. 2013 PASP 125,12

ARCONS: Array Camera for Optical to Near-IR Spectrophotometry



Palomar 200”

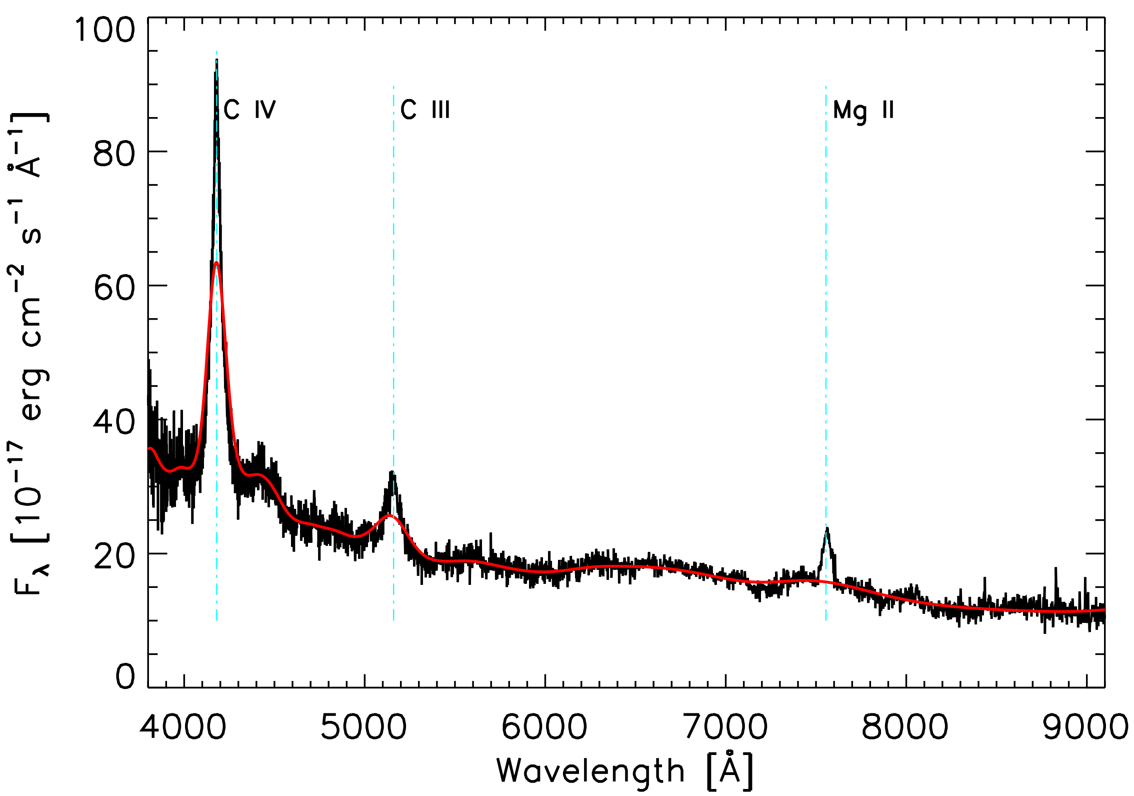
Crab pulsar

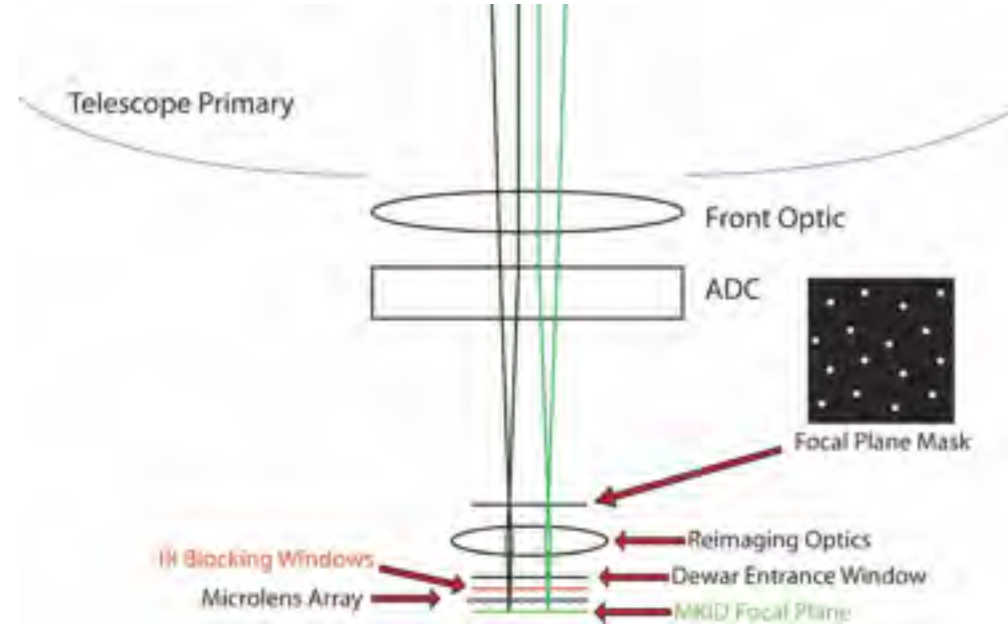


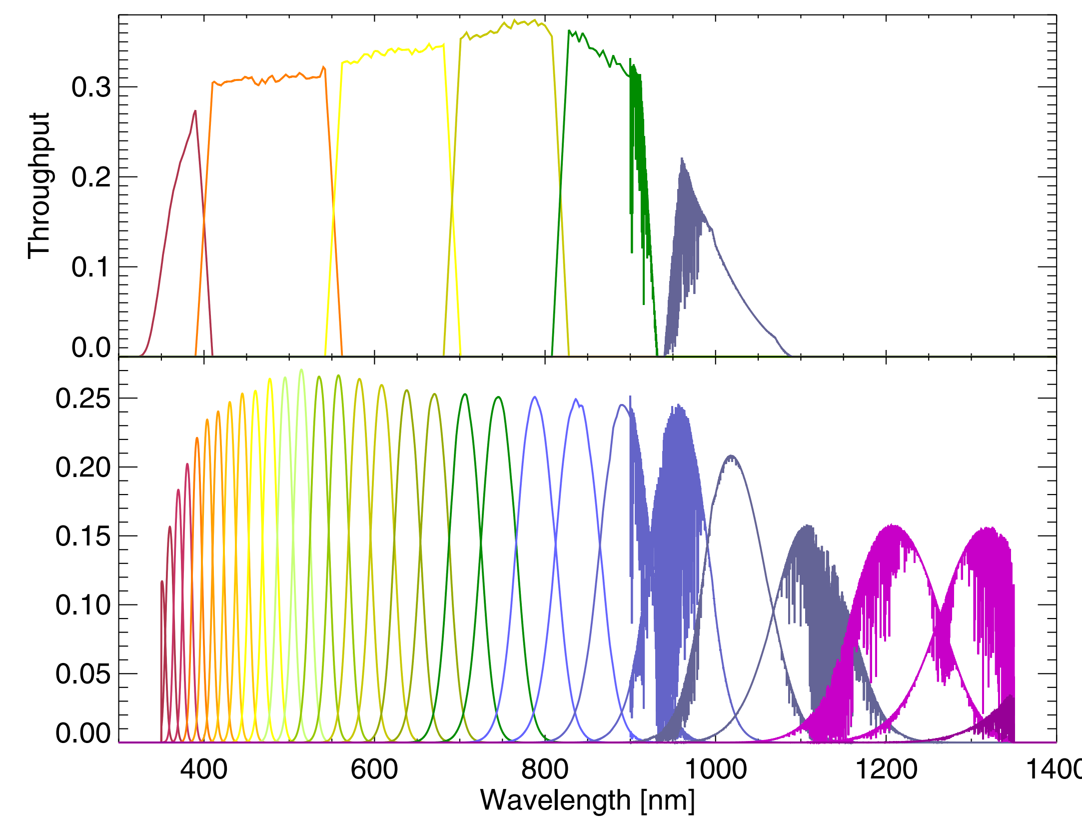
Giga-z: A 100,000 OBJECT SUPERCONDUCTING SPECTROPHOTOMETER FOR LSST FOLLOW-UP

D. W. Marsden, B. A.Mazin, K. O'Brien, C. Hirata 2013 ApJSS 208:8

- $R_{423nm} = E/\Delta E = 30$

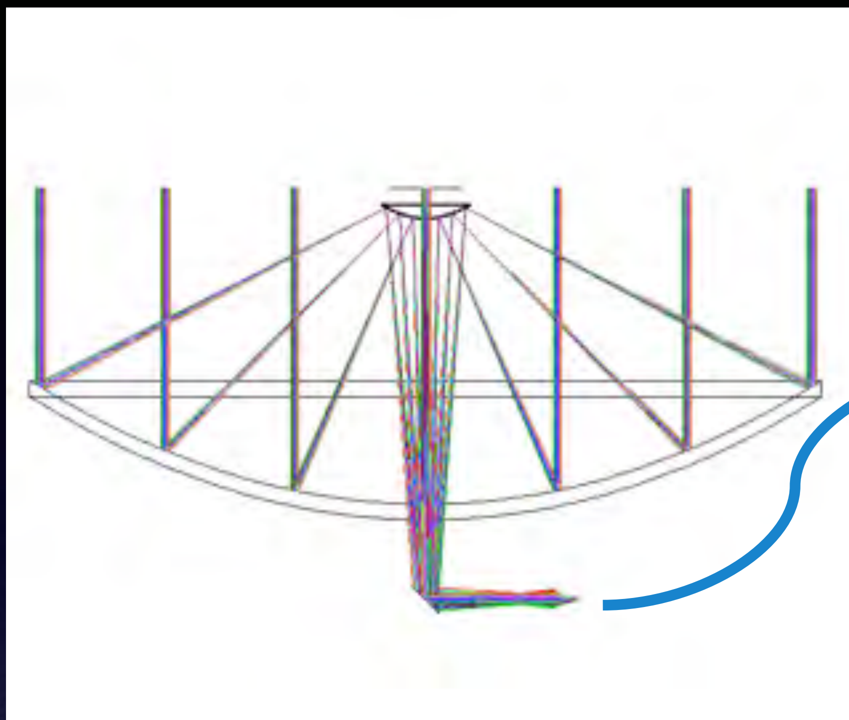


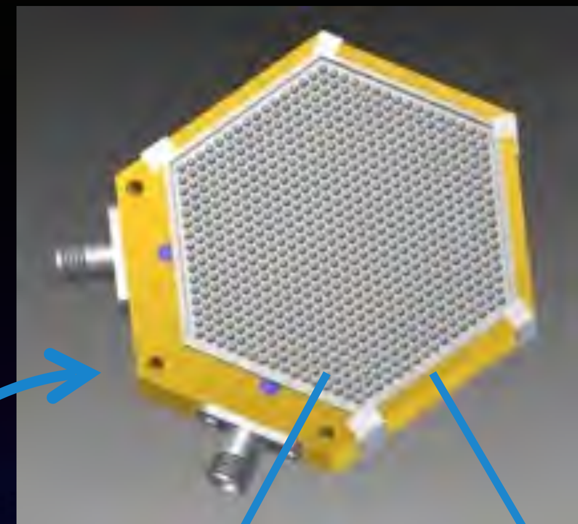




	σ(w_p)	σ(w_a)	σ(Δγ)	σ(Ω_k)
LSST photo-z	0.0382	0.695	0.221	0.0252
Giga-z photo-z	0.0348	0.576	0.168	0.0205

MKID: Microwave Kinetic Inductance Detector

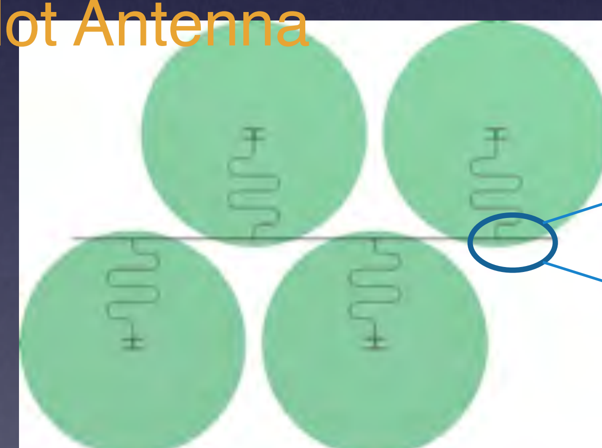




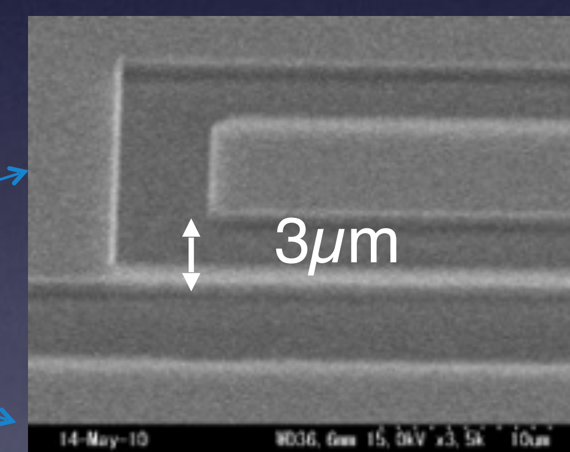
1. Photons break cooper pairs and generate quasi-particles
2. Super conducting resonator senses a change of kinetic inductance
3. Resonator frequency and amplitude changes depending on a number of incident photons

Lens Array

Double Slot Antenna

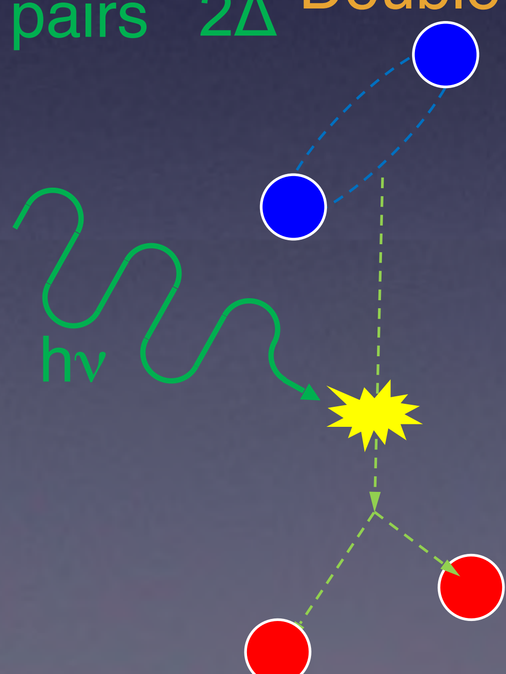


Superconducting Resonators



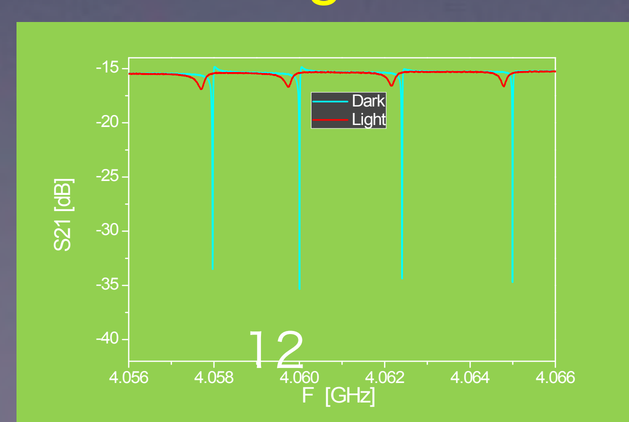
Coplanar Waveguide (CPW)

Cooper pairs 2Δ



quasi-particles

Pair Breaking Detector



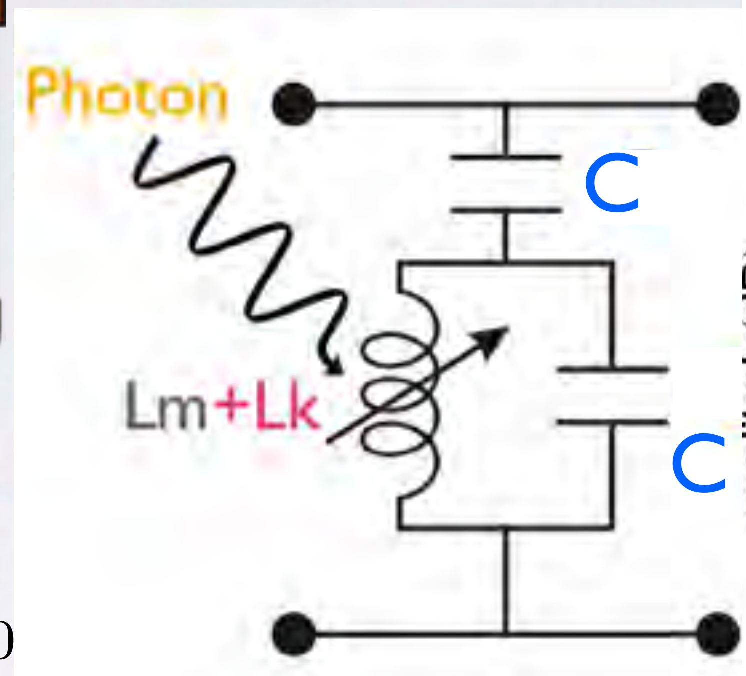
P. Day et al. 2003 Nature
J. Zmuidzinas 2012 ARCMP

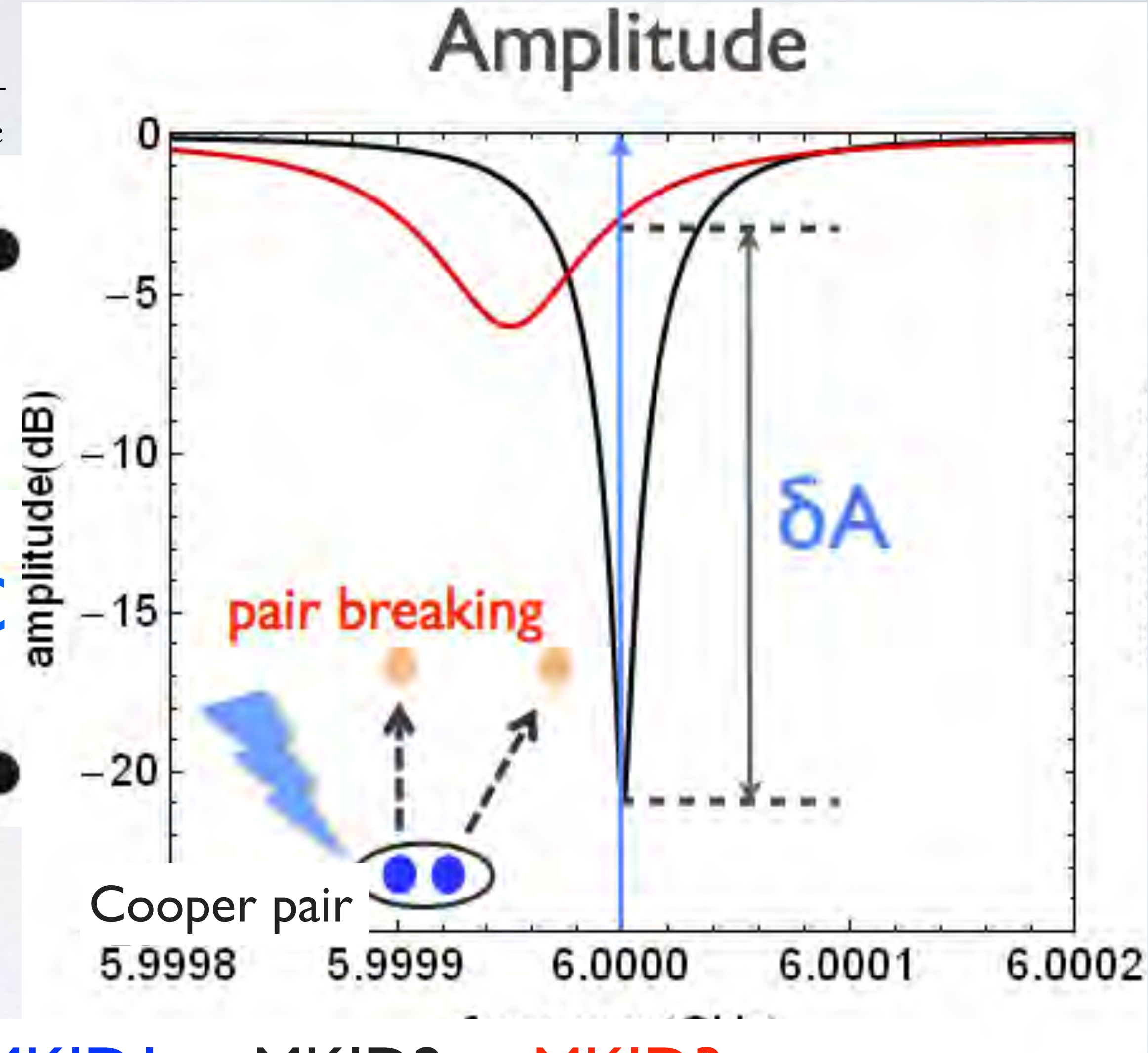
Microwave Kinetic Inductance Detector (MKID)

P. Day et al. 2003 Nature
J. Zmuidzinas 2012 ARCMP
J. Baselmans 2012 JLTP

Marimba

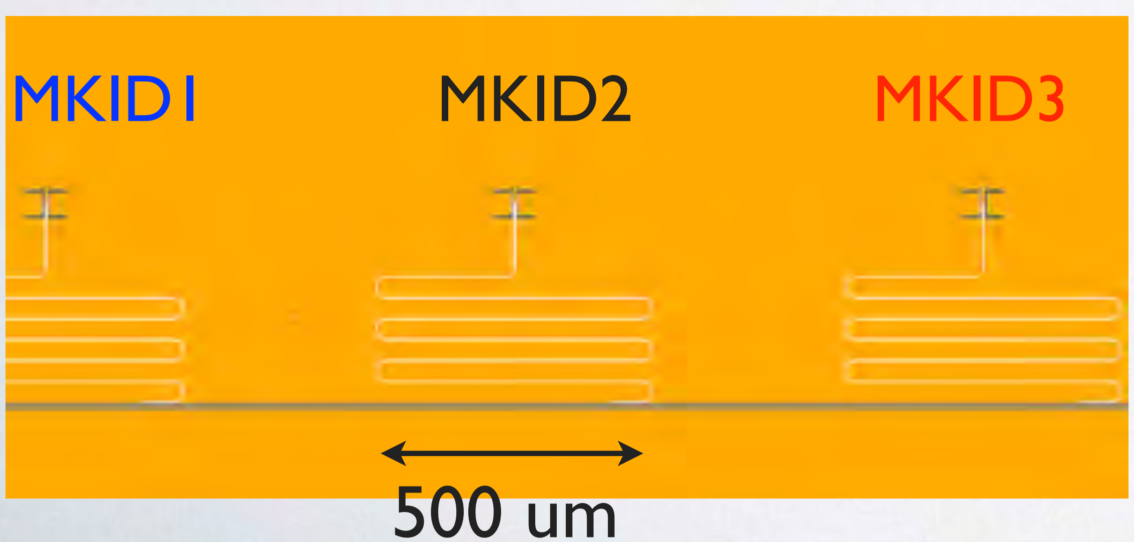
$$\frac{1}{Q_r} = \frac{1}{Q_i} + \frac{1}{Q_c}$$

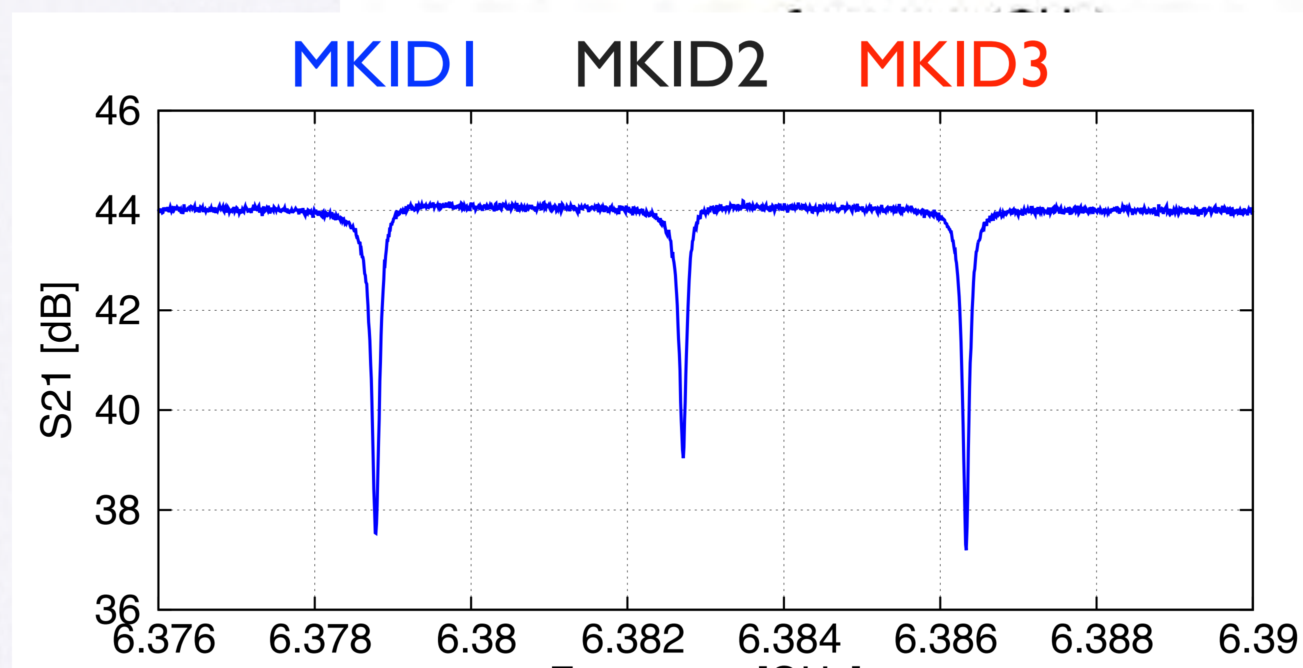




$$L_k \sim \left(1 + \frac{n_{qp}}{n_s}\right) L_{k0}$$

$$L_{k0} = \frac{m}{n_s e^2 A}$$



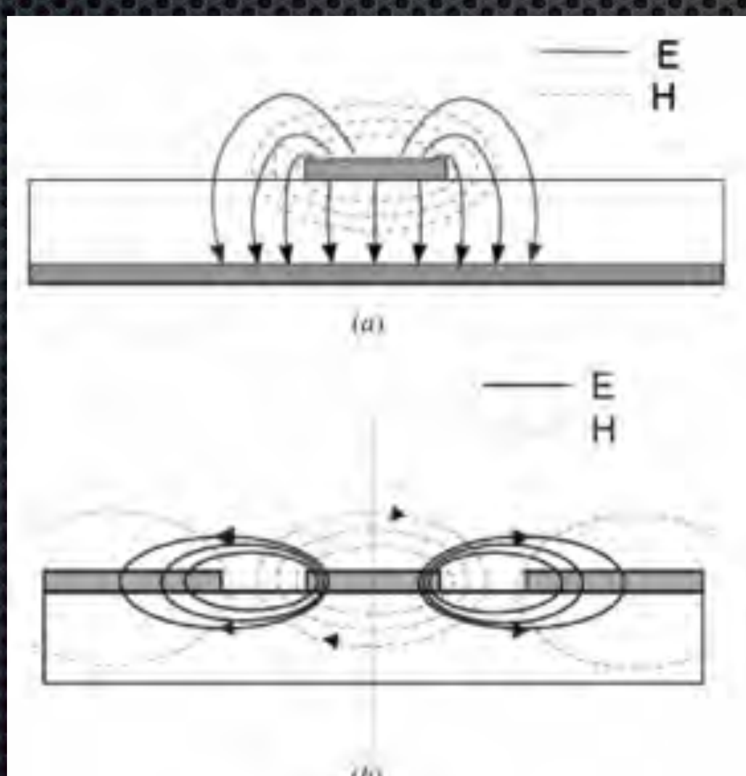


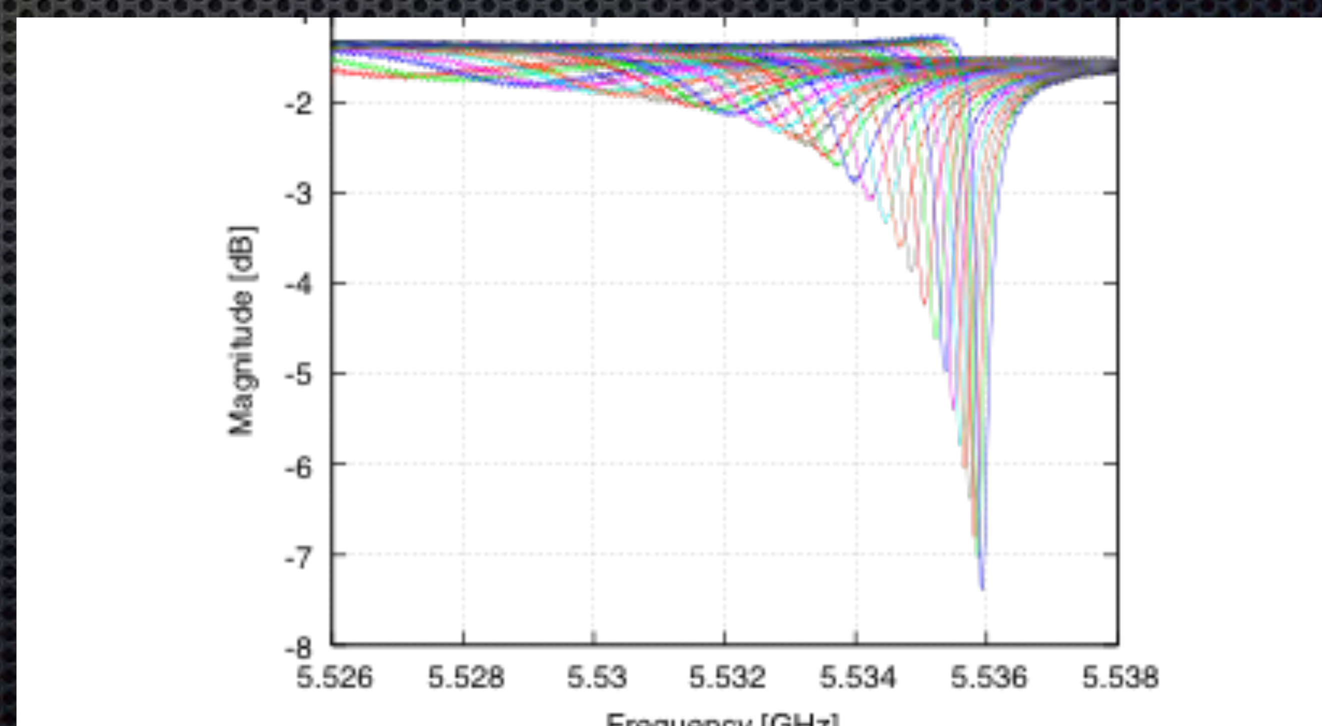
MKIDの特徴

$$f_g = \frac{2\Delta}{h} = 74\ \mathrm{GHz} \times \frac{T_c}{1\ \mathrm{K}}$$

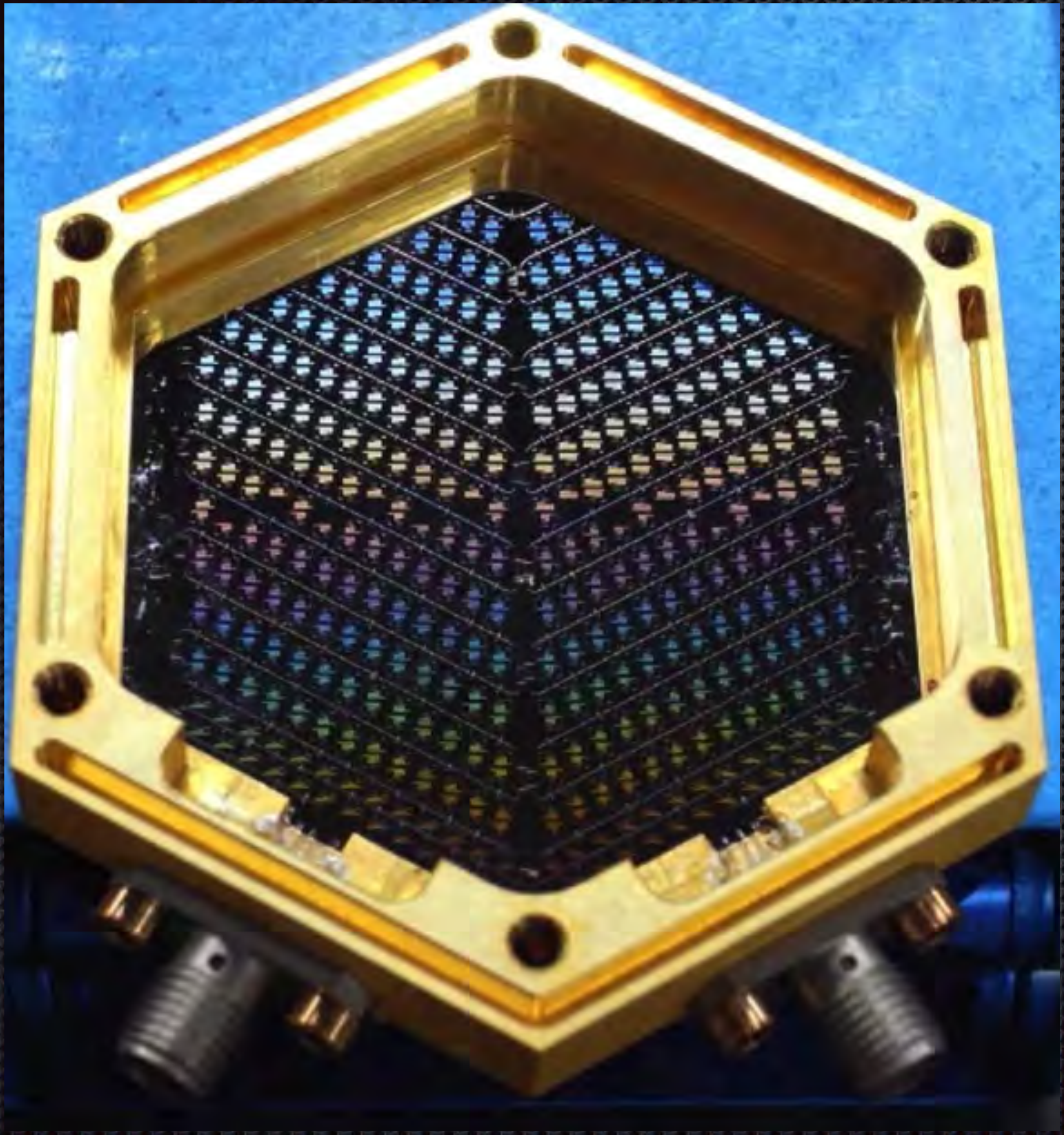
- Cooper pair breaking detector
  - ミリ波からX線まで
- 低雑音 NEP < 5 * 10^{-18} W/rHz
- 広いダイナミックレンジ ~ 10^5
- 周波数多重化1000 素子 with a LNA

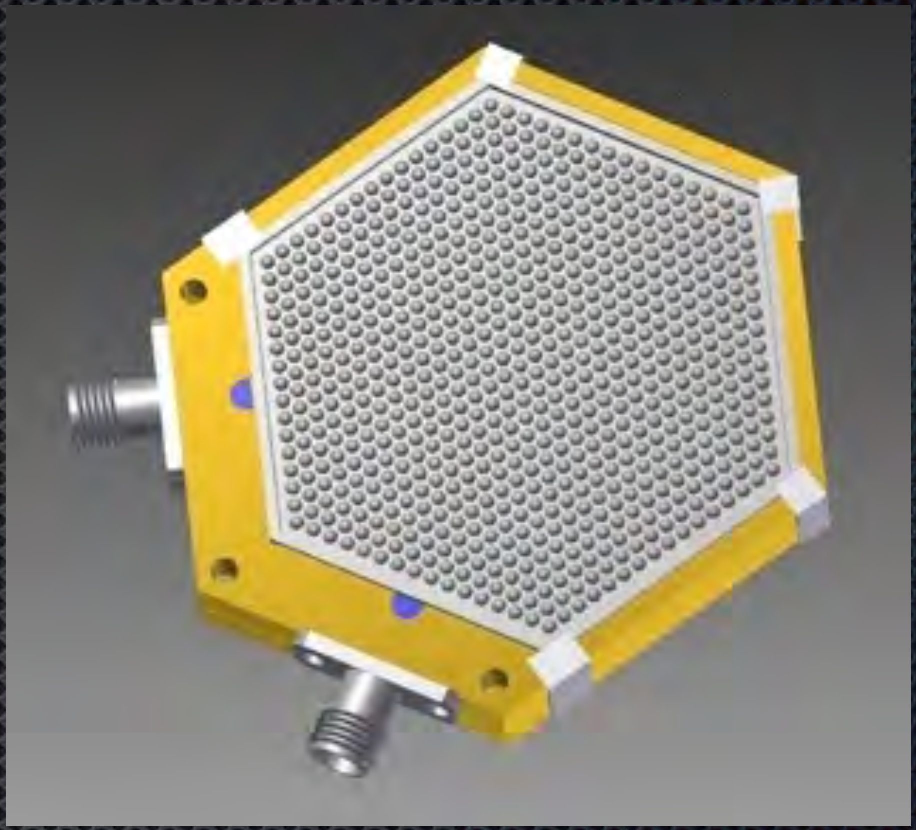
materi al	Tc [K]	Tb [K]	fg [GHz]
Al	1.2	0.24	88
Nb	9.3	1.9	678
Ti	0.4	0.08	29
NbTiN	14	2.8	1026
TiN	(0.5) -	0.9	330





220GHz-700 pixel MKID camera

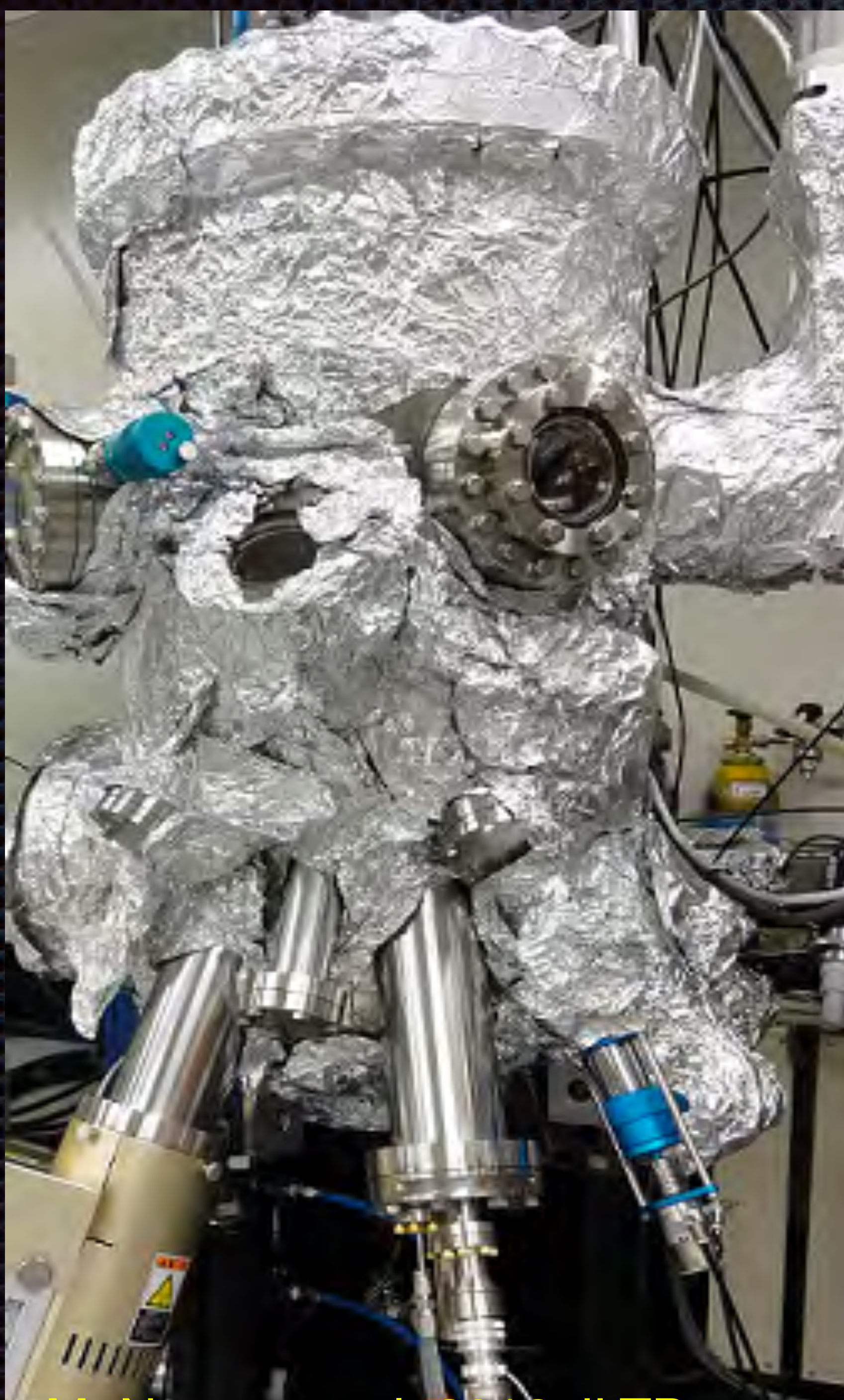




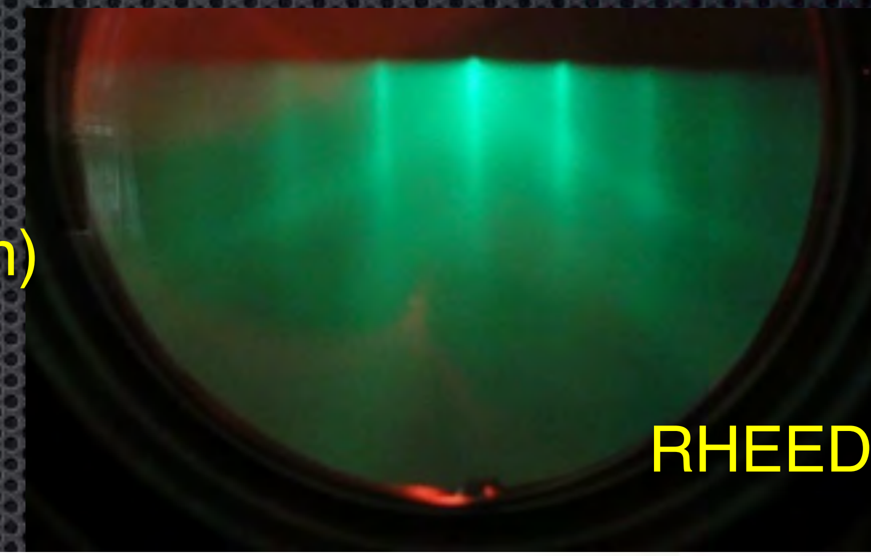
T. Nitta et al. 2013

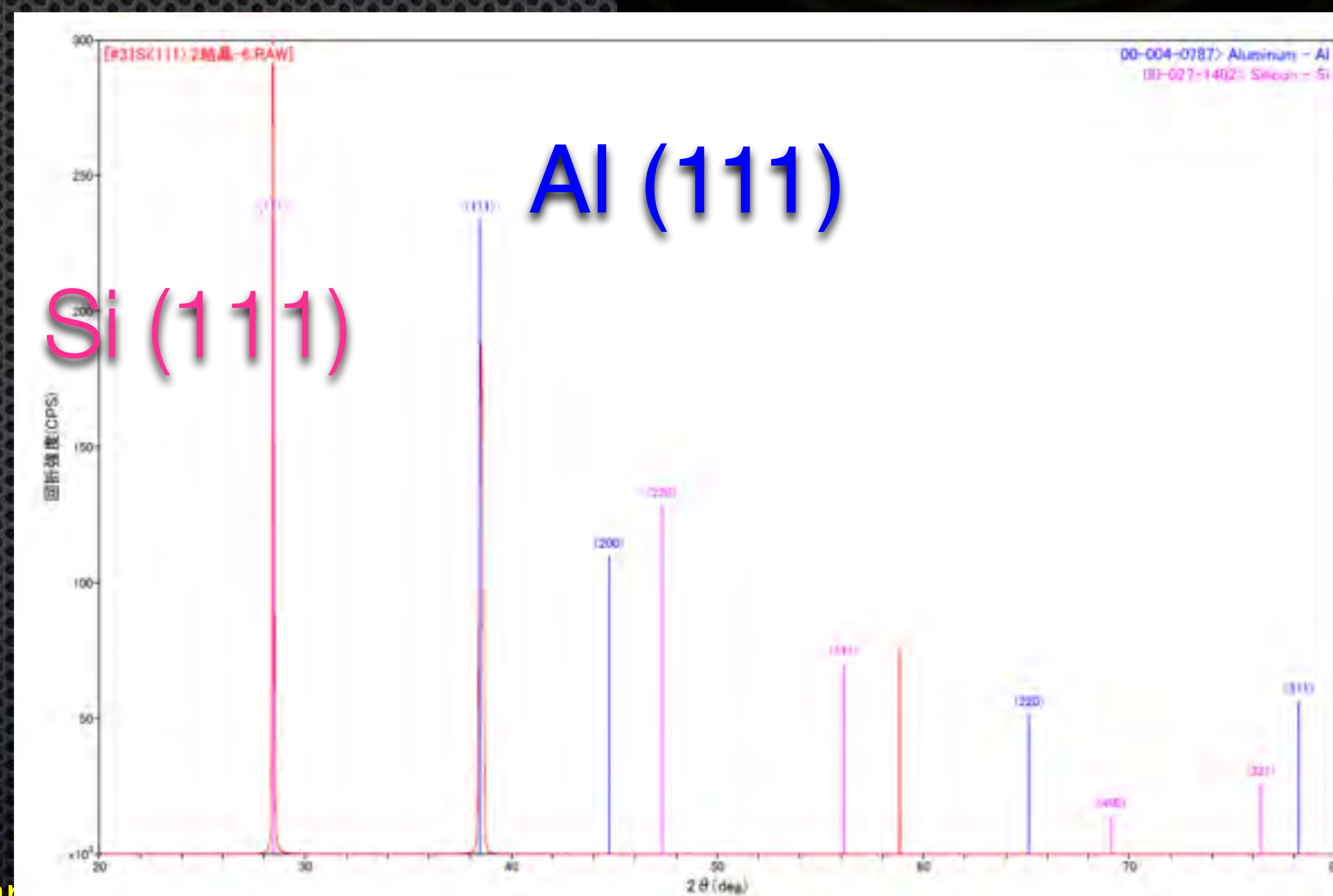
Crystal Aluminum on Si wafers

Molecular Beam Epitaxy



Al on Si (111) wafer
Thickness 160nm
Cleaning: BHF + 650 deg. (20 min)
Back ground: 2×10^-8 Pa
Wafer: 75 deg.

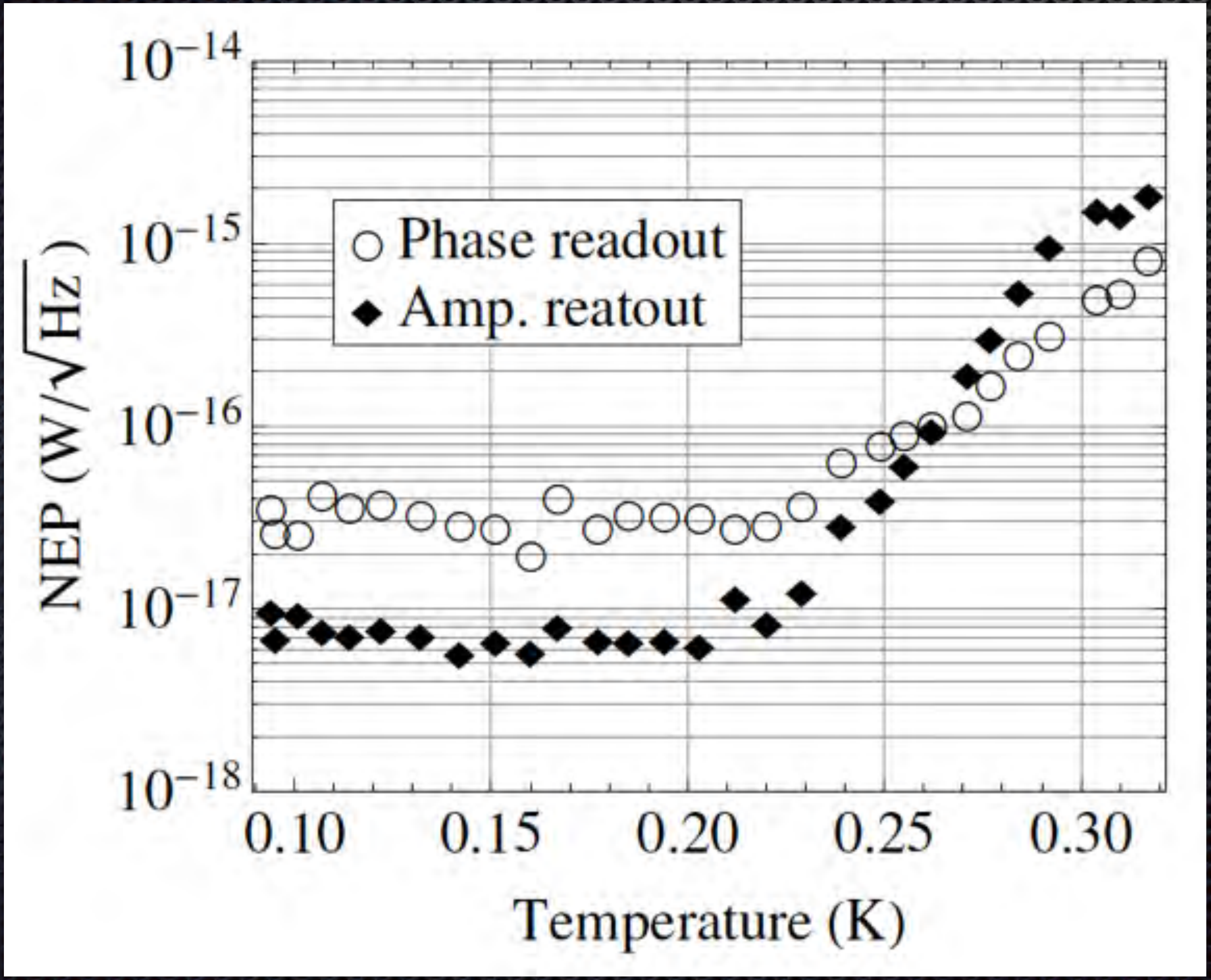




M. Naruse et al. 2012 JLTD
“Development of crystal Al MKIDs by molecular

MKID noise

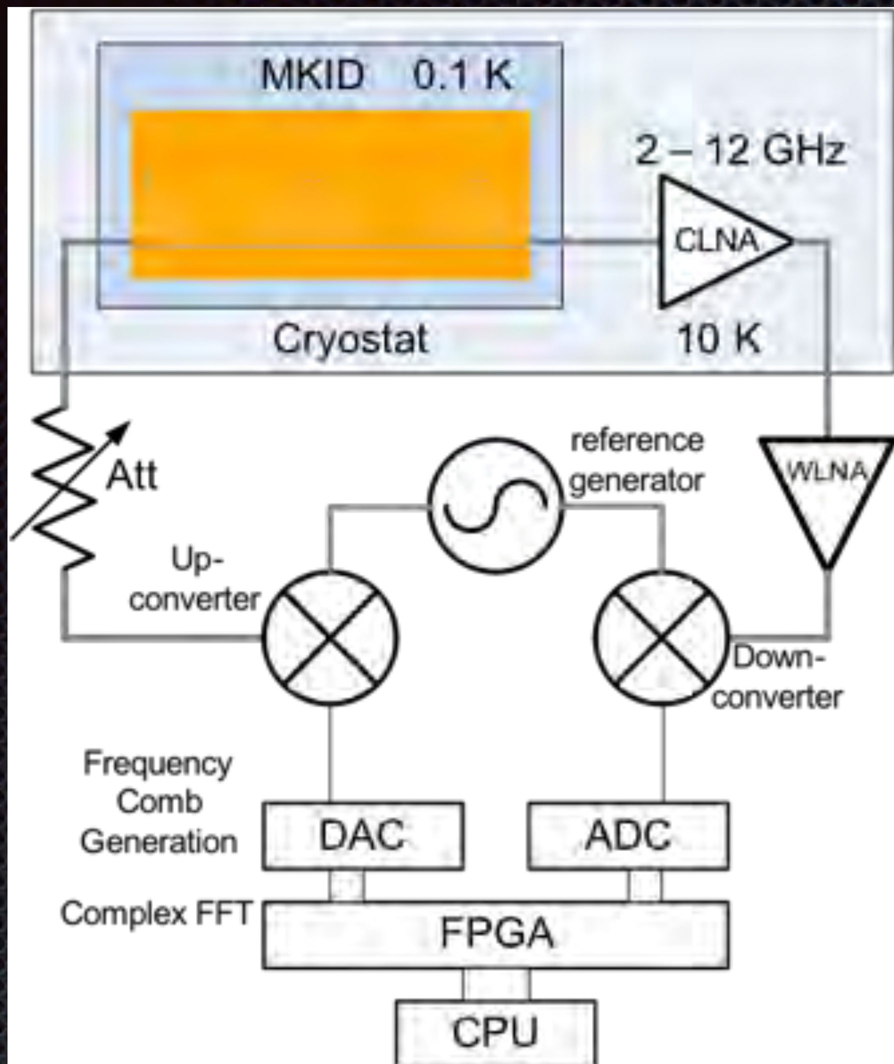
$$NEP(\omega) = \frac{\sqrt{S_{(\theta,R)}}}{\left[\frac{\eta_q \tau_r}{\Delta} \cdot \frac{\delta(\theta,R)}{\delta N_{qp}}\right]} \left(1+\omega^2\tau_r^2\right)^{1/2} \left(1+\omega^2\tau_{res}^2\right)^{1/2}$$



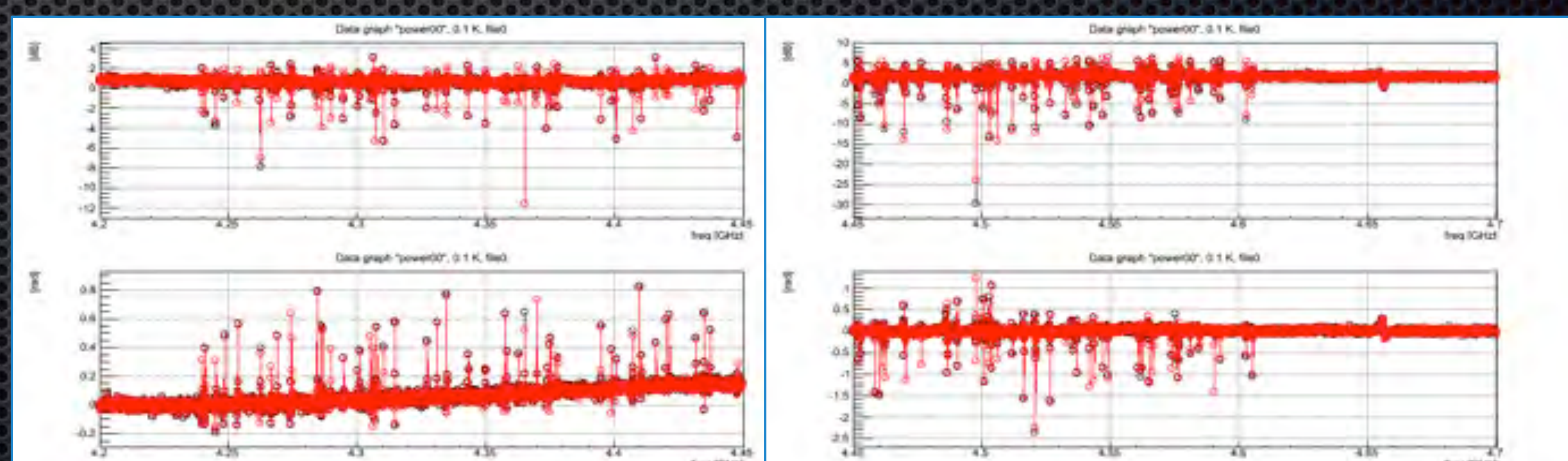
M. Naruse et al. 2013 IEEE TST

NEP 6 x 10^(-18) W/rHz

読出回路と0.1K希釈冷凍機



Readout 270 MHz/board → 1 GHz/board
Resonator 2MHz spacing → 500 pixel/board
16 us sampling



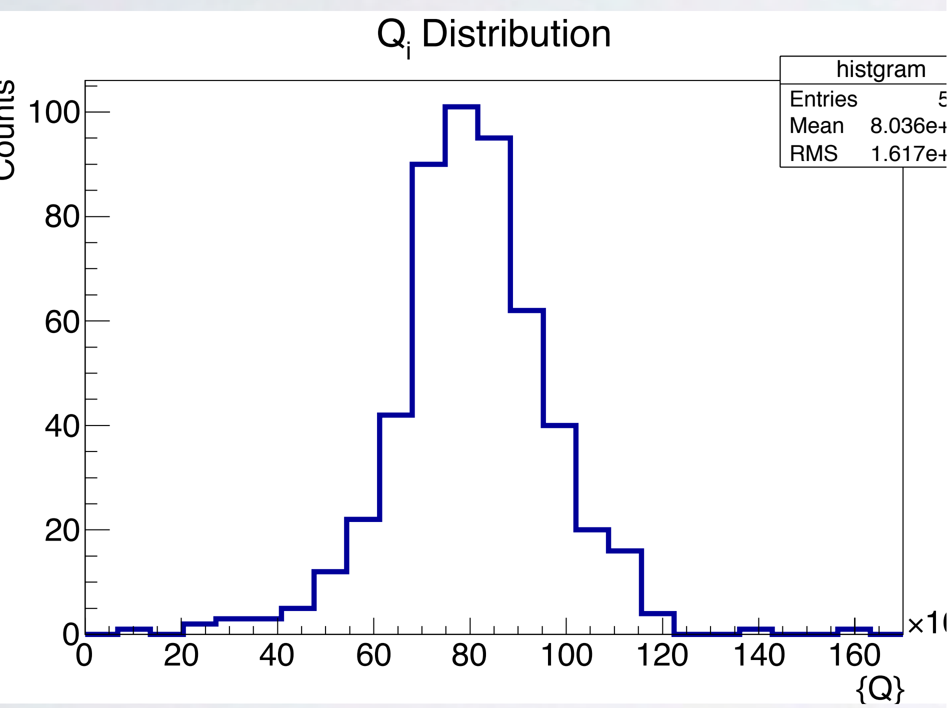
K. Karatsu + 2014 JLTP

600素子MKIDの評価

新田冬夢 2014 筑波大　博士論文

- 歩留まり：

584 / 608 (~ 95 %)

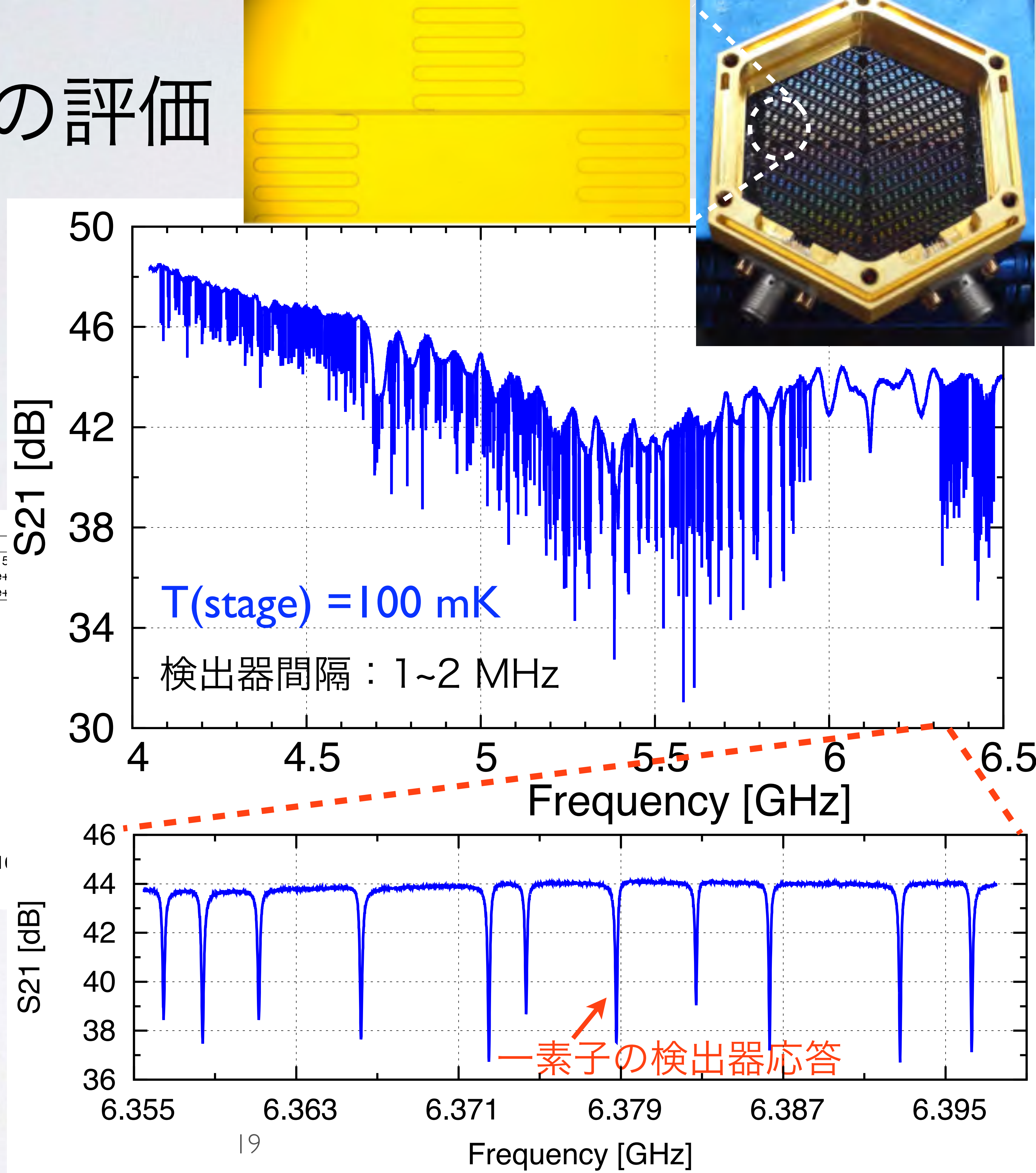


- Q値

共振の鋭さを表すパラメータ

Mean (~ 10^5)

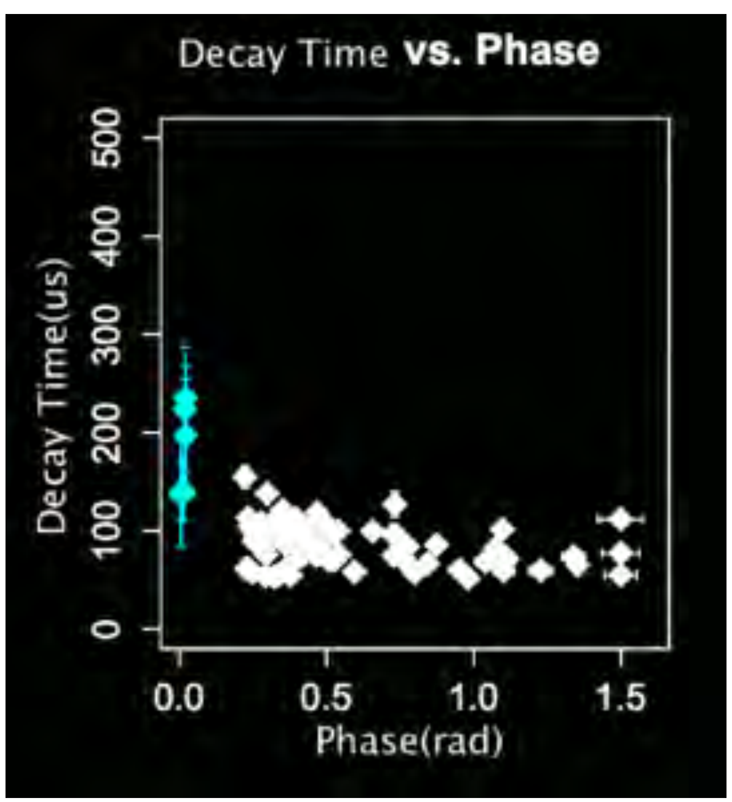
→高い値を得た

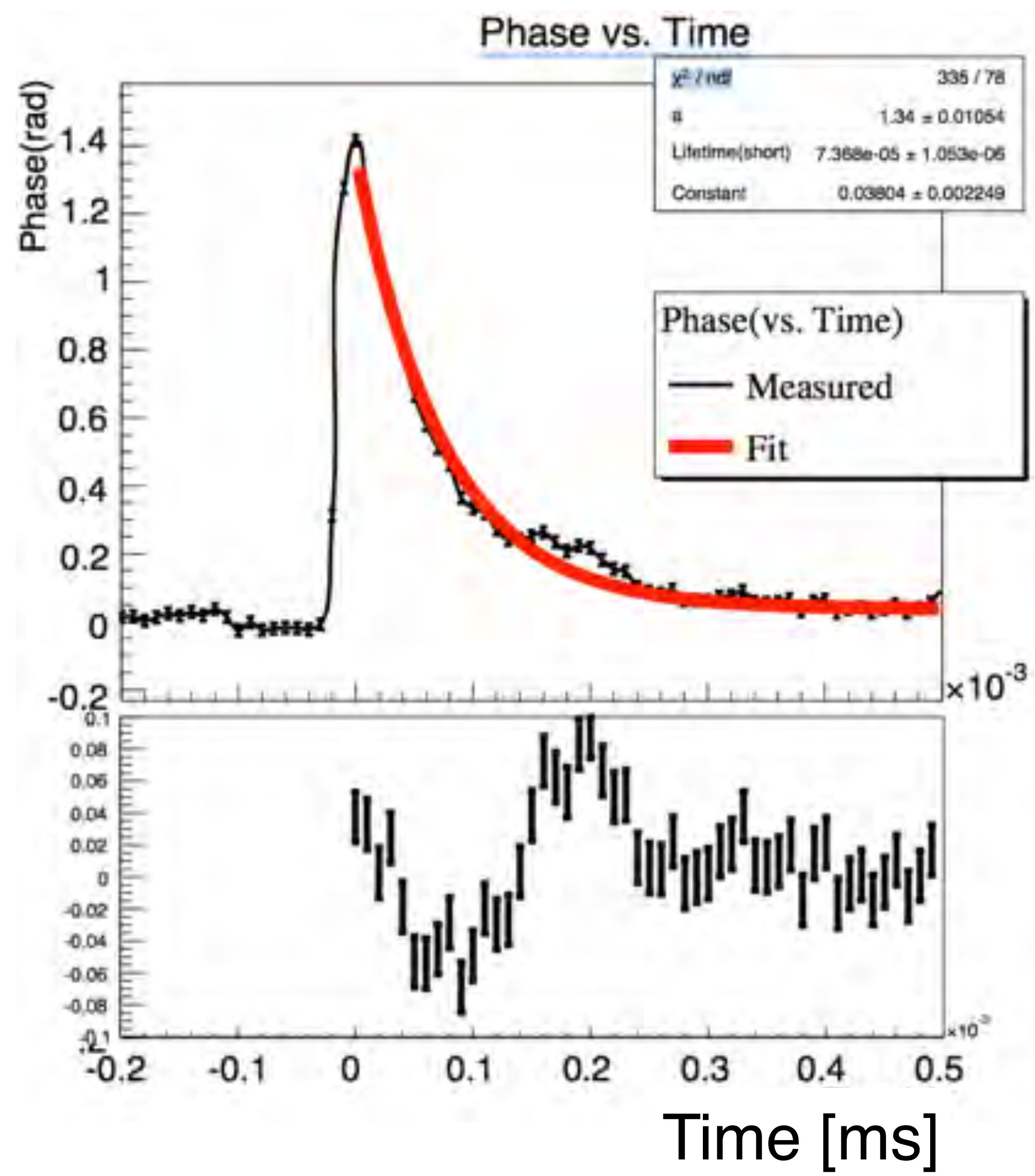


Cosmic ray events

- τ=79.9μs
- a few events per an hour
- T. Okada et al. 2014
- 1μs sampling

f=3.494GHz

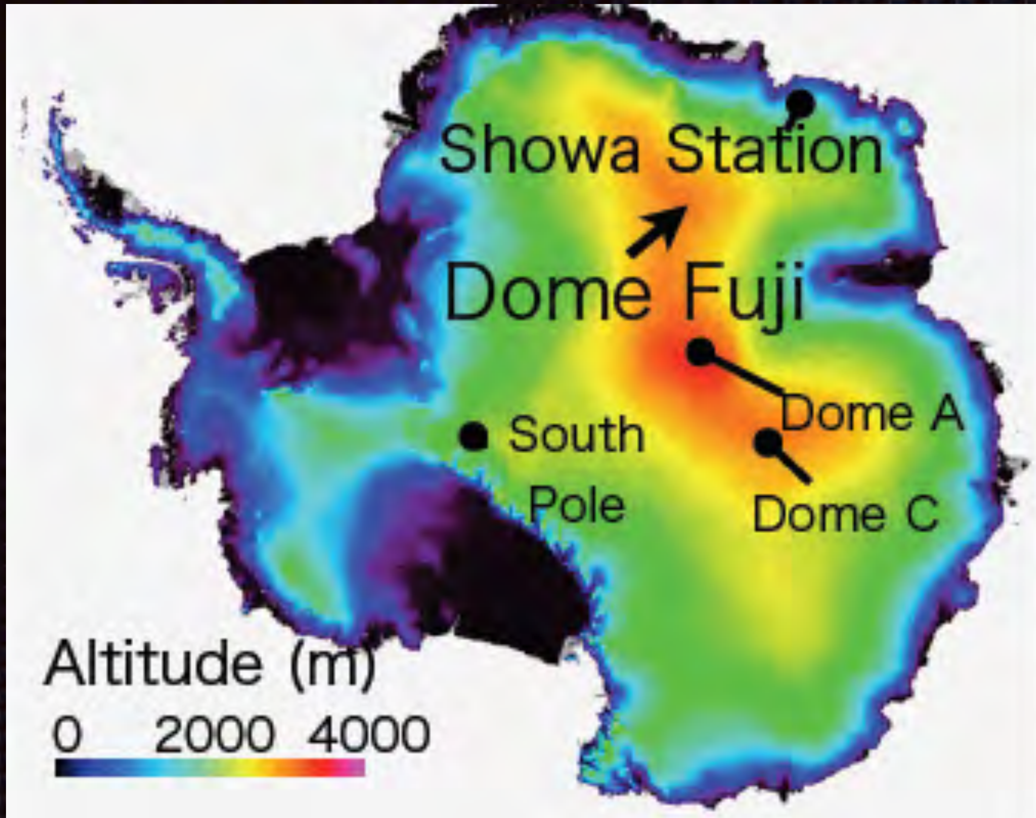


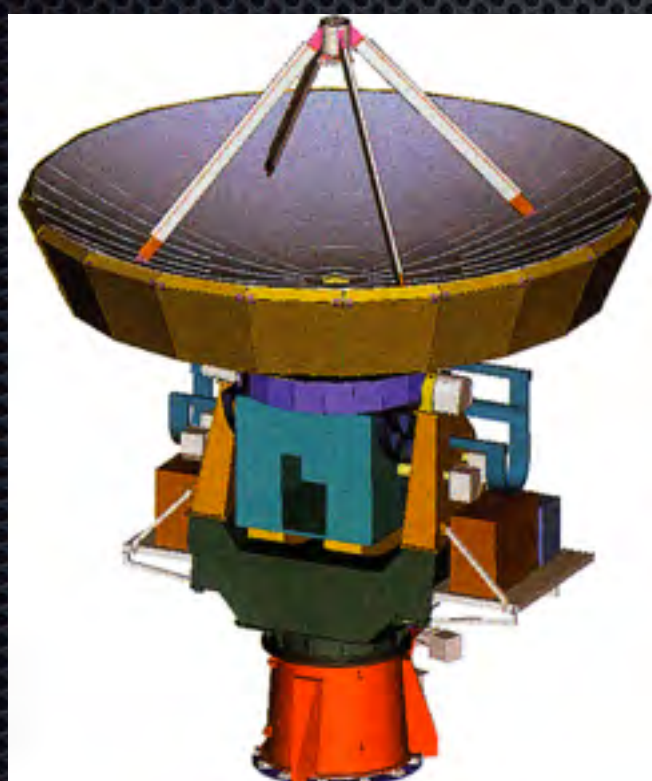


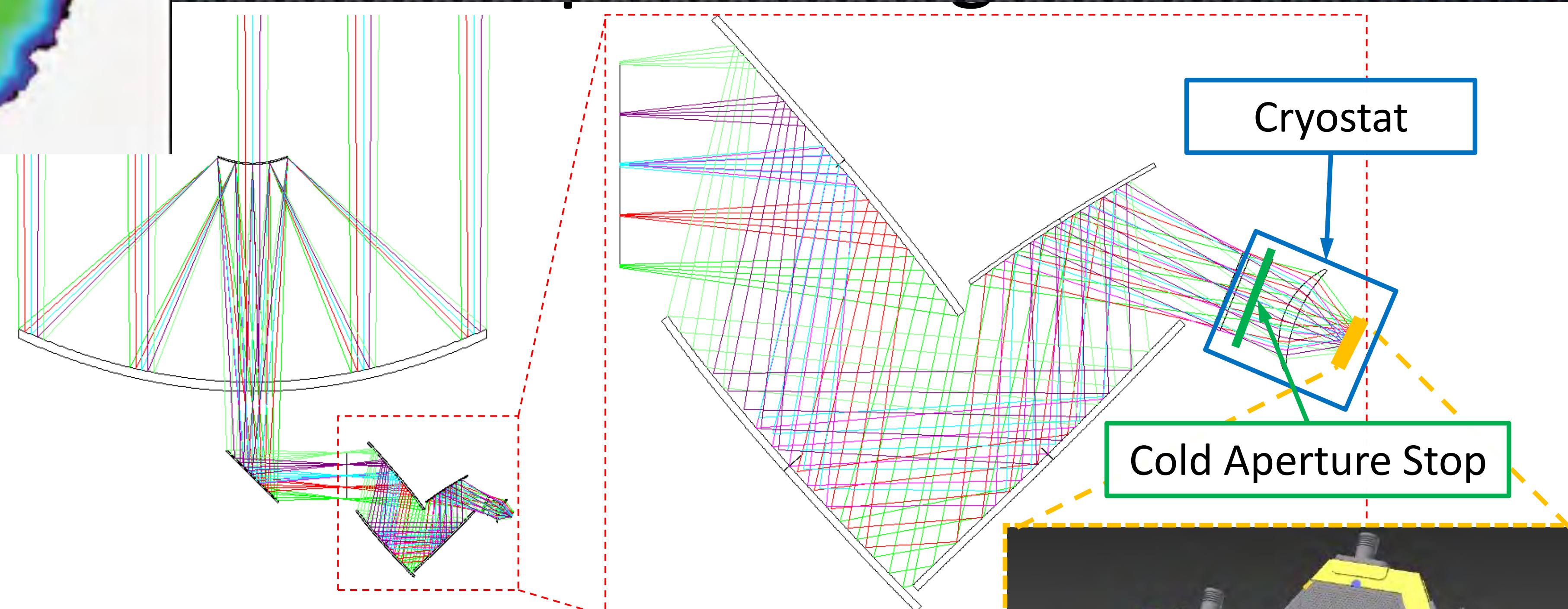
南極望遠鏡

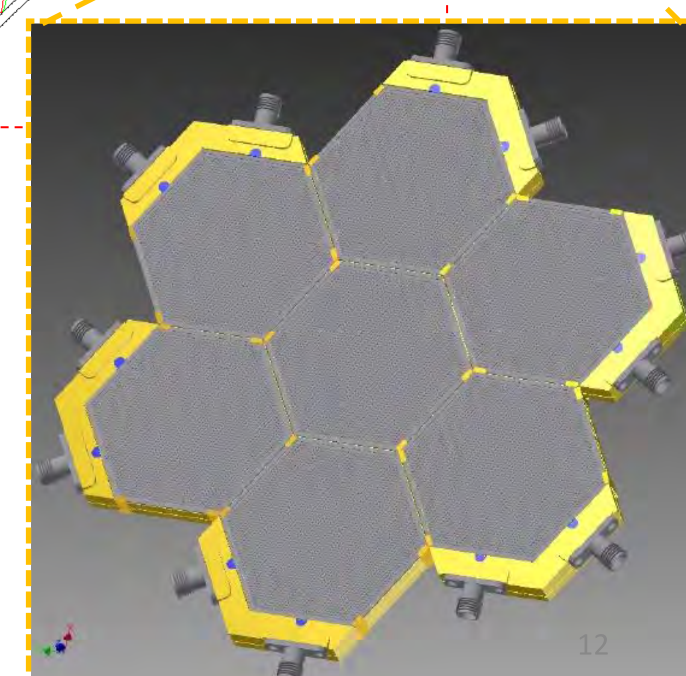
筑波大学・東北大学

- T. Tsuzuki et al. 2014 SPIE

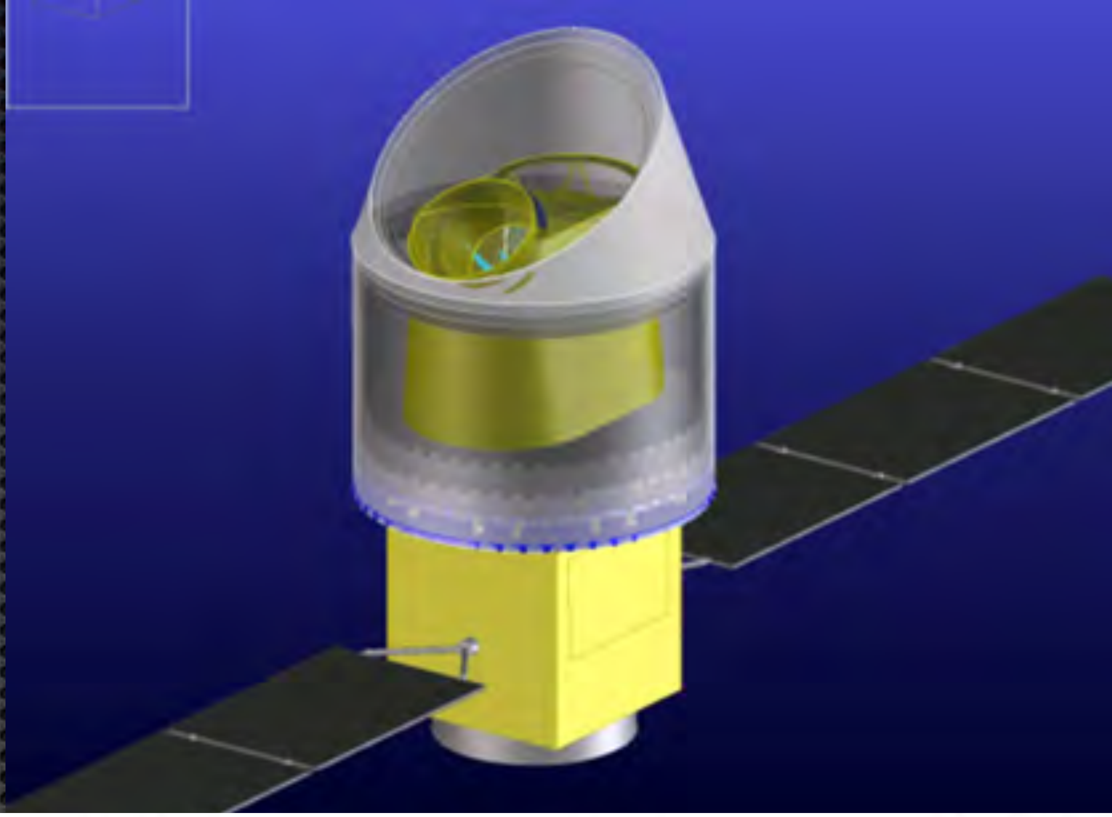








- 10 m Antarctic Terahertz Telescope
- Assemblage the 7 MKID modules
- Frequency : 850 GHz
- Detector focal plane
  - FoV : 1 deg
  - Diameter : 160 mm



LiteBIRD

Lite (light) satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection

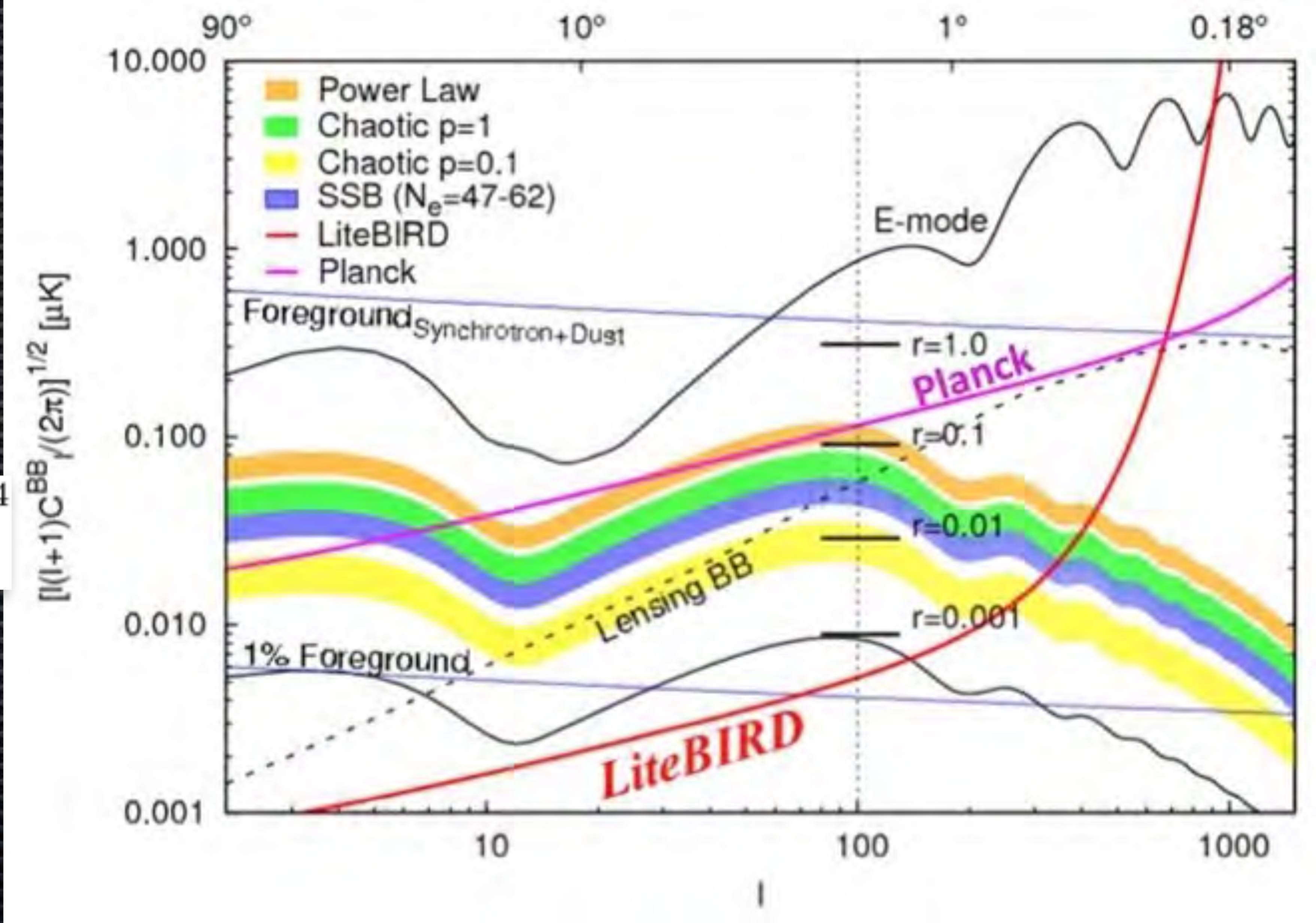
- 50 - 270 GHz ~ 600 pixel
- Launch is planned in 2022
- KEK, ISAS/JAXA, U. Tokyo, NAOJ
- M. Hazumi et al. 2012 SPIE

E-mode B-mode

Inflation potential energy

$$V^{1/4} = 1.1 \times 10^{16}\,\mathrm{GeV}\left(\frac{r}{0.01}\right)^{1/4}$$

r: tensor to scalar ratio

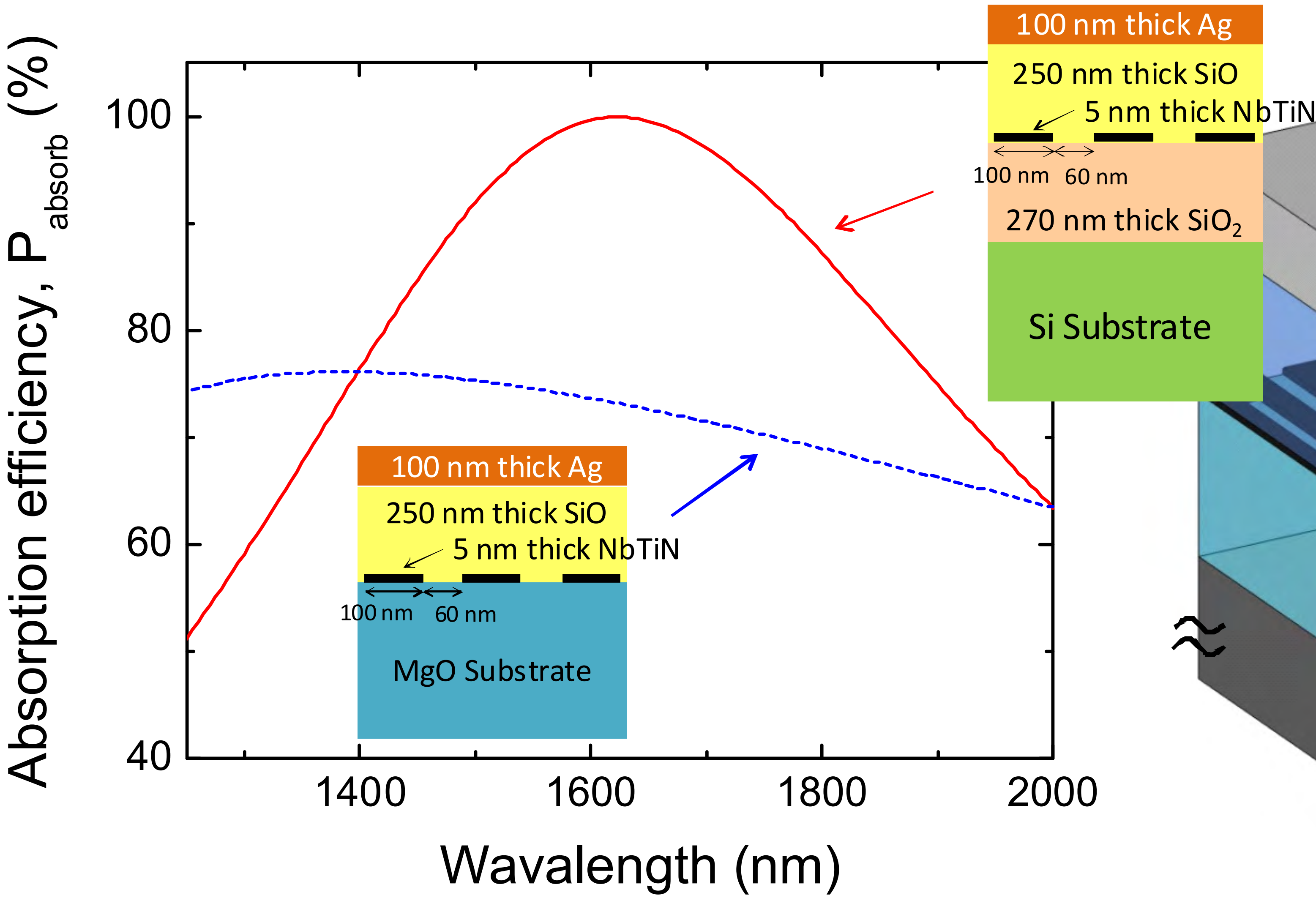


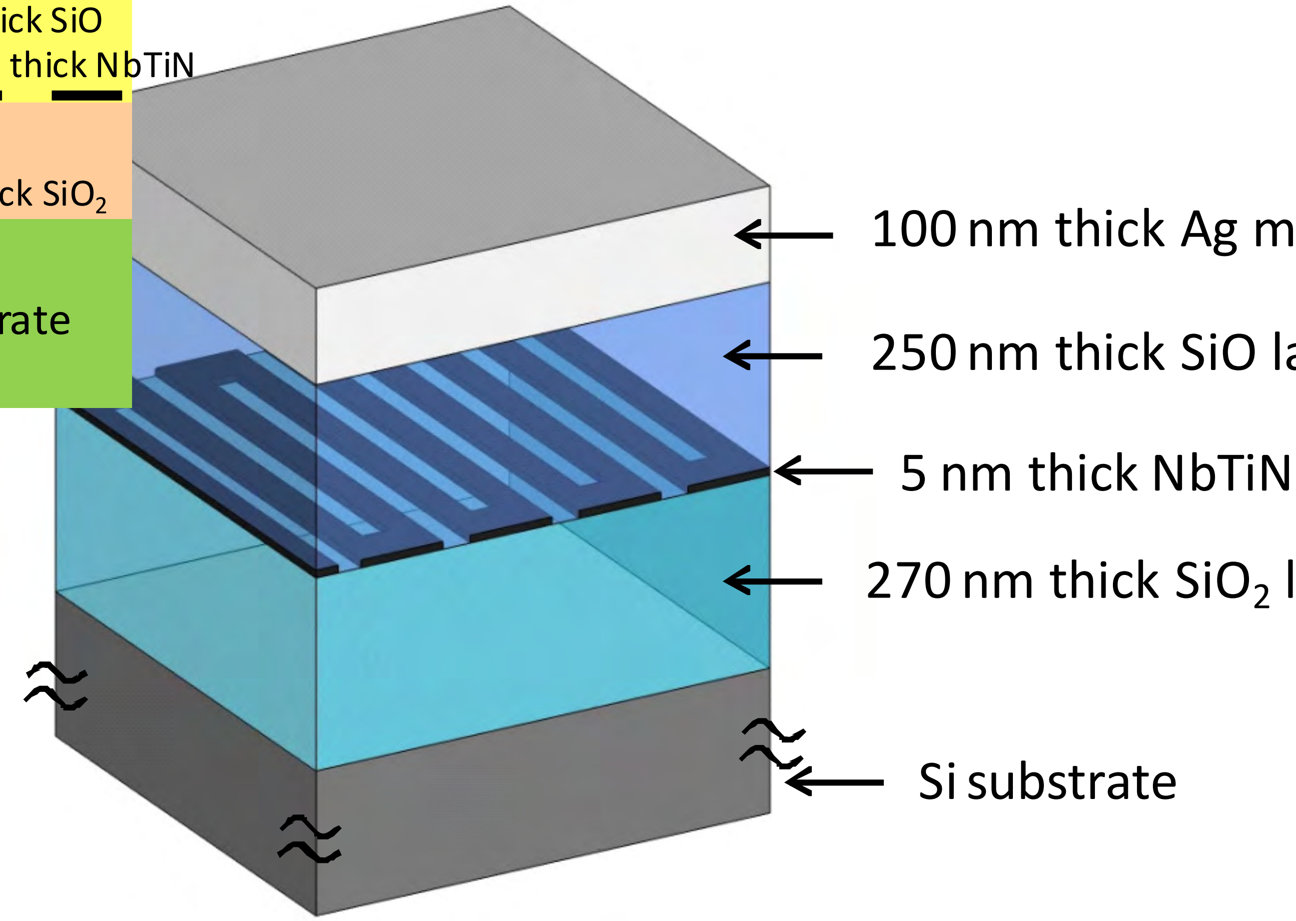
Options for Higher efficiency

1. Optical Cavity
   1. S. Miki, et al. 2013 “High performance fiber-coupled NbTiN superconducting nanowire single photon detectors with Gifford-McMahon cryocooler.,” Opt. Express, 21, 10208
2. Multilayer AR
   1. Fukuda, D. et al., 2011 “Titanium-based transition-edge photon number resolving detector with 98% detection efficiency with index-matched small-gap fiber coupling.,” Opt. Express 19(2), 870
3. New Material

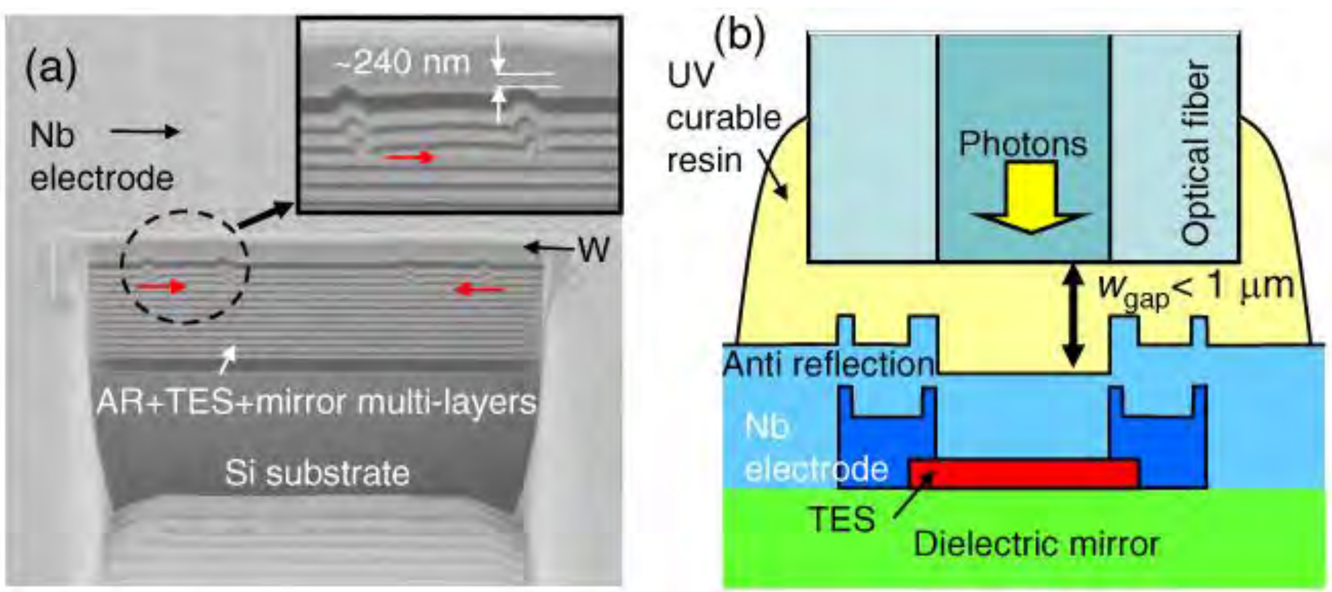
- WSi
- Ta based superconductor

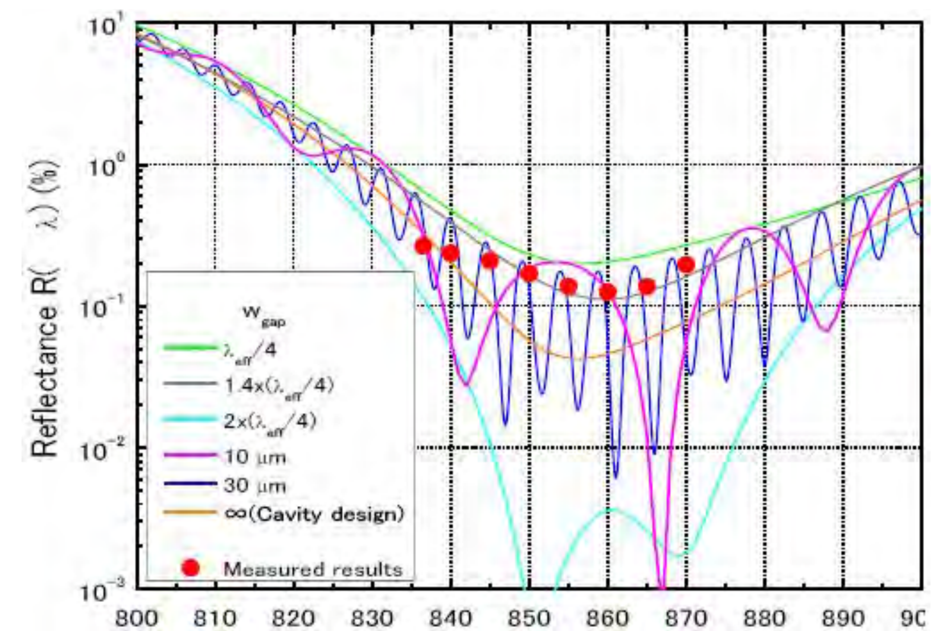
S. Miki, et al. 2013 “High performance fiber-coupled NbTiN superconducting nanowire single photon detectors with Gifford-McMahon cryocooler.,” Opt. Express, 21, 10208–14





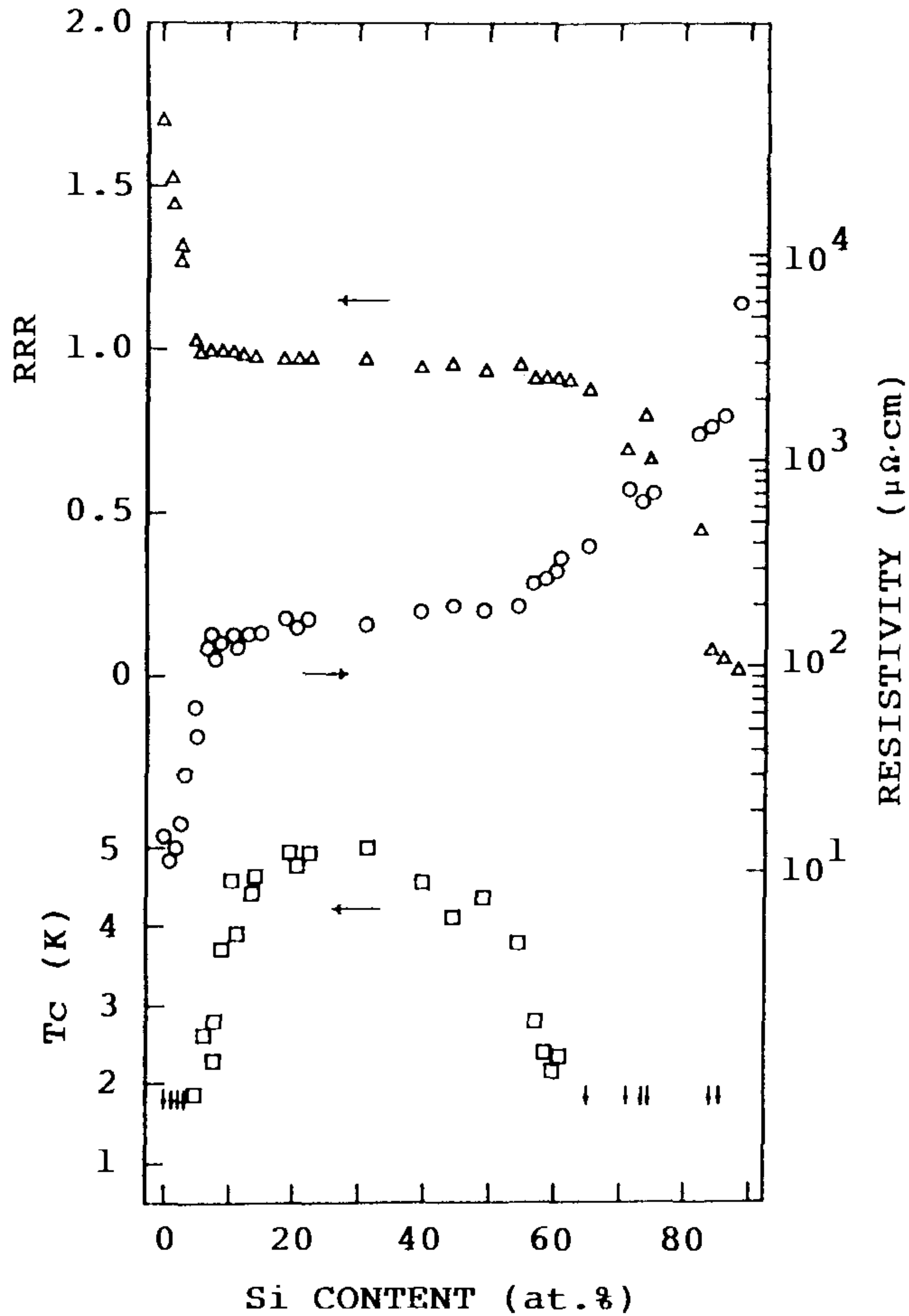
Fukuda, D. et al., 2011 “Titanium-based transition-edge photon number resolving detector with 98% detection efficiency with index-matched small-gap fiber coupling.,” Opt. Express 19(2), 870





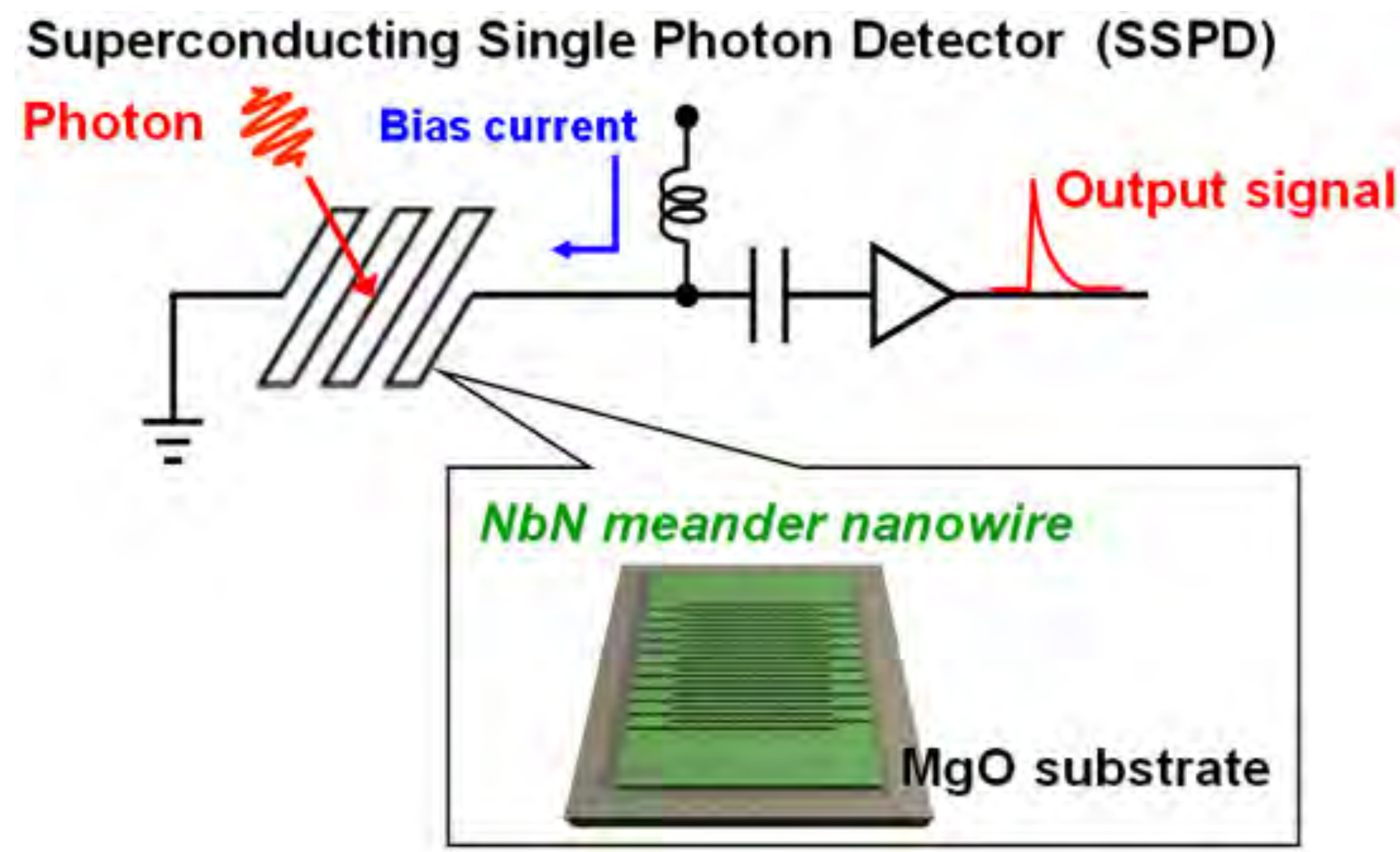
WSi

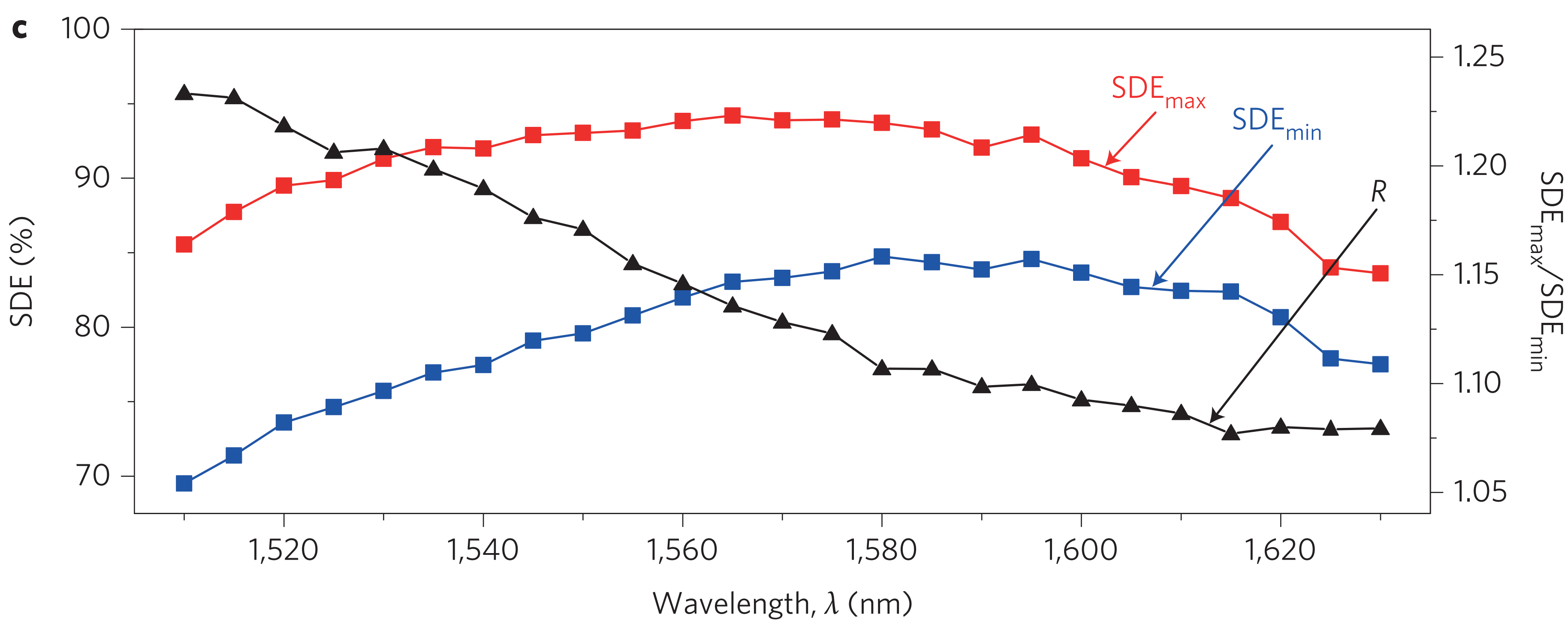
- Tungsten-Silicon
- Tc (W) = 10 mK
- 150 μΩ-cm
- low-pressure chemical vapor deposition (LPCVD) using tungsten hexafluoride (WF6) and silane (SiH4).



S. Kondo, 1991 “Superconducting characteristics and the thermal stability of tungsten-based amorphous thin films,” J. Mater. Res., 7, 853

WSi SSPD





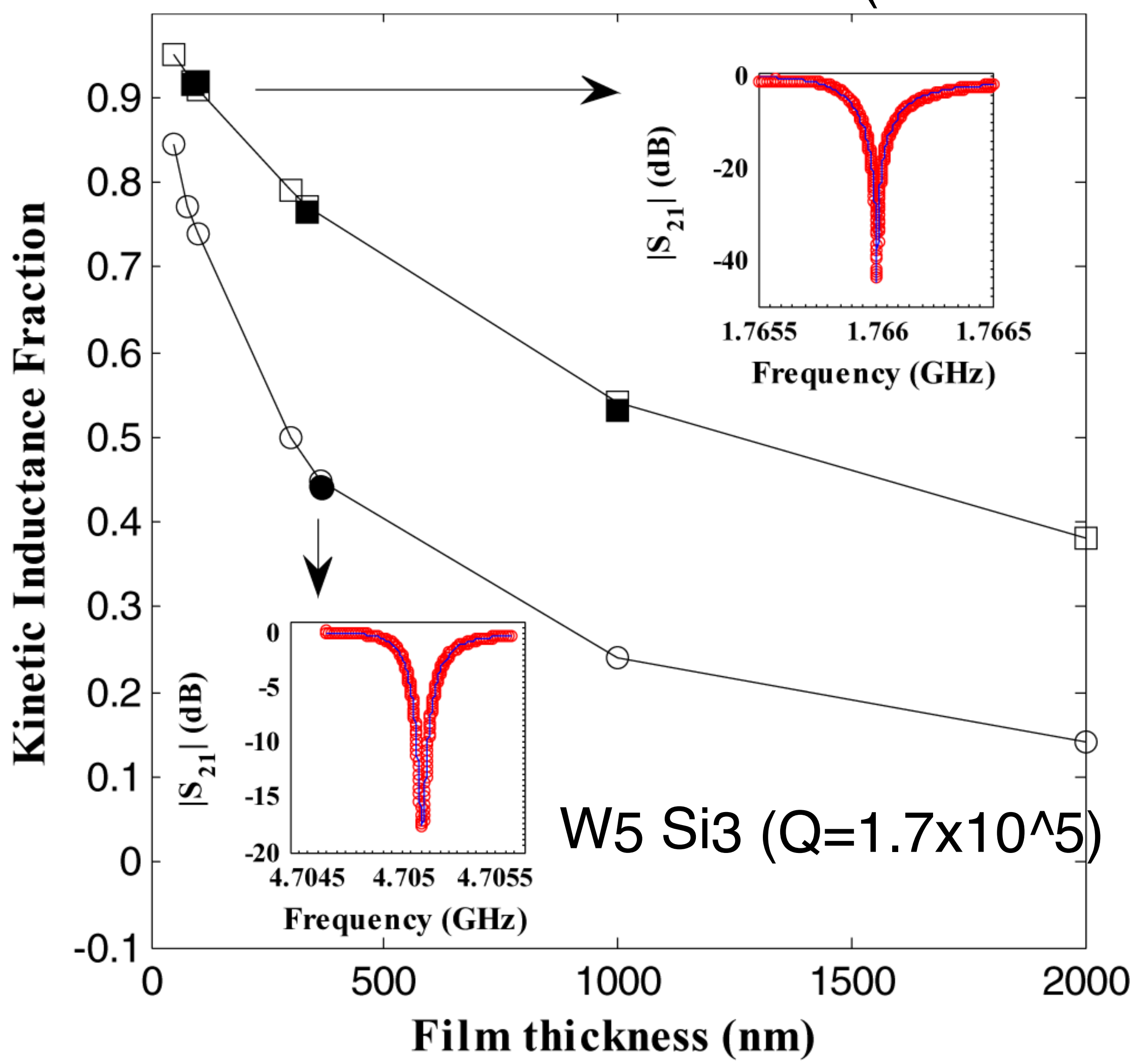
the WSi film was deposited by co-sputtering W and Si targets1, or by sputtering a W0.55Si0.45 target, onto the substrate at room temperature.

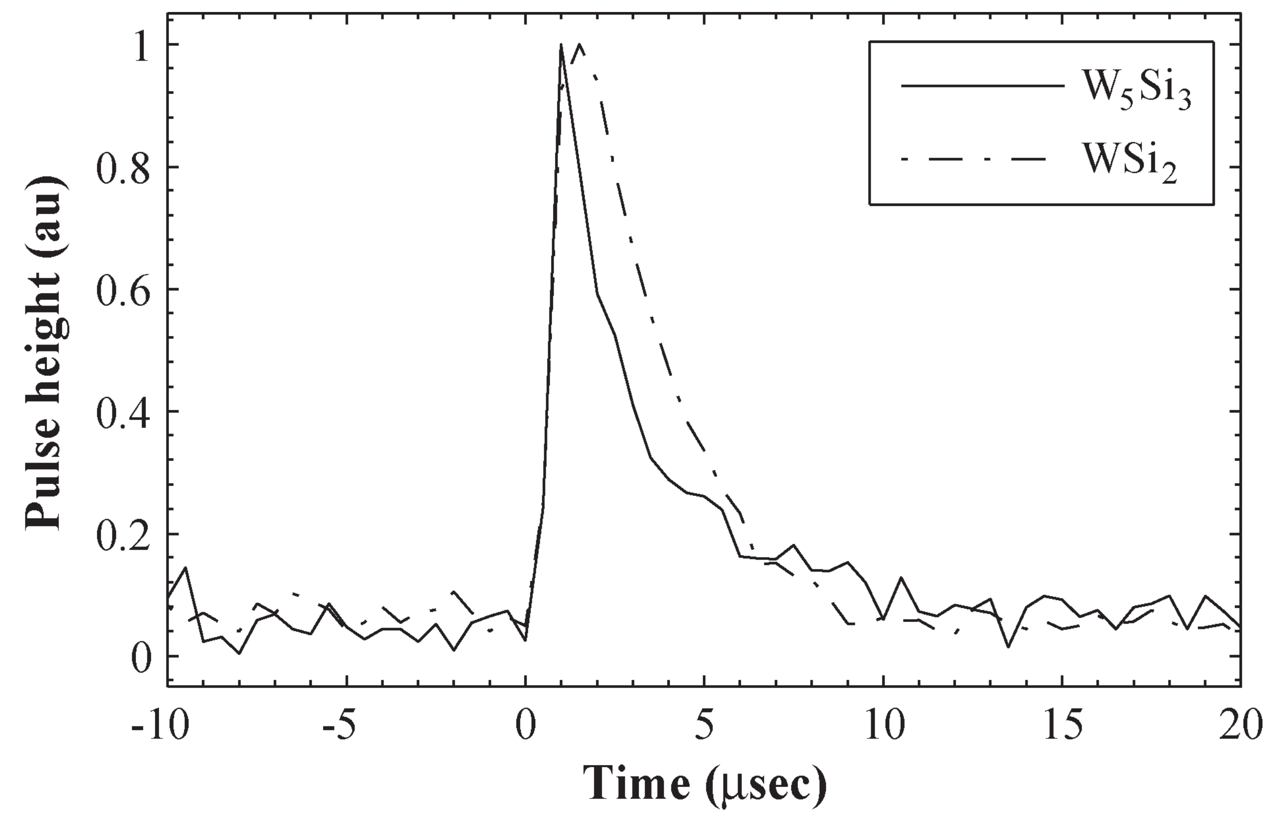
F. Marsili, et al. 2013 "Detecting single infrared photons with 93% system efficiency," Nat. Photonics, 7, 210

O. Quaranta, T. W. Cecil, and A. Miceli, 2013 “Tungsten Silicide Alloys for Microwave Kinetic Inductance Detectors,” IEEE Trans. Appl. Supercond., 23, 2400104.

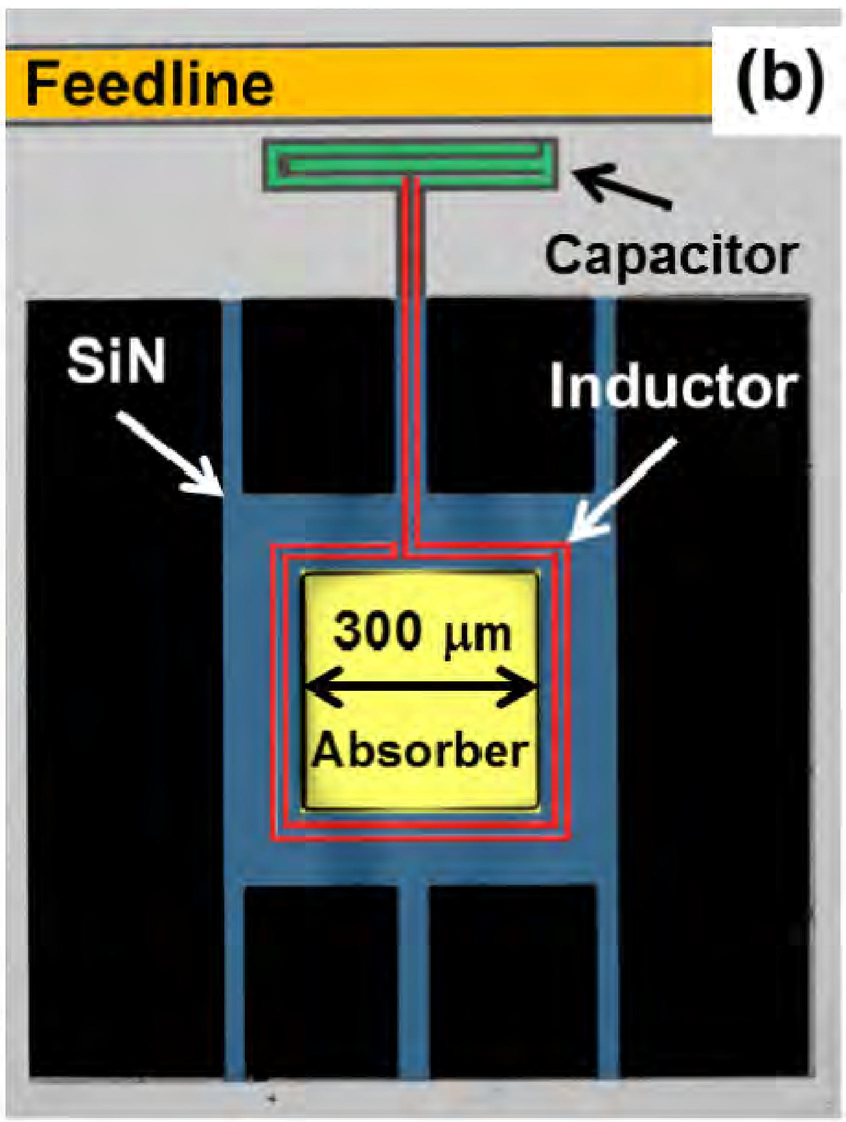
W5 Si3 (Tc = 4K) and WSi2 (Tc = 1.9K) . The films were deposited using DC magnetron sputtering from a single compound target onto both silicon and sapphire wafers.

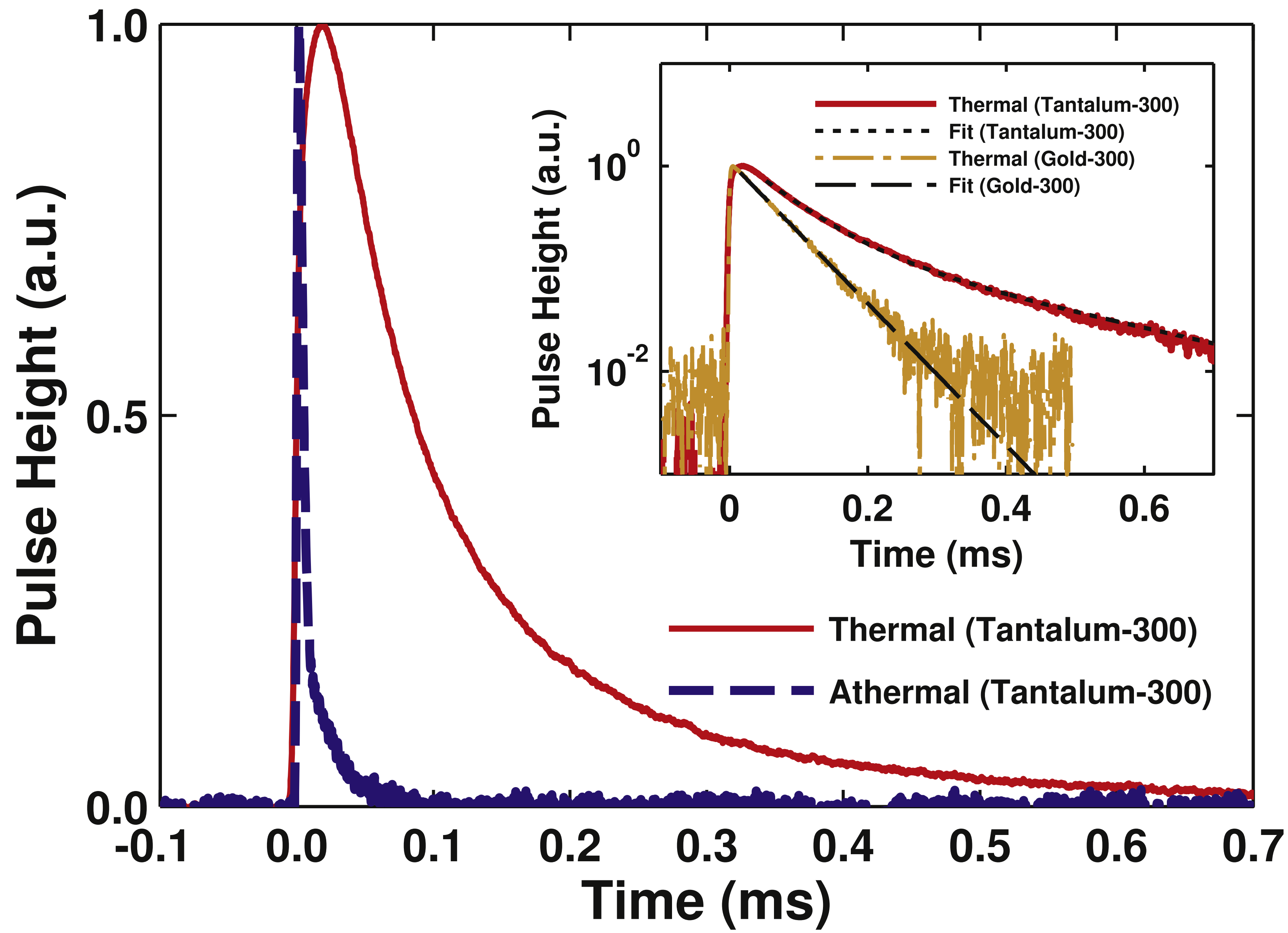
WSi2 (Q=7.1x10^6)





O. Quaranta, et al. 2013, “X-ray photon detection using superconducting resonators in thermal quasi-equilibrium,” Supercond. Sci. Technol., 26, 105021





a 100 nm thick WSi2 film (gray). The interdigitated capacitor (IDC) portion (green) is on solid SiN/Si substrate (500 nm/ 300 µm), while the inductive meander (red) lies on the suspended SiN membrane (blue). The meander encircles the absorber (yellow).

Resolution at 1.5 um

material	Tc	Tbath	fg	NIR resolution
	K	mK	GHz	at 1.5 um
NbN	16	2286	1168	13
NbTiN	14	2000	1022	14
Nb	9.3	1329	679	17
Nb/Al	7.0	1000	511	20
TiN	4.5	643	329	25
WSi	4.2	600	307	26
TiN	1.1	157	80	51
Al	1.2	171	88	48
Al/Ti	0.7	100	51	63
Ti	0.40	57	29	84

$$R = \frac{\lambda}{\Delta\lambda} = \frac{1}{2.355}\sqrt{\frac{\eta h\nu}{F\Delta}}$$

$$\eta = 0.57, \quad F = 0.2 \quad \text{Fano factor}$$

まとめ

- 超伝導検出器
  - ミリ波サブミリ波
  - 冷却が必須
  - MKIDは多ピクセル読み出しが容易
- 近赤外•可視•紫外線
  - 低分散面分光
  - 高速読出
  - 高い量子効率