Submicron Wide Coplanar Waveguide Resonators

Sensitivity improvement through width reduction

Reinier Janssen, 28th of July 2011

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Outline

Submicron Wide Coplanar Waveguide Resonators

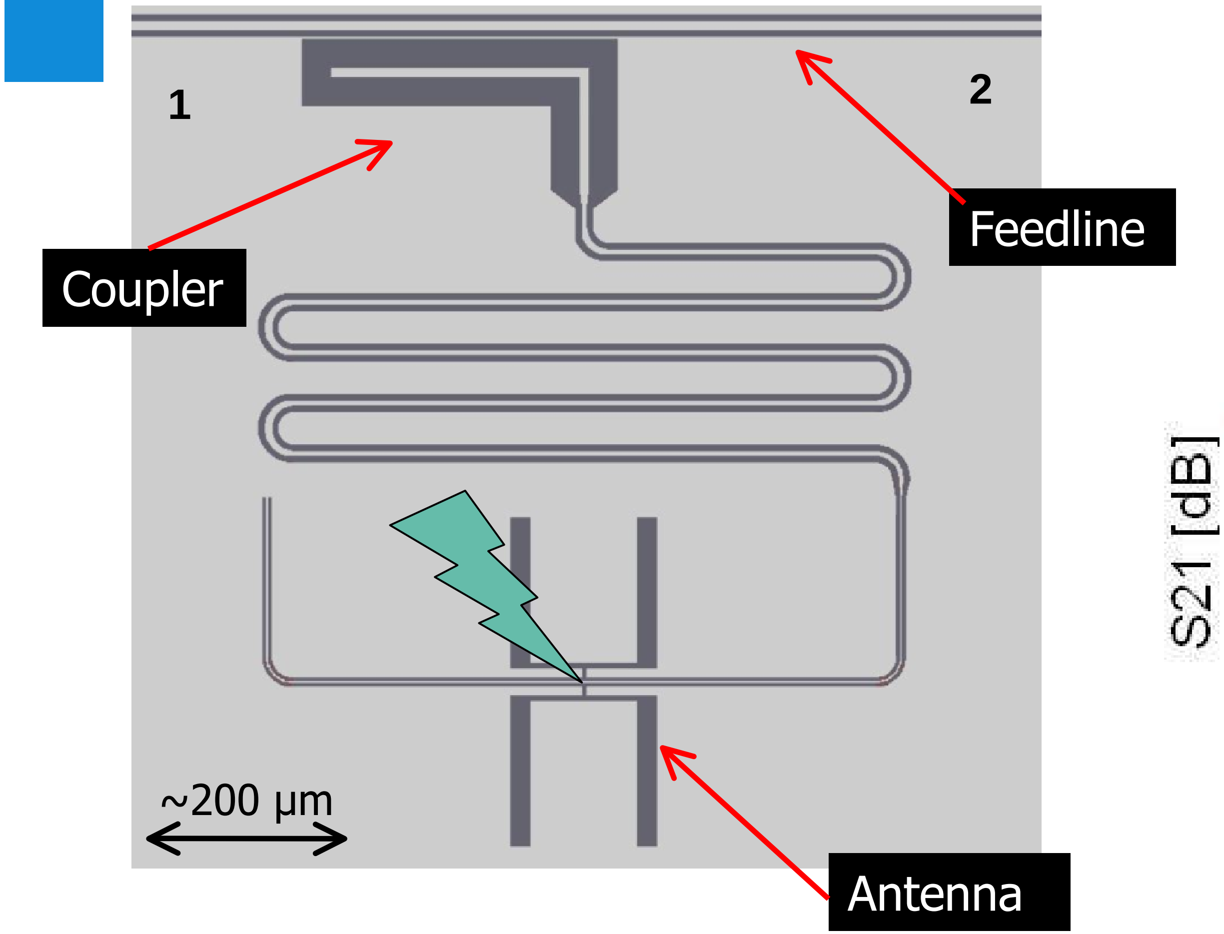
- Sensitivity Requirements for Space-Based THz Astronomy

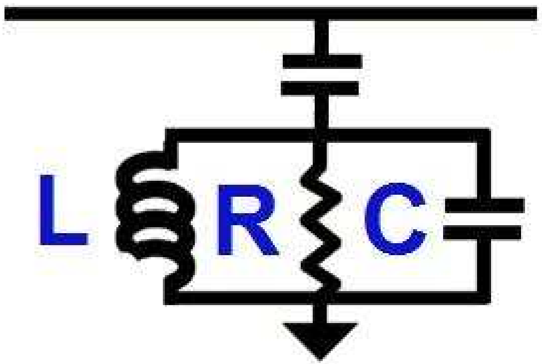
- Sensitivity Improvement by Width Reduction
  - Known width dependency
  - Fabrication of submicron wide KIDs
  - Results of a systematic study

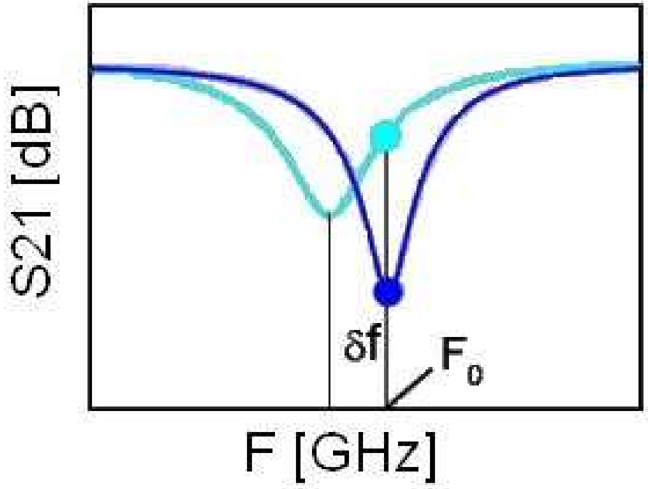
- Conclusions

Kinetic Inductance Detector

Quarterwave resonator

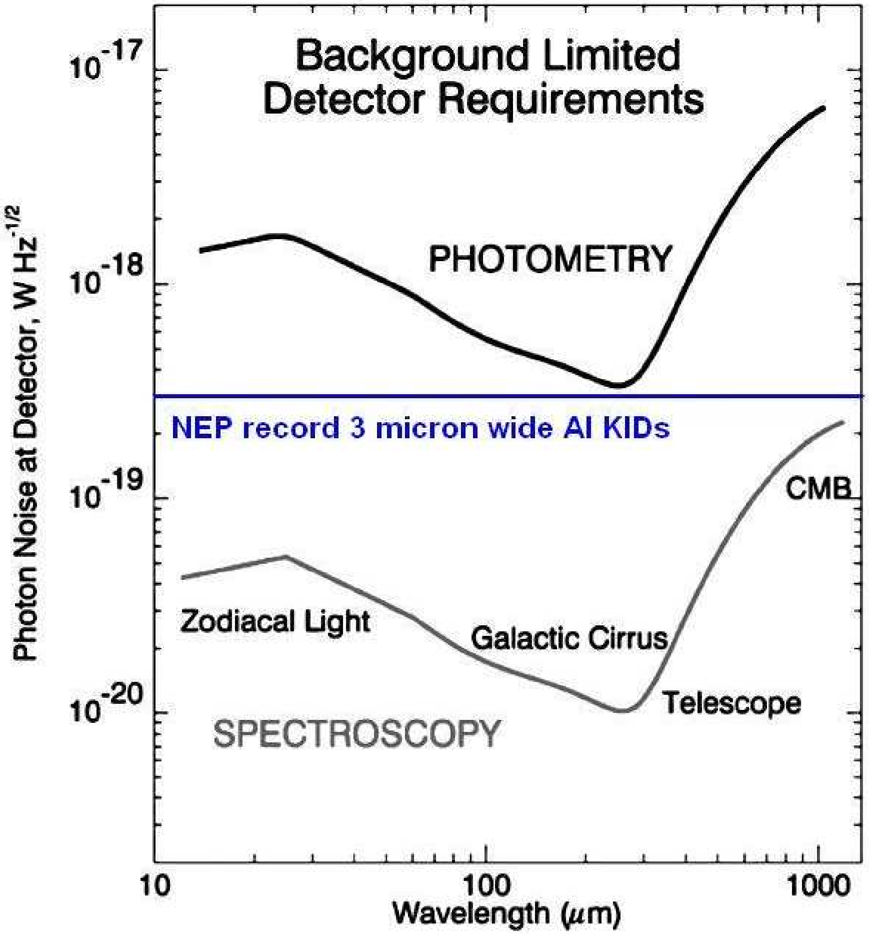


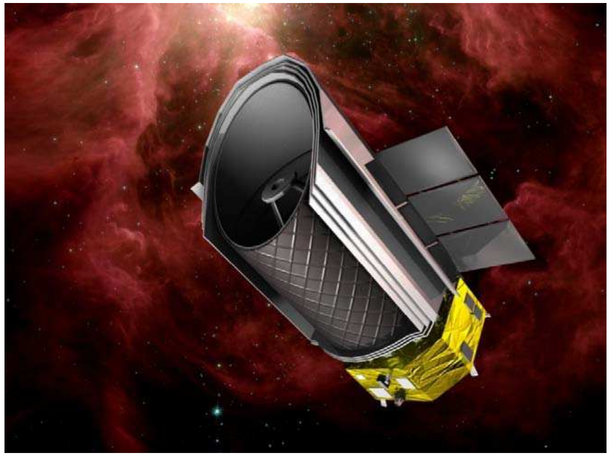


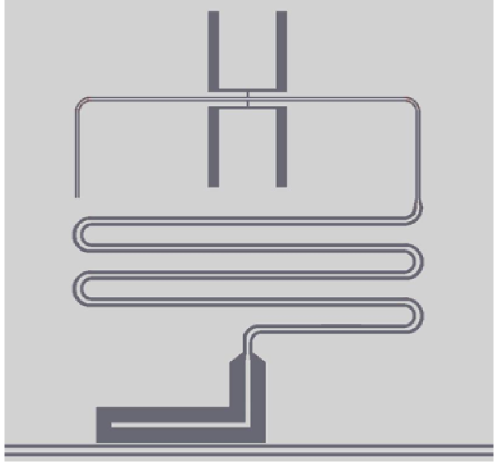


KIDs for Space-based Astronomy

Sensitivity requirements





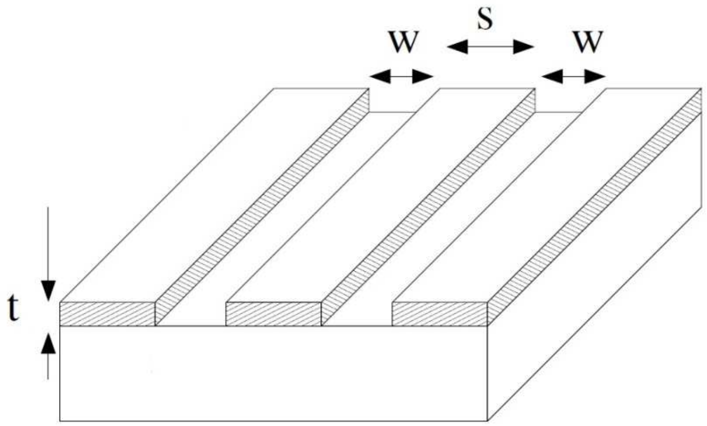


KID Noise Equivalent Power

Sensitivity improvement by width reduction

NEP = noise / responsivity

$$NEP_x(\omega) = \sqrt{S_x(\omega, P_{\mathrm{int}})}\left(\frac{\eta\tau}{\Delta}\frac{\delta x}{\delta N_{qp}}\right)^{-1}$$

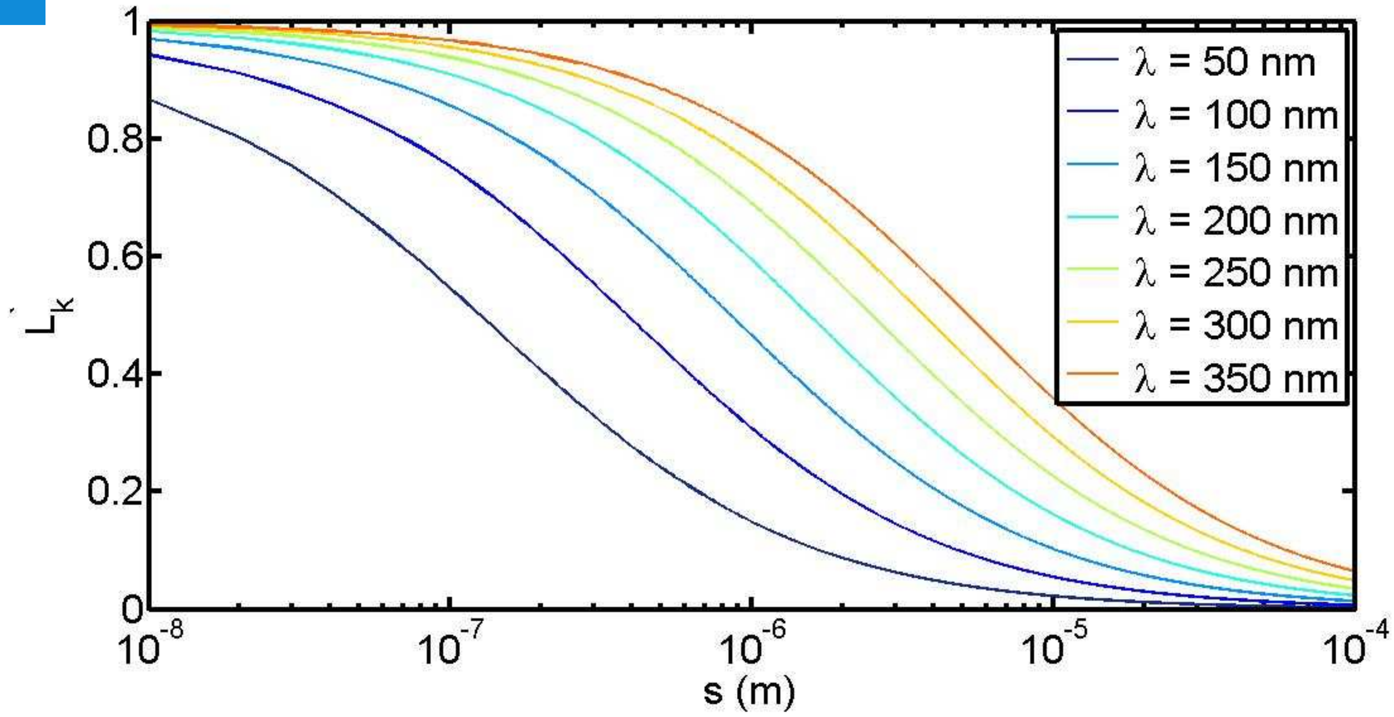


Responsivity depends on

$$\frac{\delta x}{\delta N_{qp}} \propto \frac{L_k^{'} \times Q}{V}$$

Kinetic Inductance

Width dependence



t=100 nm

Aluminum
λ = 70 nm

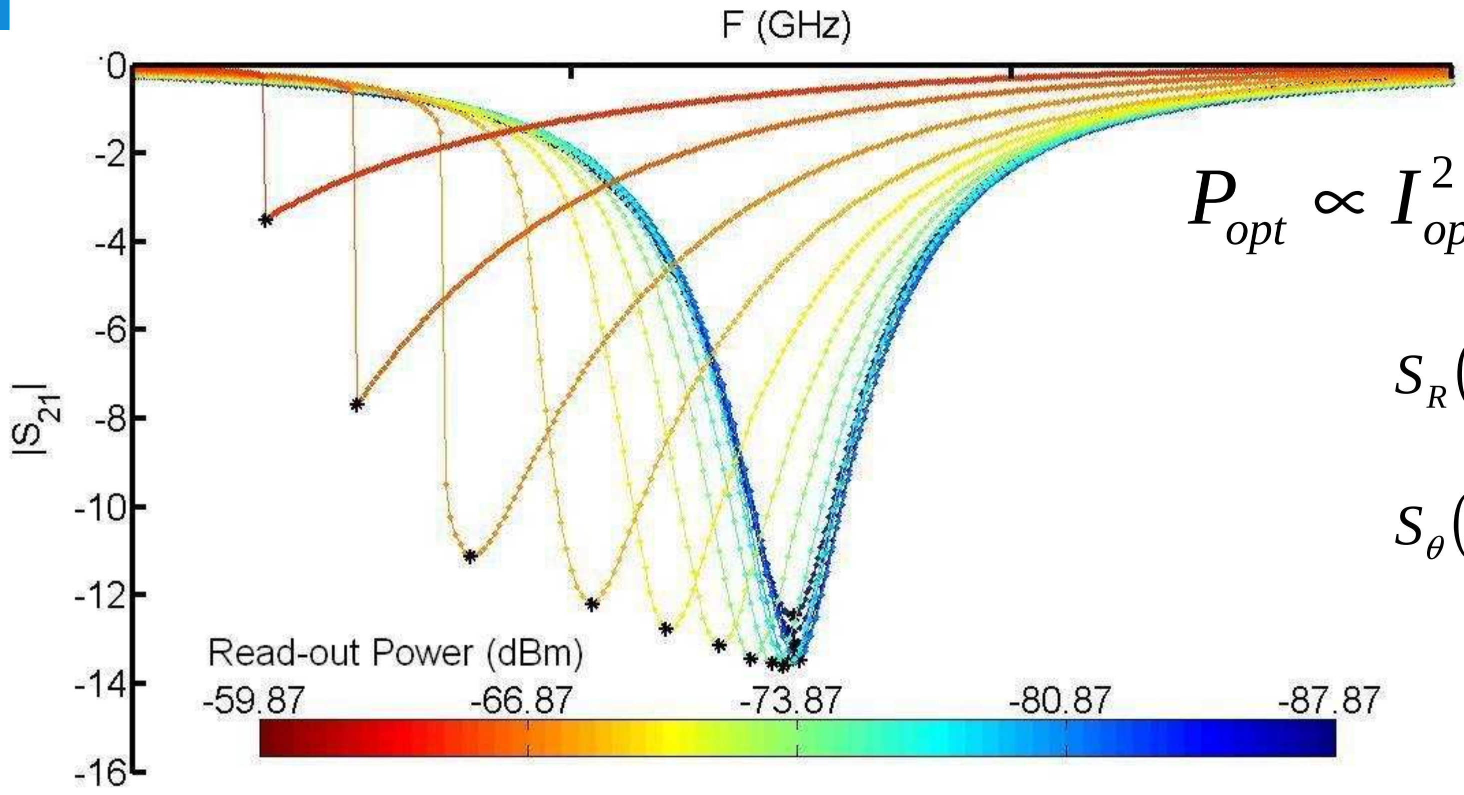
$$L_k' = \frac{L_k}{L_{tot}} \propto s^{-0.7}$$

NbTiN
λ = 300 nm

$$L_k' = \frac{L_k}{L_{tot}} \propto s^{-0.3}$$

Power Handling

Width dependence



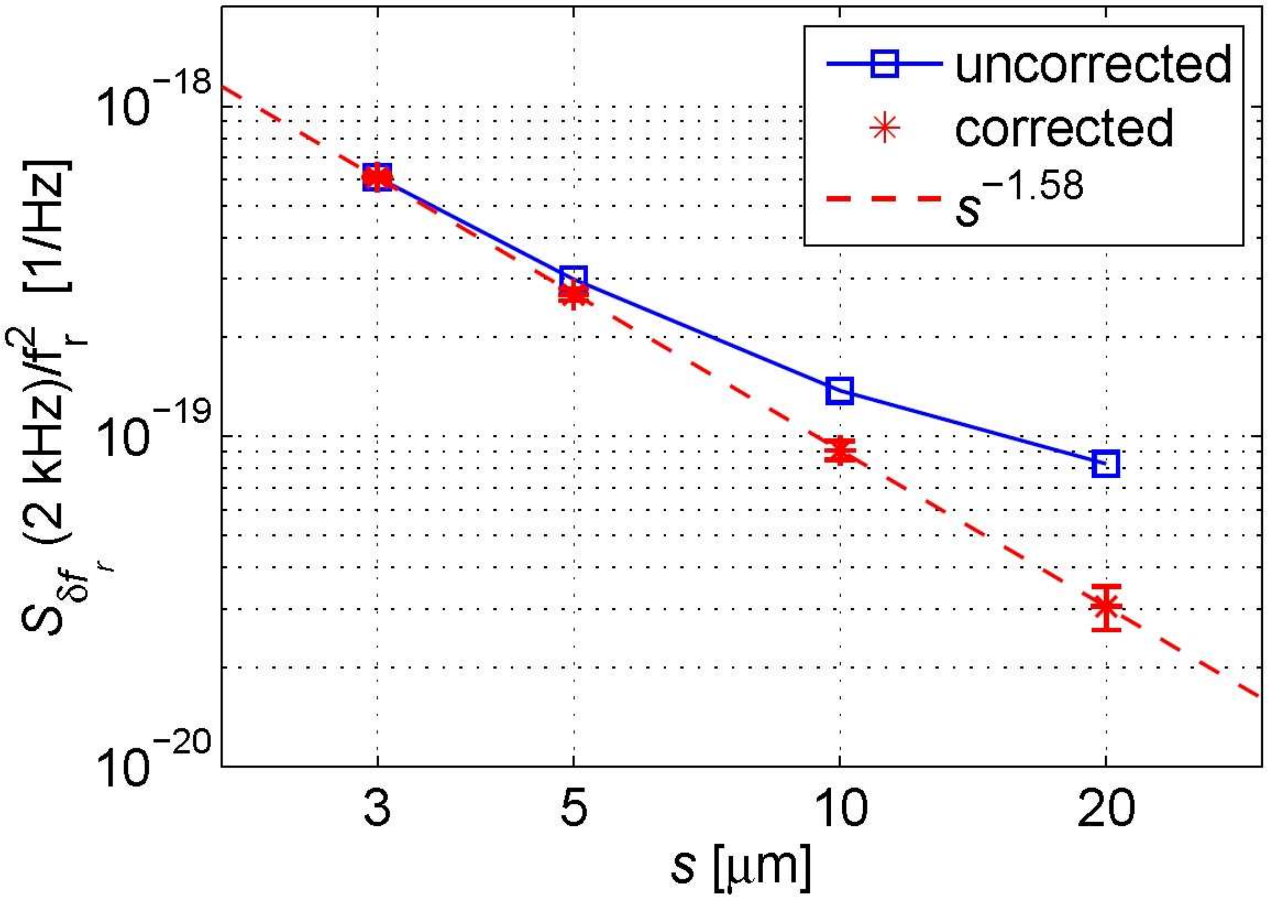
$$P_{opt} \propto I_{opt}^2 \propto s^2 t^2$$

$$S_R(\omega, P) \propto \frac{1}{P}$$

$$S_\theta(\omega, P) \propto \frac{1}{P^{0.5}}$$

Frequency Noise

Width dependence



$$S_\theta(\omega, P) \propto P^{-0.5} S^{-1.6}$$

Gao et.al. APL 2008

KID Noise Equivalent Power

Sensitivity improvement by width reduction

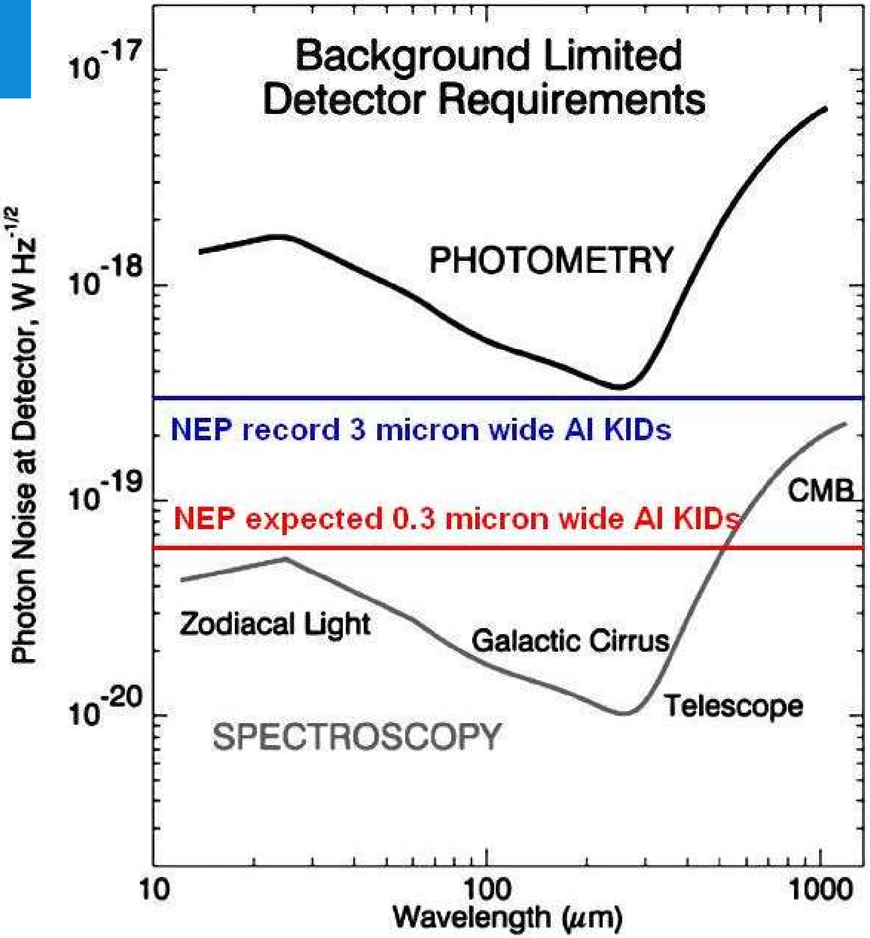
$$NEP_x(\omega) = \sqrt{S_x(\omega, P)}\left(\frac{\eta\tau}{\Delta}\frac{\delta x}{\delta N_{qp}}\right)^{-1}$$

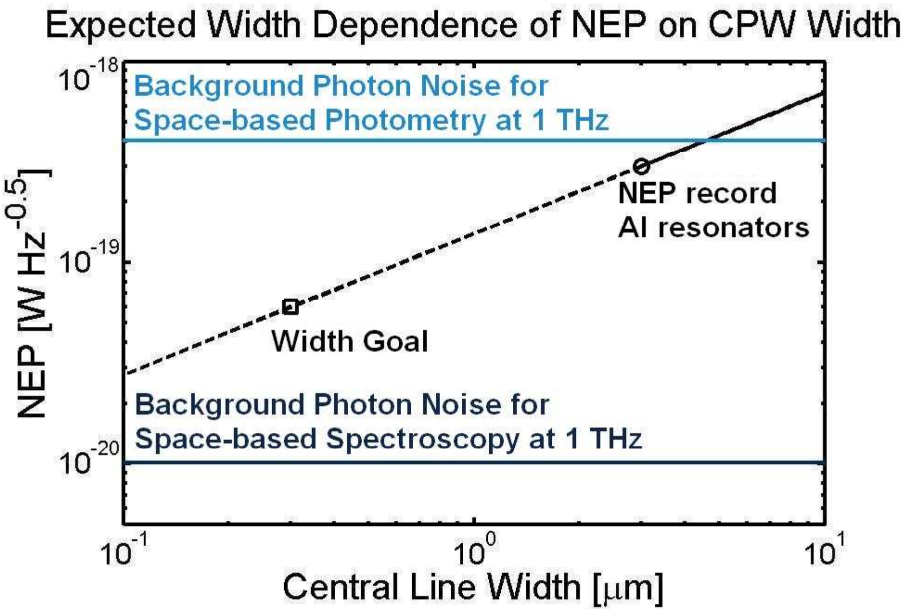
Width (S) dependence	S_θ	S_R	$\delta x/\delta N_{qp}$	NEP_θ	NEP_R
Al expected	$S^{-2.6}$	$S^{-2.0}$	$S^{-1.7}$	$S^{0.4}$	$S^{0.7}$
NbTiN expected	$S^{-2.6}$	$S^{-2.0}$	$S^{-1.3}$	$S^{0.0}$	$S^{0.3}$

Do these relationships hold for CPW widths below a few μm?

MKIDs for Space-based Astronomy

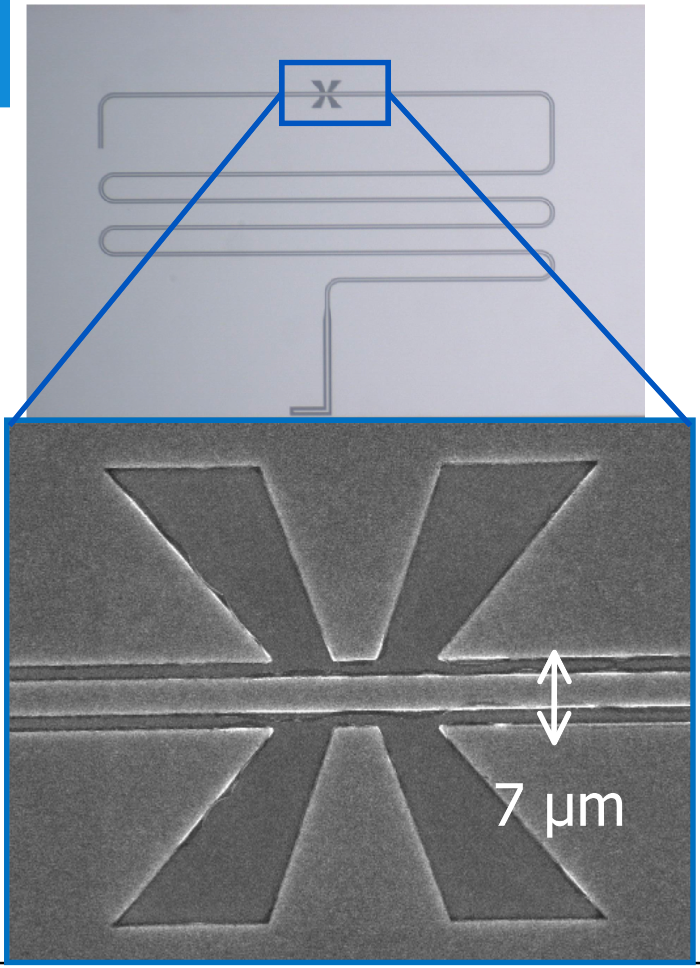
Sensitivity requirements





Submicron Resonator Fabrication

Fabrication Changes

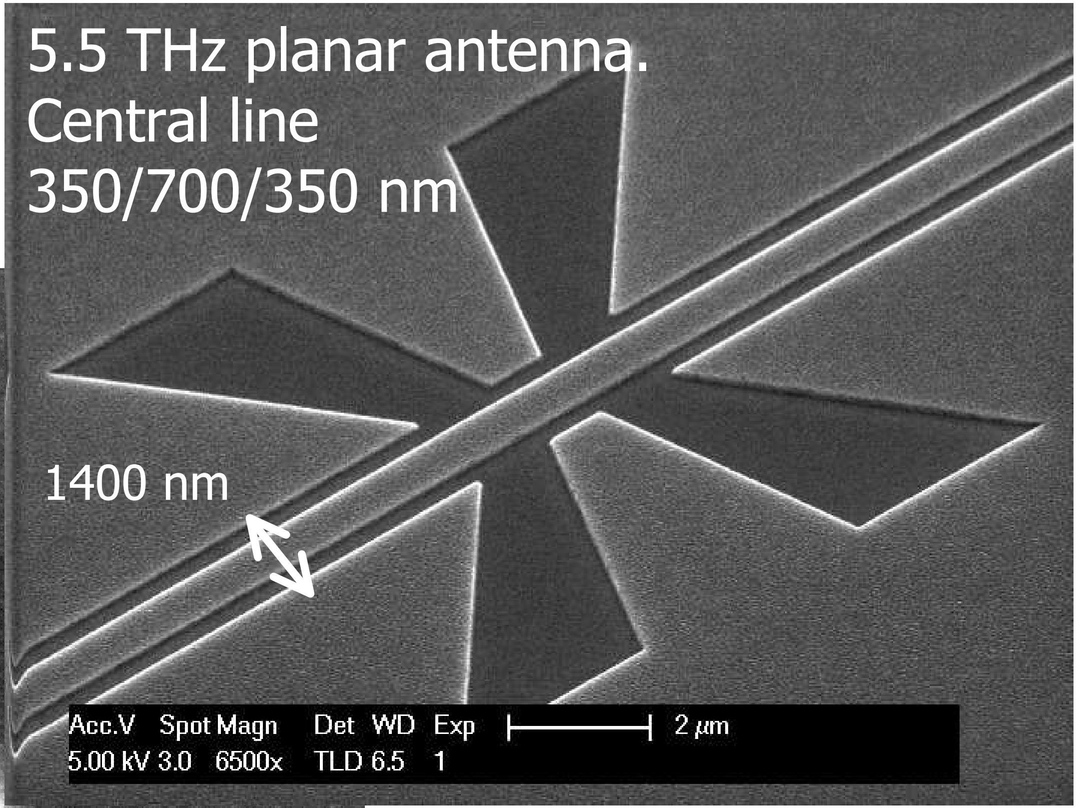


Conventional
- Optical Lithography
- Wet Etching

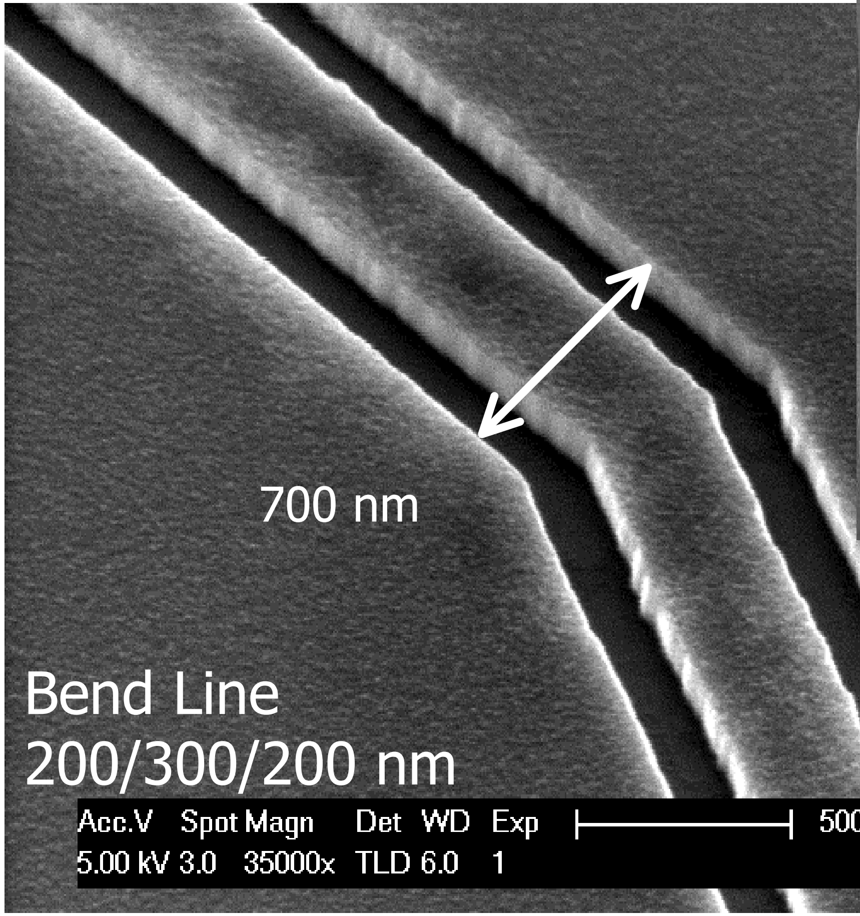
Submicron resonators
- Electron-beam Lithography
- Reactive Ion Etching

Submicron Fabrication

Results



5.5 THz planar antenna.
Central line
350/700/350 nm



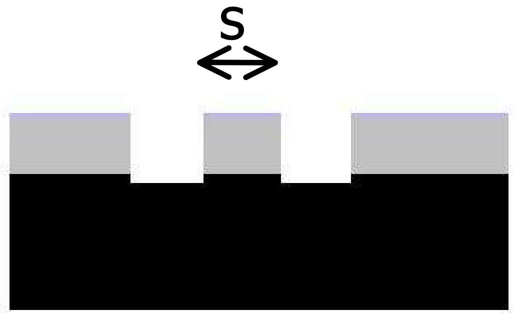
Bend Line
200/300/200 nm

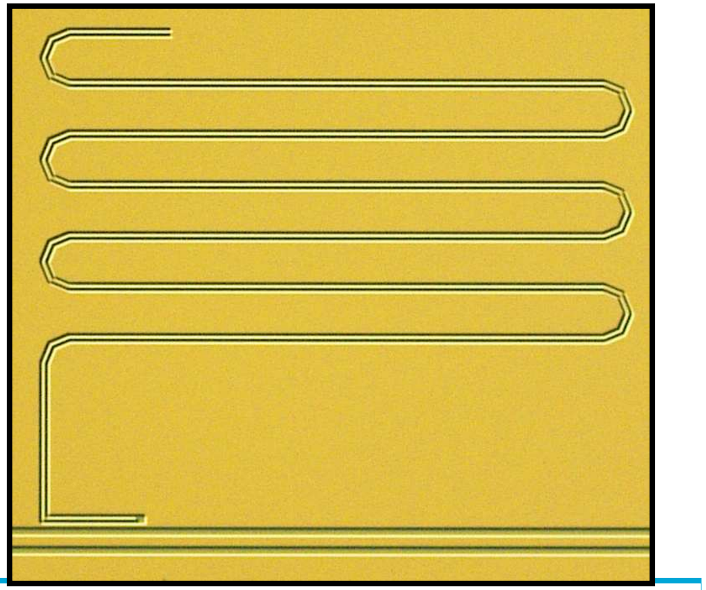
Systematic Width Study

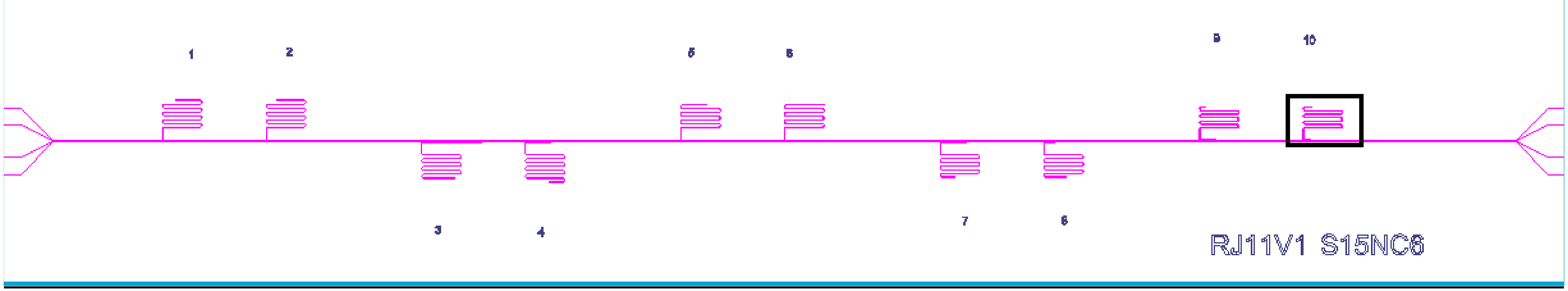
Using NbTiN submicron resonators

Central line width (s)

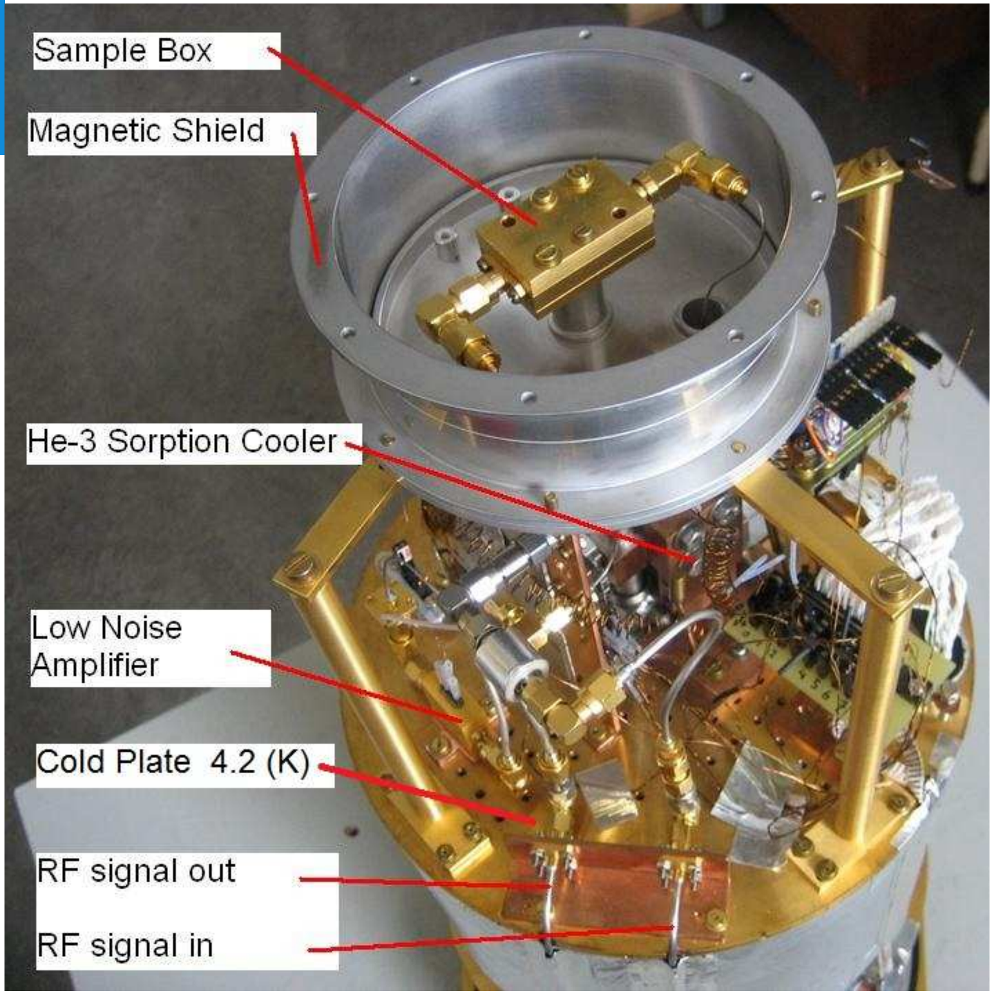
- 300 nm
- 600 nm
- 1000 nm
- 1500 nm
- 3000 nm

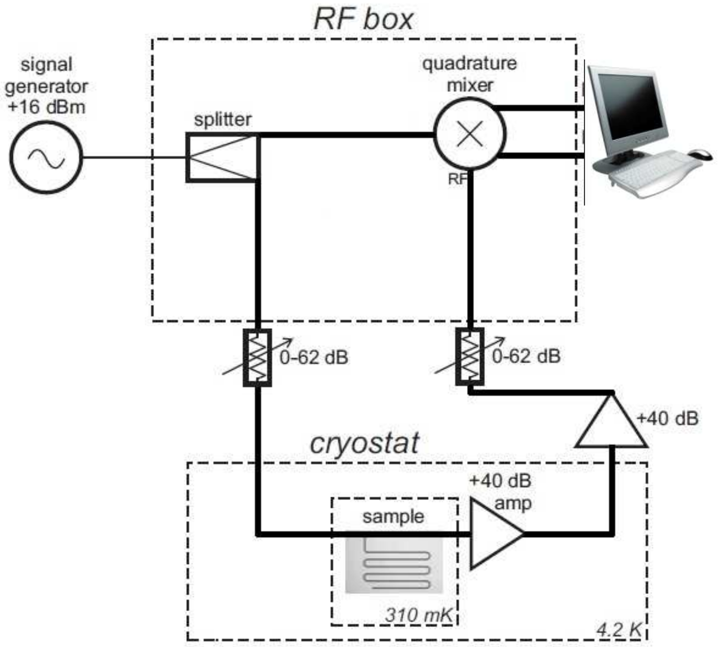


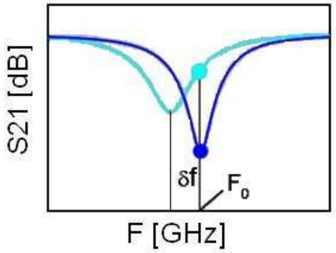




Measurement Setup







Systematic Width Study

Using NbTiN submicron resonators

Central line width (s)

- 300 nm
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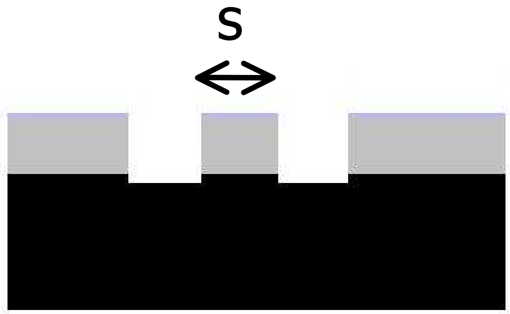


Investigate:

- Responsivity
- Frequency Noise
- Power Handling

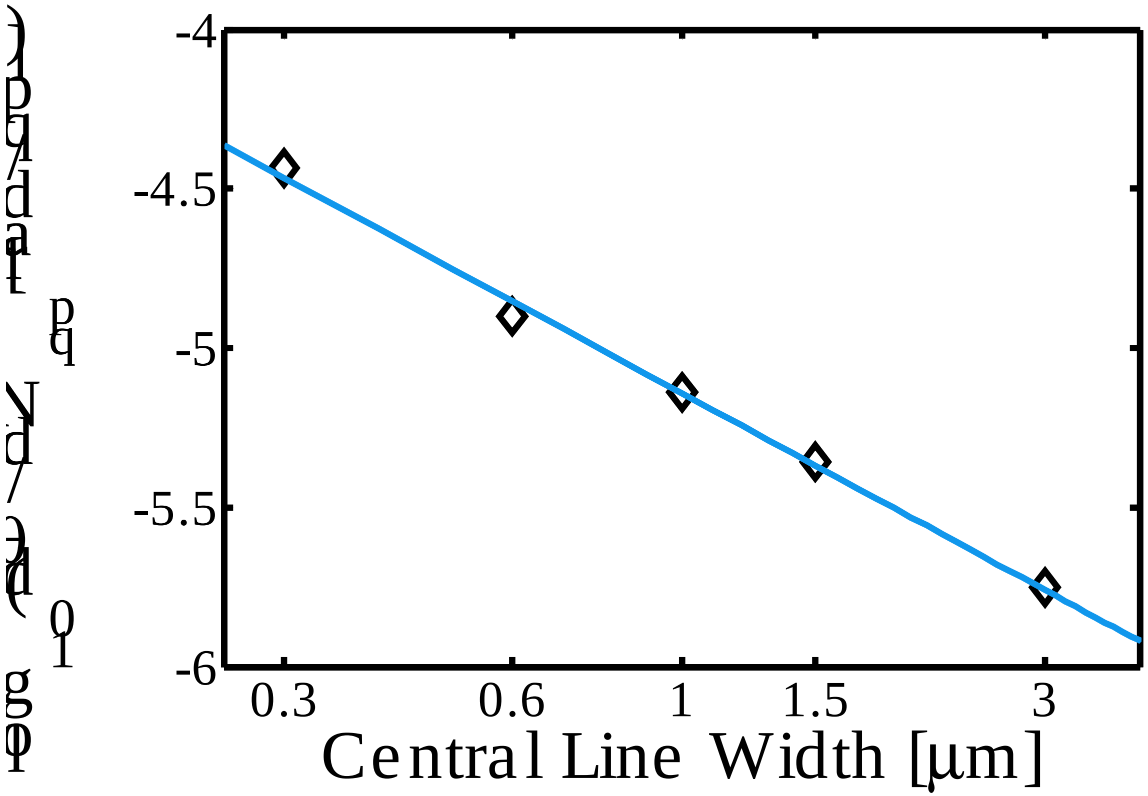
- Noise Equivalent Power

$$NEP(\omega) \propto \sqrt{S(\omega,P)}\left(\frac{\Delta}{\tau}\frac{\delta\theta}{\delta N_{qp}}\right)$$

Responsivity

NbTiN width study

$$NEP(\omega) = \sqrt{S(\omega, P)}\,\frac{\Delta}{\eta\tau}\left(\frac{\delta\theta}{\delta N_{qp}}\right)^{-1}$$



Theory:

$$\frac{\delta\theta}{\delta N_{qp}} \propto s^{-1.3}$$

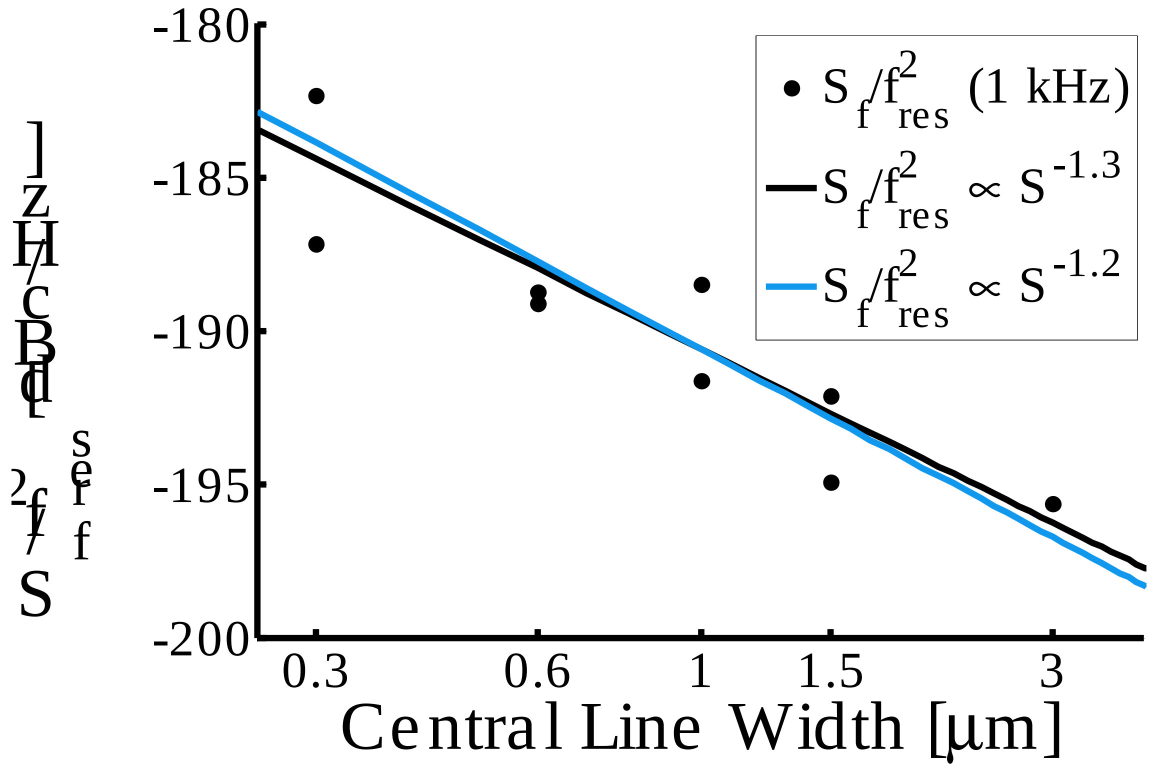
This work:

$$\frac{\delta\theta}{\delta N_{qp}} \propto s^{-1.29\pm0.04}$$

Frequency Noise

NbTiN width study

$$NEP(\omega) = \sqrt{S(\omega,P)}\,\frac{\Delta}{\eta\tau}\left(\frac{\delta\theta}{\delta N_{qp}}\right)^{-1}$$



Frequency Noise at P_{int} = -30 dBm

Theory:

$S_\theta \propto s^{-1.6} P^{-0.5}$

This work:

- Fit to all data

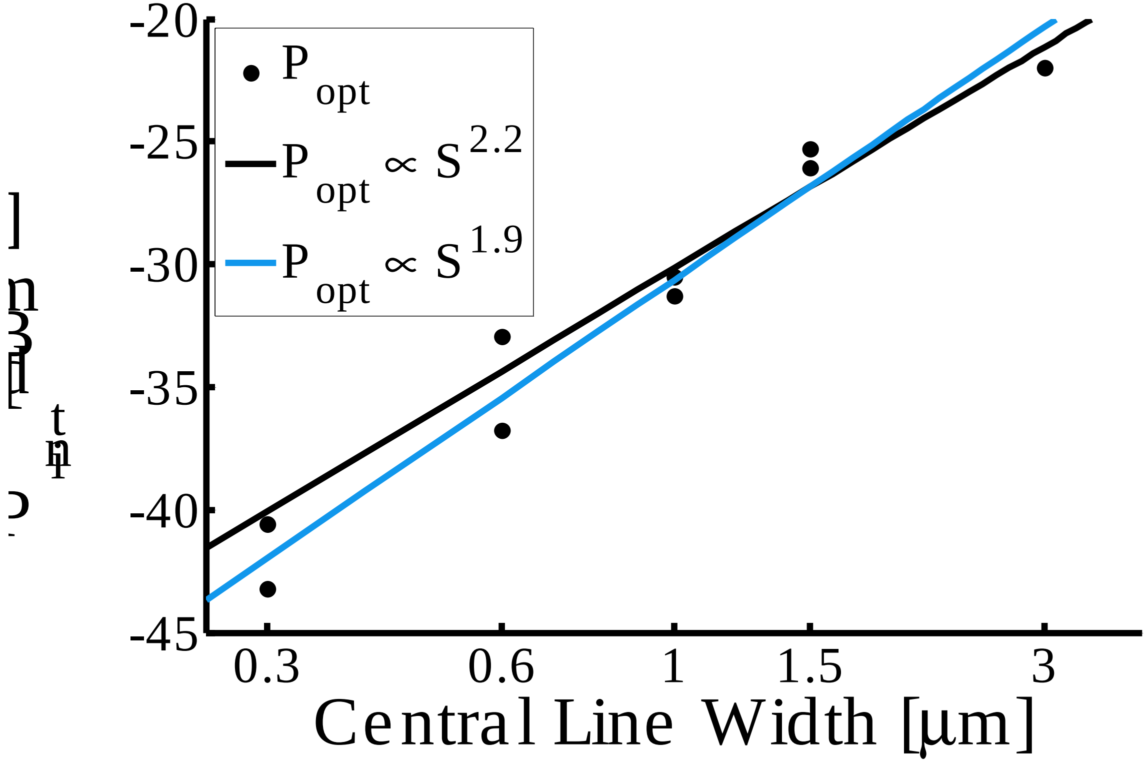
$S_\theta \propto s^{-1.28\pm0.21}$

- Fit to S ≥ 1 µm

$S_\theta \propto s^{-1.19\pm0.50}$

Power Handling

NbTiN width study



$$NEP(\omega) \propto \sqrt{S(\omega, P)}\left(\frac{\Delta}{\tau}\frac{V}{L_k^{'} Q}\right)$$

Theory:

$$P_{opt} \propto I_{opt}^2 \propto s^2 t^2$$

This work:

- Fit to all data

$$P_{opt} \propto s^{2.16 \pm 0.20}$$

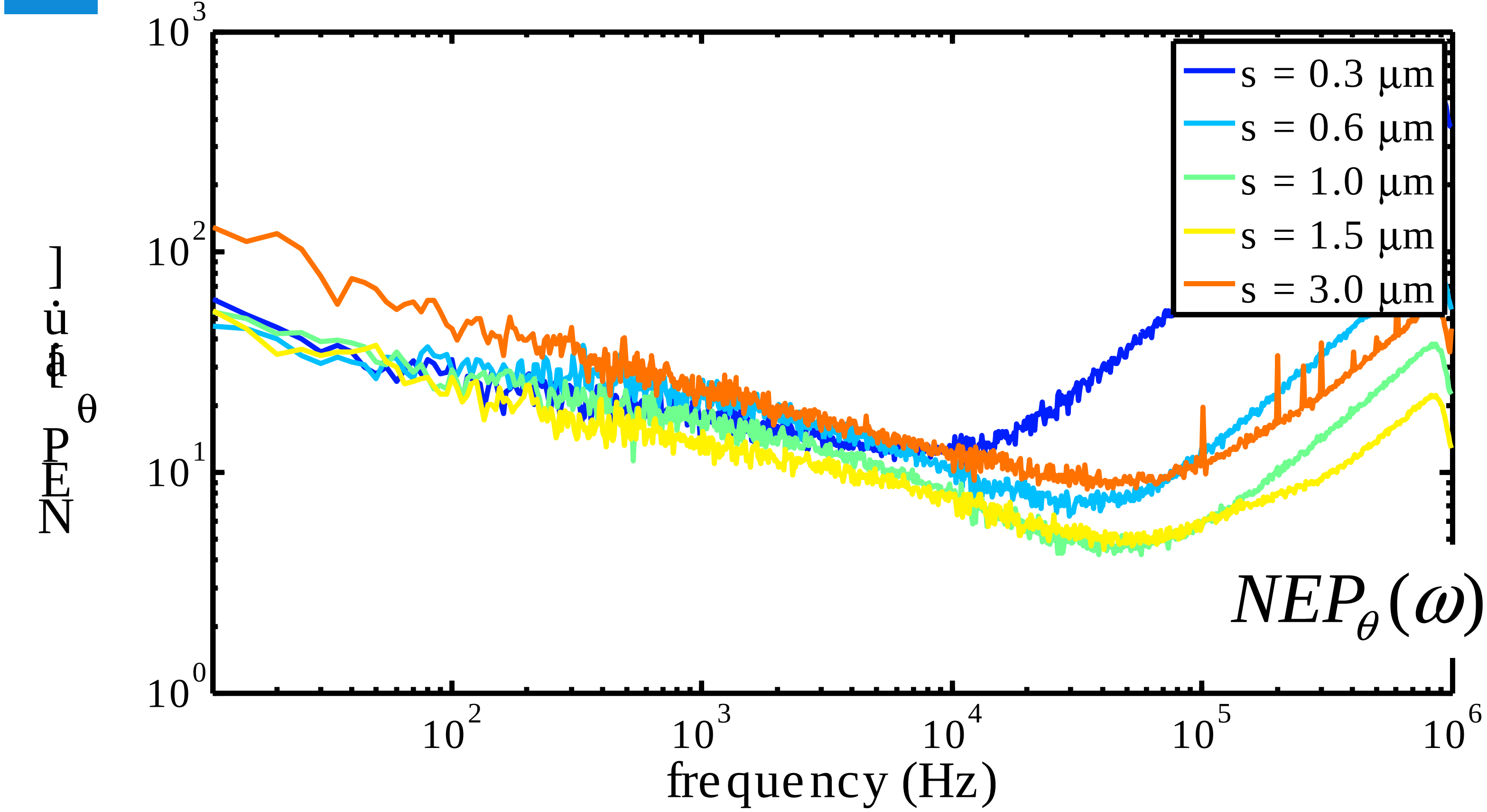
- Fit to S ≥ 1 μm

$$P_{opt} \propto s^{1.89 \pm 0.34}$$

Noise Equivalent Power

NbTiN width study

$$NEP_\theta(\omega) = \sqrt{S_\theta(\omega, P)}\frac{\Delta}{\eta\tau}\left(\frac{\delta\theta}{\delta N_{qp}}\right)^{-1}$$



$$NEP_\theta(\omega) \propto s^{0.11 \pm 0.27}$$

Noise Equivalent Power

$$NEP_x(\omega) \propto \sqrt{S_x(\omega, P_{\text{int}})}\left(\frac{\delta x}{\delta N_{qp}}\right)^{-1}$$

Width (S) dependence	S_θ	S_R	$\delta x/\delta N_{qp}$	NEP_θ	NEP_R
Al expected	$S^{-2.6}$	$S^{-2.0}$	$S^{-1.7}$	$S^{0.4}$	$S^{0.7}$
NbTiN expected	$S^{-2.6}$	$S^{-2.0}$	$S^{-1.3}$	$S^{0.0}$	$S^{0.3}$
NbTiN measured	$S^{-2.36\pm0.25}$	$S^{-2.16\pm0.20}$	$S^{-1.29\pm0.04}$	$S^{0.11\pm0.27}$	$S^{0.21\pm0.11}$

No change in width dependency found for S < 1 μm.

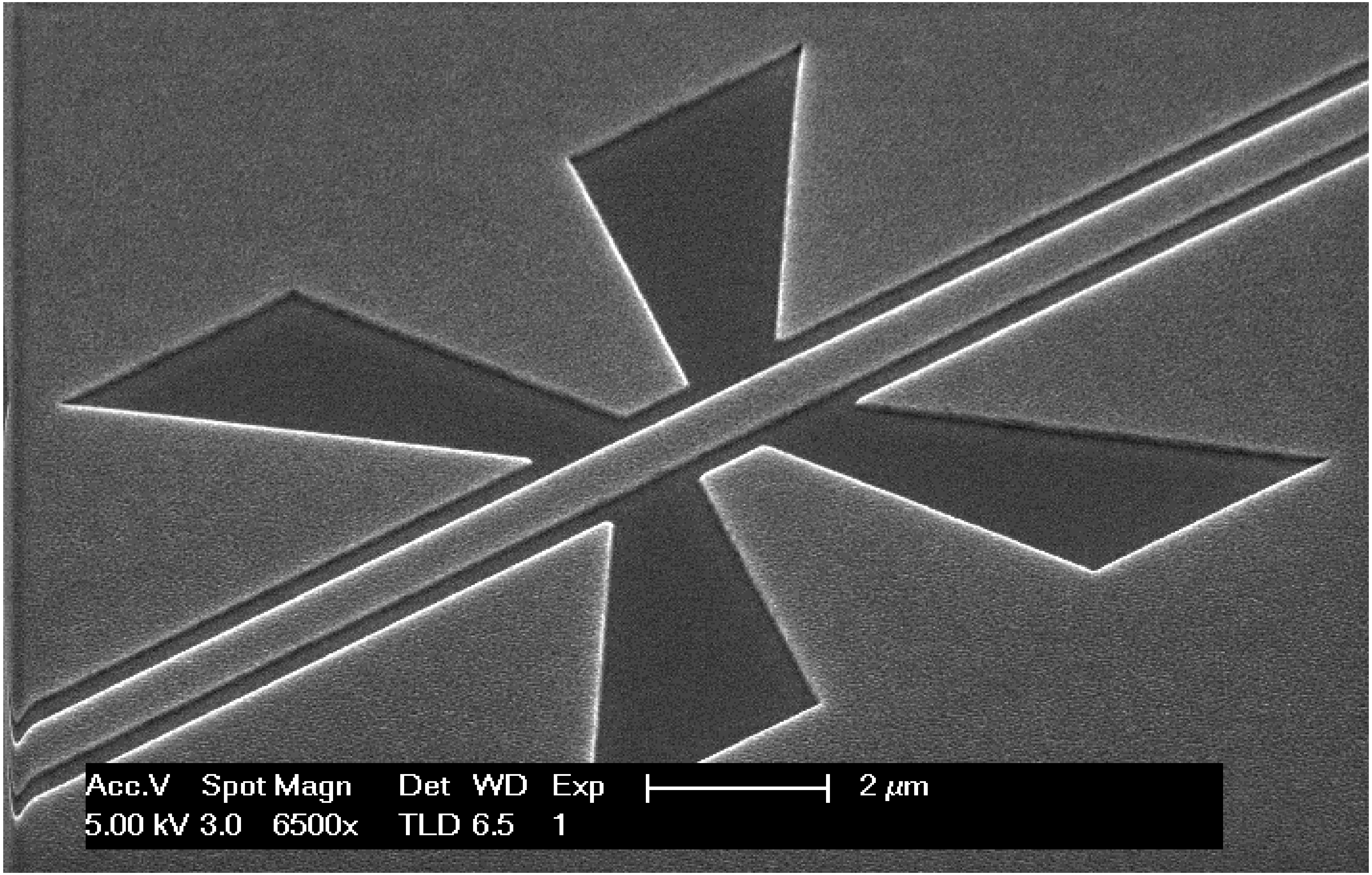
Conclusions

Submicron KIDs for Astronomy

- Submicron KIDs (1000 nm ≥ W ≥ 200 nm) can be made reliably.

- A systematic width study of NbTiN resonators shows
  - no significant sensitivity improvement in phase read-out for NbTiN
  - no change in the width dependencies of responsivity, noise and power handling for submicron resonators

- This encourages a similar study using Al or TiN resonators


Acc.V Spot Magn Det WD Exp
5.00 kV 3.0 6500x TLD 6.5 1
2 μm

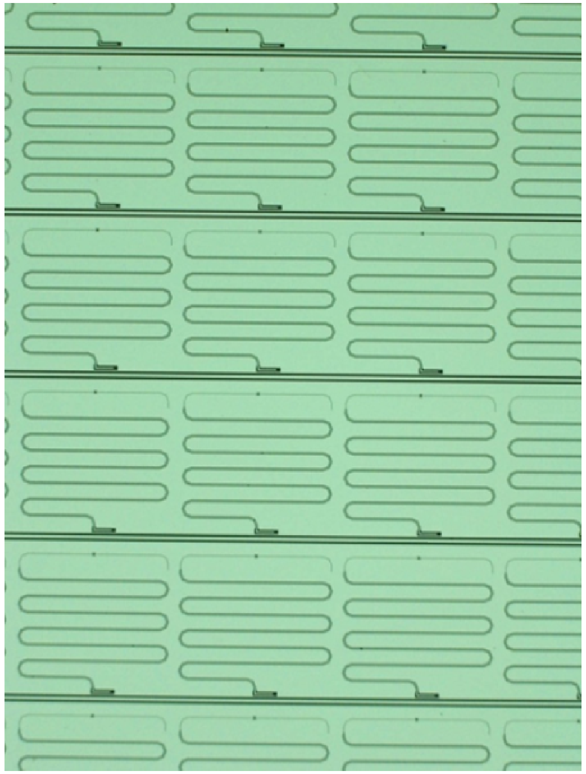
Kinetic Inductance Detectors (KIDs)

Requirement:

Promising detector technology for astronomy

Current Performance:

- Large arrays
- High sensitivity
- Large dynamic range



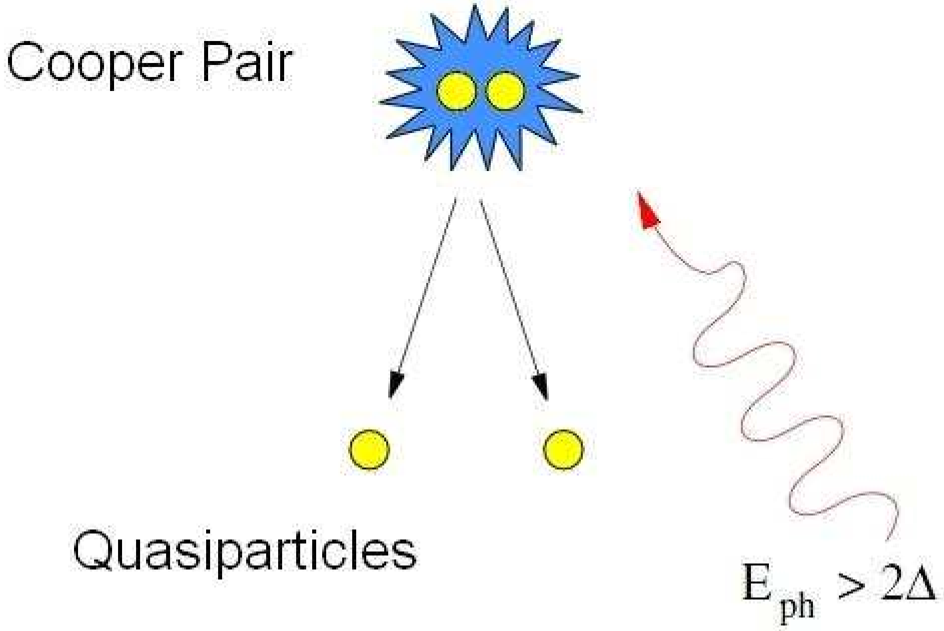
Superconducting Pair-Breaking

Cooper pairs

- Supercurrent
- Inductance (L)

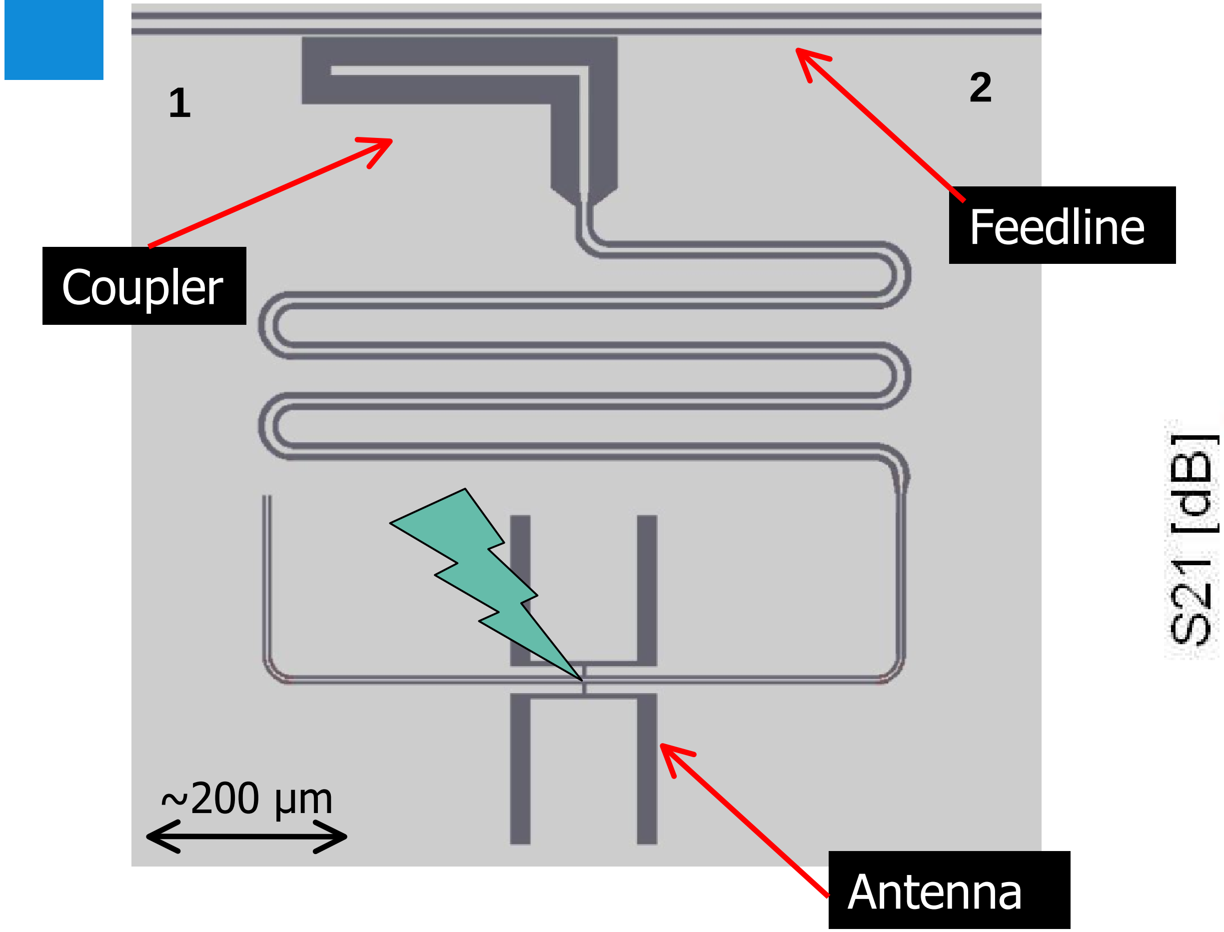
Quasiparticles

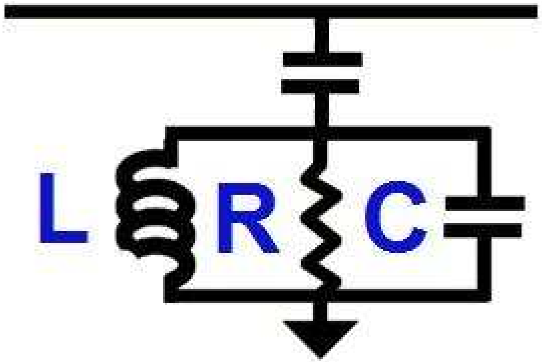
- Normal Current
- Resistance (R)

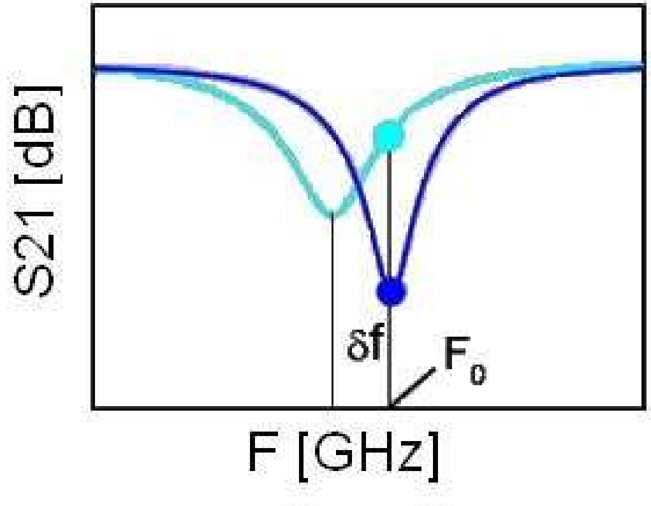


Kinetic Inductance Detector

Quarterwave resonator





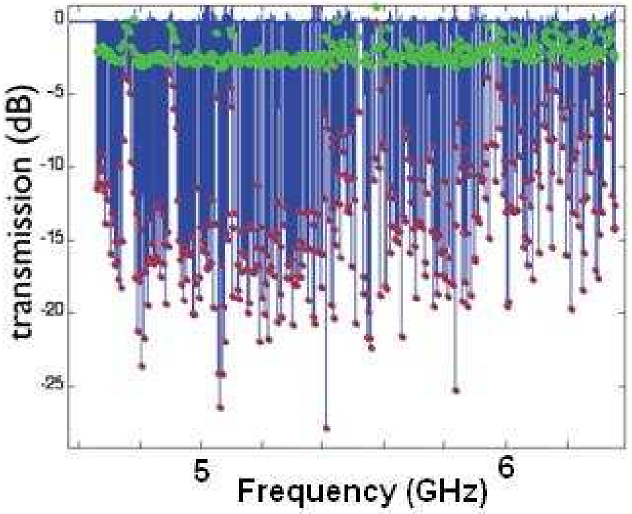


Kinetic Inductance Detector

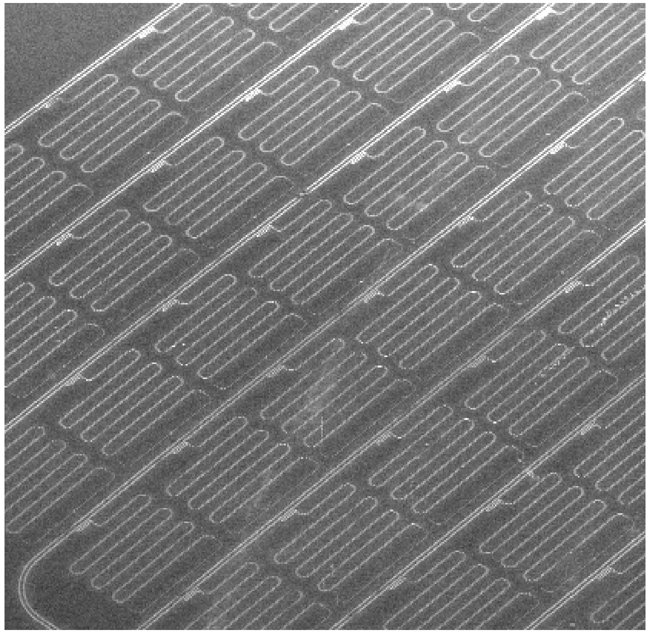
Frequency Domain Multiplexing

Large arrays:

Resonators of Varying Length
Frequency Domain Multiplexing
2 coax cables ≈ 5.000 pixels

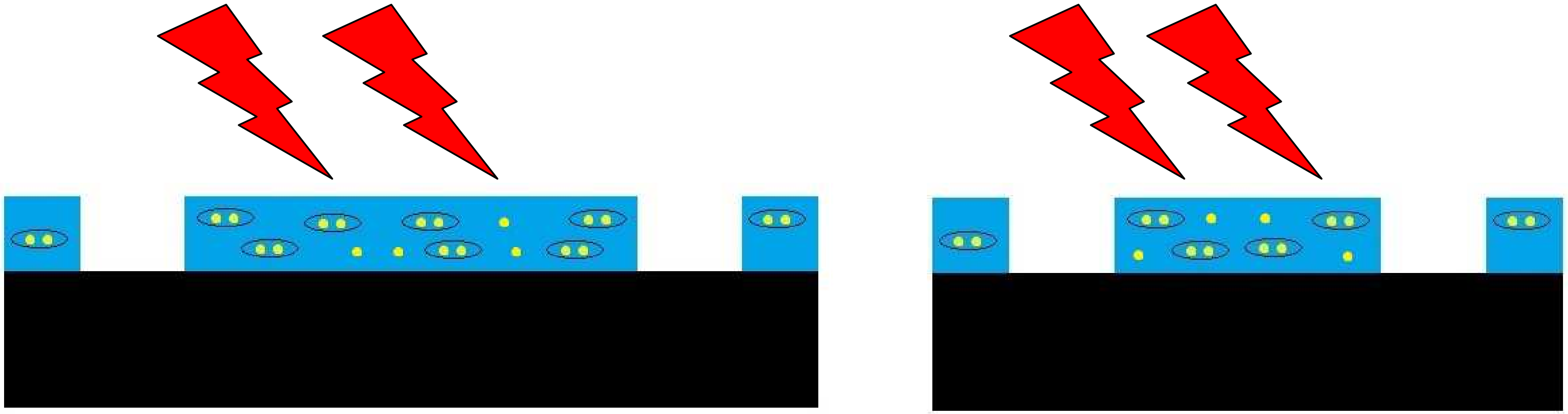


Multiplexed readout of 400 KIDs



Volume

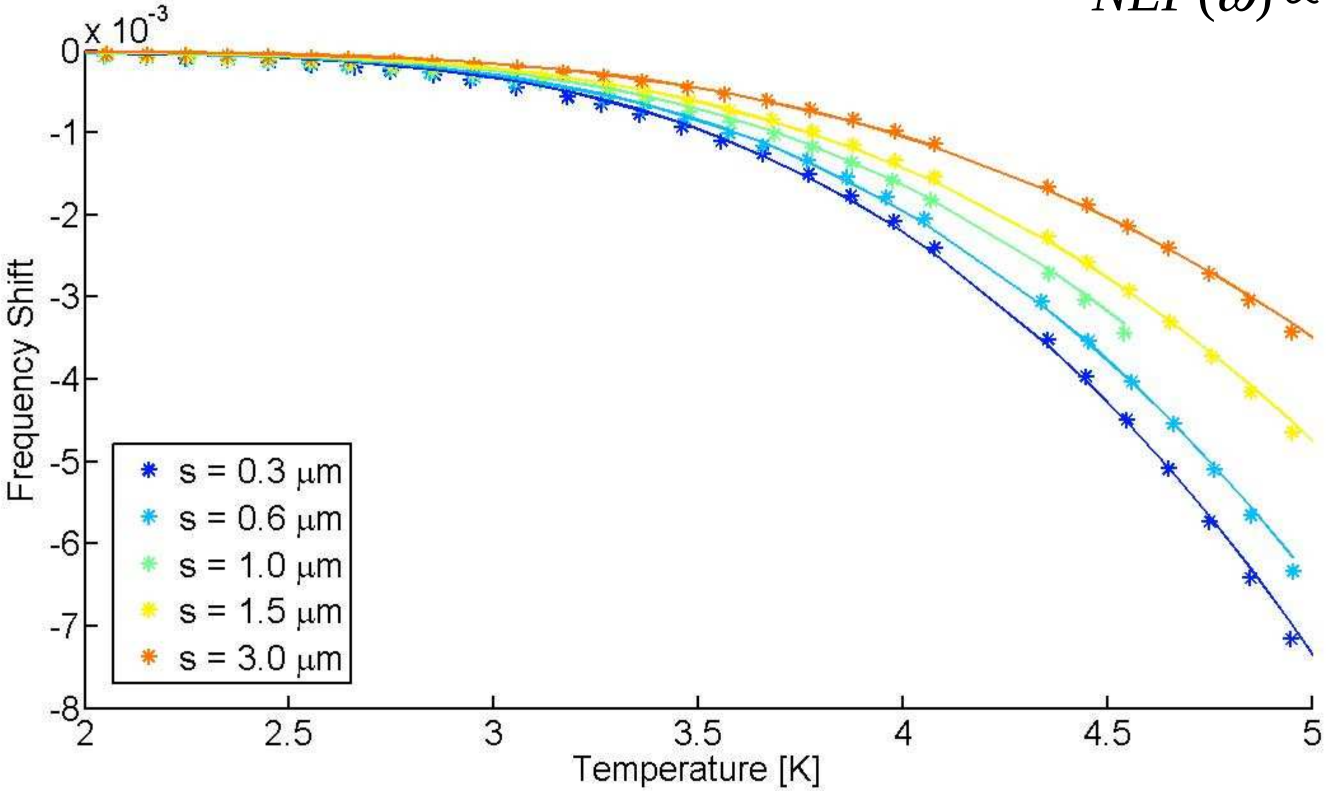
Effect on responsivity



Kinetic Inductance

NbTiN width study

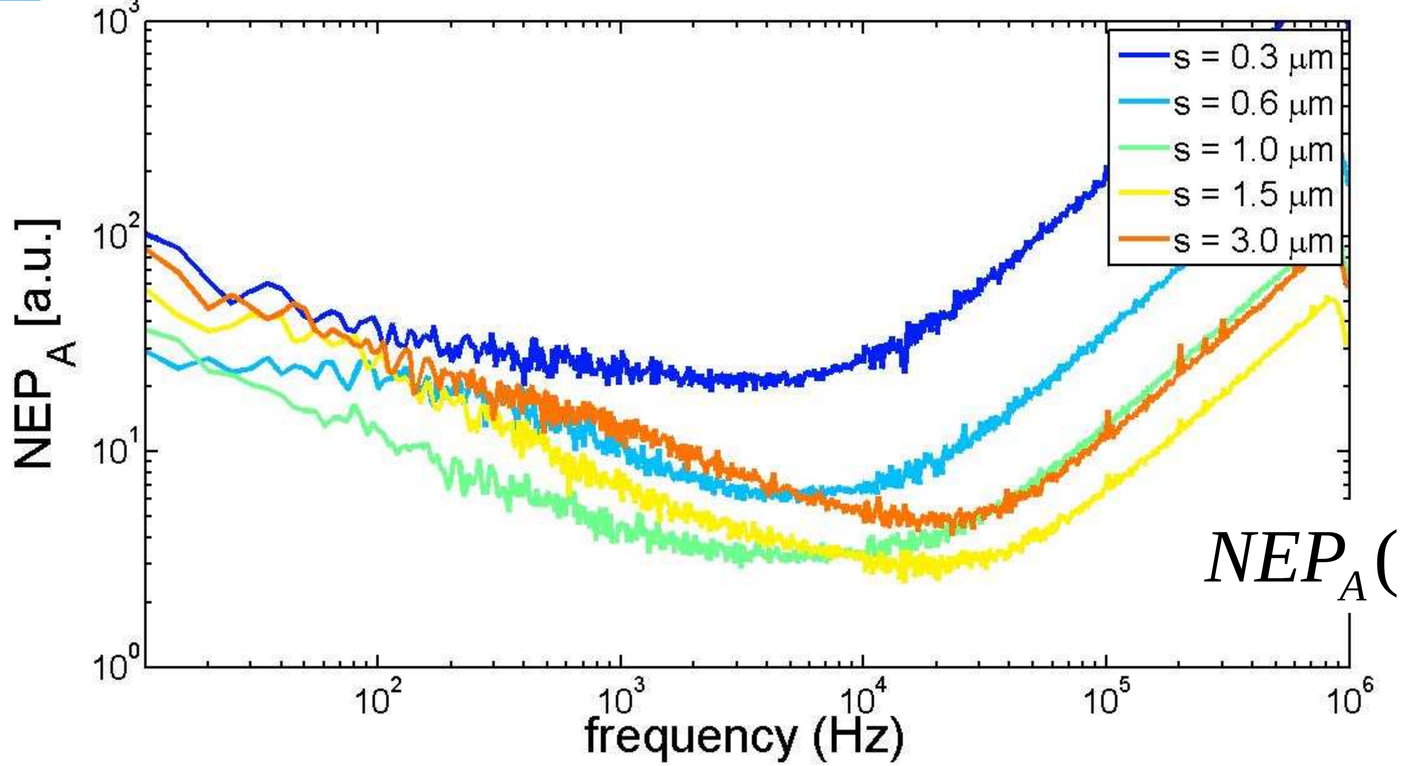
$$NEP(\omega) \propto \sqrt{S(\omega, P)}\left(\frac{\Delta}{\tau}\frac{V}{L_k^{'}Q}\right)$$



“Noise Equivalent Power”

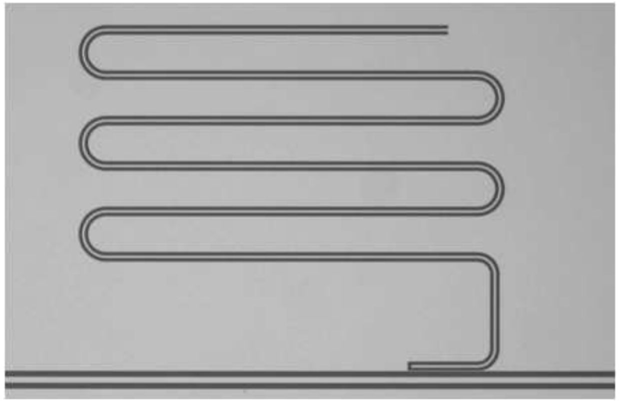
NbTiN width study

$$NEP(\omega) = \sqrt{S(\omega,P)}\frac{\Delta}{\eta\tau}\left(\frac{\delta A}{\delta N_{qp}}\right)^{-1}$$



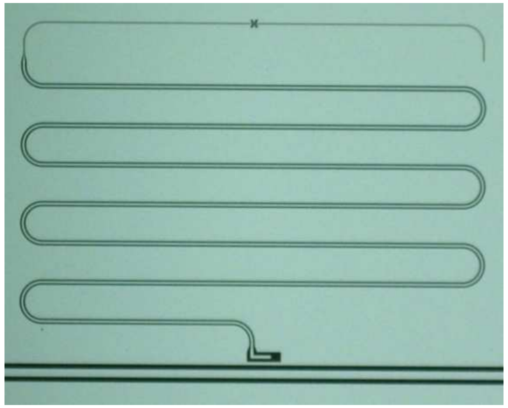
$$NEP_A(\omega) \propto s^{0.21\pm0.11}$$

Aluminum Submicron KID Prototypes



Regular micron KID

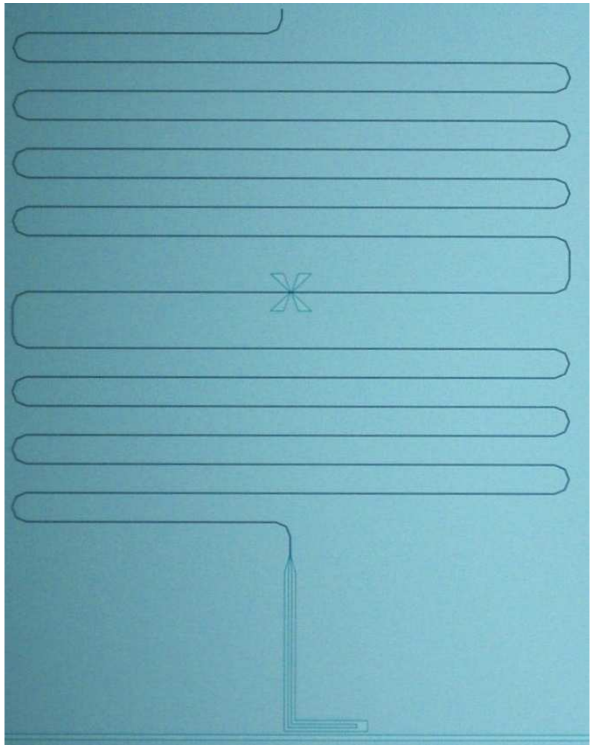
1 – 2 - 1 µm



Width Hybrid KID

80% 1 – 2 - 1 µm

20% 0.3 - 0.6 - 0.3 µm

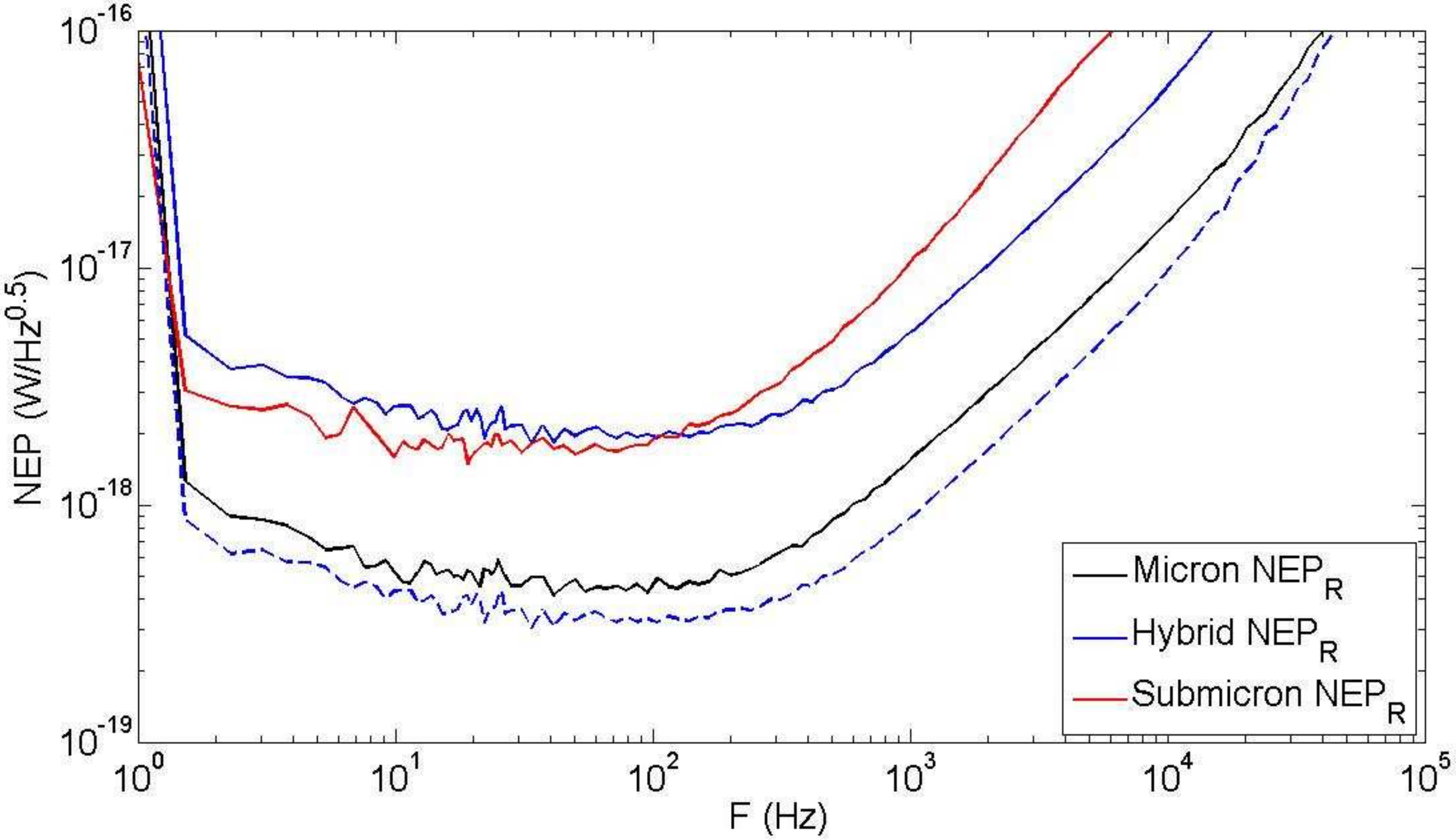


Fully submicron KID

0.3 - 0.6 - 0.3 µm

KID Prototype Comparison

Noise Equivalent Power



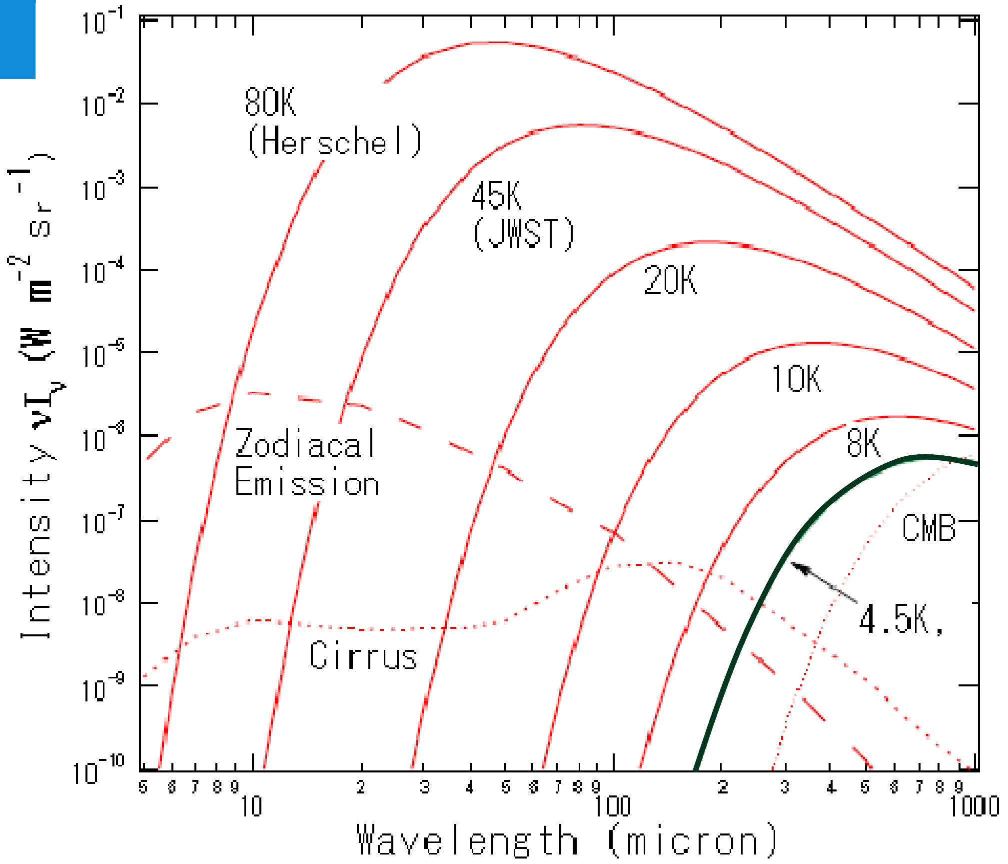
Drinks and Labtour

Labtour:
Pieter de Visser

Drinks:
Room F357/F366

SPICA Far-Infrared Instrument

SAFARI: Instrument Overview



- Fourier Transform Image Spectrometer
- FIR (35-210 μm)

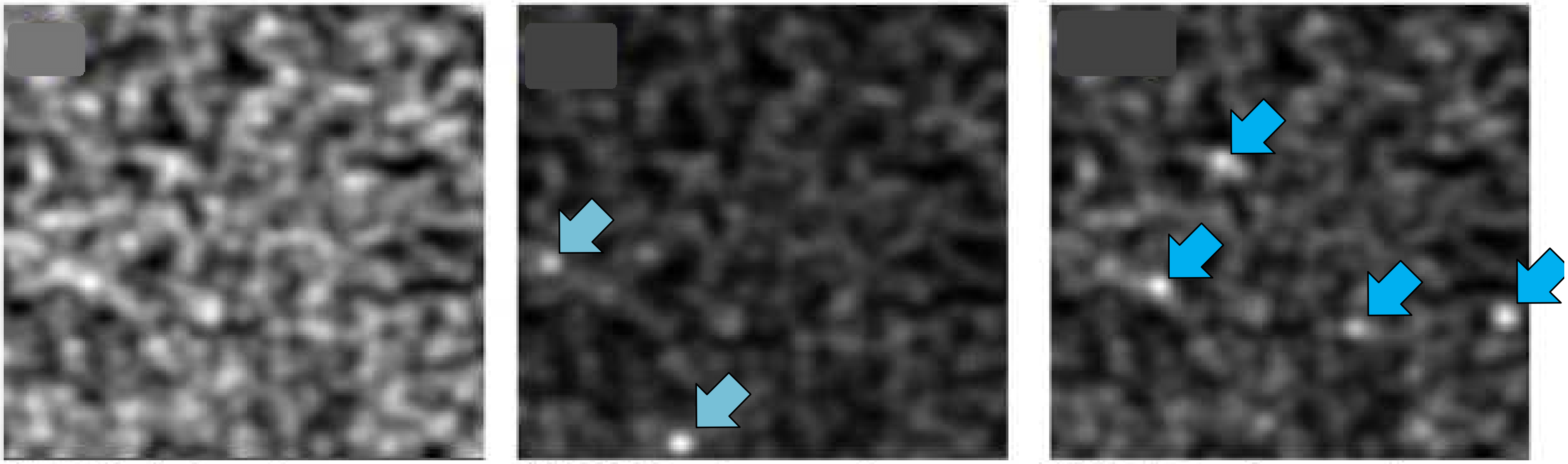
- R ~ 1000
- FoV: 2x2 arcmin

- Mounted on SPICA
  3.0 meter telescope
  4.5 K

T. Nakagawa (2008)

Confusion Limit

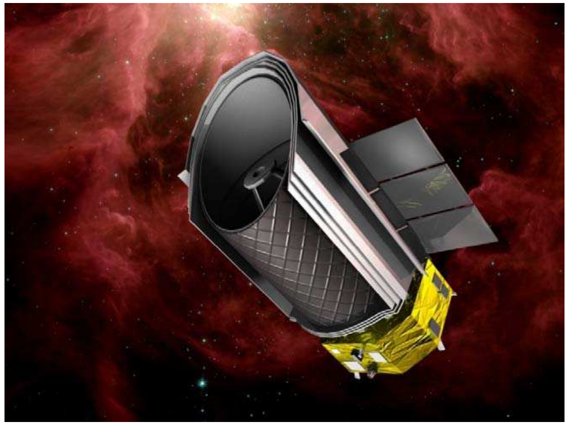
Using spectroscopy to resolve individual sources

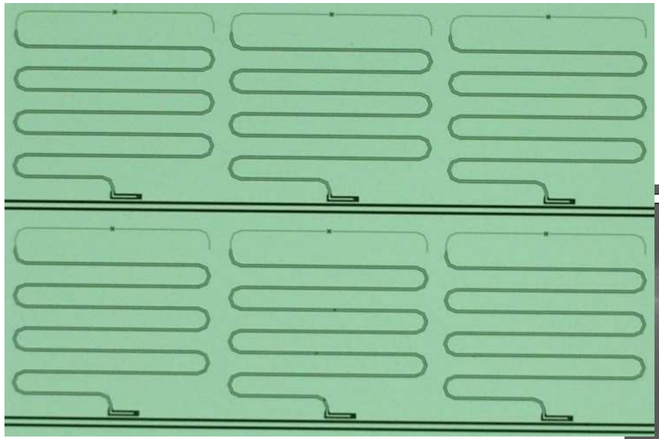


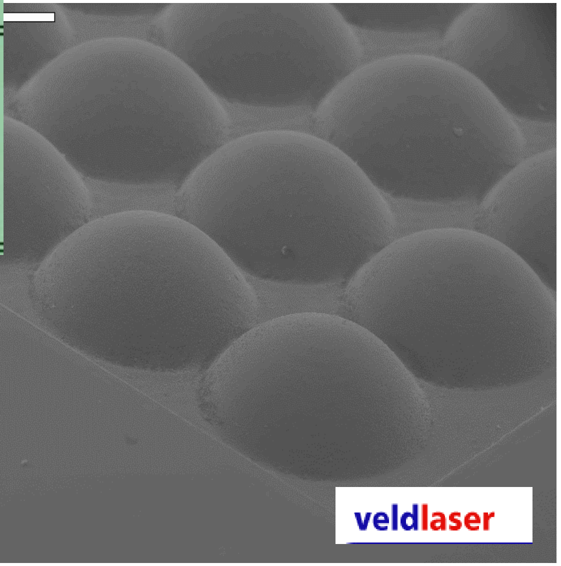
Photometry @ 120 µm Slice @ 63.2 µm Slice @ 58.3 µm

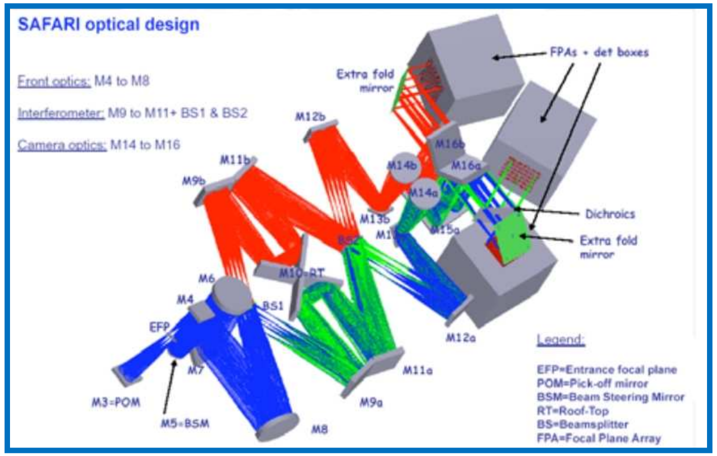
Sources with lines at different redshift appear in different wavelength "slices"

From primairy mirror to detection









SAFARI optical design

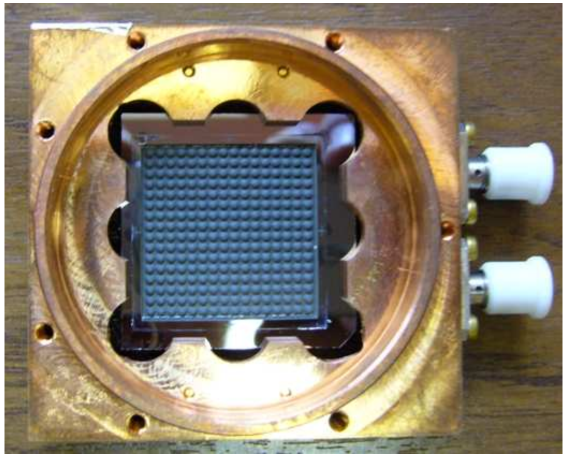
Front optics: M4 to M8

Interferometer: M9 to M11+ BS1 & BS2

Camera optics: M14 to M16

Legend:

EFP=Entrance focal plane
POM=Pick-off mirror
BSM=Beam Steering Mirror
RT=Roof-Top
BS=Beamsplitter
FPA=Focal Plane Array



Fabrication

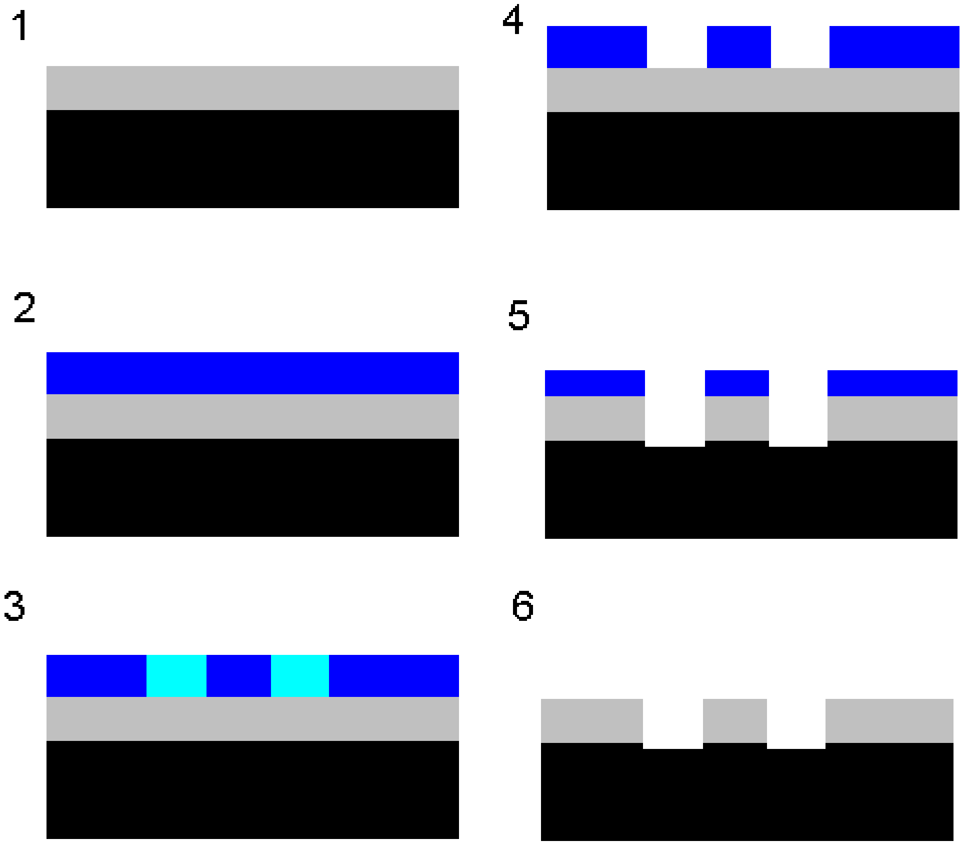
Single layer process

Optical lithography:

Structures ≥ 1 µm

E-beam lithography:

Structures ≥ 5 nm

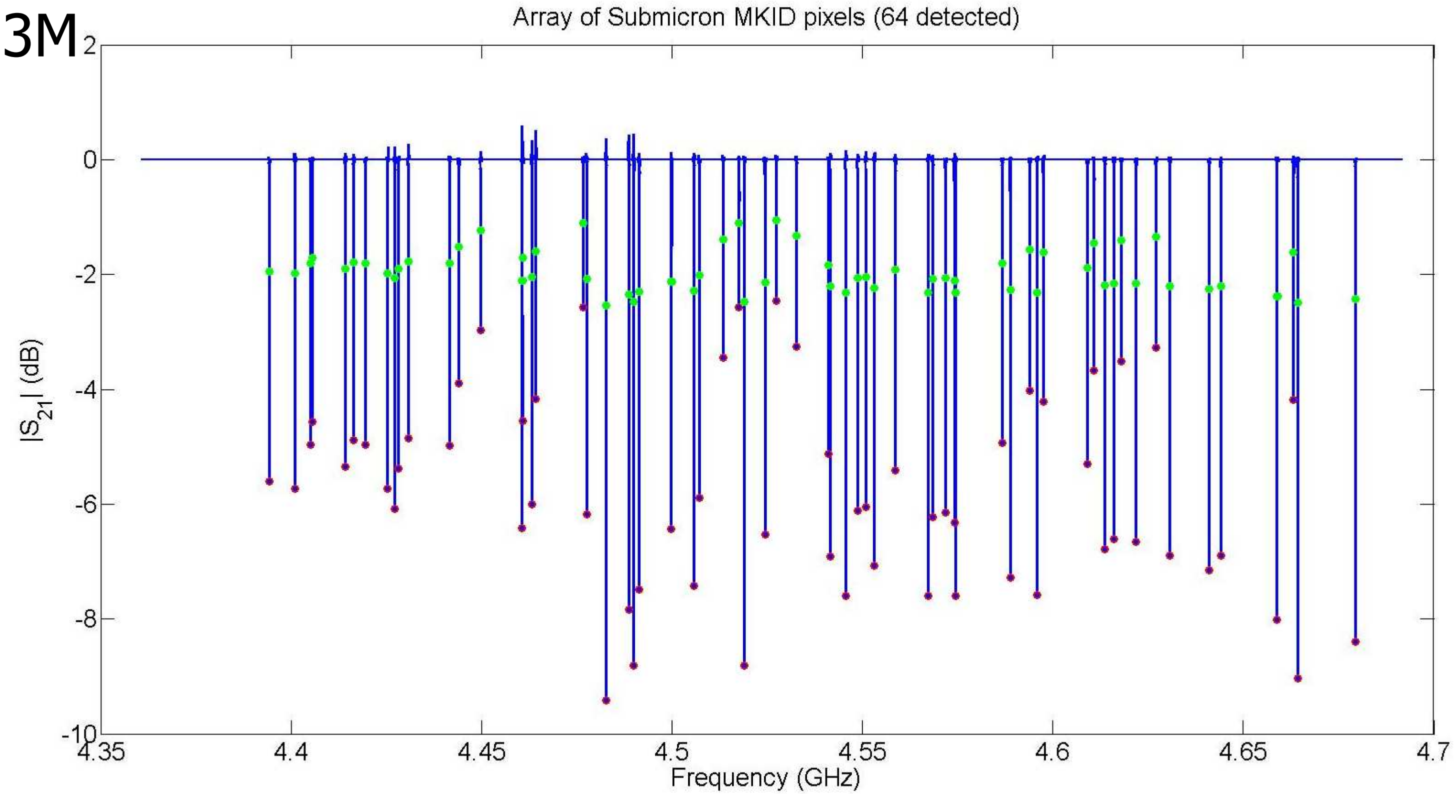


KID Prototype Comparison

Submicron 8x9 pixel array

dF = 4.53 ± 3.7 (MHz)

Q_i = 1.4M ± 0.3M



Kinetic Inductance Detector

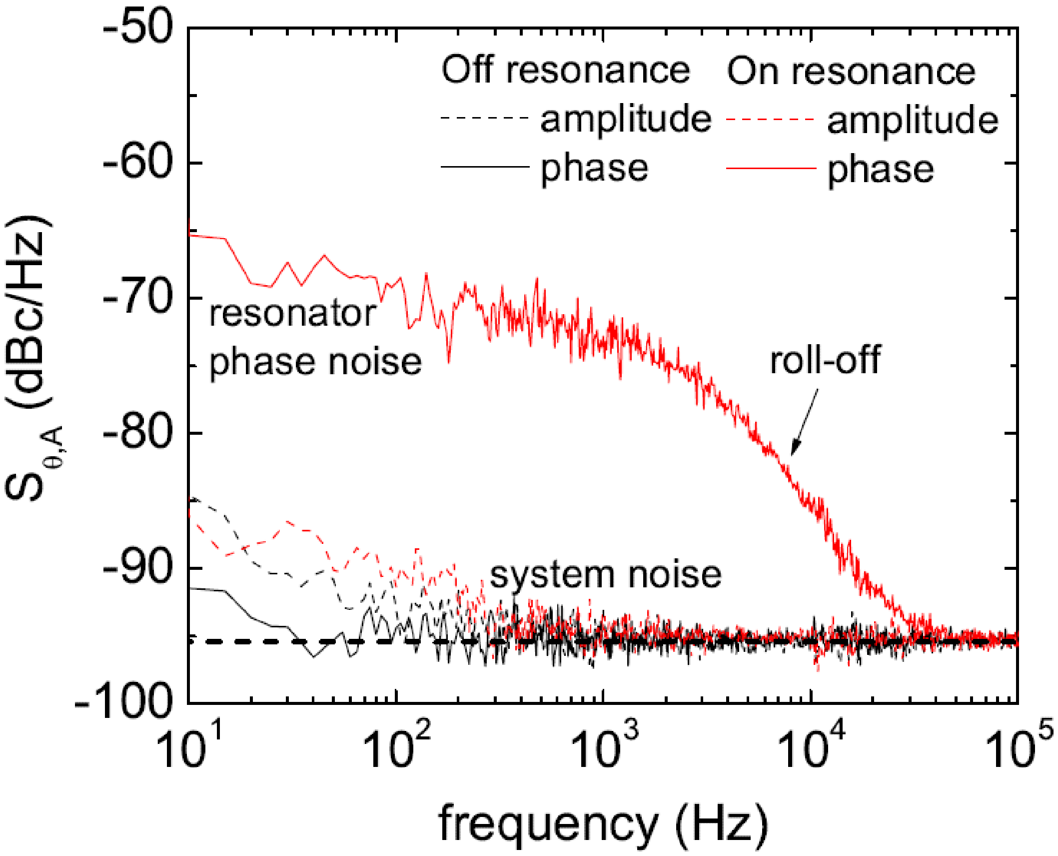
Noise Sources

Fundamental:

- Generation – Recombination Noise
- Fano Noise

Reality:

- HEMT amplifier (amplitude)
- TLS noise (phase)



NbTiN Submicron Resonators

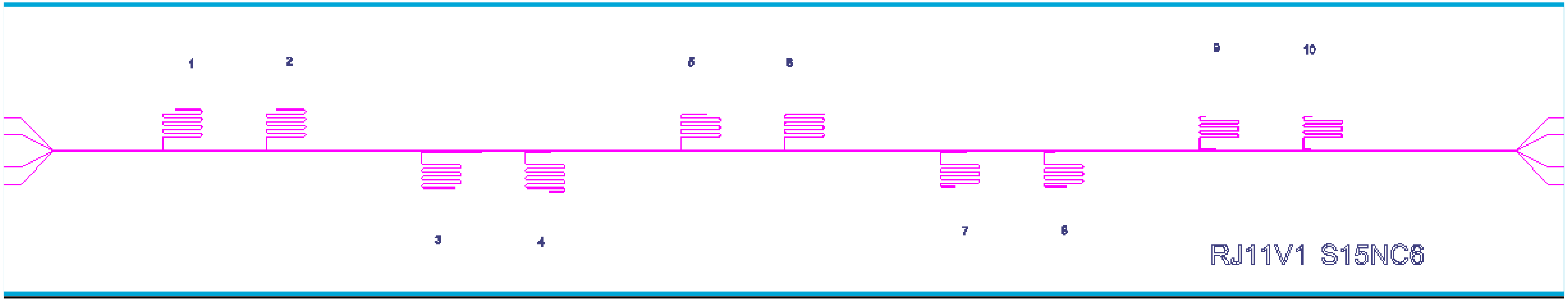
Basic results

8 of 10 resonators work regularly.

- 300 nm resonator detected as λ/2.
- 3 μm resonator missing

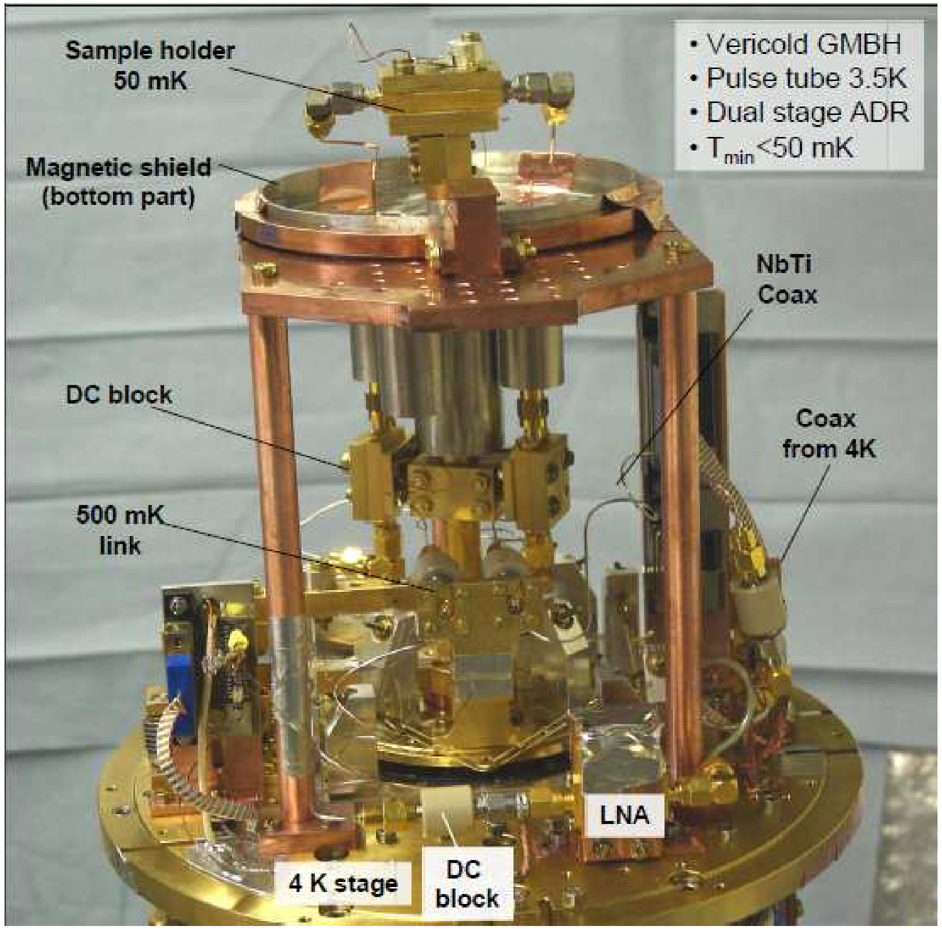
NbTiN: $T_c = 13.7$ (K)

$$NEP(\omega) \propto \sqrt{S_x(\omega, P)} \left(\frac{\Delta}{\tau} \boxed{\frac{V}{\alpha Q}} \right)$$



Cryogenic System SRON

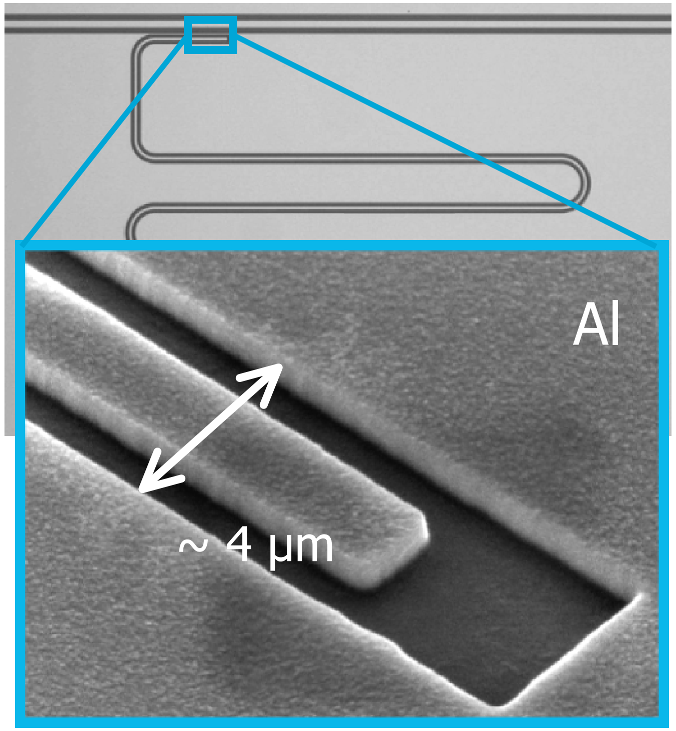
Vericold GMBH dual stage ADR

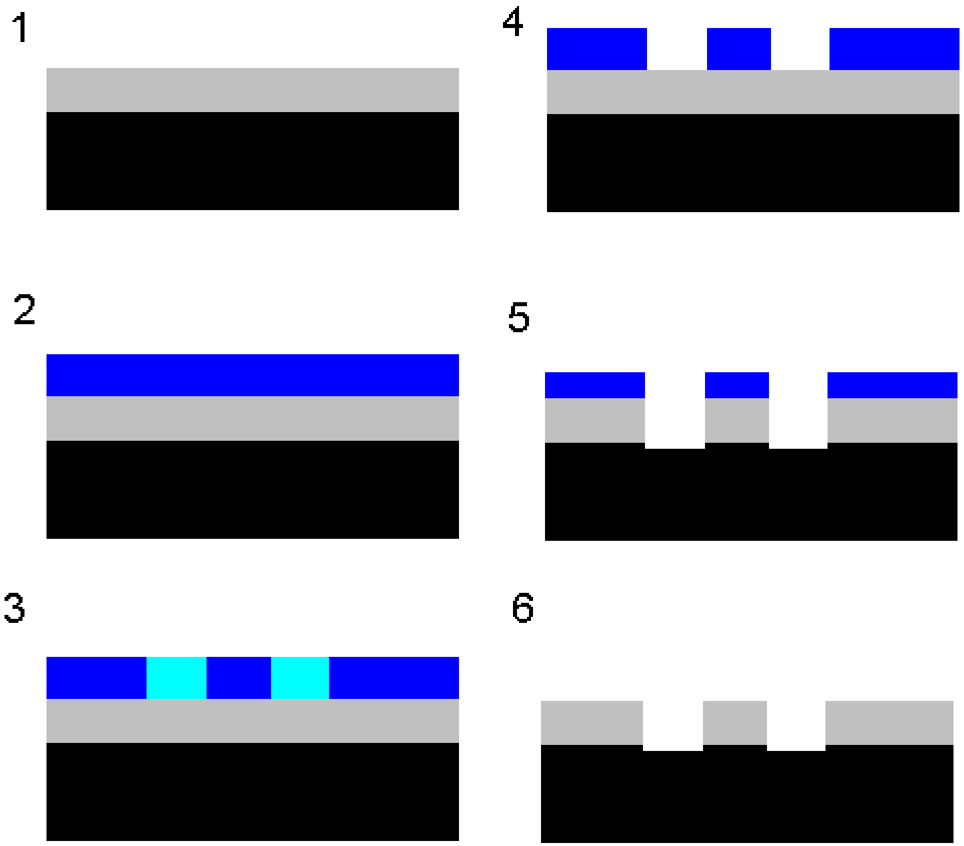


- Vericold GMBH
- Pulse tube 3.5K
- Dual stage ADR
- T_{min}<50 mK

Fabrication

Single layer process





KID Prototype Comparison

Responsivity

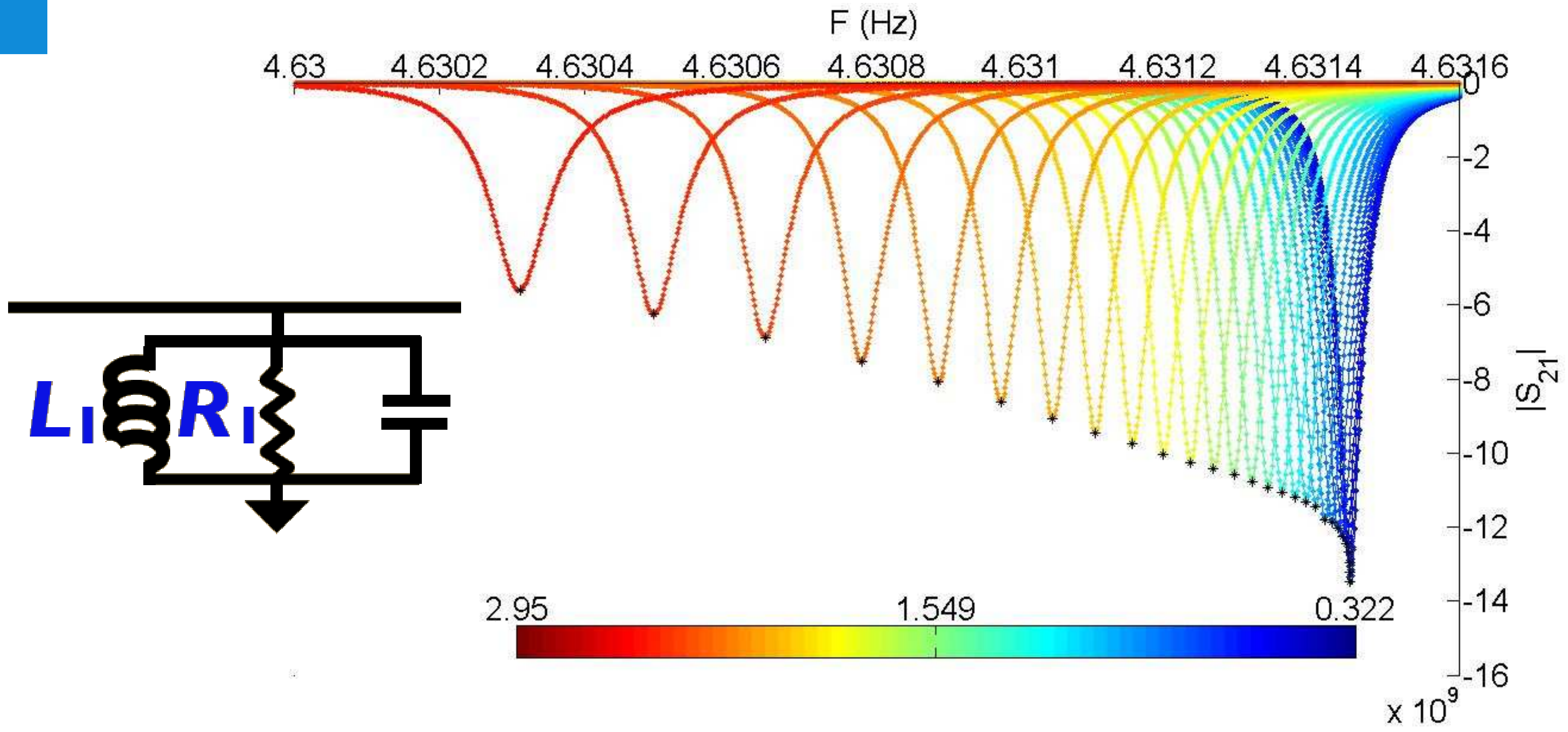
	T_c (K)	T_{qp} (ms)	Q	α	V (µm³)	dR/dN_{qp}	$d\theta/dN_{qp}$
Micron	1.11	1.3	130k	13%	560	$2.98 \cdot 10^{-6}$	$1.54 \cdot 10^{-5}$
Hybrid	1.2	400	184k	9%	1300	$0.12 \cdot 10^{-5}$	$0.60 \cdot 10^{-5}$
Submicron	1.11	1.2	311k	23%	325	$0.41 \cdot 10^{-4}$	$0.17 \cdot 10^{-3}$

$$NEP(\omega) \propto \sqrt{S_x(\omega, P)}\left(\frac{\Delta}{\eta\tau}\frac{V}{\alpha Q}\right)$$

$$\frac{\delta x}{\delta N_{qp}} \propto \frac{\alpha \times Q}{V}$$

Kinetic Inductance Detector

Response to energy input

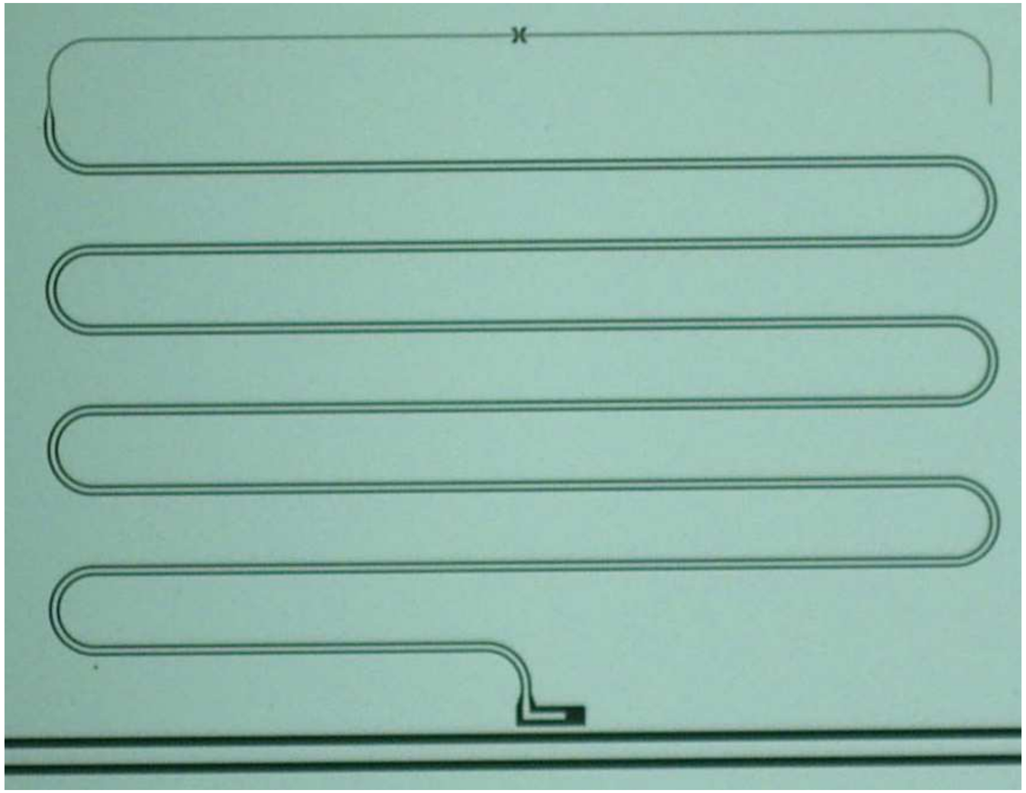


SAFARI Submicron KID Prototypes

Design Choices:
Aluminum on sapphire
X-slot antenna

Comparison

- Micron sized (1-2-1 μm)
- Submicron sized (0.3-0.6-0.3 μm)
- Hybrid
  80% micron sized
  20% submicron sized



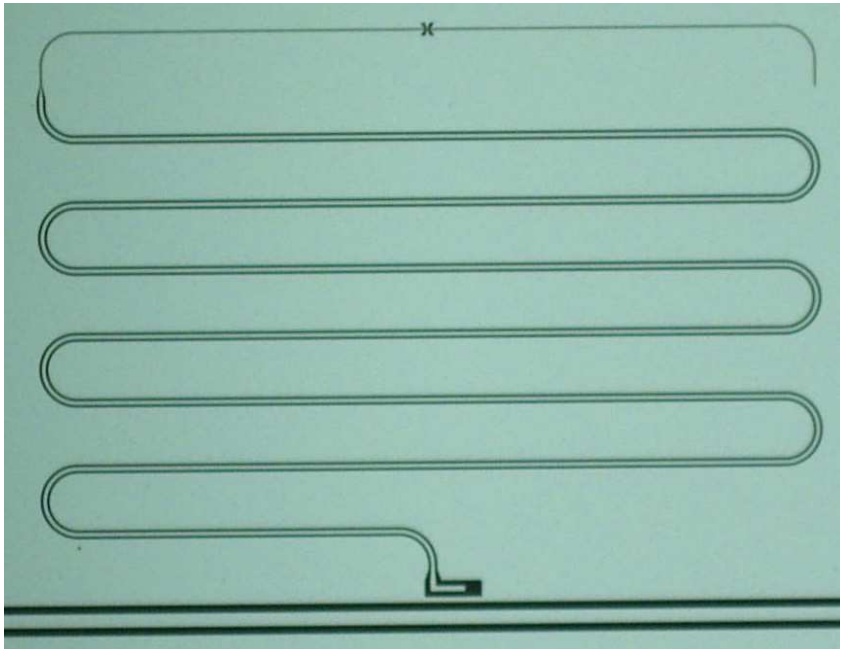
SAFARI Submicron KID Prototypes

Comparison

- Micron
- Submicron
- Hybrid

Compare

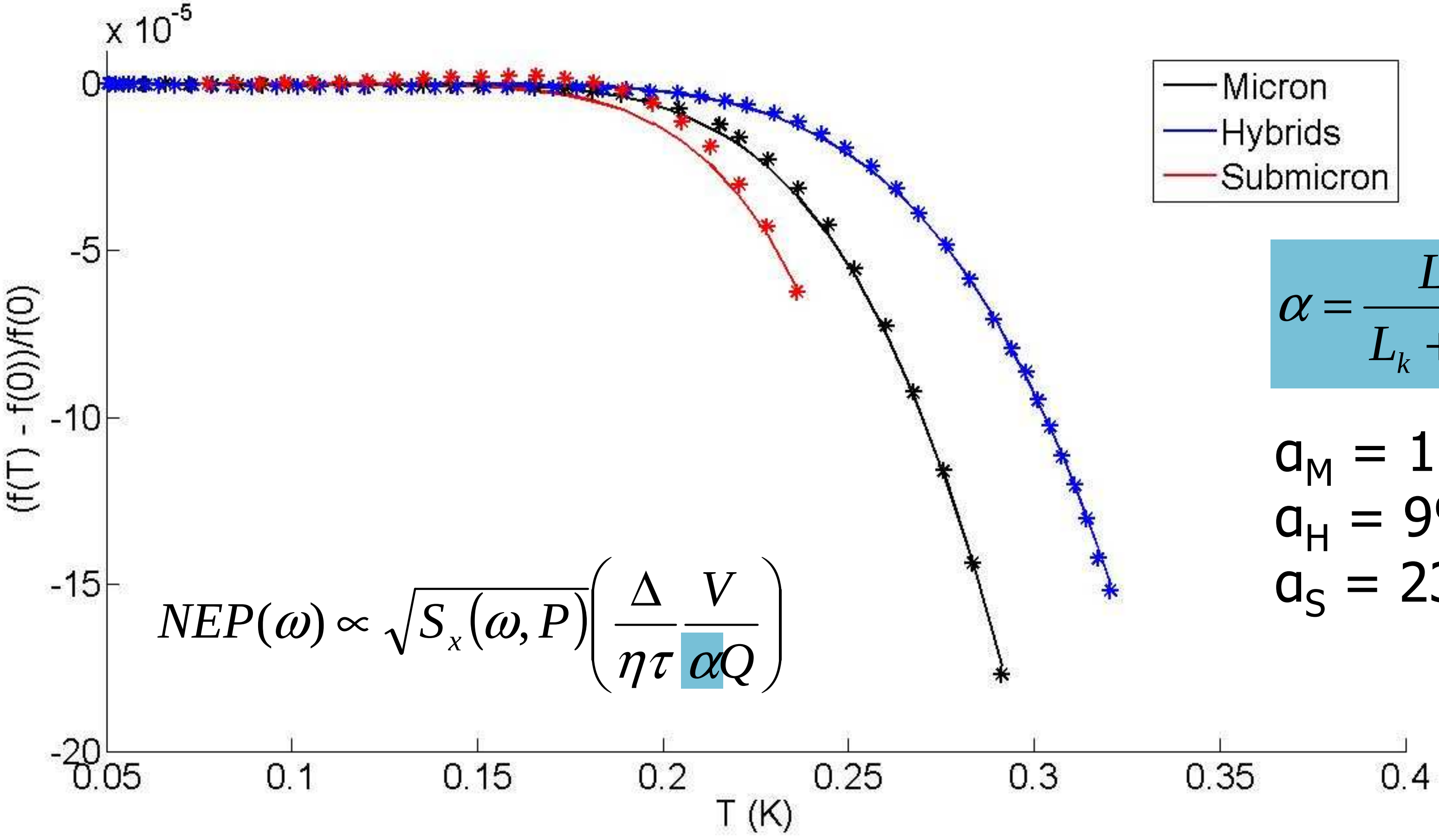
- Kinetic inductance fraction
- Noise spectrum
- Power handling
- Noise equivalent power



$$NEP(\omega) \propto \sqrt{S_x(\omega, P)}\left(\frac{\Delta}{\eta\tau}\frac{V}{\alpha Q}\right)$$

KID Prototype Comparison

Kinetic Inductance Fraction



$$NEP(\omega) \propto \sqrt{S_x(\omega, P)}\left(\frac{\Delta}{\eta\tau}\frac{V}{\alpha Q}\right)$$

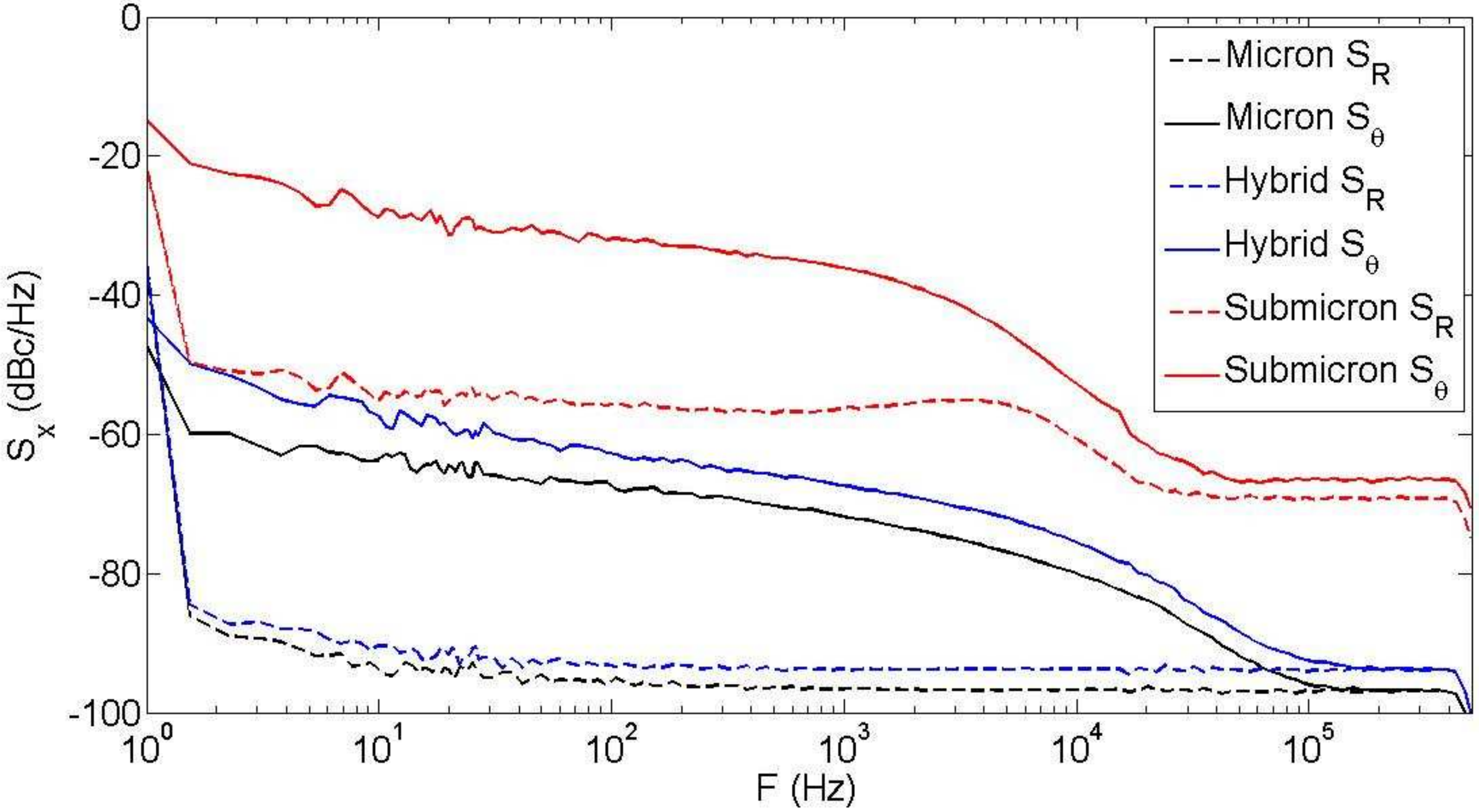
$$\alpha = \frac{L_k}{L_k + L_g}$$

$\alpha_M = 13\%$
$\alpha_H = 9\%$
$\alpha_S = 23\%$

KID Prototype Comparison

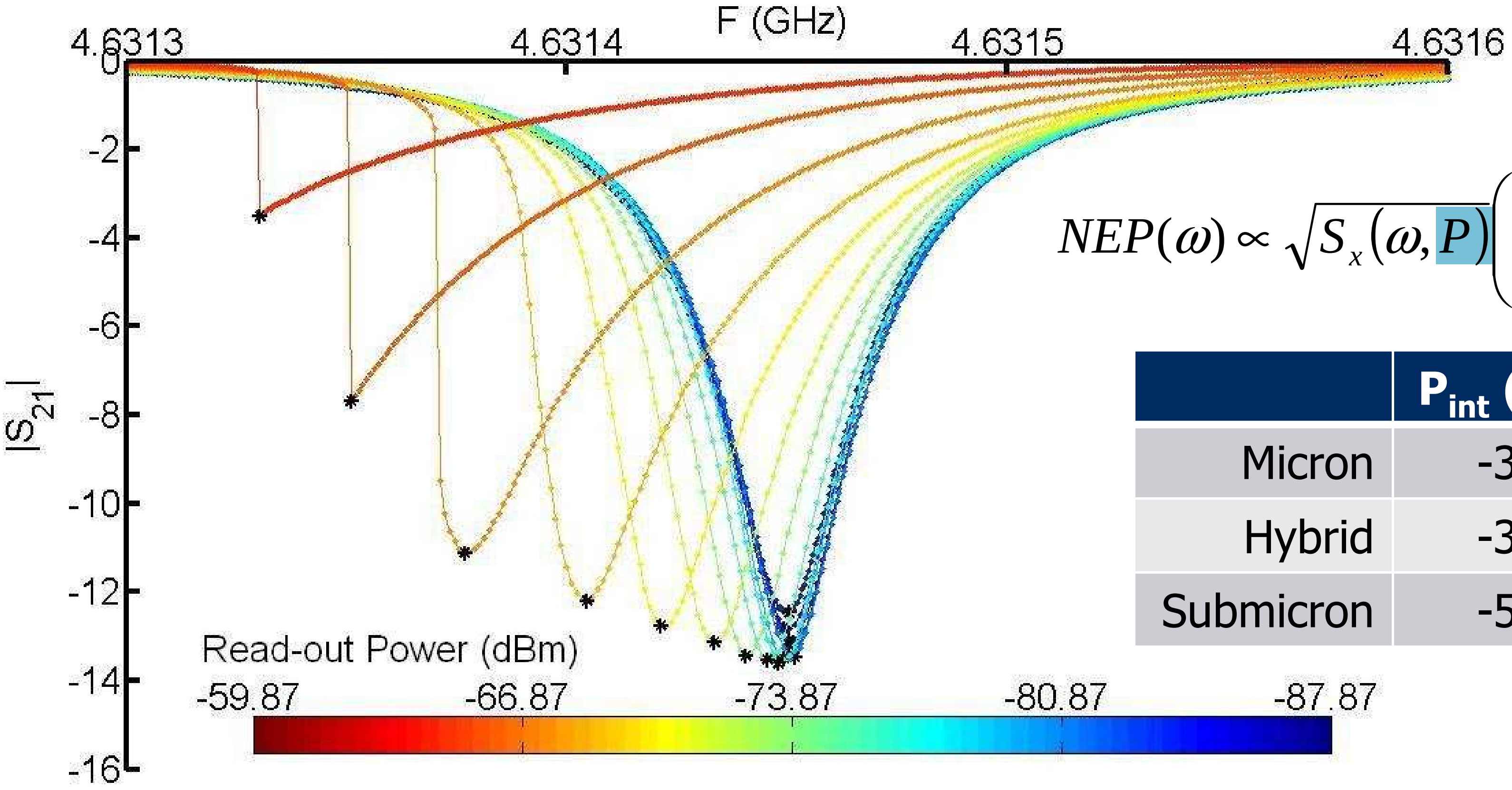
Noise Spectrum

$$NEP(\omega) \propto \sqrt{S_x(\omega, P)}\left(\frac{\Delta}{n\tau}\frac{V}{\alpha Q}\right)$$



KID Prototype Comparison

Power Handling

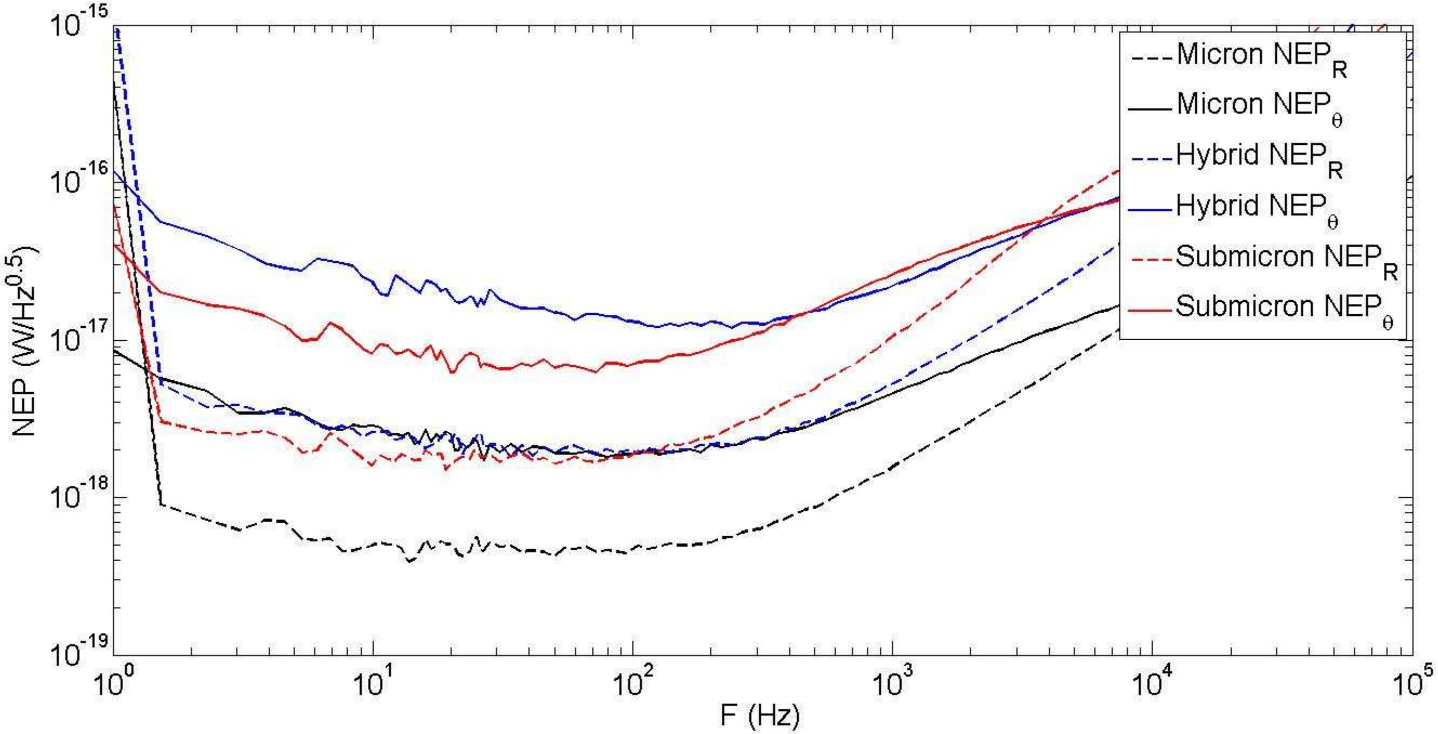


$$NEP(\omega) \propto \sqrt{S_x(\omega, P)}\left(\frac{\Delta}{\eta\tau}\frac{V}{\alpha Q}\right)$$

	P_{int} (dBm)
Micron	-38.7
Hybrid	-34.5
Submicron	-59.0

KID Prototype Comparison

Noise Equivalent Power



$W\ Hz^{-0.5}$	**Micron**	**Hybrid**	**Submicron**
NEP_R (15 Hz)	$5.2*10^{-19}$	$2.3*10^{-18}$	$1.8*10^{-18}$
NEP_θ (15 Hz)	$3.8*10^{-18}$	$2.2*10^{-17}$	$8.2*10^{-18}$

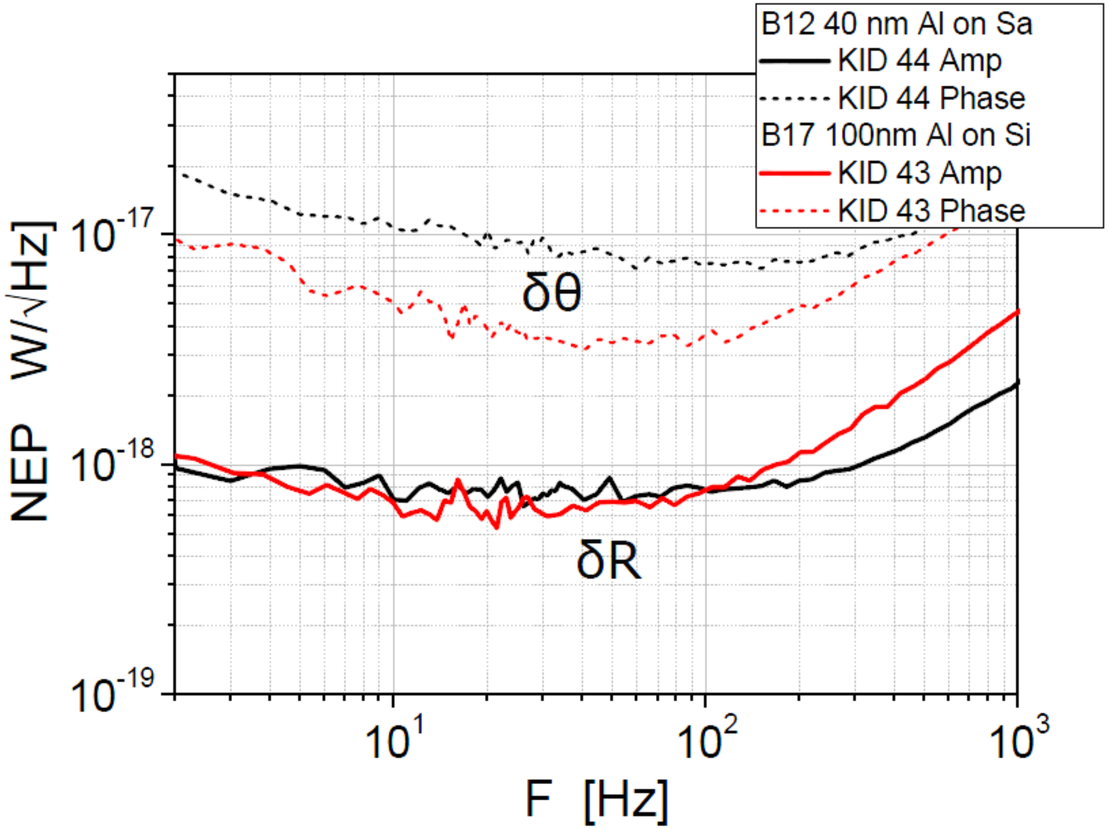
Kinetic Inductance Detector

Noise Equivalent Power

$$NEP(\omega) = \sqrt{S_x(\omega)}\left(\frac{\eta\tau}{\Delta}\frac{\delta x}{\delta N_{qp}}\right)^{-1}$$

$$\frac{\delta x}{\delta N_{qp}} \propto \frac{\alpha \times Q}{V}$$

Current NEP_R:
$7*10^{-19}$ W $Hz^{-0.5}$



Yates et.al., J. Low. Temp. Physics (2009)

KID Prototype Comparison

Noise equivalent power improvements

Hybrid resonators:

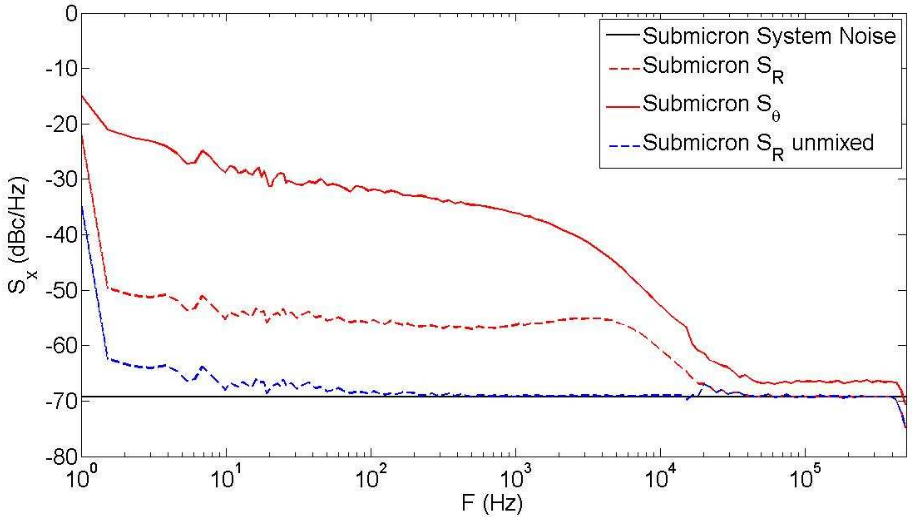
- Quasiparticle lifetime
  0.4 ms ➔ 1.2 ms
- Volume (film thickness)
  100 nm ➔ 50 nm

$$NEP(\omega) \propto \sqrt{S_x(\omega,P)}\left(\frac{\Delta}{\eta\tau}\frac{V}{\alpha Q}\right)$$

Factor 6

Submicron resonators:

- Power handling
- 13 dB excess amplitude noise



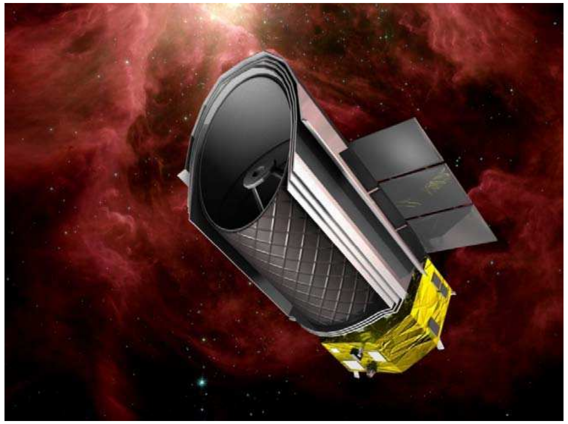
Factor 4.5

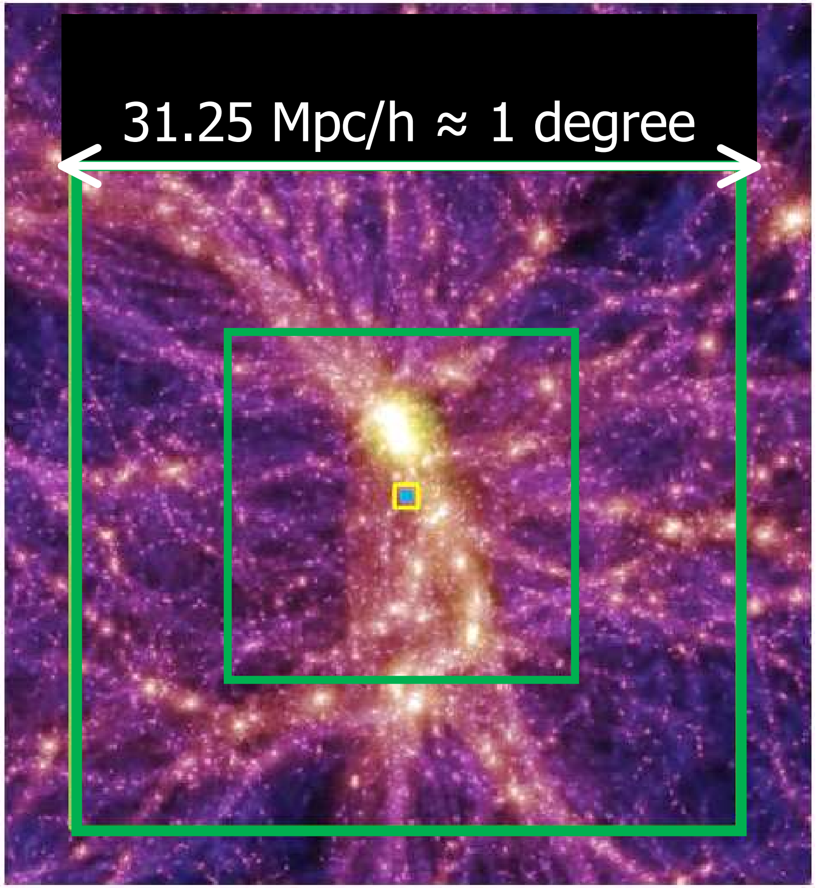
Sensitivity Improvement of KIDs

SPICA Far-Infrared Instrument

Current Technology:
1800 hours (2 months)
Blue Square (1 arcmin^2)

SPICA/SAFARI:
900 hours (1 month)
Green Box (1 deg^2)

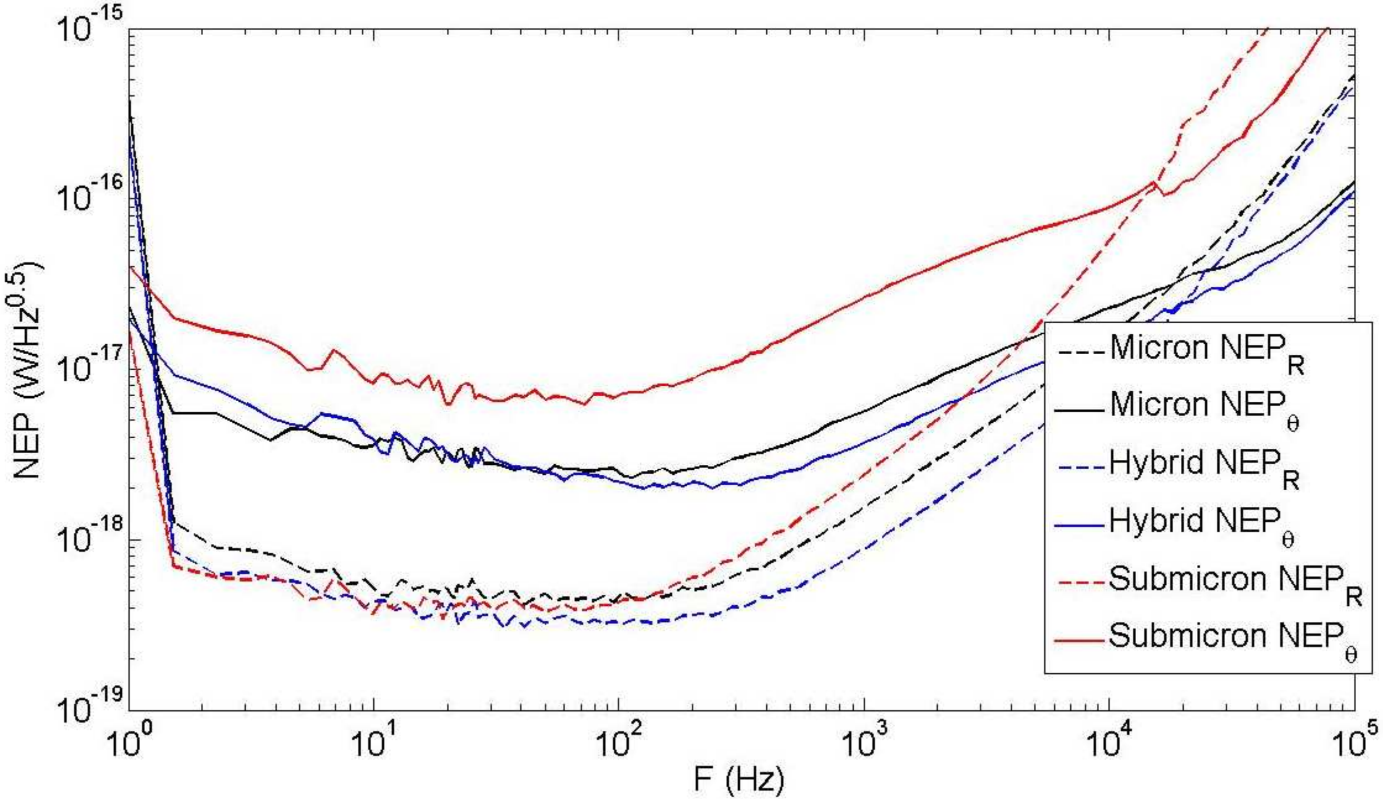




V. Springel et.al., Nature (2006)

KID Prototype Comparison

“Expected” Noise Equivalent Power



W Hz$^{-0.5}$	Micron	Hybrid	Submicron
NEP$_R$ (15 Hz)	5.2×10^{-19}	3.9×10^{-19}	4.1×10^{-19}
NEP$_\theta$ (15 Hz)	3.8×10^{-18}	3.6×10^{-18}	8.2×10^{-18}