Performance of a 961 pixel Kinetic Inductance Detector system for future space borne observatories

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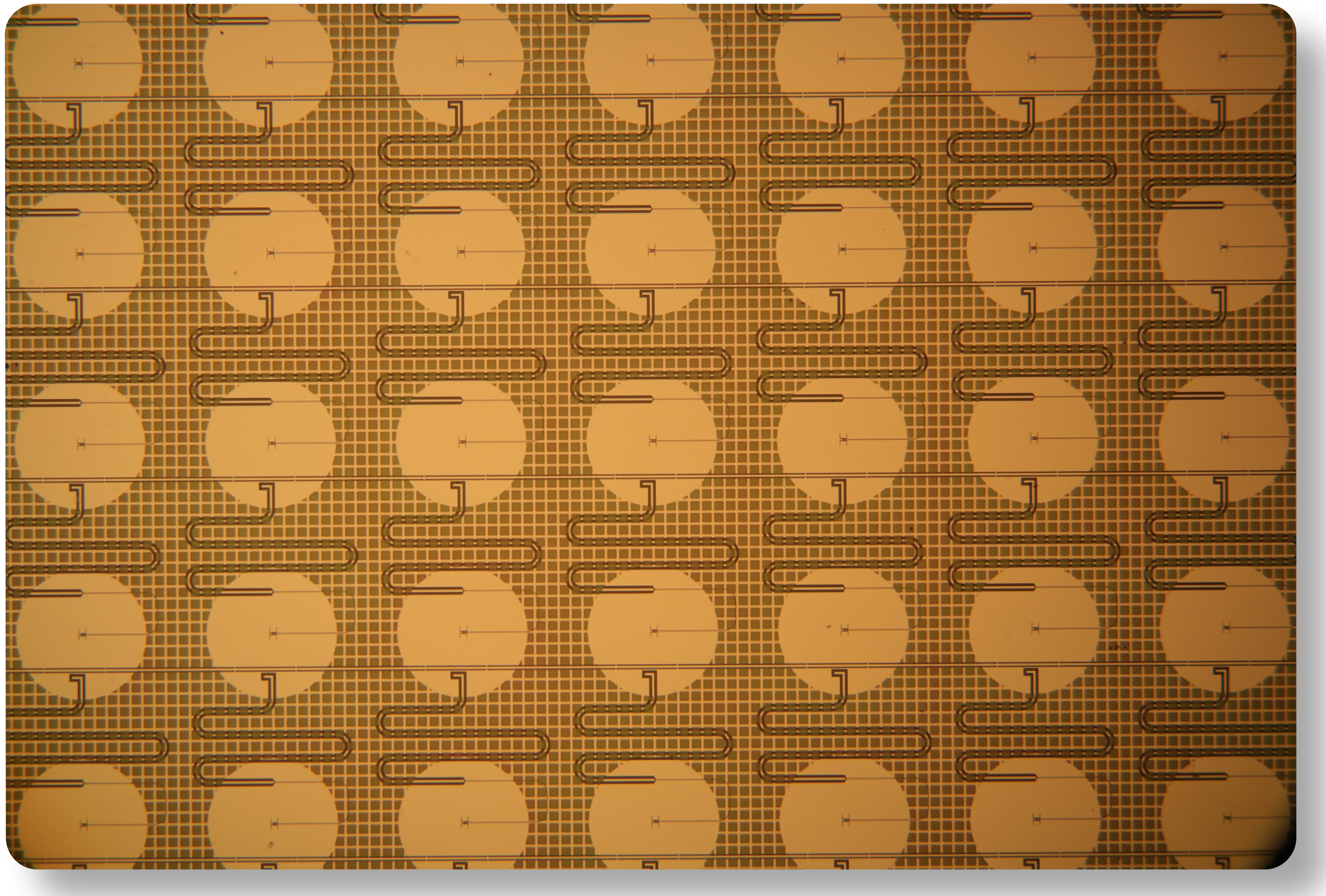


SRON Netherlands Institute for Space Research

spaceKIDS Kinetic Inductance Detectors for Space

THz Sensing Group

TU Delft

Future instrumentation for FIR astronomy

Type	F/ΔF	Frequency Range	Power per pixel	NEP_{ph} (W/√Hz)	# pixels
single dish camera, **ground**	3	50-950 GHz	10-50 pW	$>3\cdot10^{-16}$	10^5
single dish spectrometer, **ground**	1000	100-950 GHz	10-100 fW	$>1\cdot10^{-17}$	$>10^5$
CMB observatory, **space**	3	50-500 GHz	~100 fW	$4\cdot10^{-18}$	10^3
single dish camera, **space**	3	1-10 THz	30-300 aW	$>2\cdot10^{-19}$	10^4
single dish spectrometer, **space**	1000	0.8-10 THz	0.05-0.5 aW	$>0.5\cdot10^{-20}$	10^4

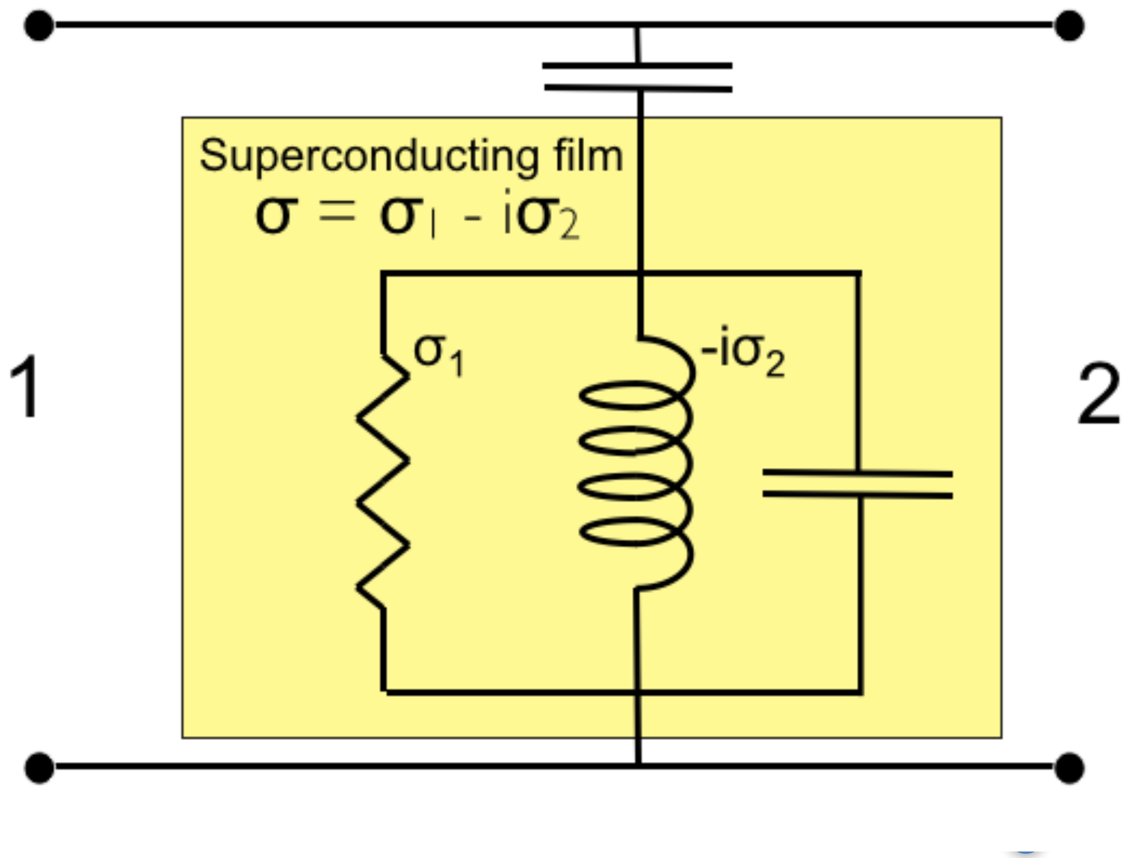
MKID principle of operation

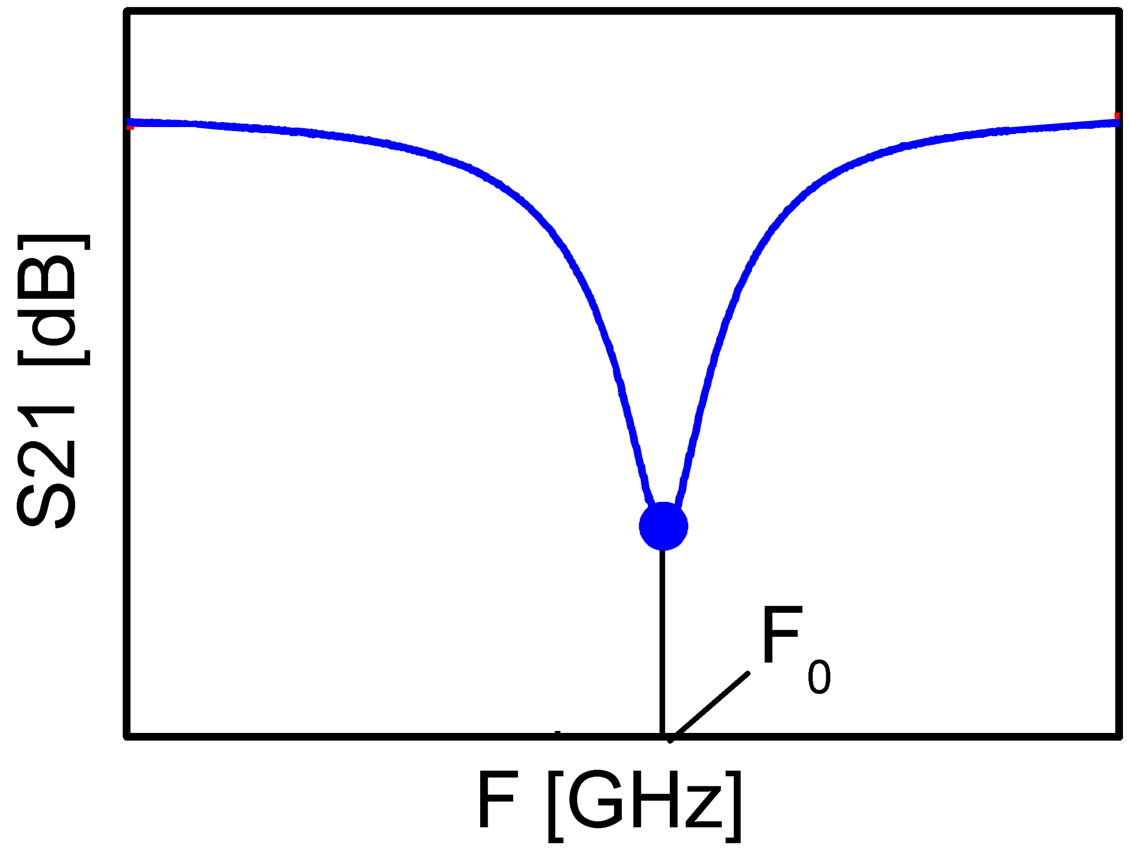
Day et al., Nature ***425*** *817 (2002)*

Superconducting microwave resonance circuit

Capable of coupling to radiation

- $Q \sim 10^4 - 10^6$
- F ~0.1-8 GHz



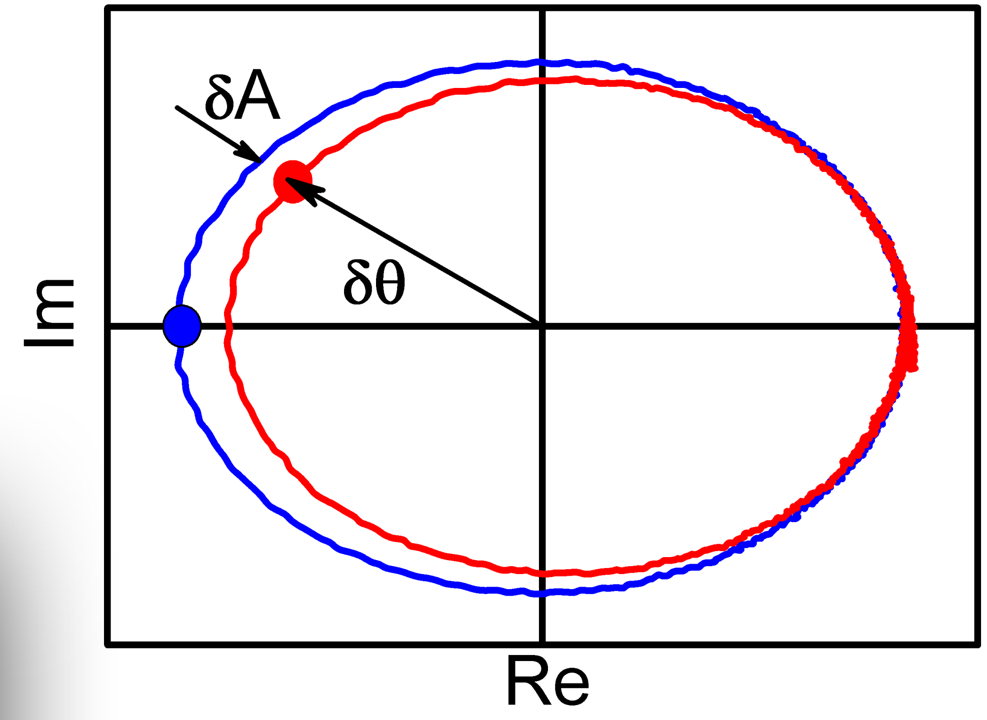


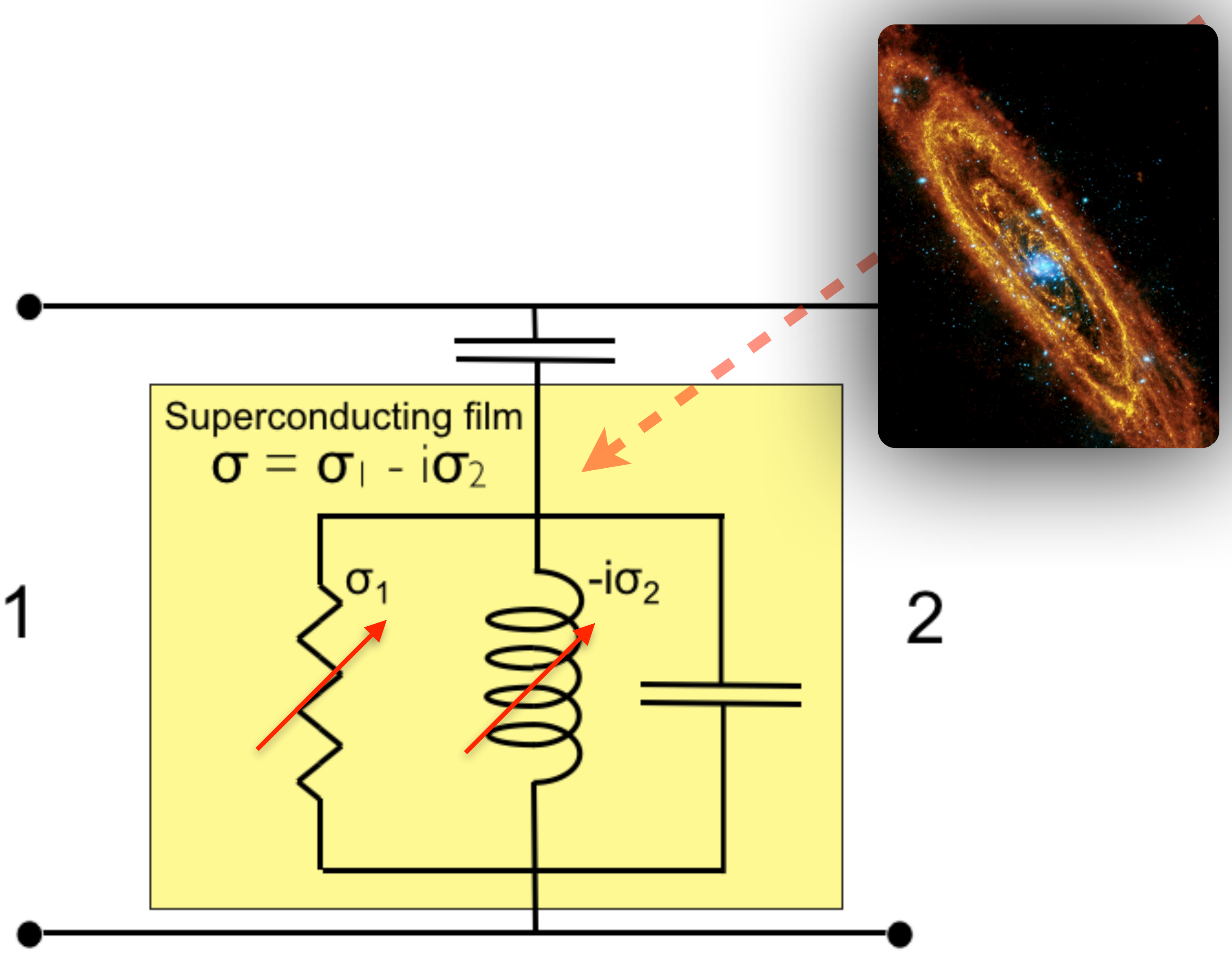
MKID principle of operation

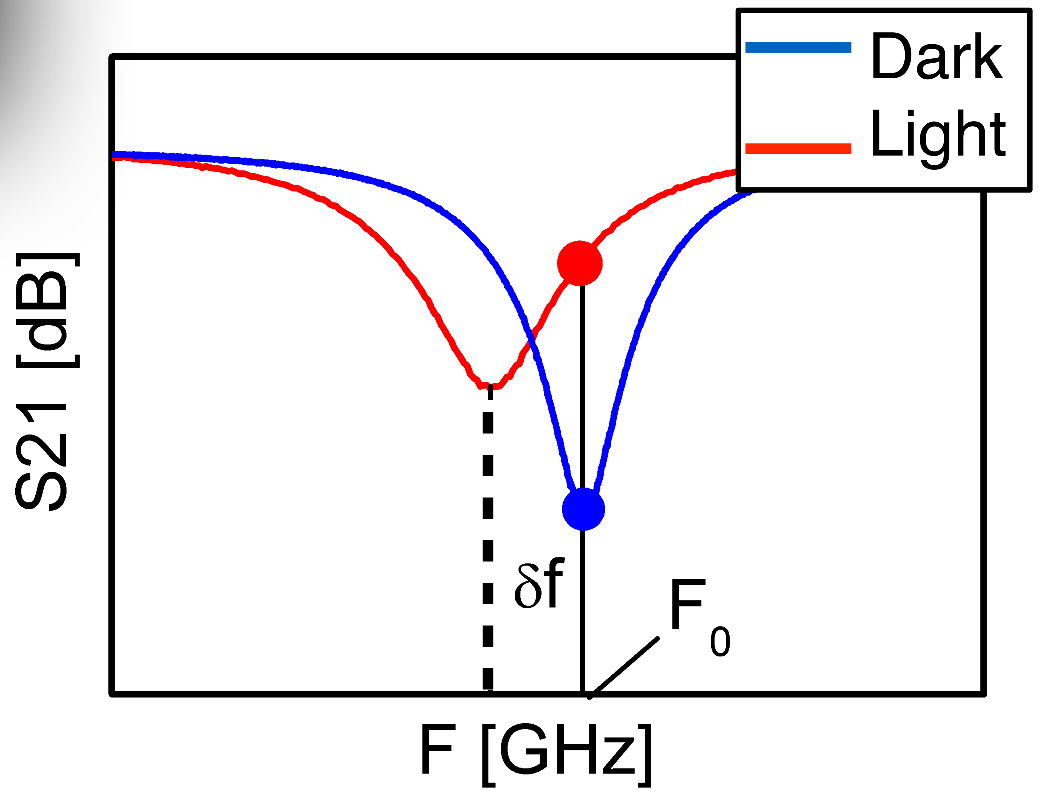
Radiation absorption

- Changes **σ**
- Changes resonance feature

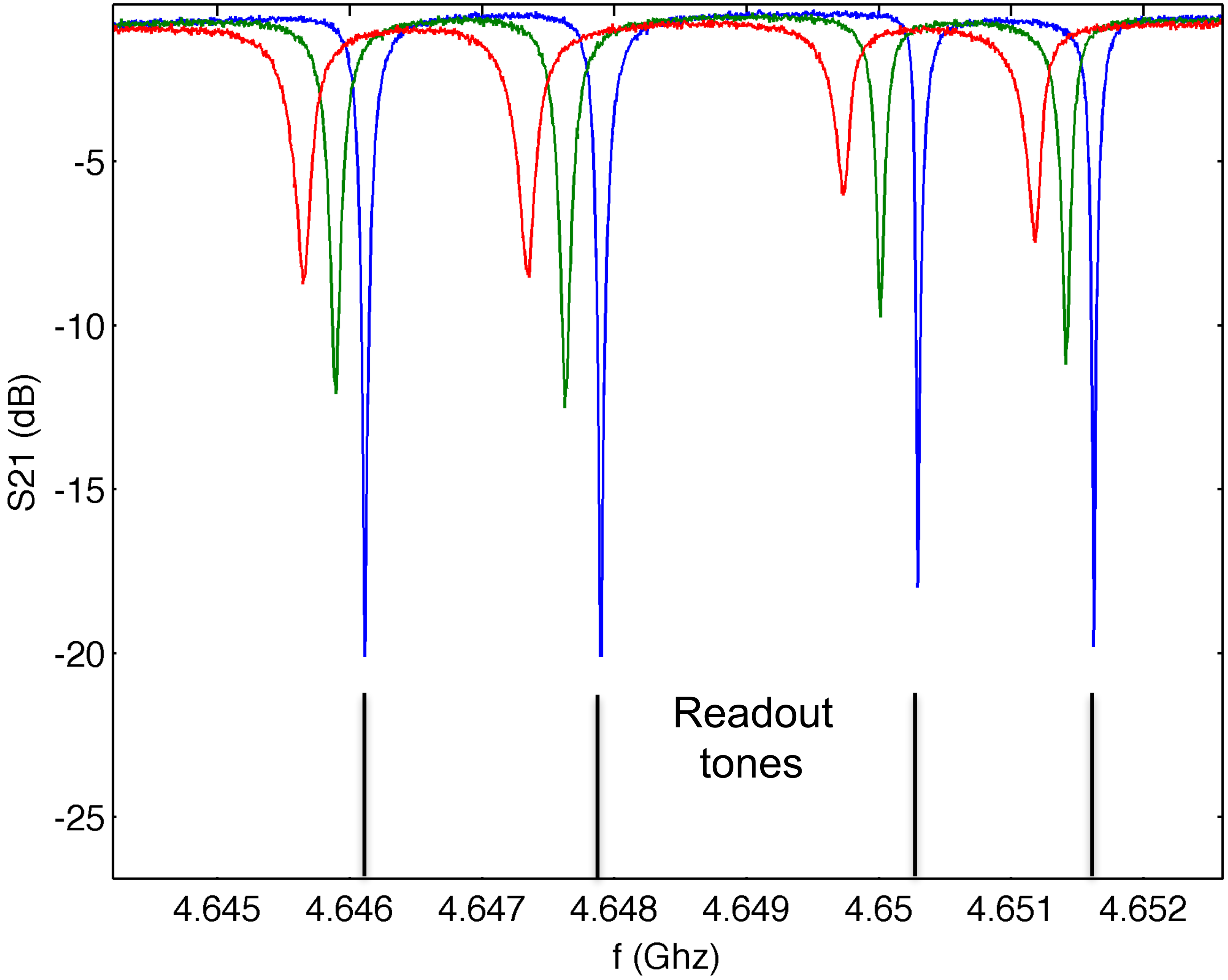
Can be read out using 1 frequency tone





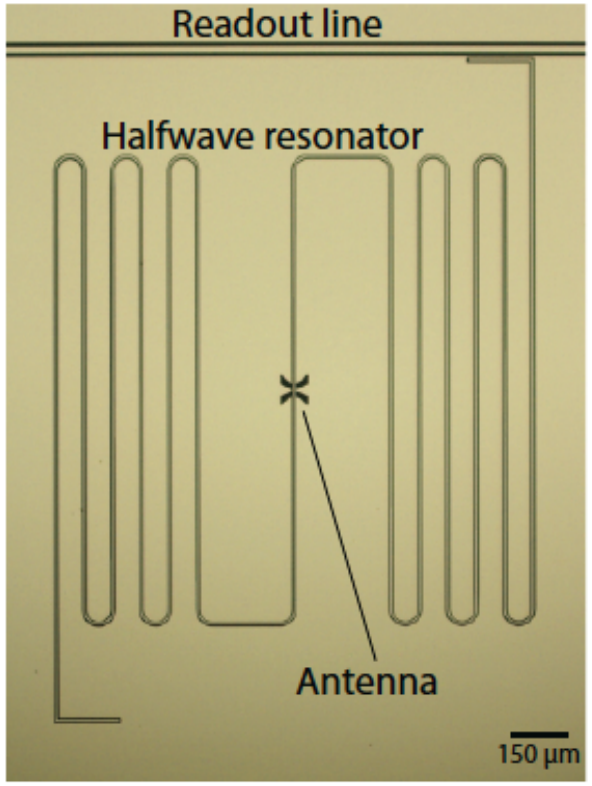


Frequency Domain Multiplexing



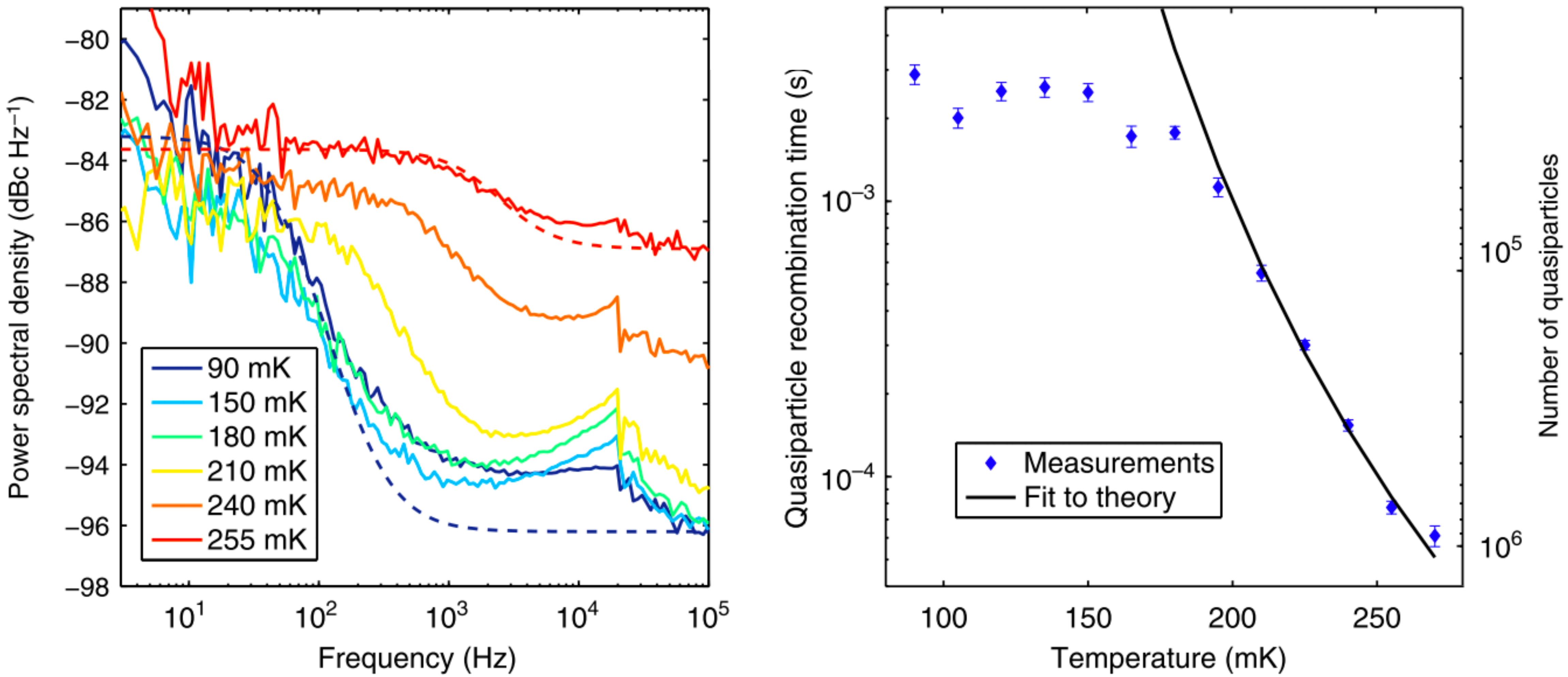
Noise signatures: Fundamental

P.J. de Visser et al., Nature Communications, **3130**, (2014) DOI: 10.1038/ncomms4130



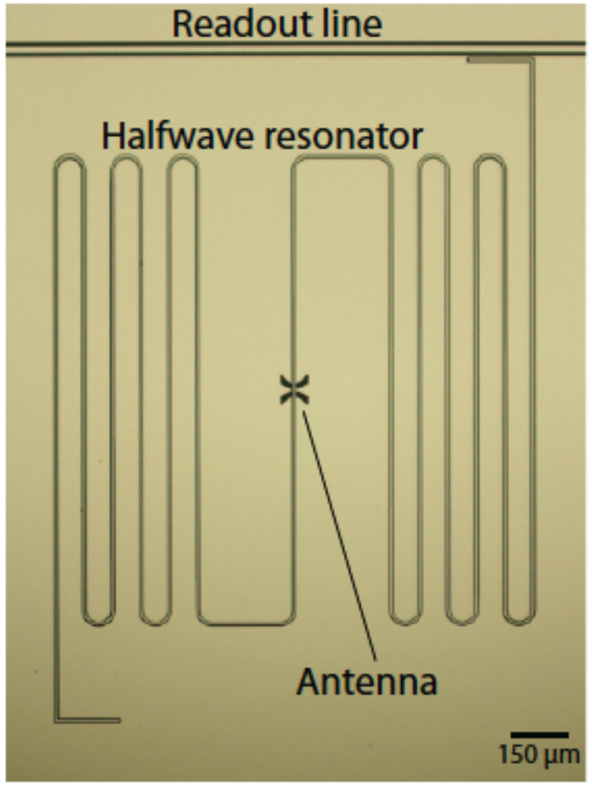
1: Quasiparticle fluctuations

- White noise spectrum
- T dependent roll-off (qp recombination)



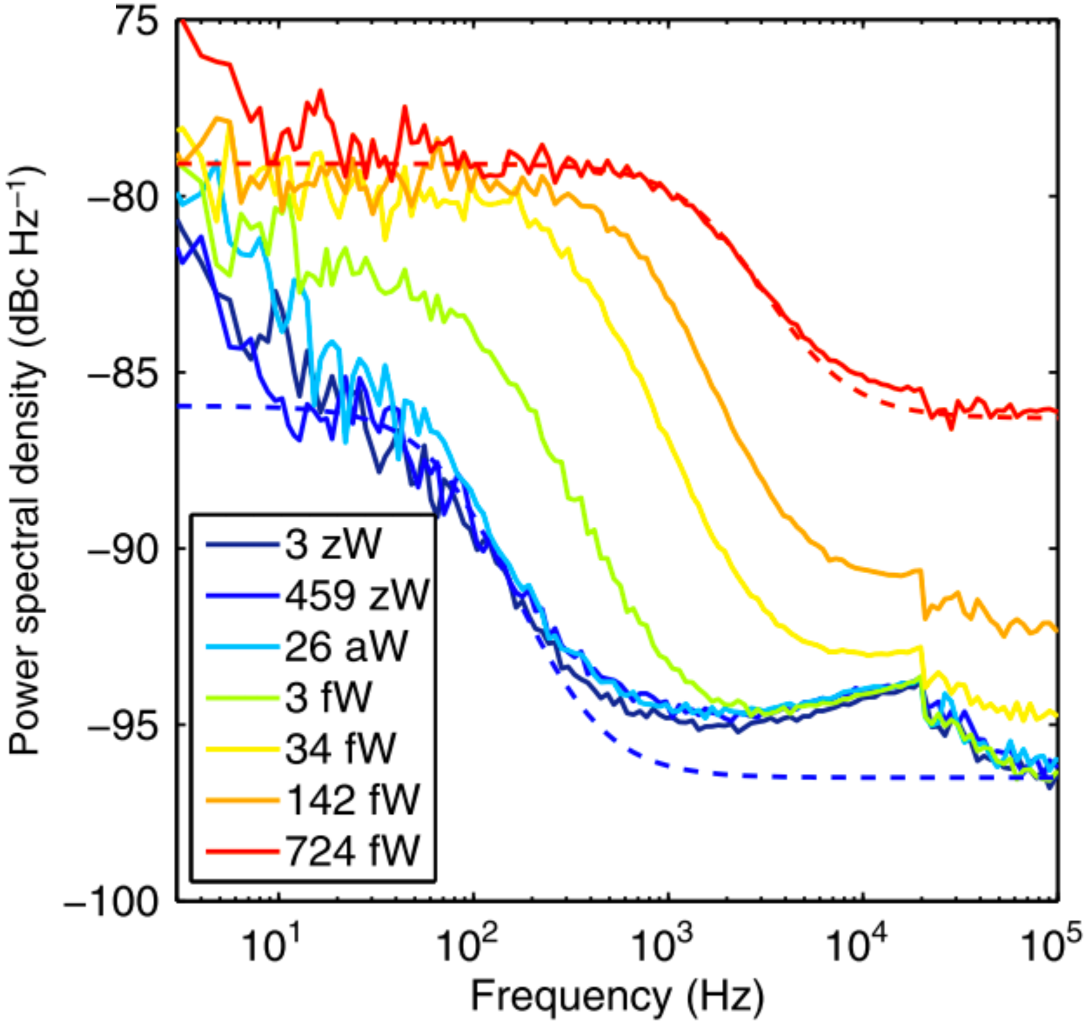
Noise signatures: Fundamental

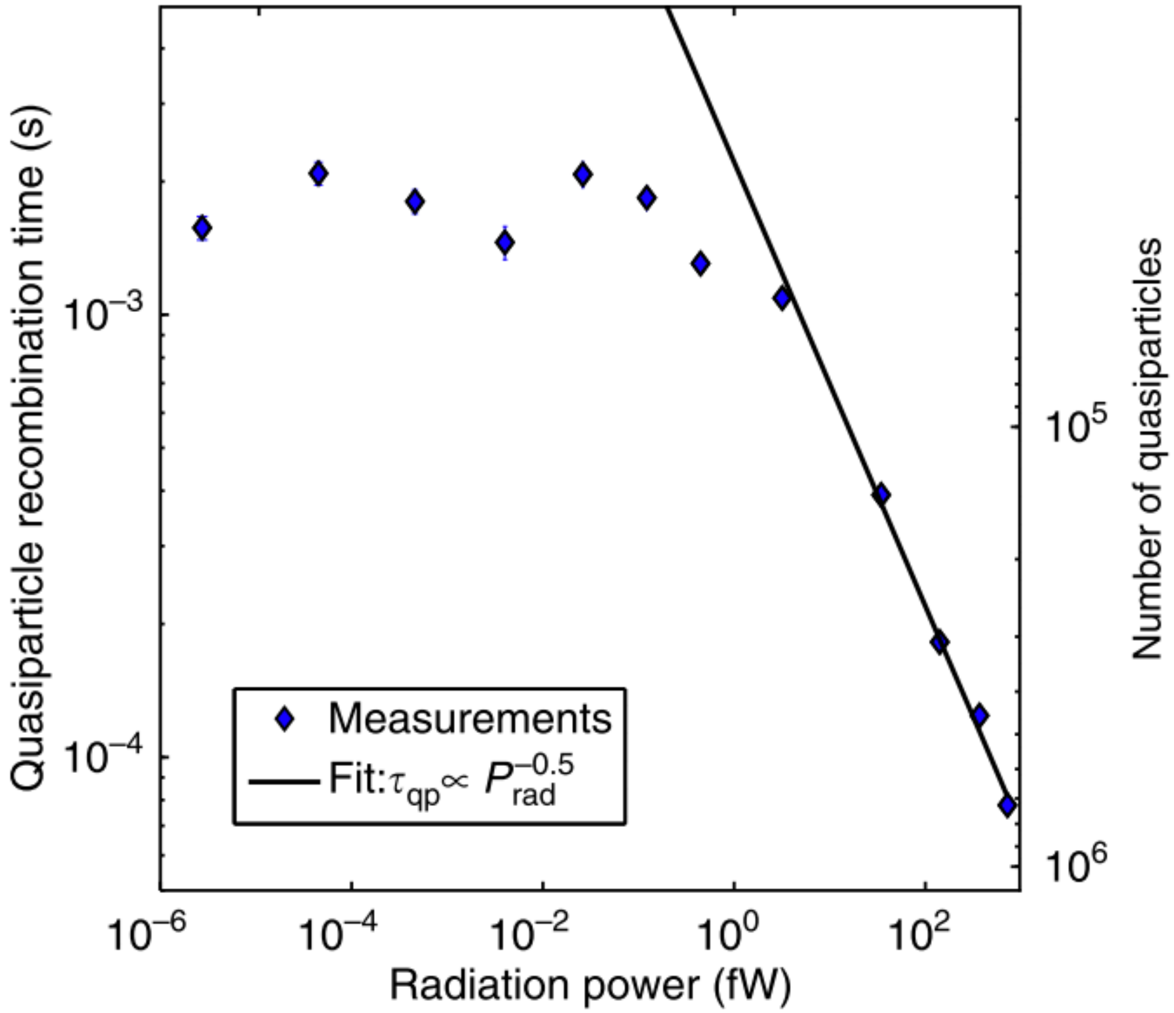
P.J. de Visser et al., Nature Communications, **3130**, (2014) DOI: 10.1038/ncomms4130



2: Photon fluctuations

- White noise spectrum
- T dependent roll-off (qp recombination)



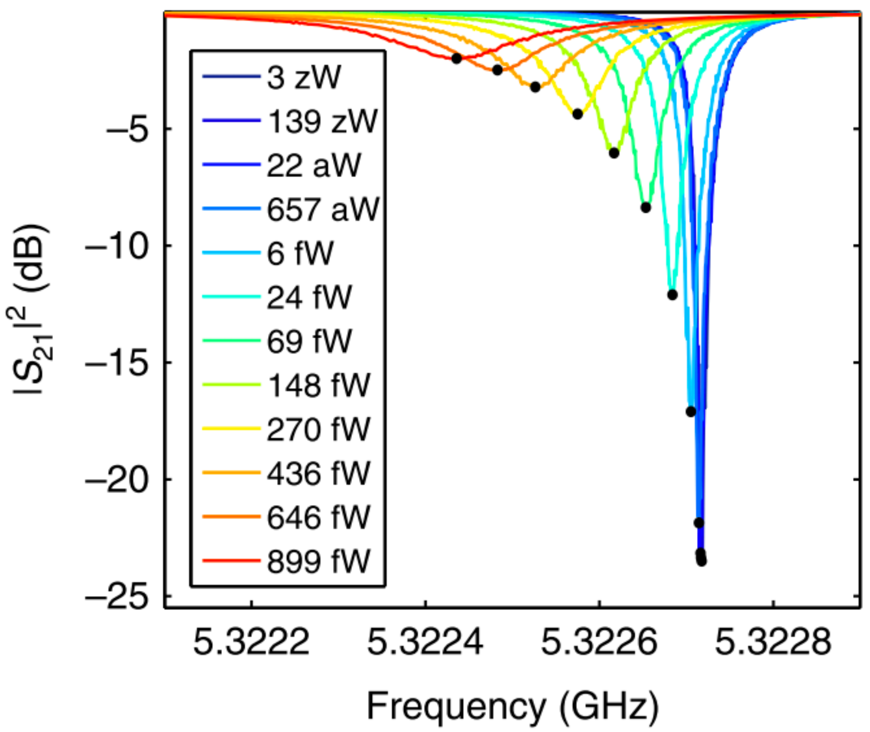


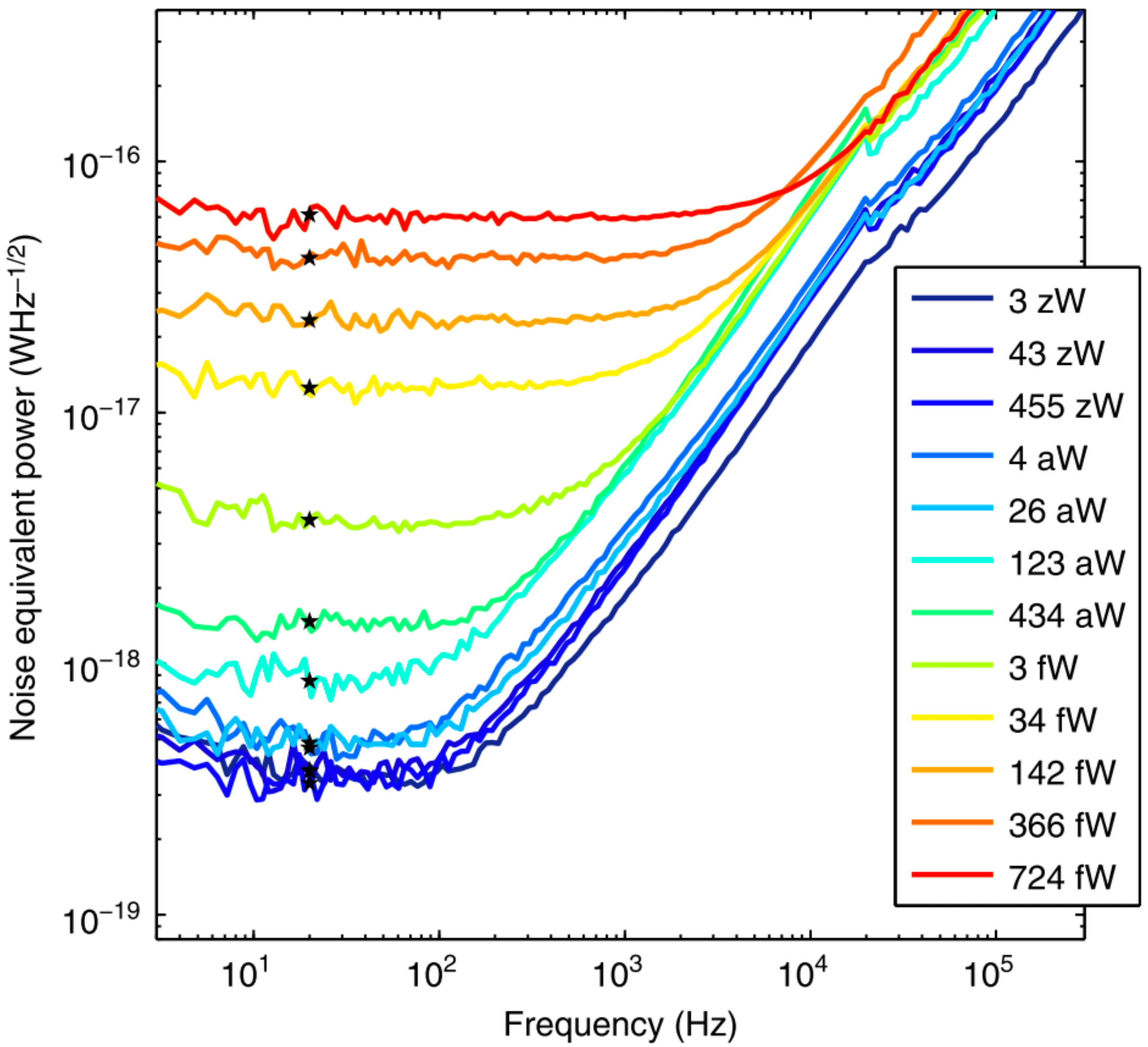
aluminium MKID Sensitivity limit

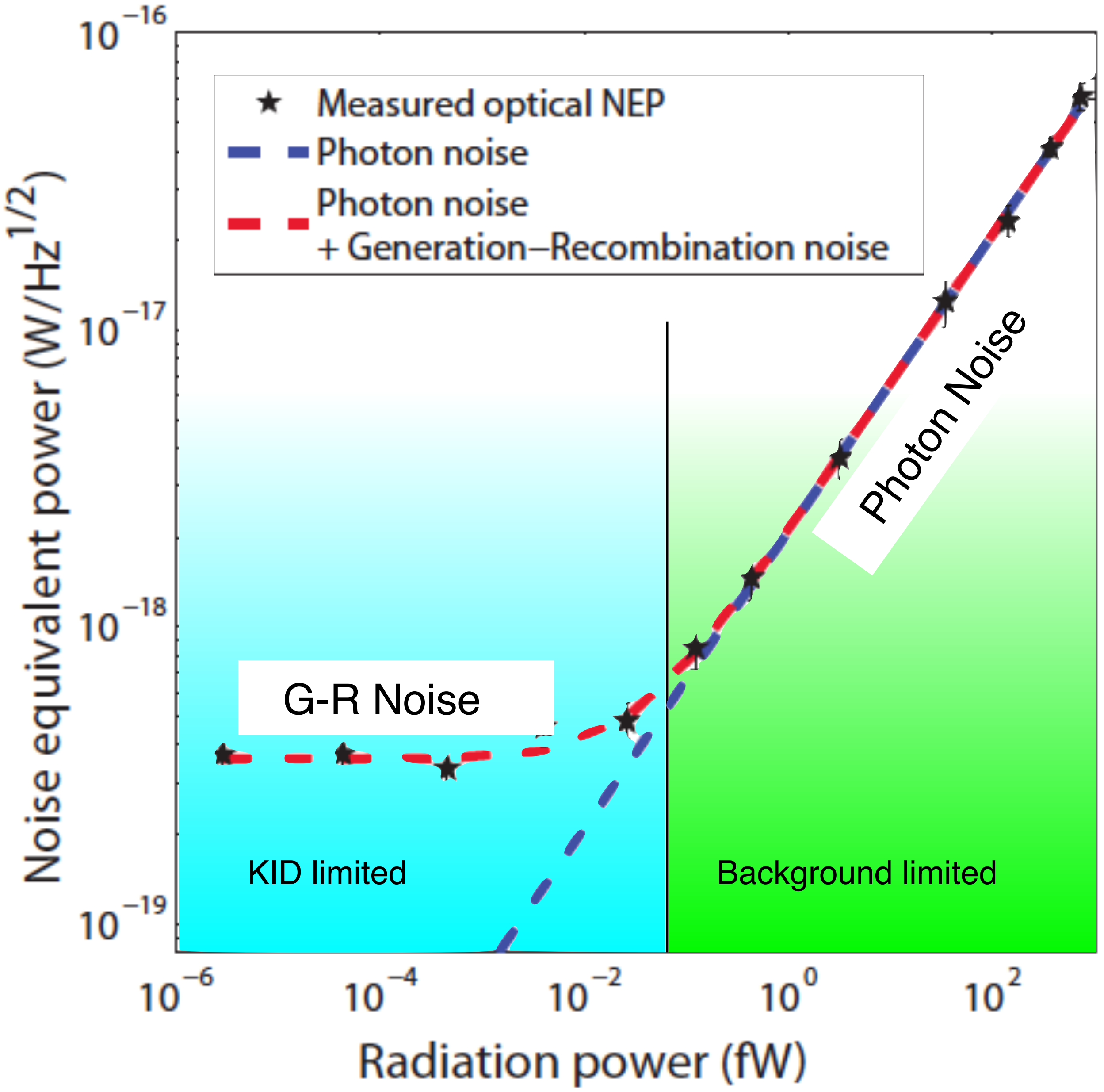
NEP ~ $3.8 \cdot 10^{-19}$ W/√Hz

We can see the fundamental limits

Good enough for most applications







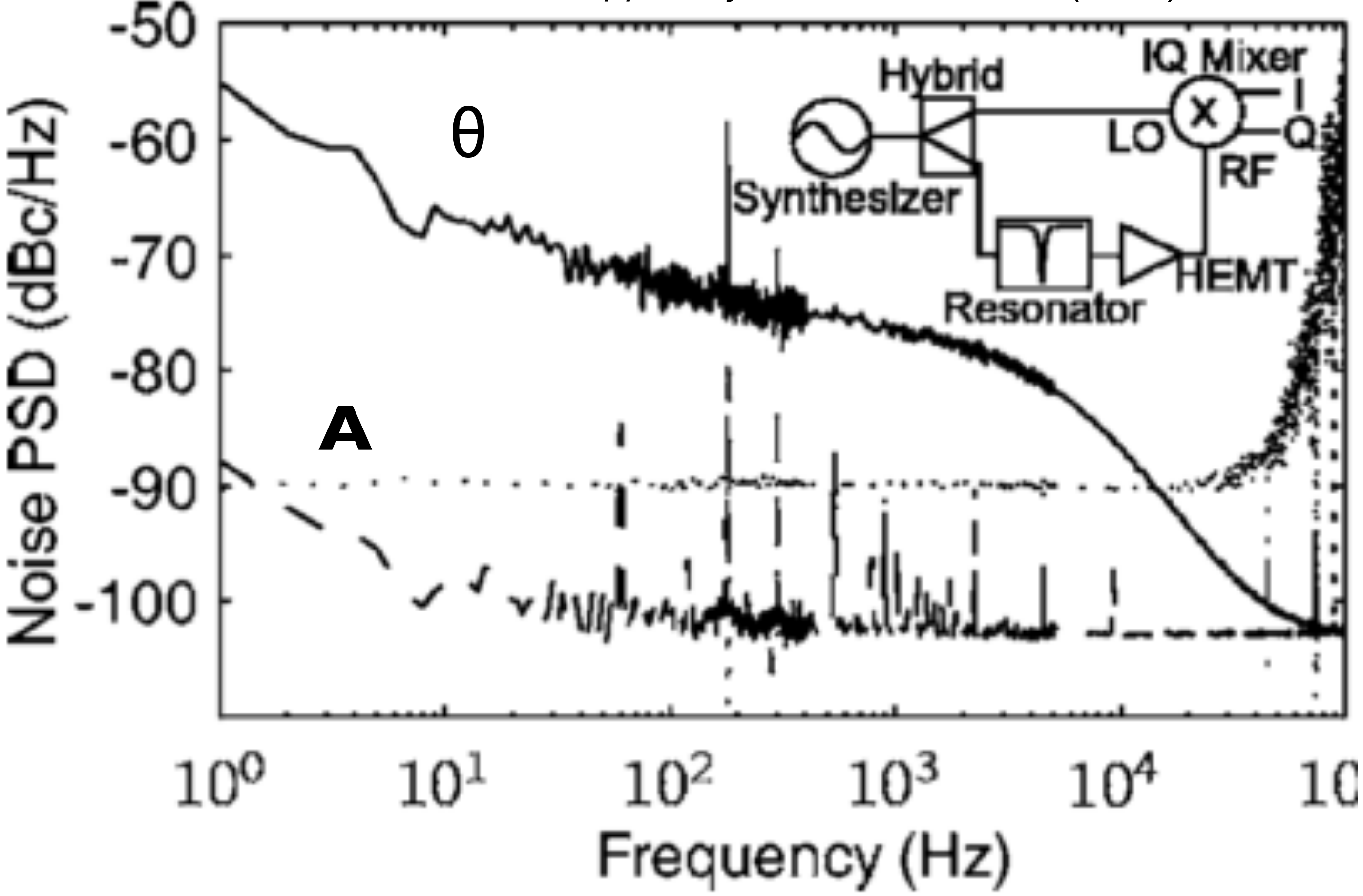
P. J. de Visser, et al., *Nature Communications*, vol. 5, pp. 3130 (2014)

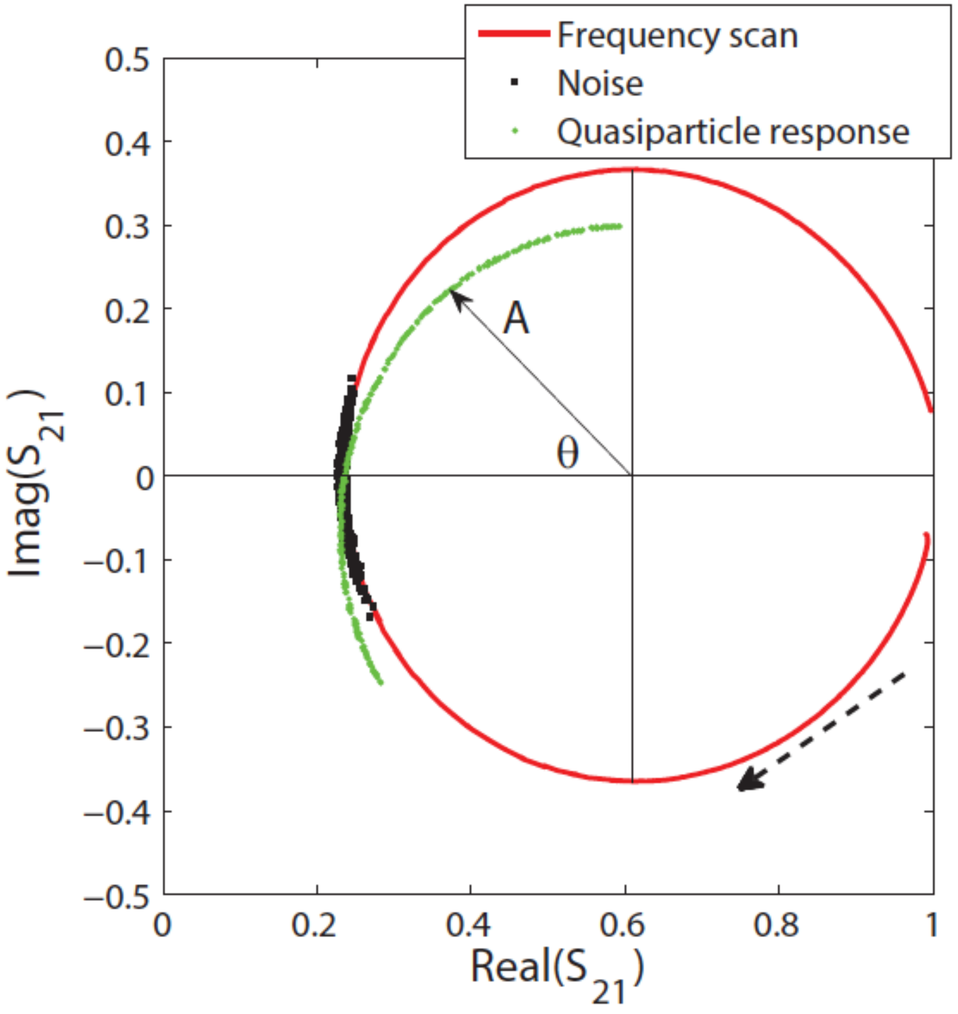
Excess noise sources

- excess *phase* noise
  - TLS fluctuations
- Amplitude noise
  - due to readout

- Phase readout
  - Larger response
  - Monotonic in P

Gao et al, Appl. Phys. Lett, **90** *105507 (2007)*





Future Space instrumentation with MKIDs

SpaceKID project (2012-2016)

Lab demonstrator system

- 961 pixels
- 1 readout chain

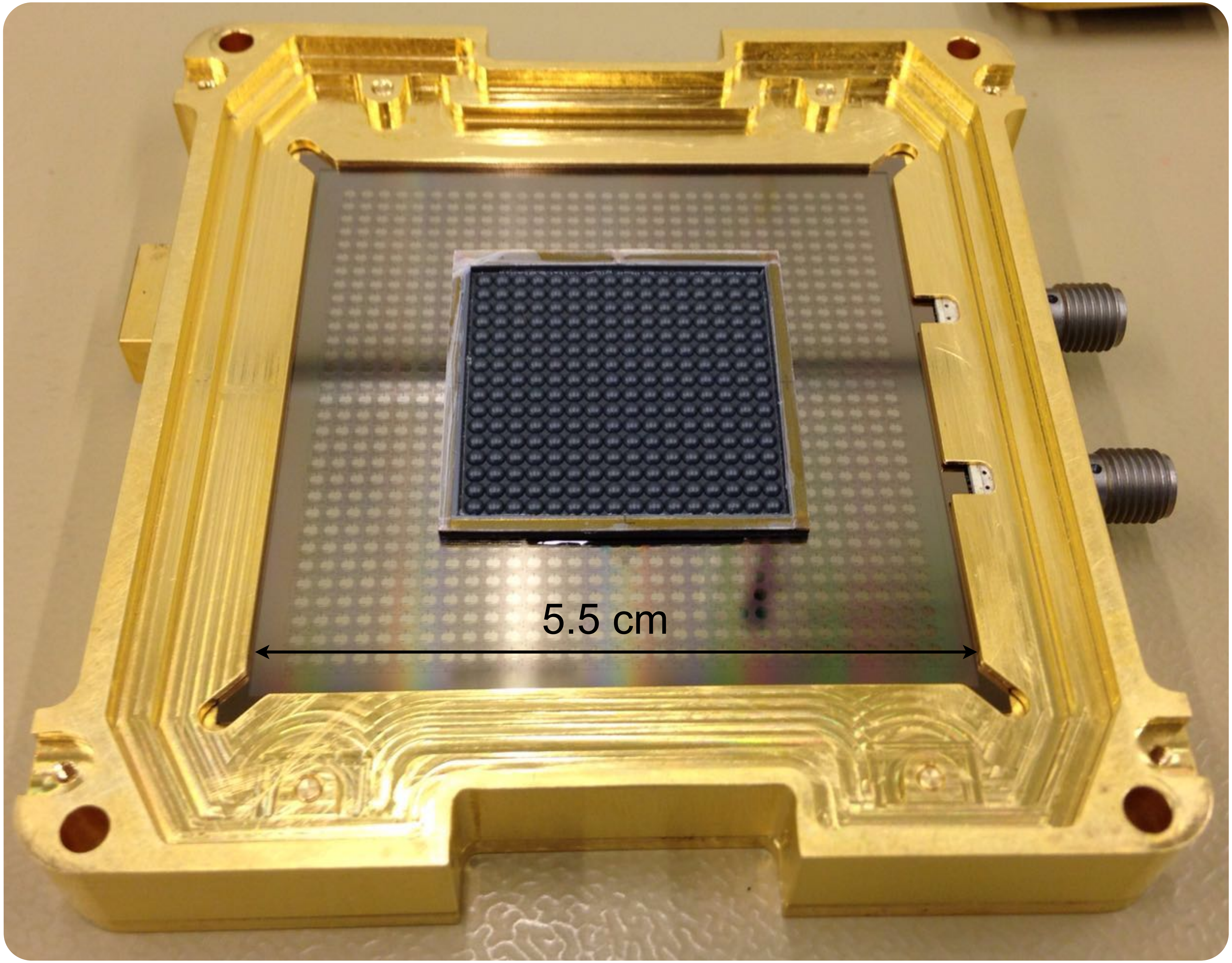
For a future imaging system in space (Safari, OST)

- 5 m class, cryogenically cooled telescope (4K)

The following generic requirements:

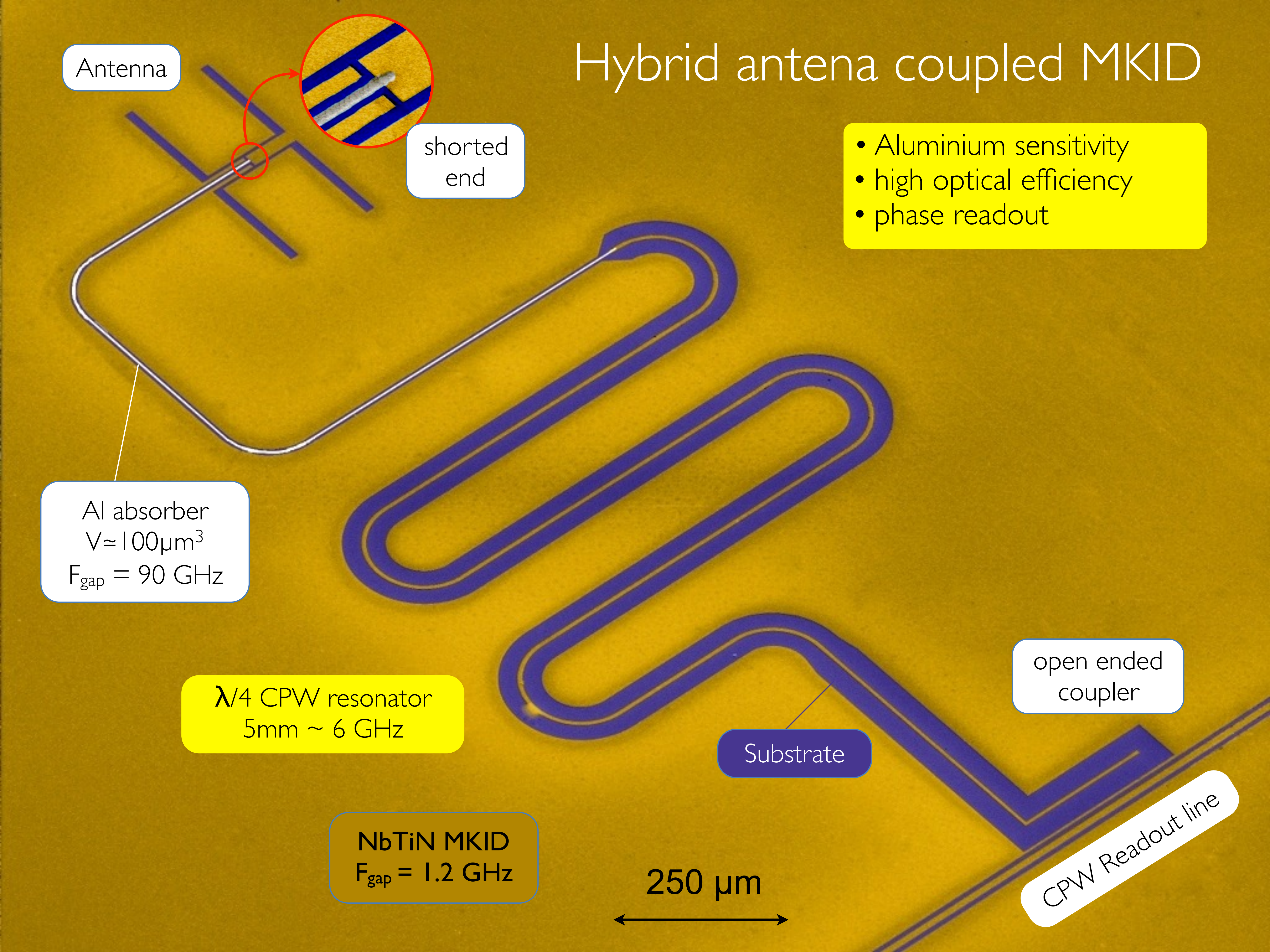
	MUX (factor)	λ	$\lambda/\Delta\lambda$	$\mathrm{NEP}_{\mathrm{det}}$	Absorption efficiency	dynamic range	Cosmic ray dead time	Crosstalk	$1/f$ knee	Yield
Baseline	500	350 μm	5	5×10^{-19} W/$\sqrt{\mathrm{Hz}}$	>0.5	>1000	<30%	<−20 dB	<0.5 Hz	>60%
Goal	1000	200 μm	1.5	1×10^{-19} W/$\sqrt{\mathrm{Hz}}$	>0.7	$>10^4$	<10%	<−30 dB	<0.1 Hz	>70%

961 pixel, 850 GHz demonstrator array



Hybrid antena coupled MKID

- Aluminium sensitivity
- high optical efficiency
- phase readout



Antenna

shorted
end

Al absorber
$V \simeq 100 \mu m^3$
$F_{gap} = 90$ GHz

λ/4 CPW resonator
5mm ~ 6 GHz

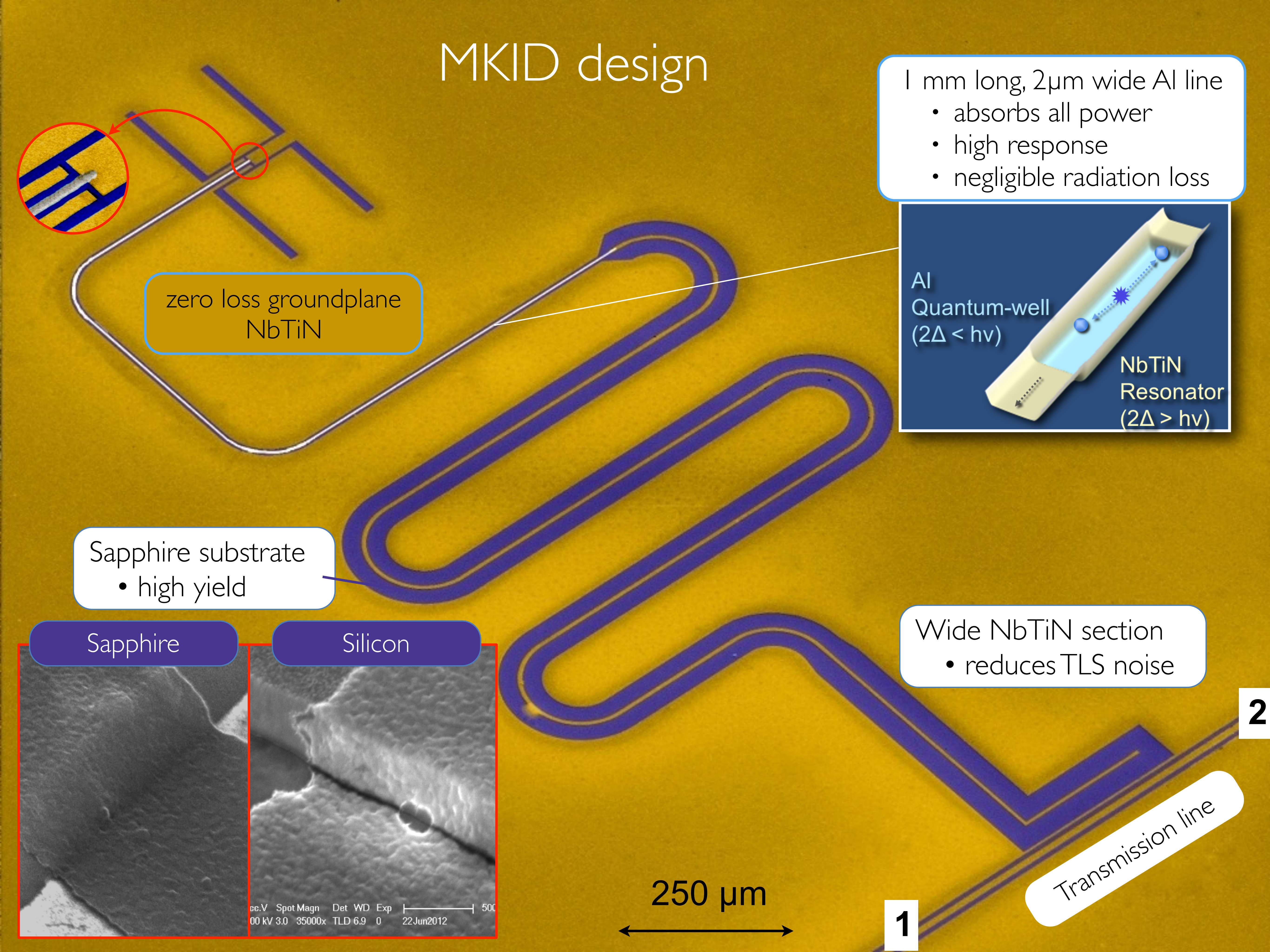
NbTiN MKID
$F_{gap} = 1.2$ GHz

Substrate

open ended
coupler

CPW Readout line

MKID design



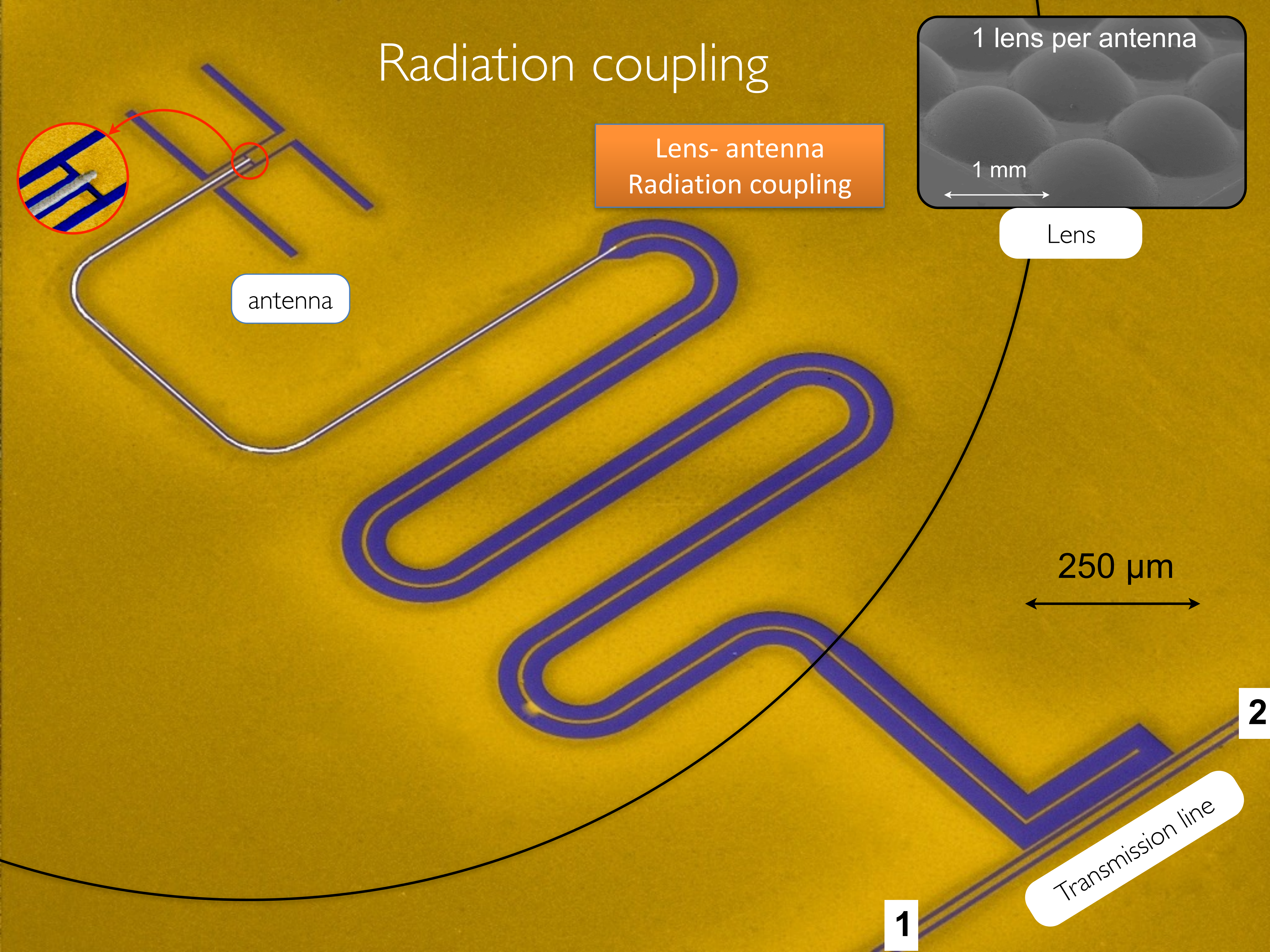
I mm long, 2µm wide Al line
- absorbs all power
- high response
- negligible radiation loss

zero loss groundplane
NbTiN

Sapphire substrate
- high yield

Wide NbTiN section
- reduces TLS noise

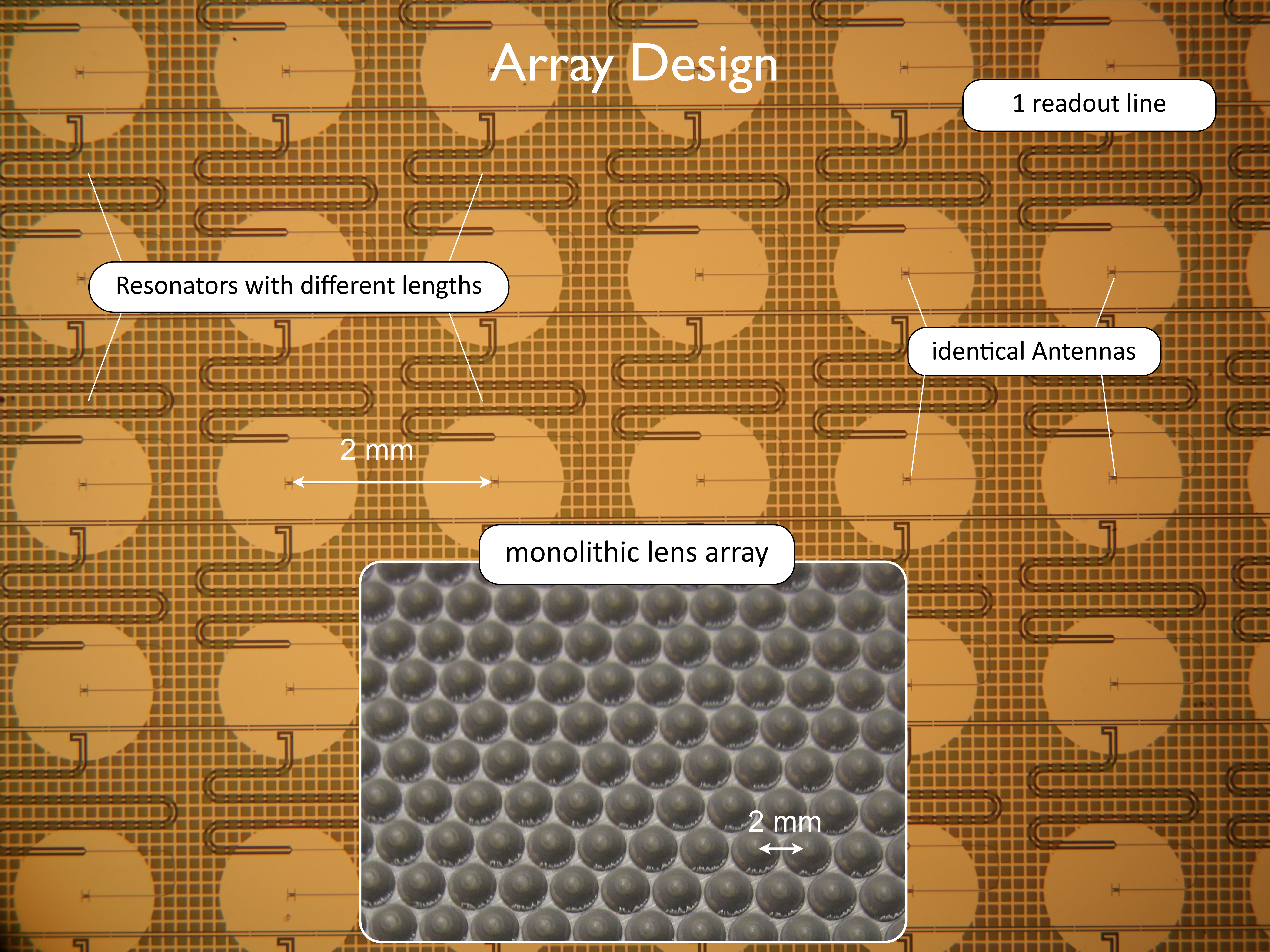
Radiation coupling



Lens- antenna
Radiation coupling

1 lens per antenna

Array Design



1 readout line

Resonators with different lengths

identical Antennas

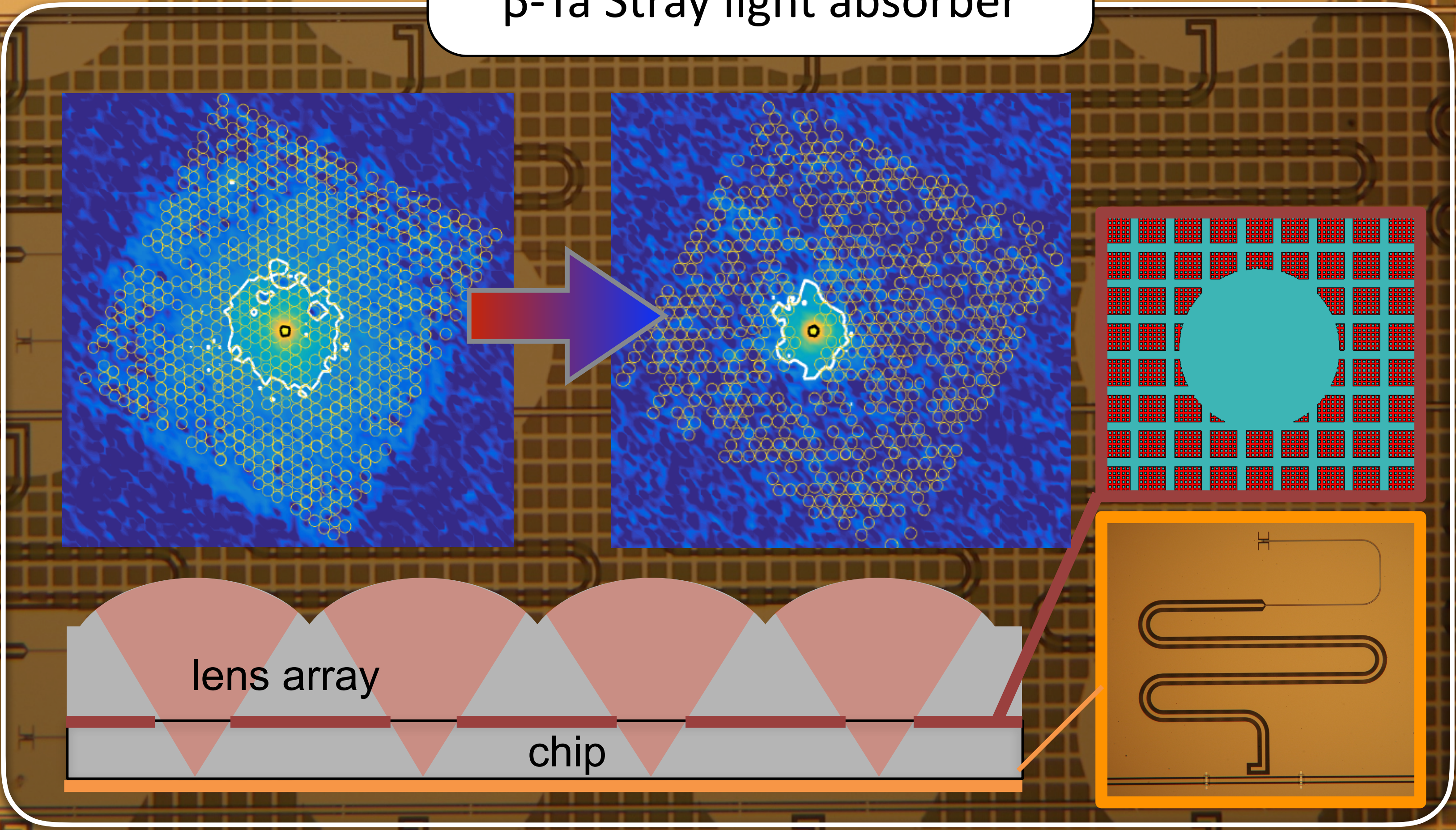
2 mm

monolithic lens array

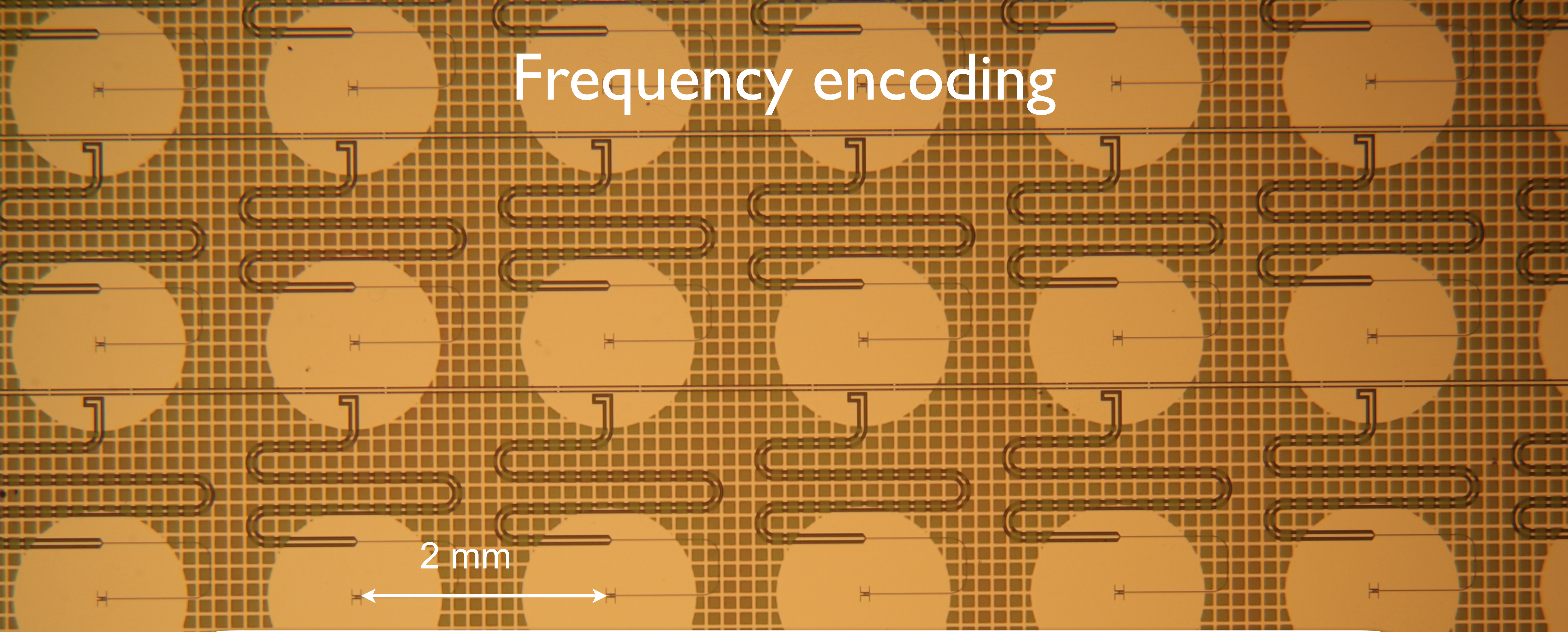
2 mm

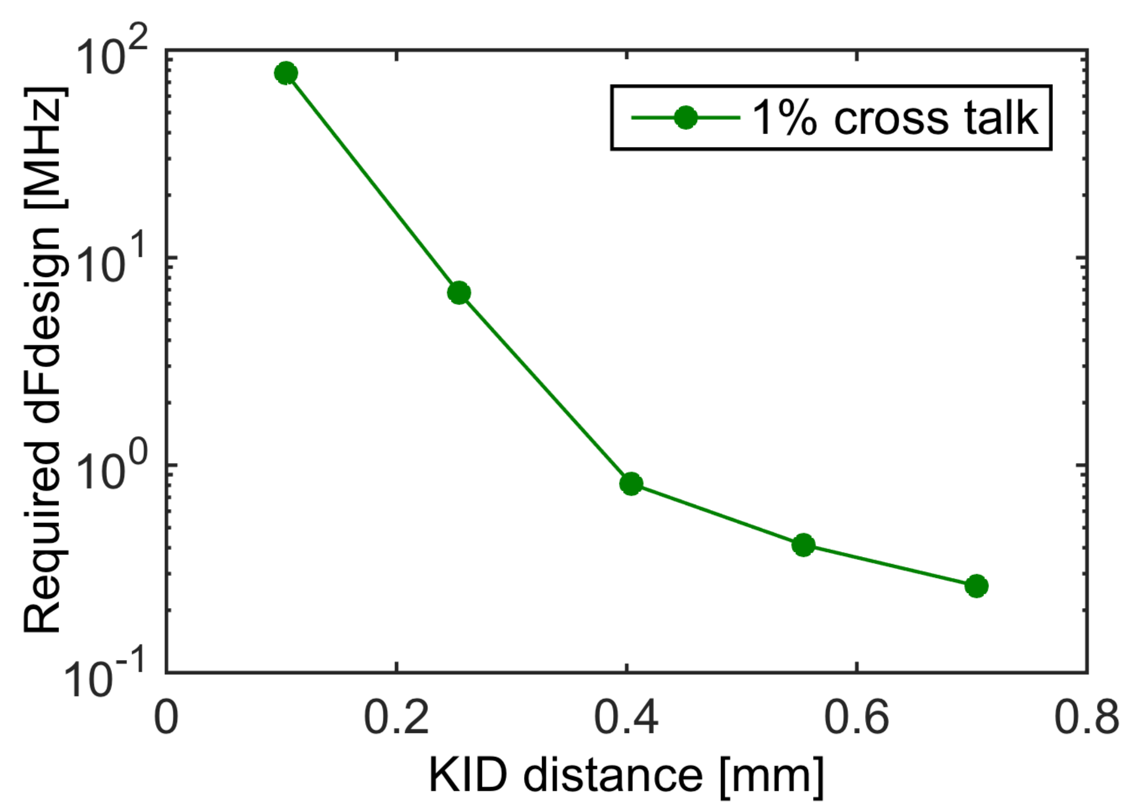
Stray light absorber

β-Ta Stray light absorber



Frequency encoding





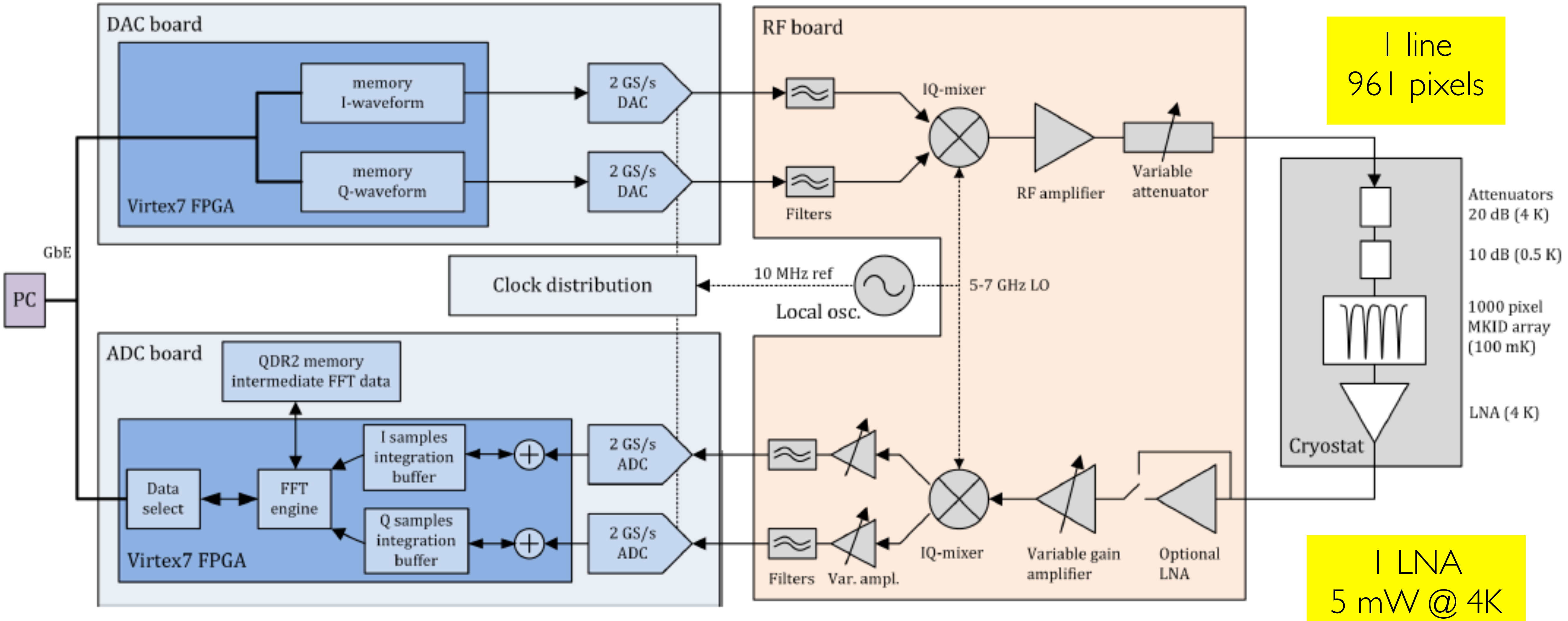
Fres = $F_0 + \mathbf{M} \cdot dF$

$$\mathbf{M} = \begin{array}{|c|c|c|c|c|} \hline 10 & -11 & 11 & -12 & 12 \\ \hline -10 & 3 & -4 & 4 & -5 \\ \hline 9 & -3 & 0 & -1 & 5 \\ \hline -9 & 2 & -2 & 1 & -6 \\ \hline 8 & -8 & 7 & -7 & 6 \\ \hline \end{array}$$

SpaceKIDs Readout System: 2 GHz bandwidth, ≤4000 MKIDs

J. Van Rantwijk, et al. IEEE Trans. Microw. Theory Tech., 2016.

~20 mW/pixel @ 300K

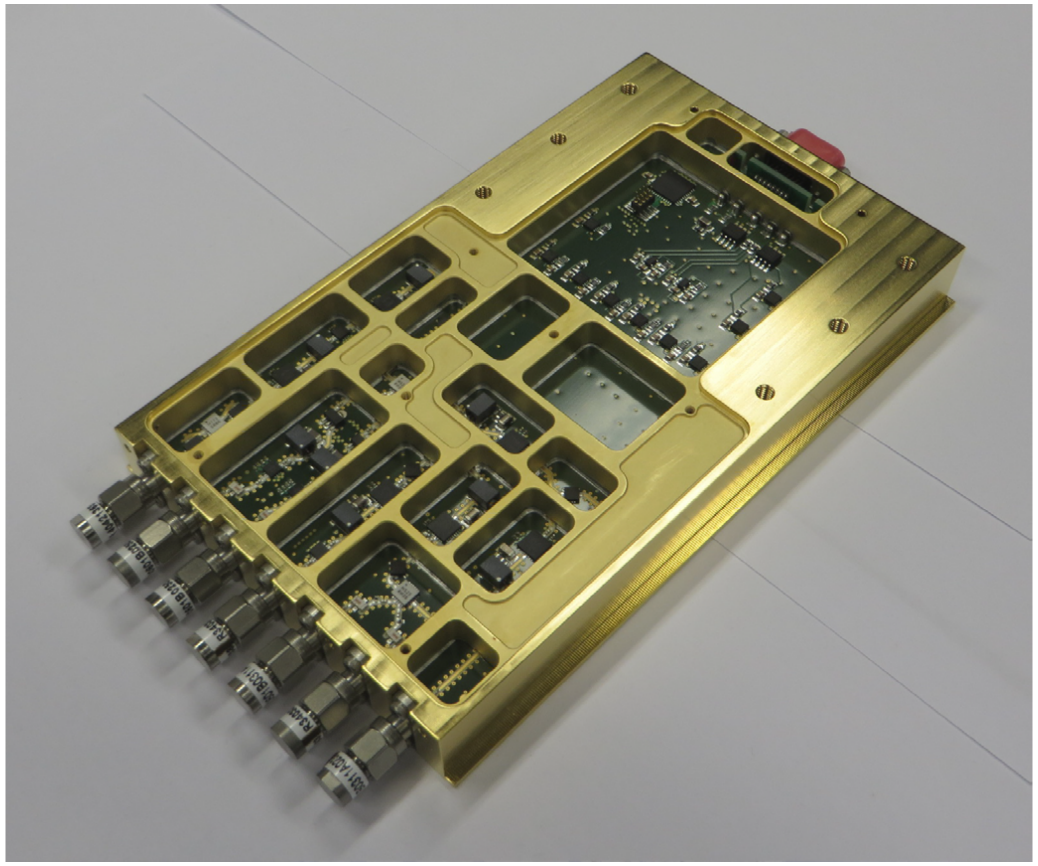


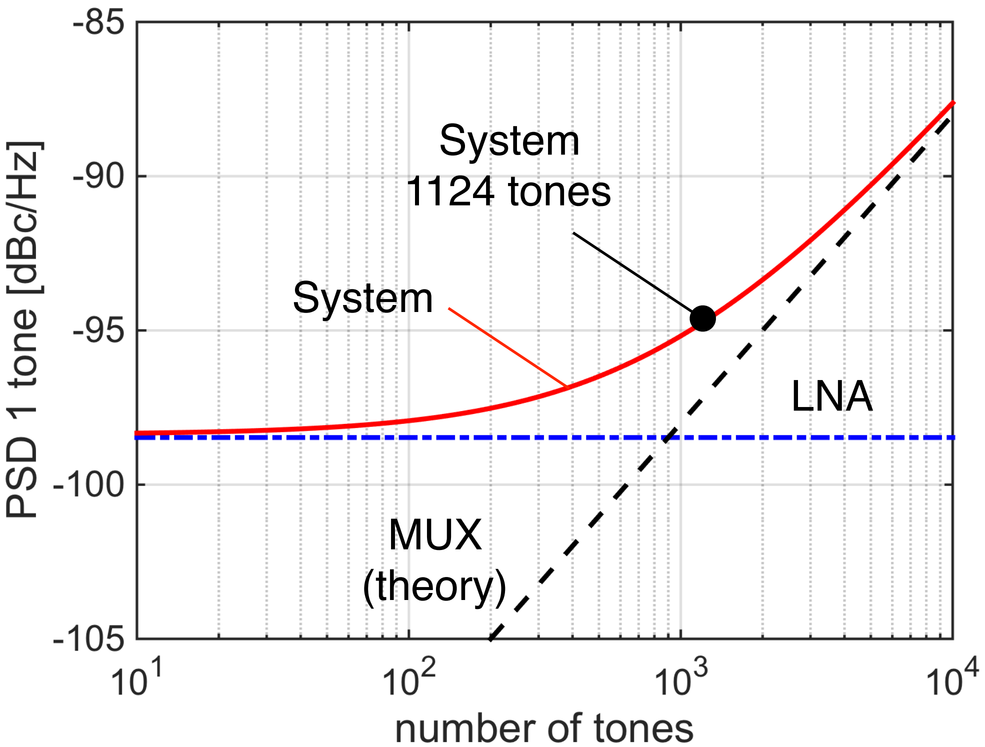
1 line
961 pixels

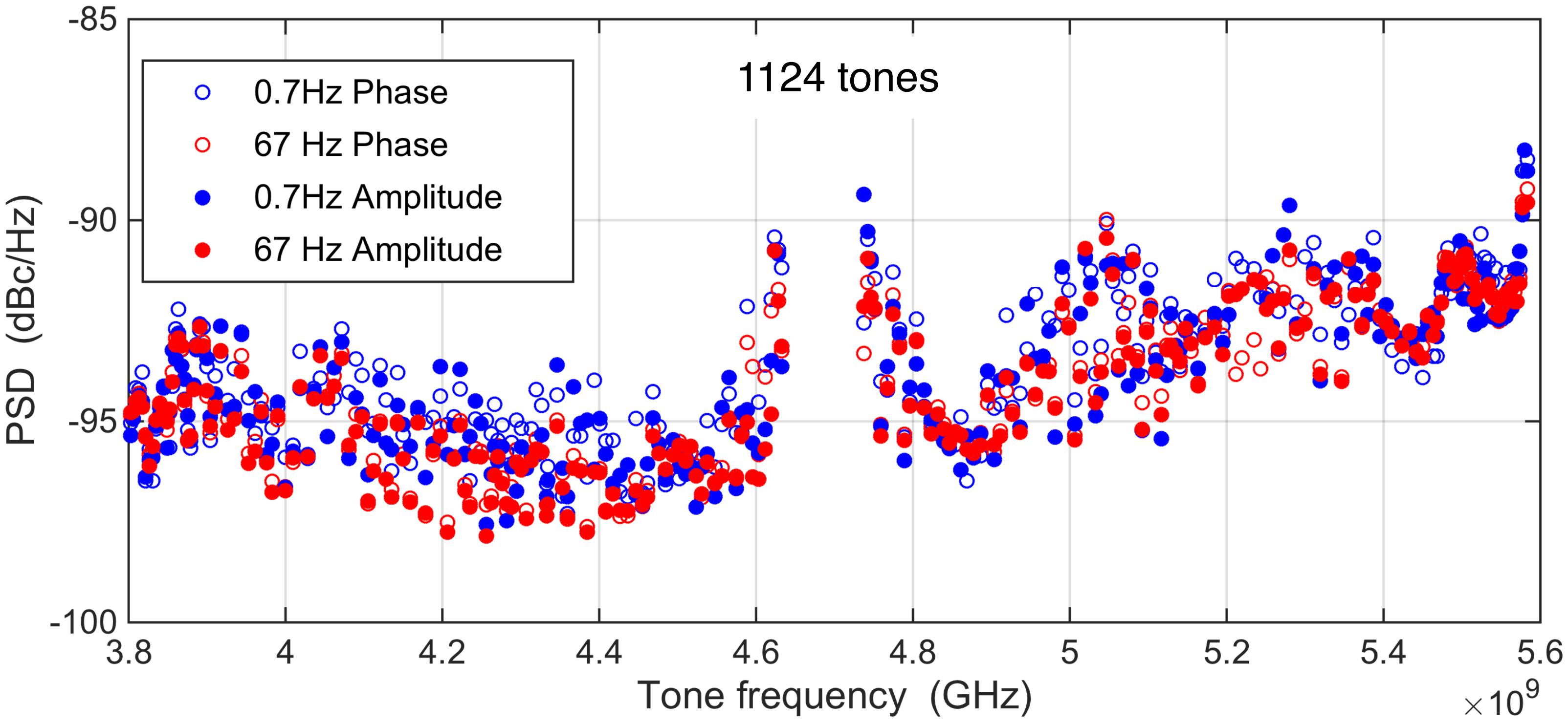
1 LNA
5 mW @ 4K

SpaceKIDs Readout System: 2 GHz bandwidth, ≤4000 MKIDs

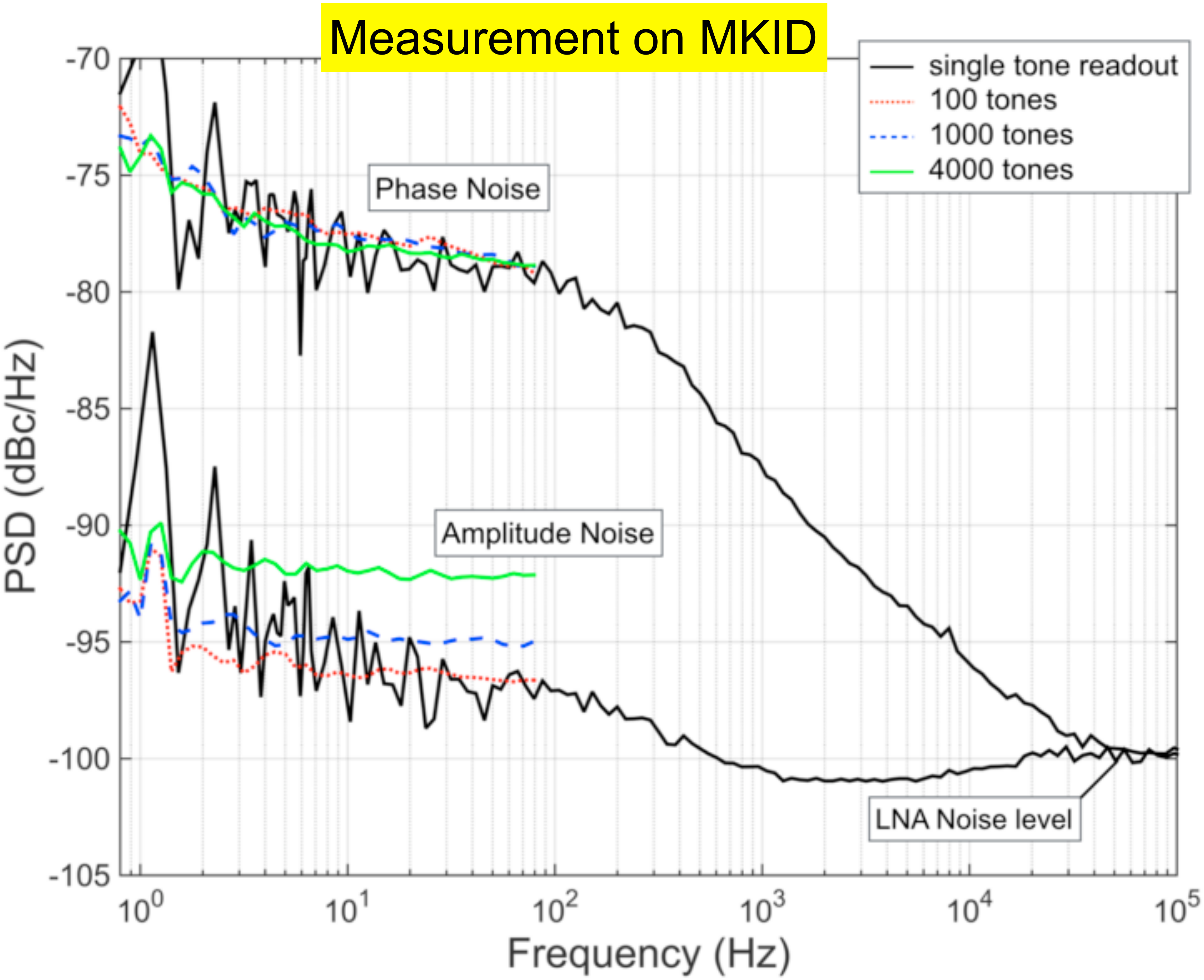
J. Van Rantwijk, et al. IEEE Trans. Microw. Theory Tech., 2016.

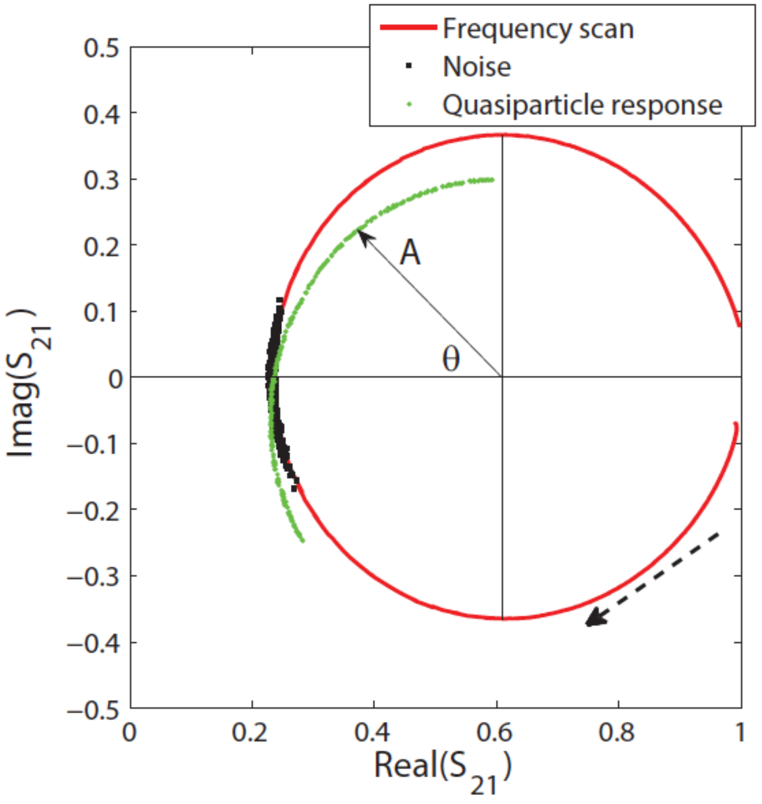






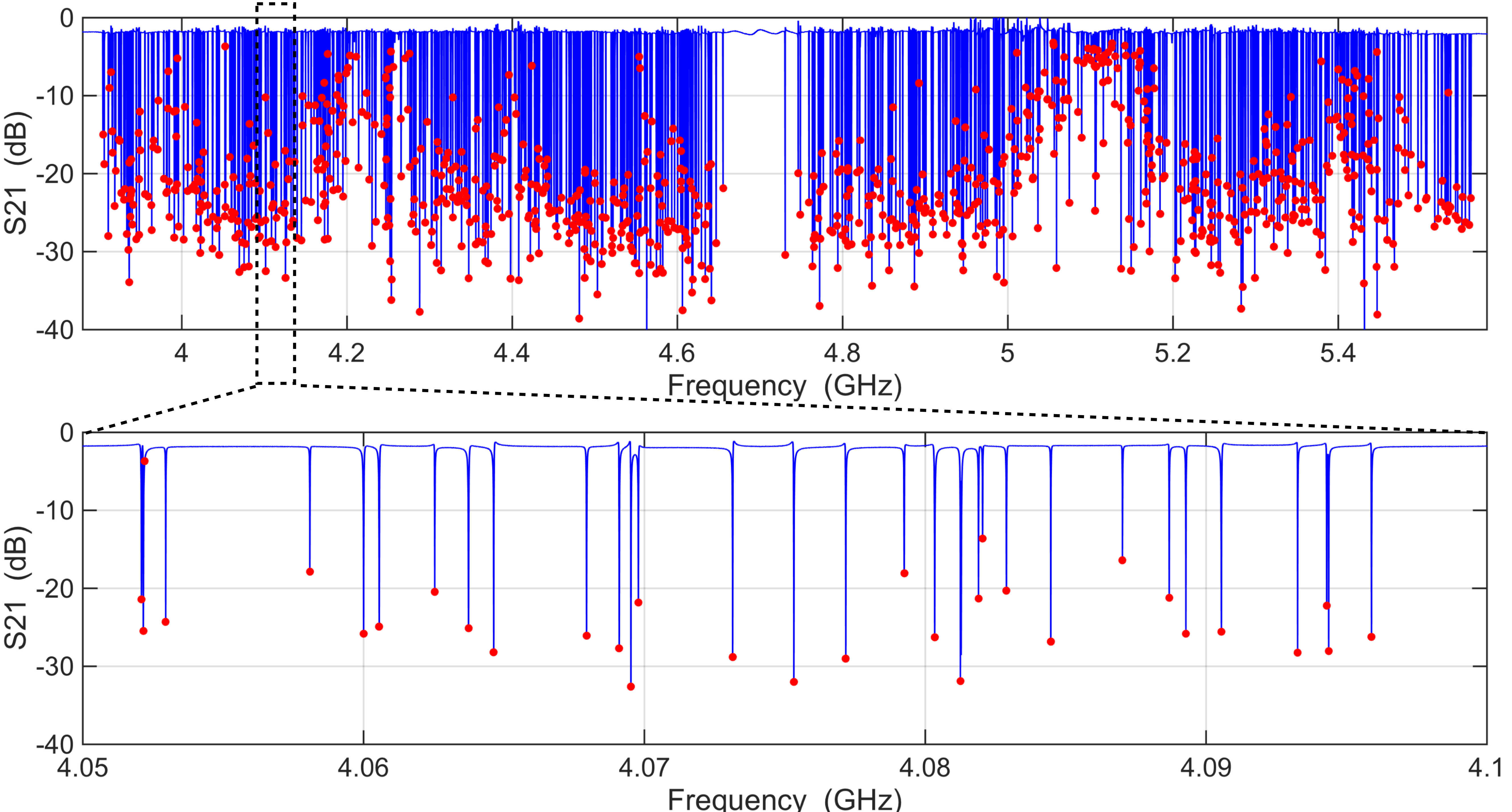
Phase readout superior



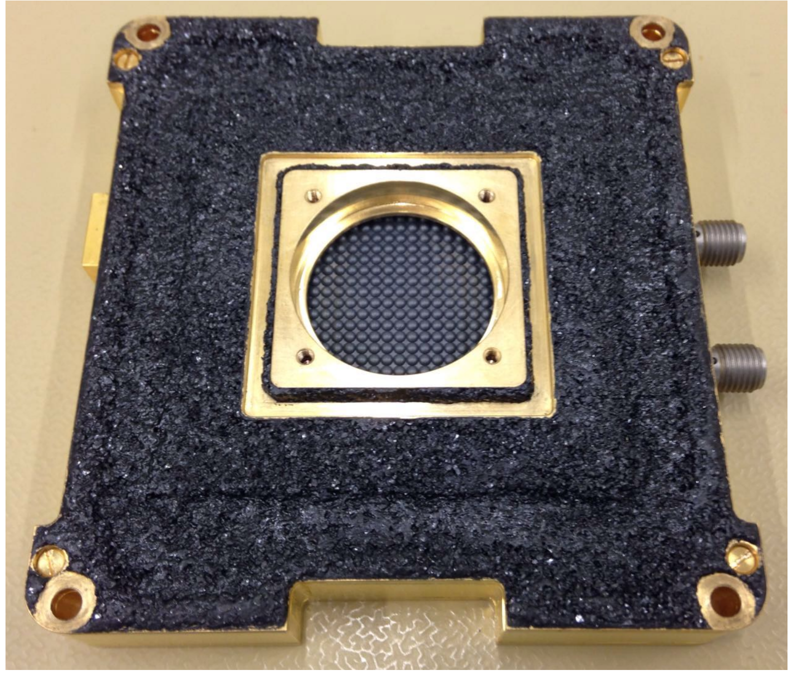


Array Analysis

Frequency range	3.67 – 5.3 GHz
# resonators:	896 (93%)



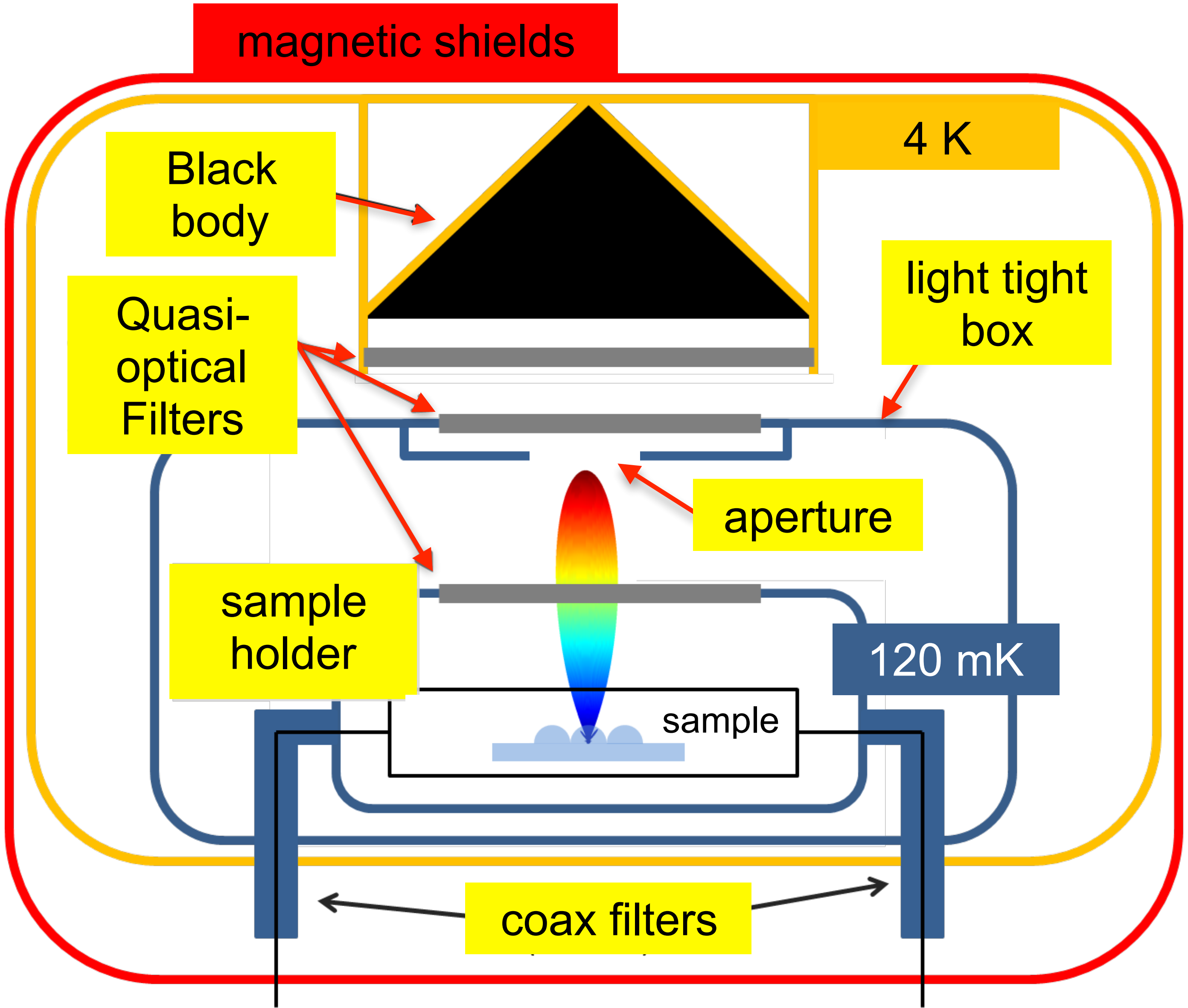
Sensitivity measurements



Array in box-in-box stray light shield

Lens-antenna beams couple partially to black body

- Calculations from antenna-lens model:
- $\eta_{opt} = \eta_{rad}\,\eta_{SO} = 0.61$ (setup)
- $\eta_{Ap} = \eta_{rad}\,\eta_{Tap} = 0.58$ (generic, limit = 0.8)



Lens - antenna coupling

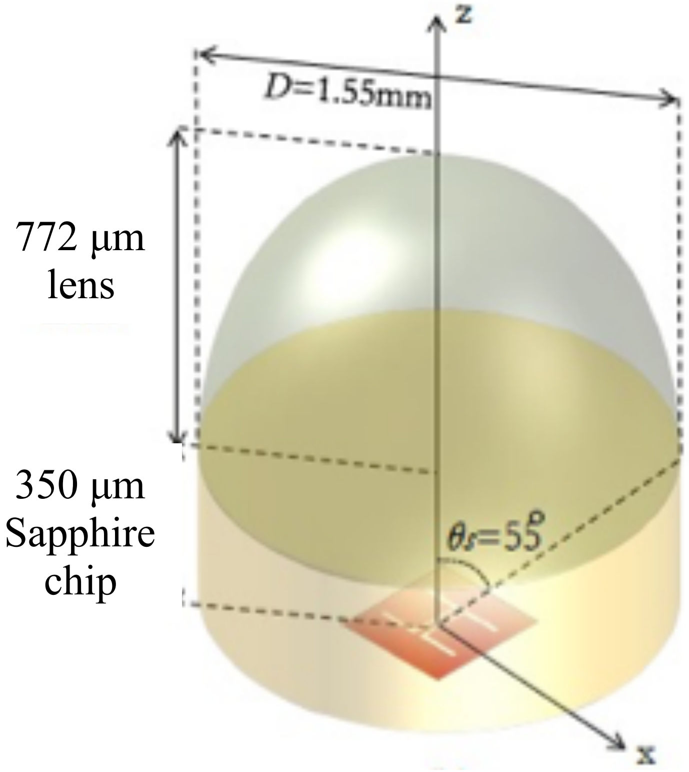
Twin slot antenna + Si lens (850 GHz)

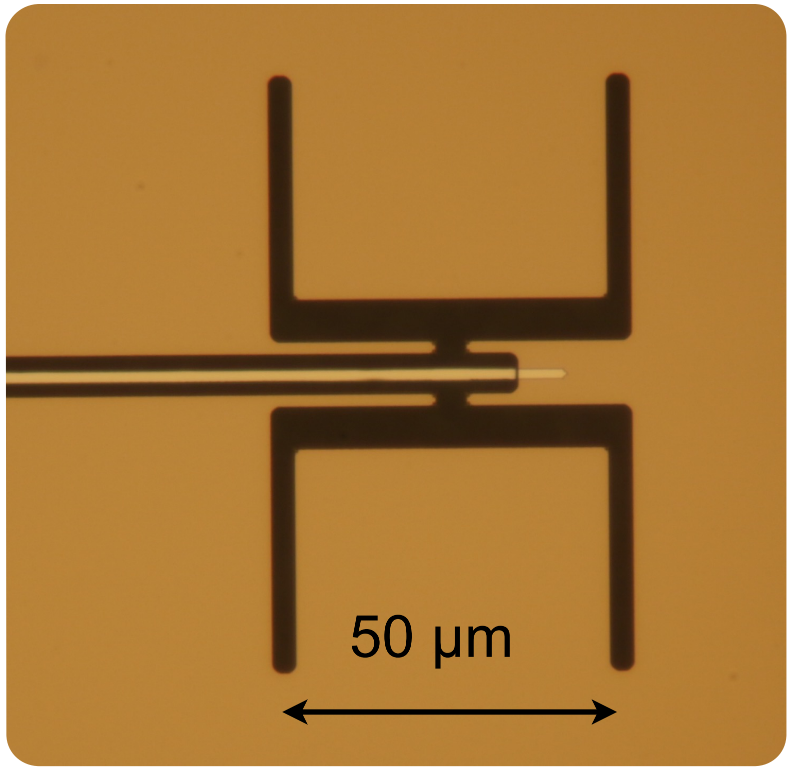
- Sapphire C plane substrate
- Si lens
- Thick superconductors

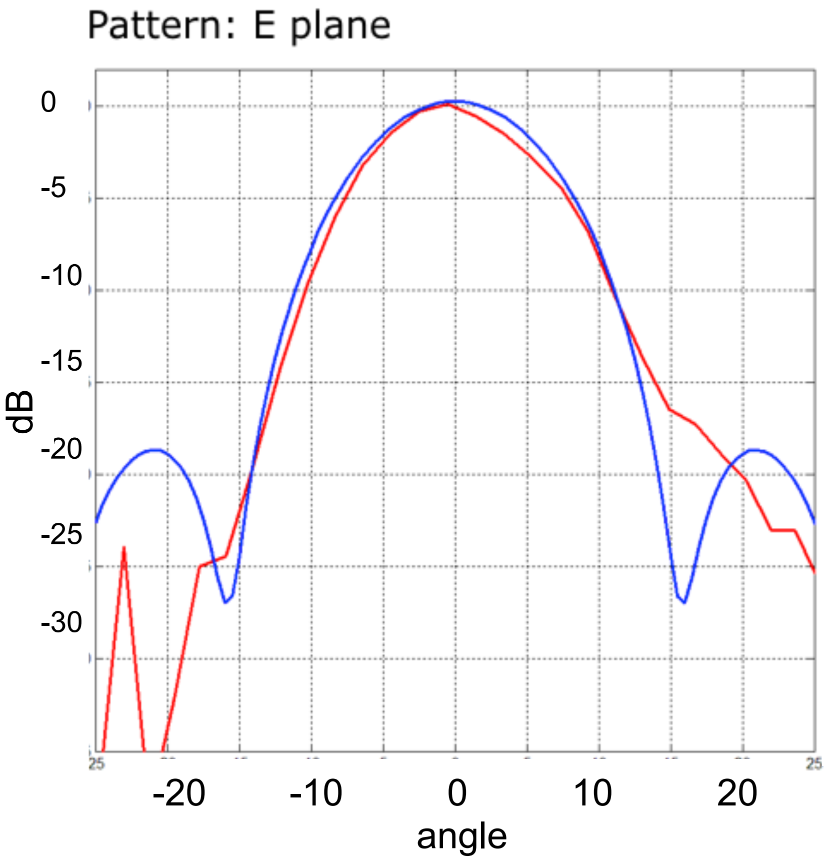
Excellent agreement model - measurements

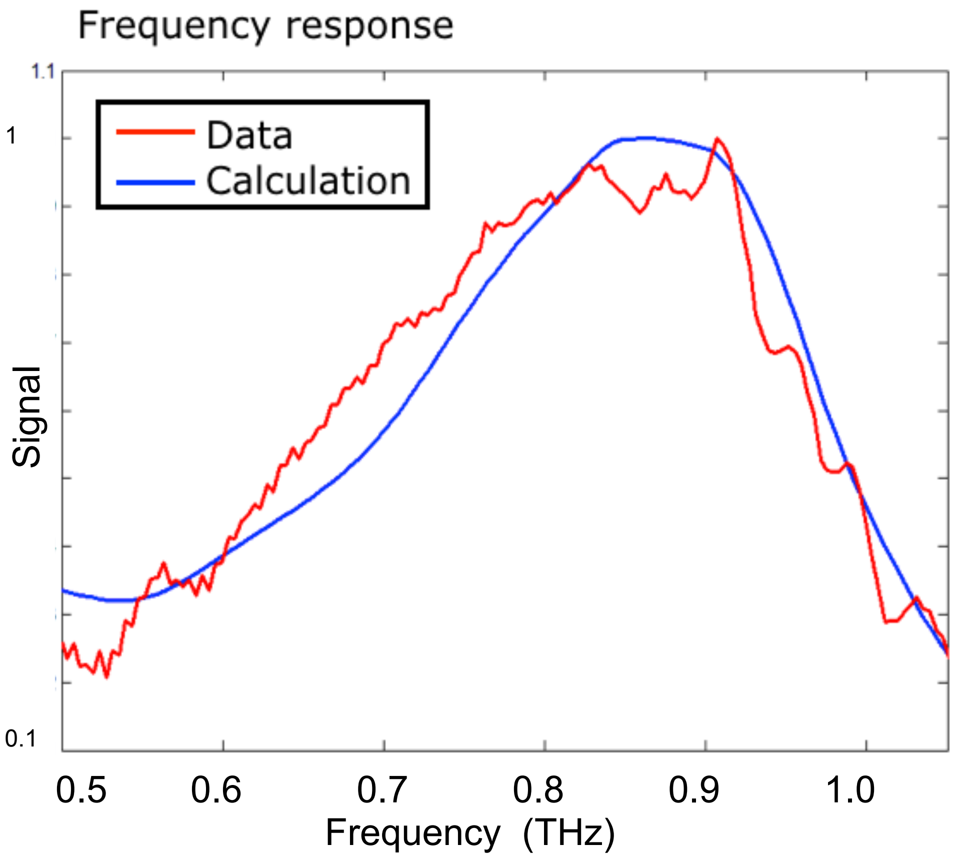
- Validates η_{SO}= 0.82 (setup)
- Validates η_{Tap}= 0.78 (generic)

Now we need to measure η_{Rad}





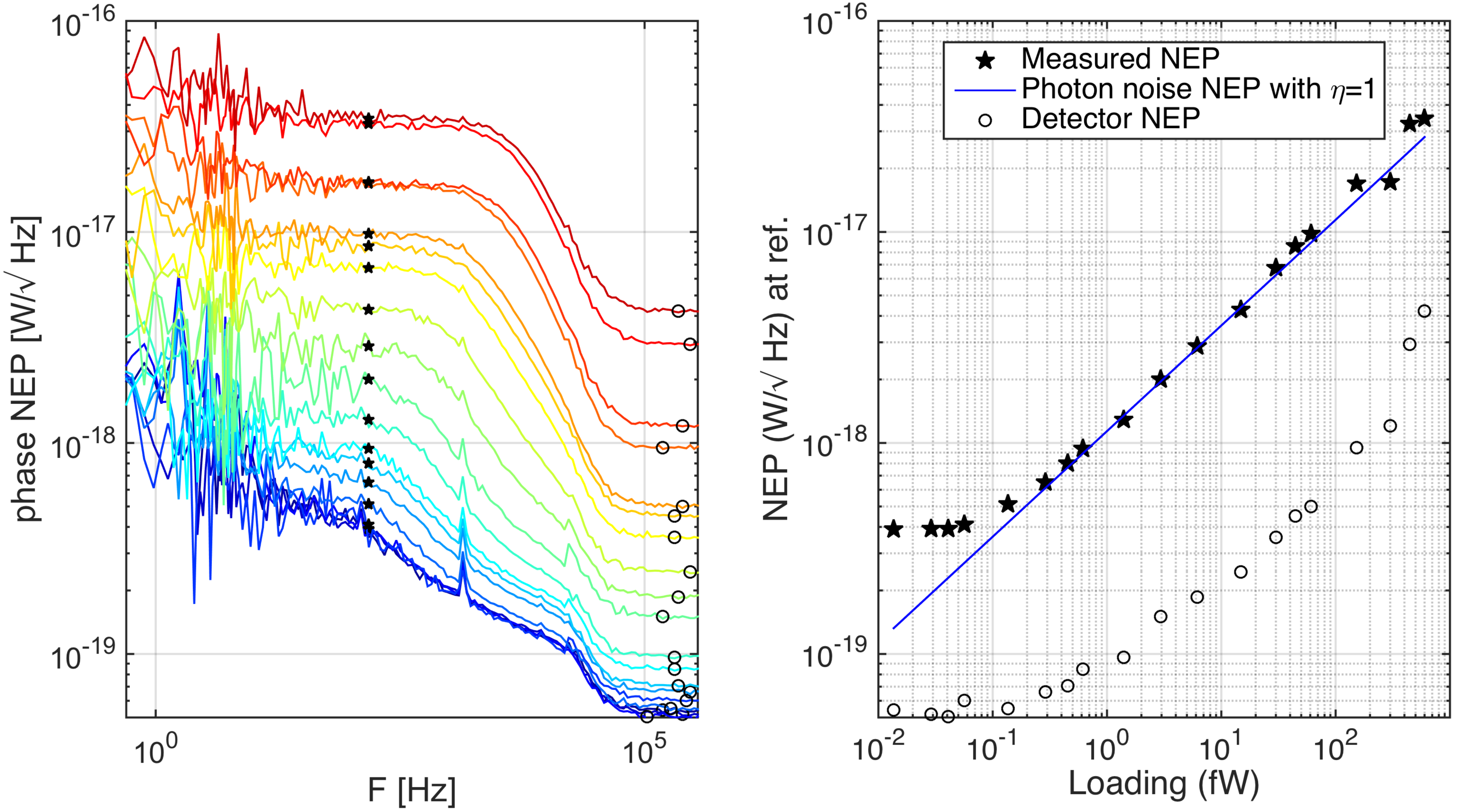

Pattern: E plane


Frequency response

Sensitivity vs. FIR illumination (1 pixel)

Background limited performance @ relevant sky load

Readout tones tuned to MKID Fres



Determining $\eta_{opt} = \eta_{rad} \cdot \eta_{so}$

For a photon noise limited detector:

Poisson Bunching Recombination

$$NEP^2_{blip} = 2\eta_{opt}P_s h\nu(1 + \eta_{opt}F_\nu B_\nu) + 4\Delta\eta_{opt}P_s/\eta_{pb}$$

So we can obtain the optical efficiency using the calculated source power Ps

- if η_{SO} is known from the beam pattern

Poisson Recombination

$$\eta_{opt} = \frac{2P_s h\nu + 4\Delta\eta_{opt}P_s/\eta_{pb}}{S_x\left(dx/dP_s\right)^{-1} - 2P_s h\nu F_\nu B_\nu}$$

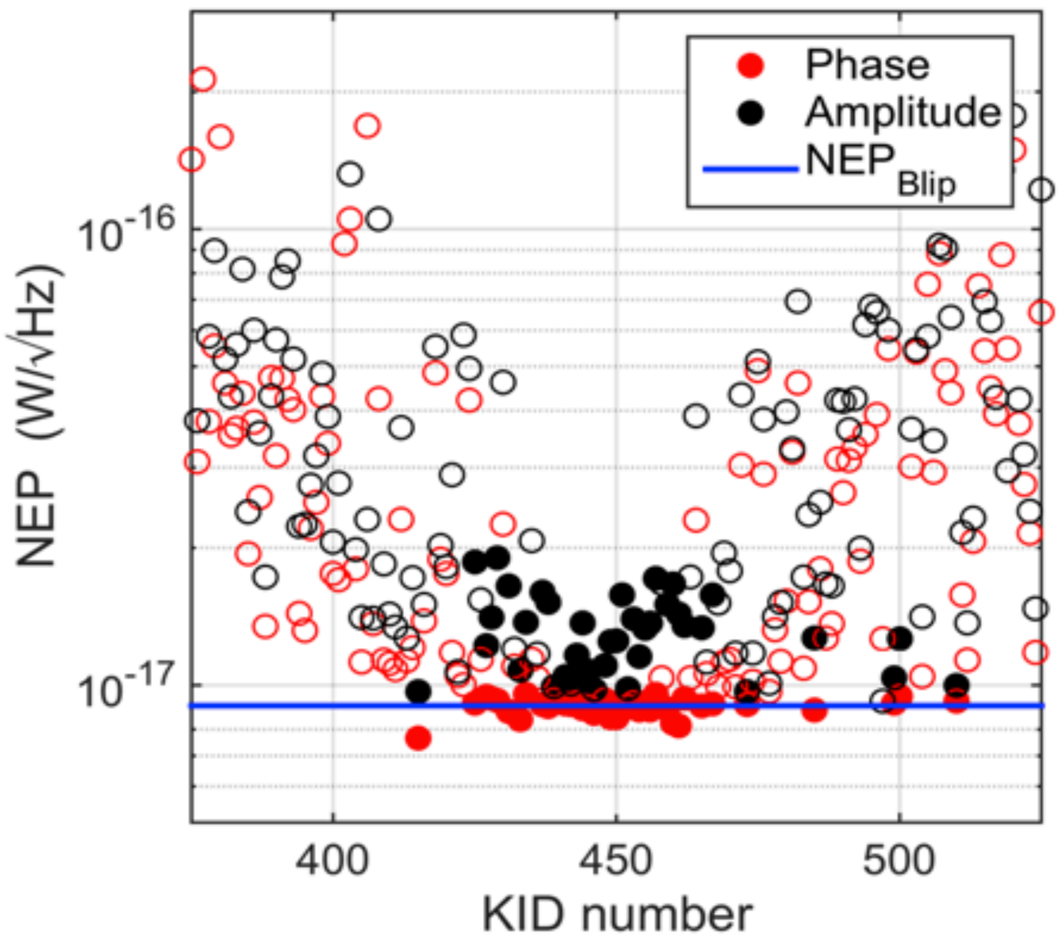
measured NEP Bunching

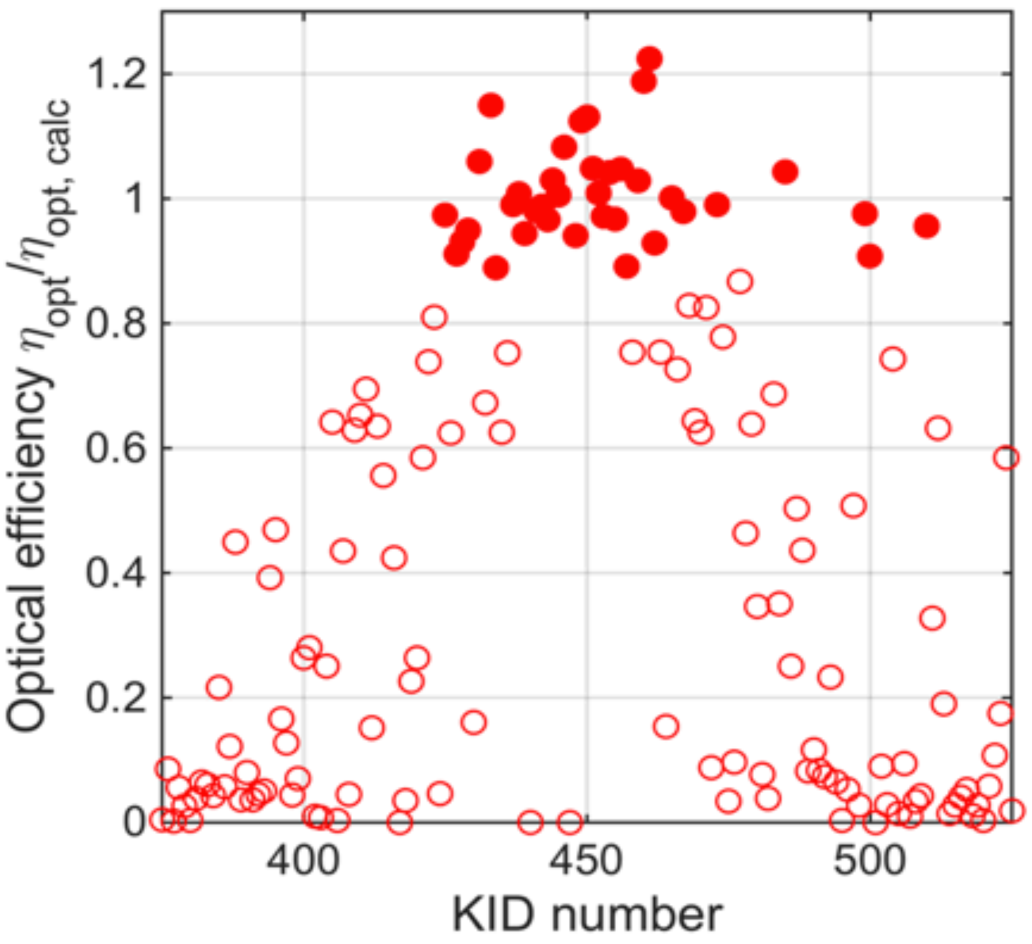
Optical efficiency: $P_s = 50$ fW

Optical coupling to radiator = calculation: $\eta_{opt} = 0.61$

So we confirm our model calculation:

- $\eta_{ap} = \eta_{rad}\,\eta_{tap} = 0.58$ (72%)





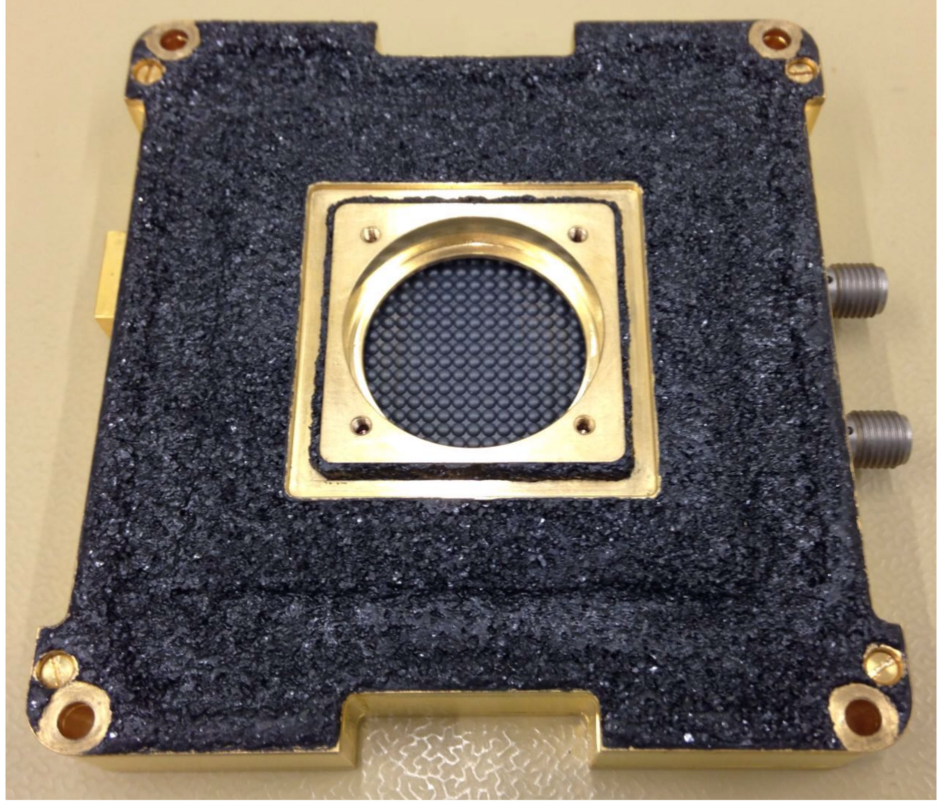
Limiting optical NEP

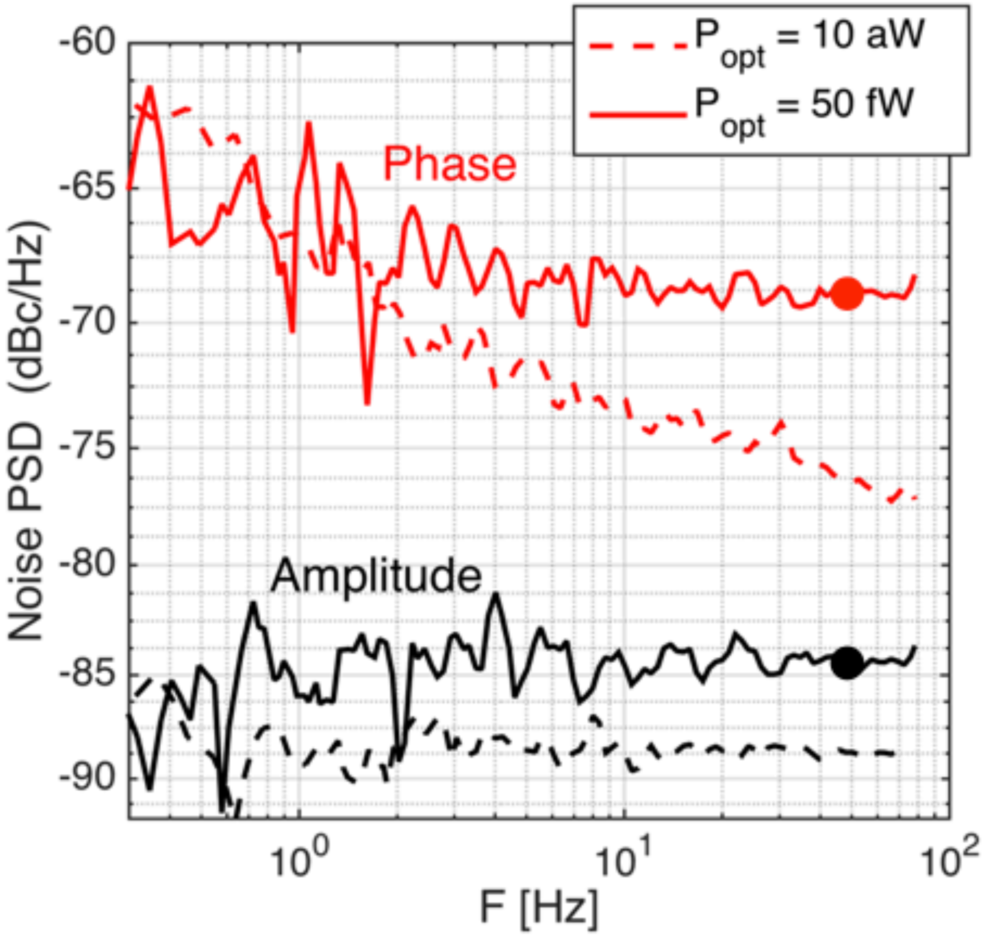
NEP = 3 · 10^{-19} W/√Hz @ detector

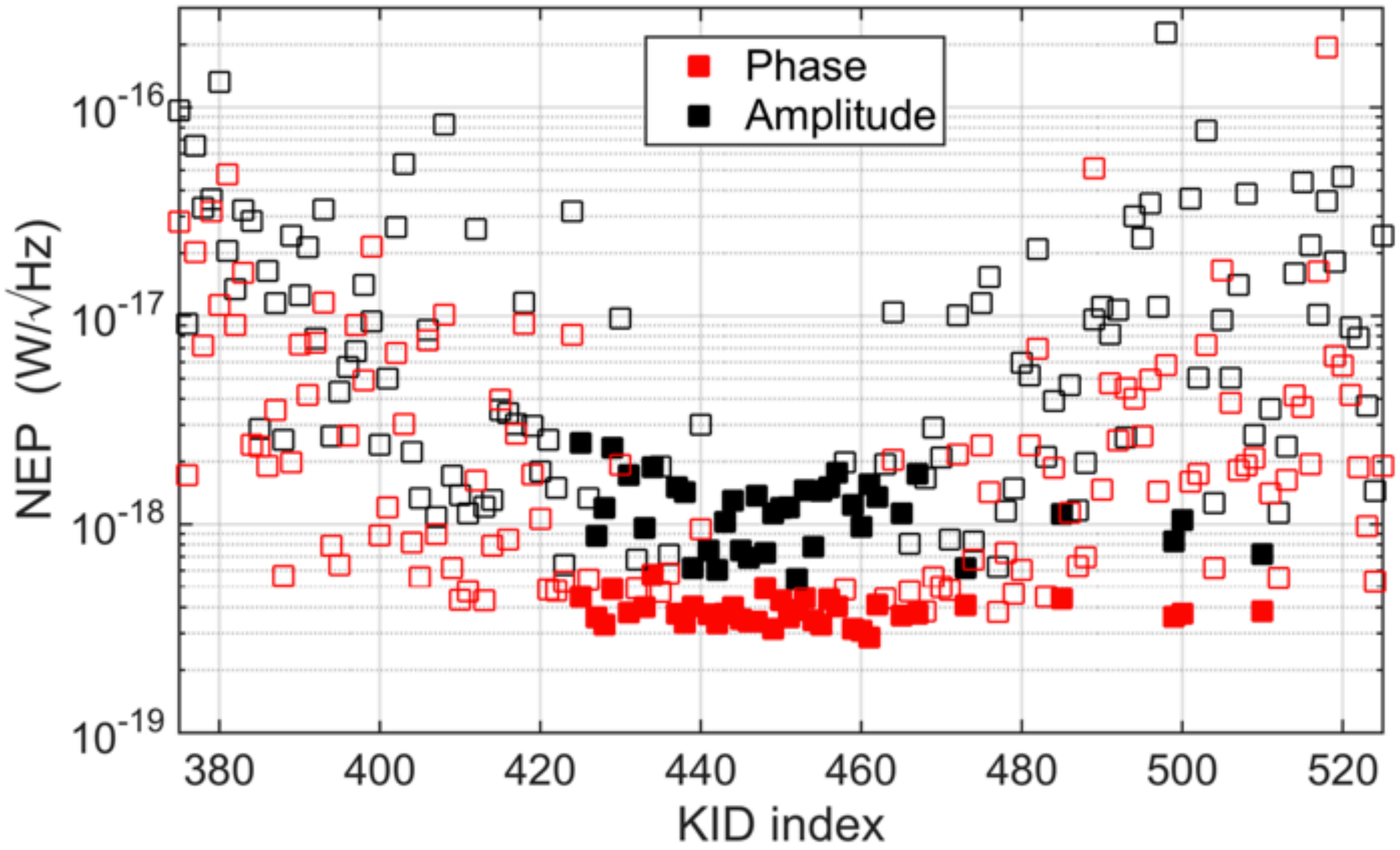
- referred to $P_{abs} = \eta_{opt} Ps$

spectra white for

- P >10 fW
- F>0.5 Hz





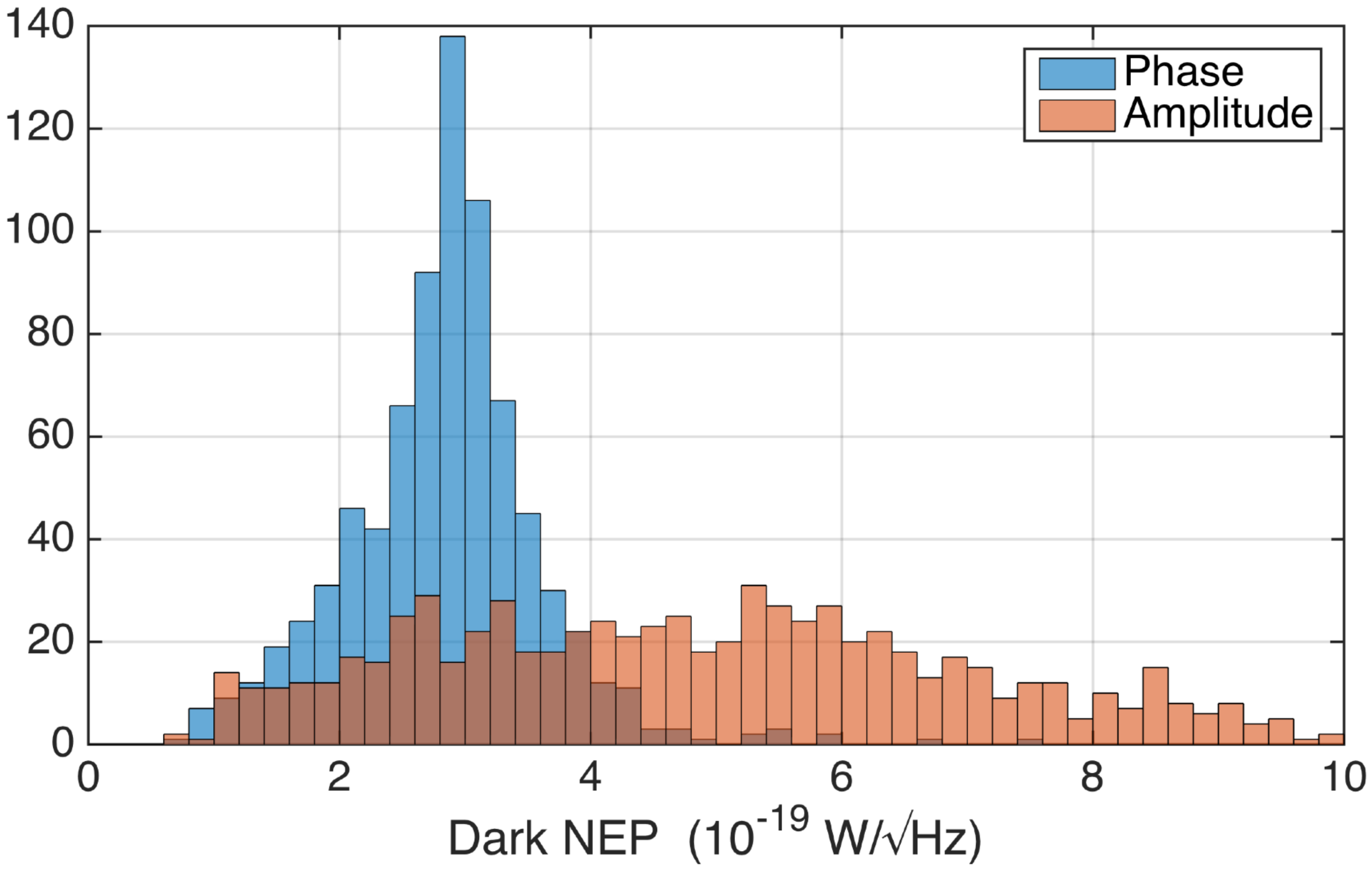


Electrical NEP

Dark measurement where we use dT in stead of dP

<Electrical NEP> = 2.8 ± 0.8 · 10^{-19} W/√Hz

identical to optical NEP



Cosmic Rays (K. Karatsu)

55x55x0.35 mm chip of Si

Ground: CRY (http://nuclear.llnl.gov/simulation/)

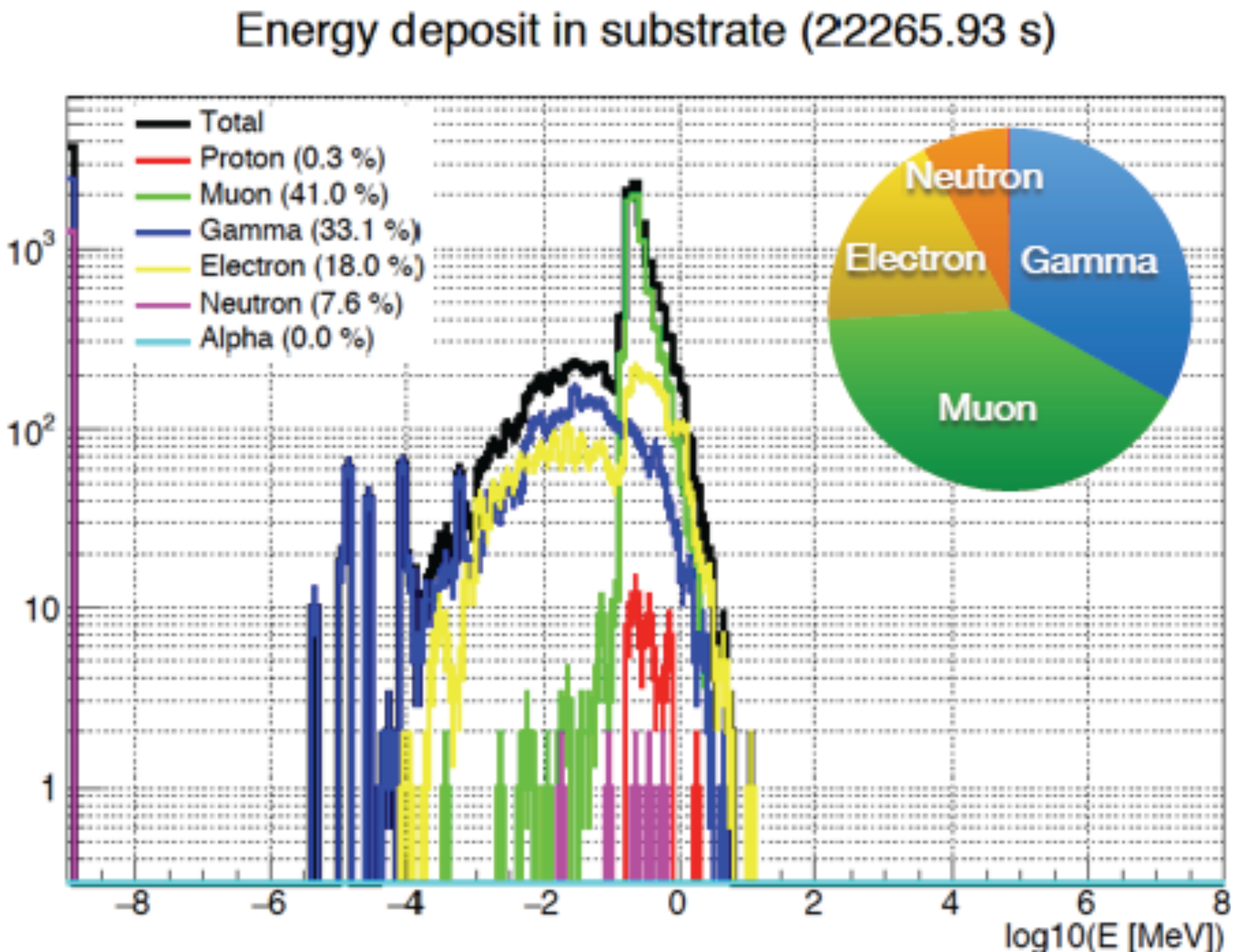
L2: http://www.sciencedirect.com/science/article/pii/S0168900212005554

Energy deposition simulation (incl. cryostats/shields etc): GEANT4

- https://geant4.web.cern.ch/geant4/

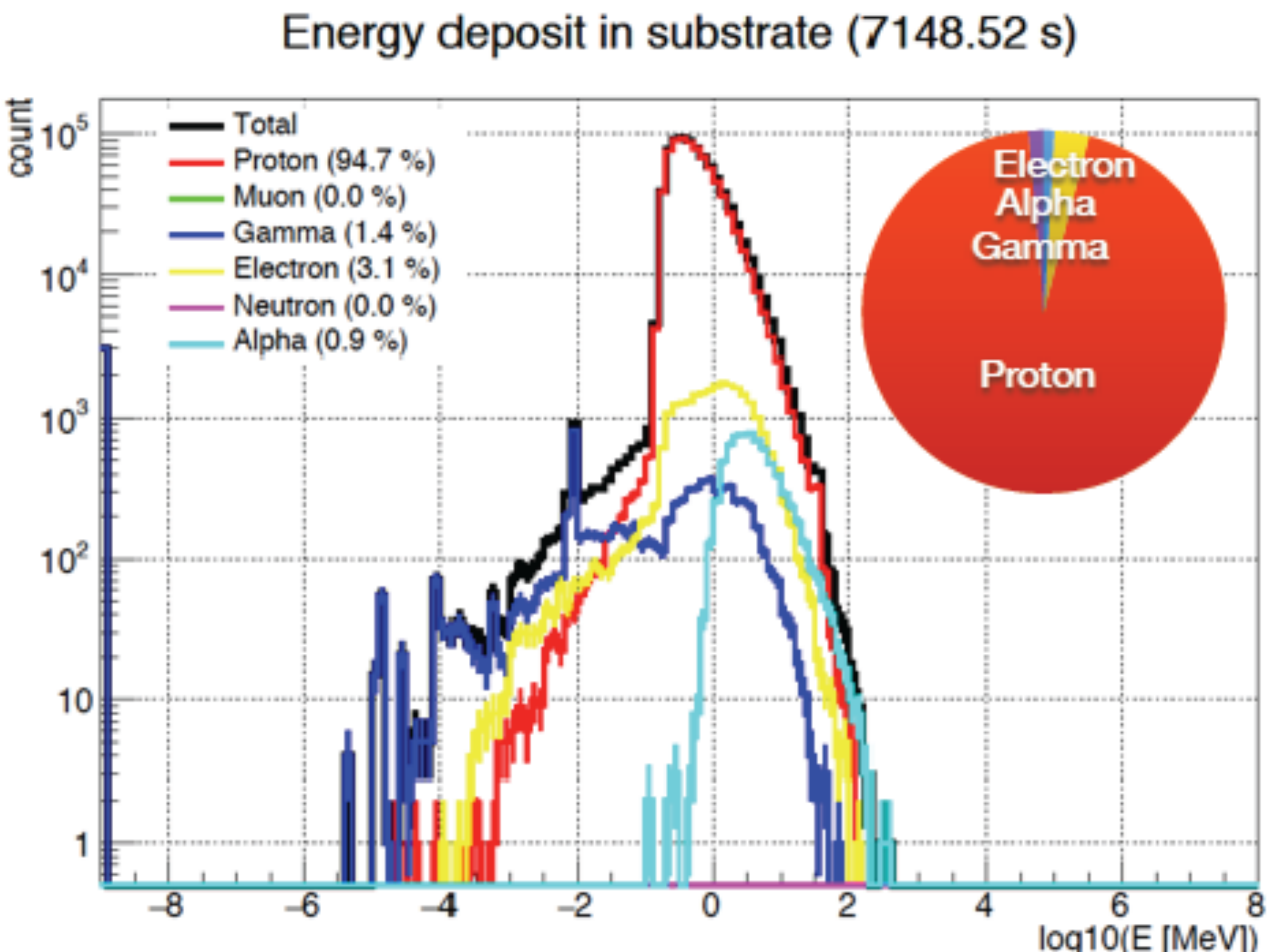
Ground

247 counts/m^2/sec



L2

3.8 · 10^4 counts/m^2/sec



Cosmic Rays - lab tests

Single glitches with time constant ~ 1 msec

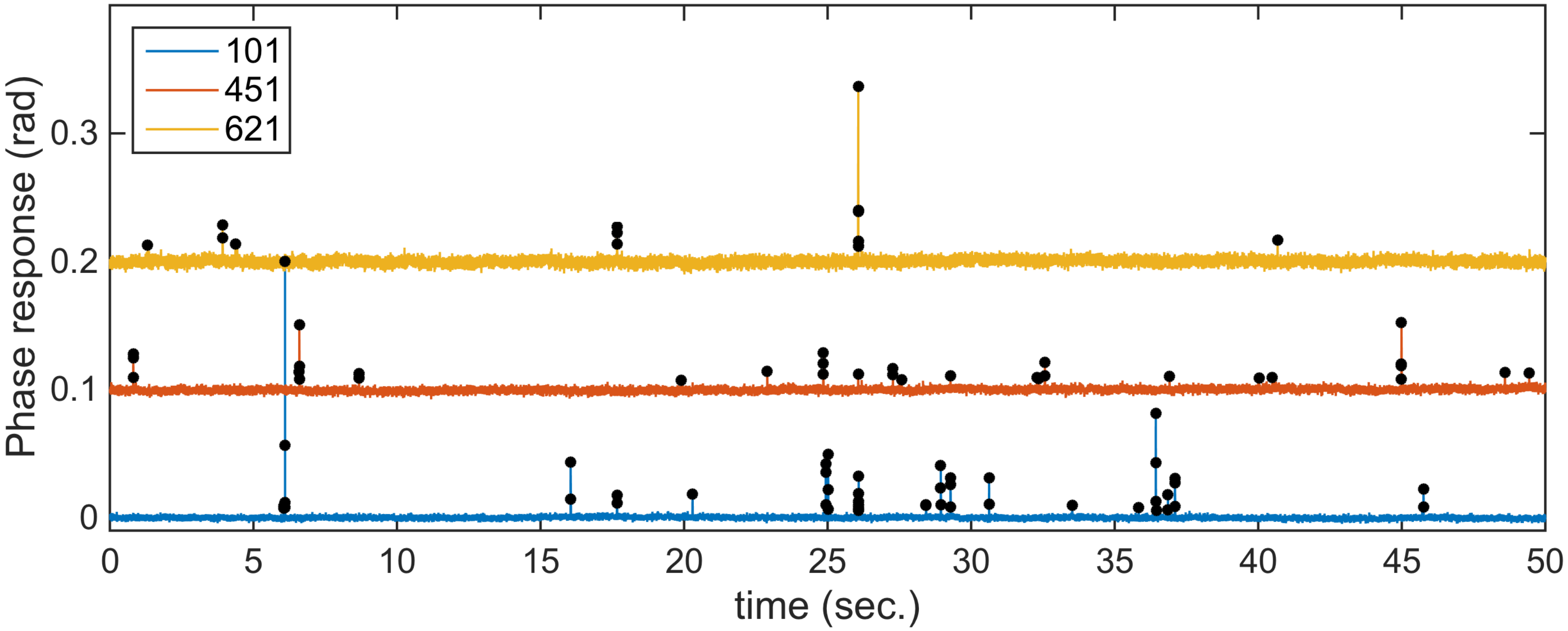
1.3 events/sec. on the chip (425 $sec^{-1}m^{-2}$)

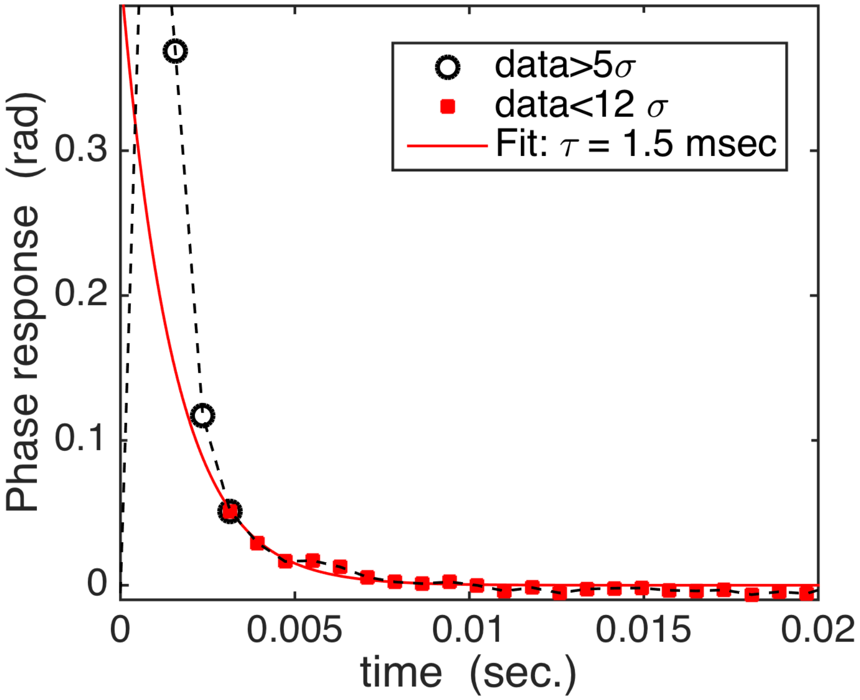
- fractional dead time (all data > 5σ): 3.2 · 10^{-4}
- array without Ta backside: 14 · 10^{-4}

L2 estimation (5 · 10^{4} $sec^{-1}m^{-2}$): 4%

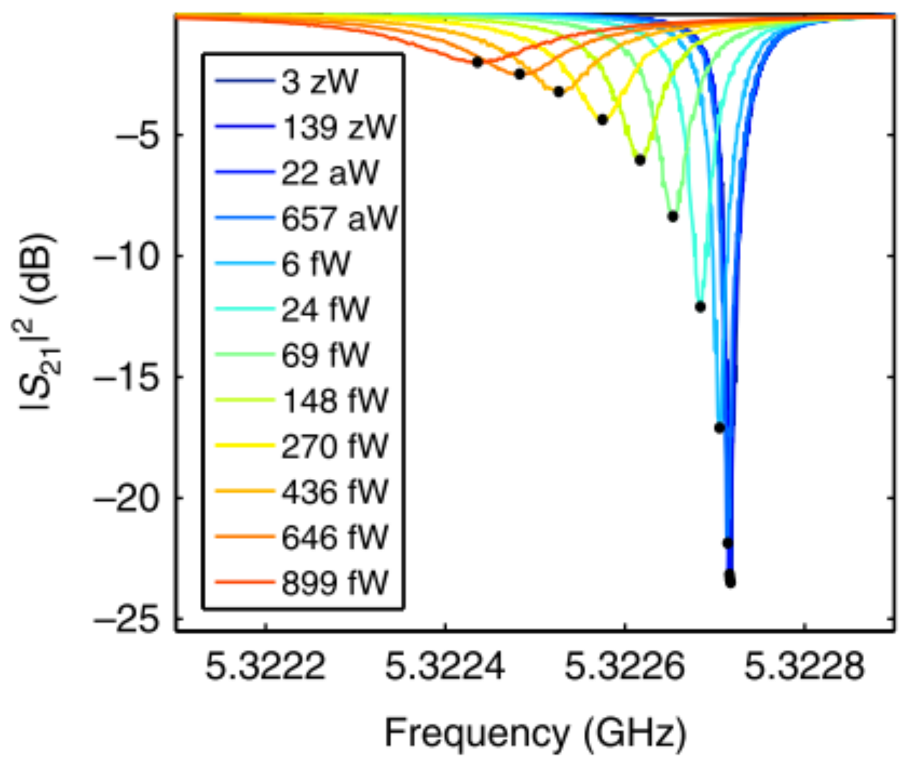
No effects on integration: Catalano, A.,et al. 2016, A&A, 592, A26

See Karatsu et al.,
Poster PA-7





Dynamic Range (typical pixel)

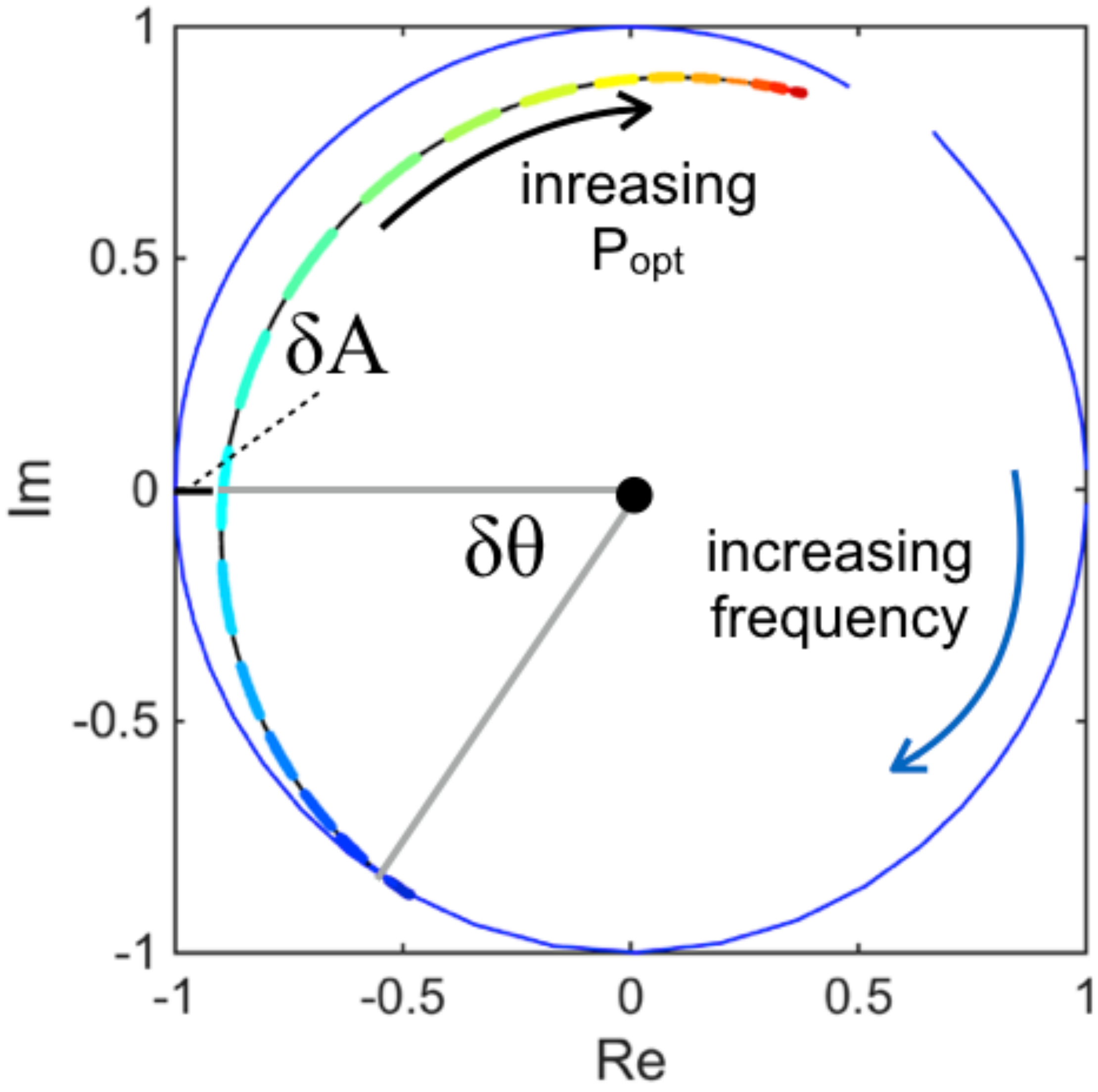


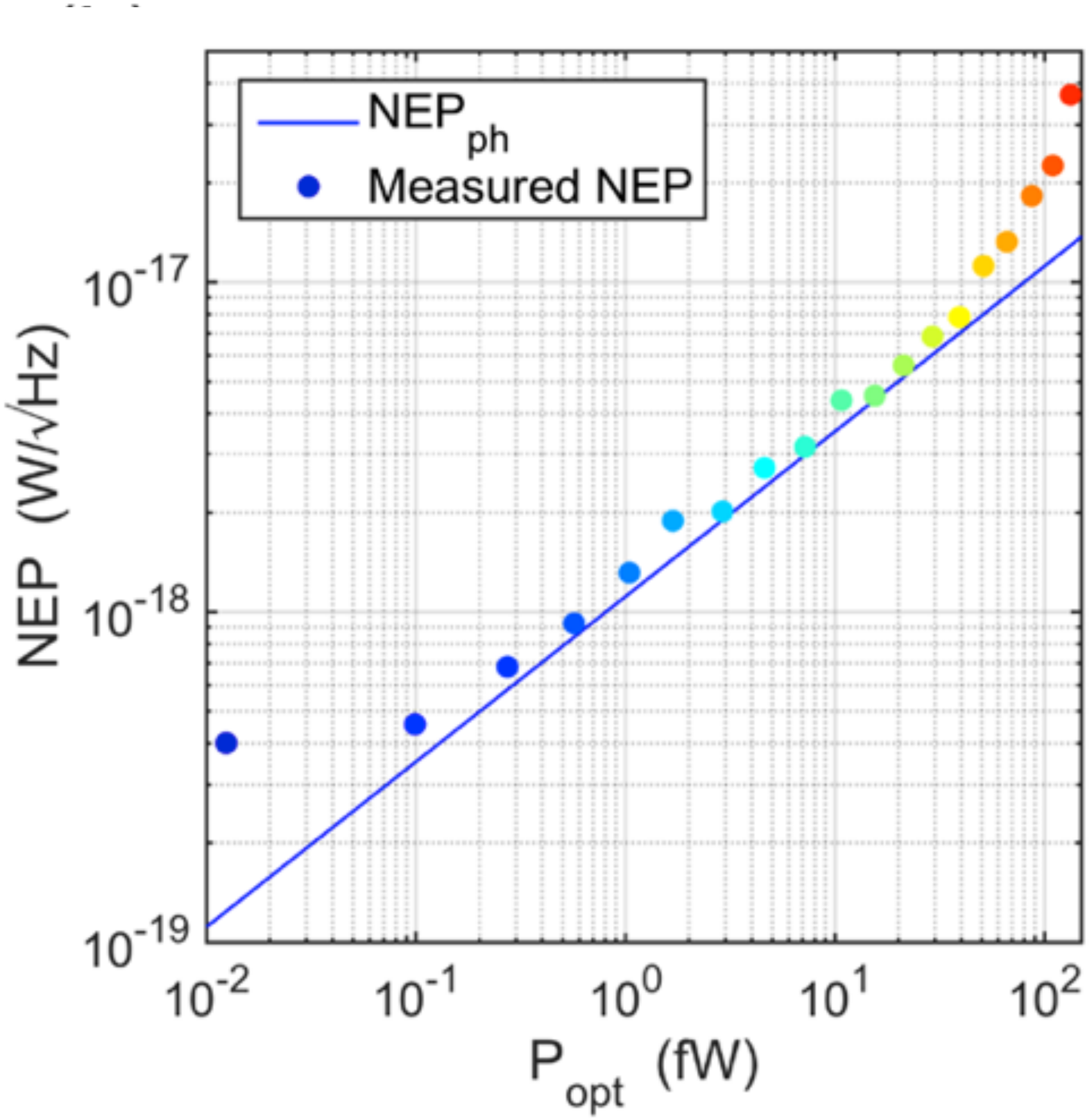
fixed readout tone

background limited: 0.1 fW<P_{abs}<40fW

- factor 400

$P_{Saturation}/NEP_{limit} = 1 \times 10^5$



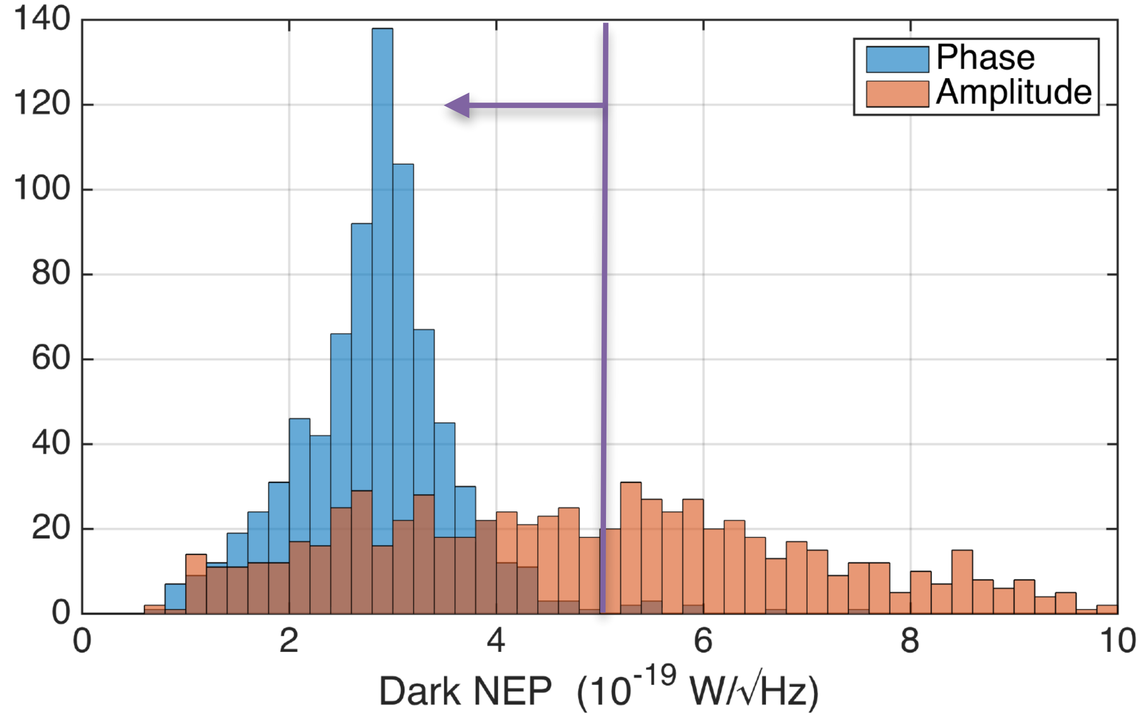


System yield

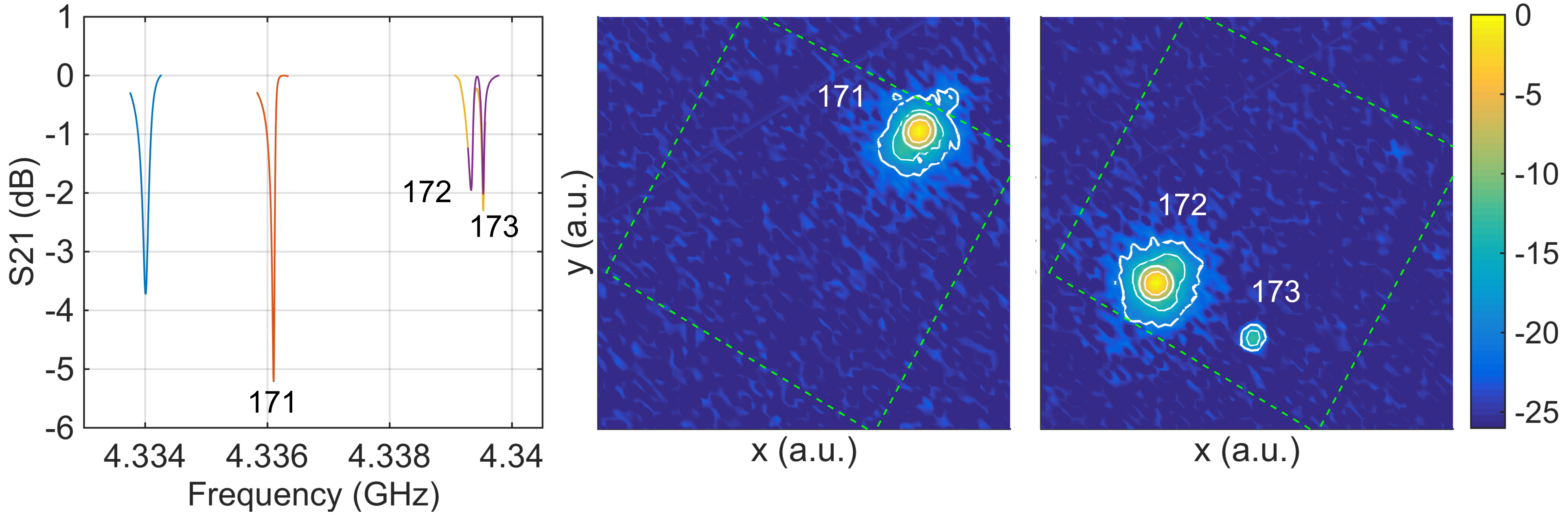
Yield = 83% using:

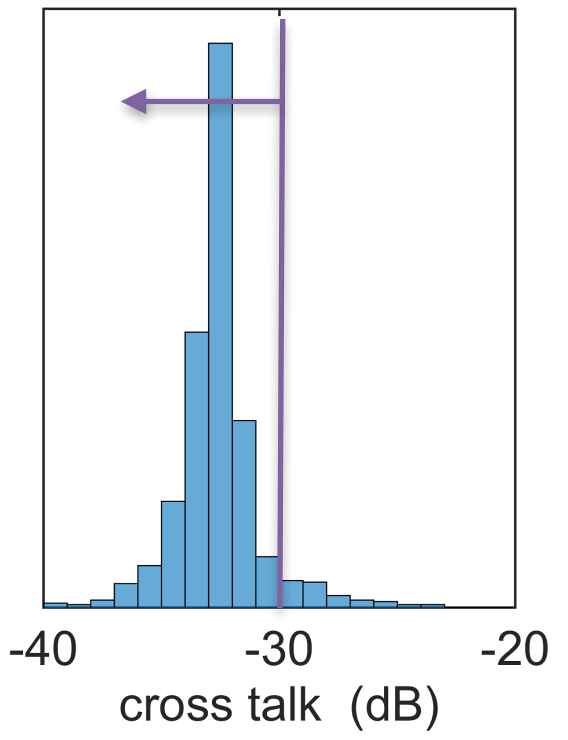
- NEP < 5 · 10^{-19} W/√Hz
- cross talk < -30 dB
  - overlapping resonators
- Cosmic ray dataloss <10%

Dark NEP



cross talk

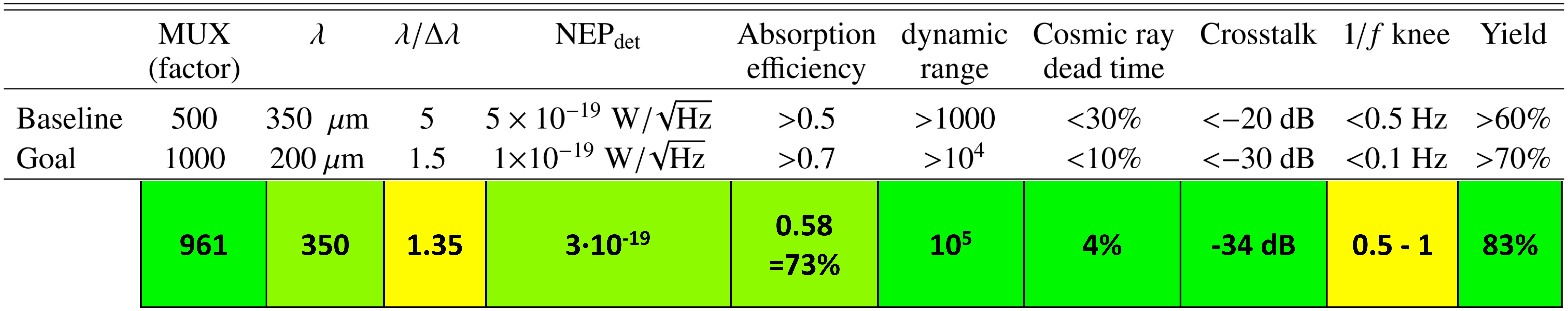




Concluding Remarks

We have made a 'space' ready demonstrator

- 850 Hz, 961 pixel array
- MUX readout
- ***reach the sensitivity for STO/Safari like imaging system***
- Low cosmic ray dead time, high yield, high dynamic range, good coupling efficiency



	MUX (factor)	λ	$\lambda/\Delta\lambda$	$\mathrm{NEP}_{\mathrm{det}}$	Absorption efficiency	dynamic range	Cosmic ray dead time	Crosstalk	$1/f$ knee	Yield
Baseline	500	350 μm	5	5×10^{-19} W/$\sqrt{\mathrm{Hz}}$	>0.5	>1000	<30%	<−20 dB	<0.5 Hz	>60%
Goal	1000	200 μm	1.5	1×10^{-19} W/$\sqrt{\mathrm{Hz}}$	>0.7	$>10^4$	<10%	<−30 dB	<0.1 Hz	>70%
	961	**350**	**1.35**	**$3\cdot10^{-19}$**	**0.58 =73%**	**10^5**	**4%**	**-34 dB**	**0.5 - 1**	**83%**

http://arxiv.org/abs/1609.01952
Baselmans, J. J. A. et al., A&A 601, A89 (2017)