# Terahertz Low Background Photon Noise Limited Performance Quantum Capacitance Detector

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Electron Beam Lithography by
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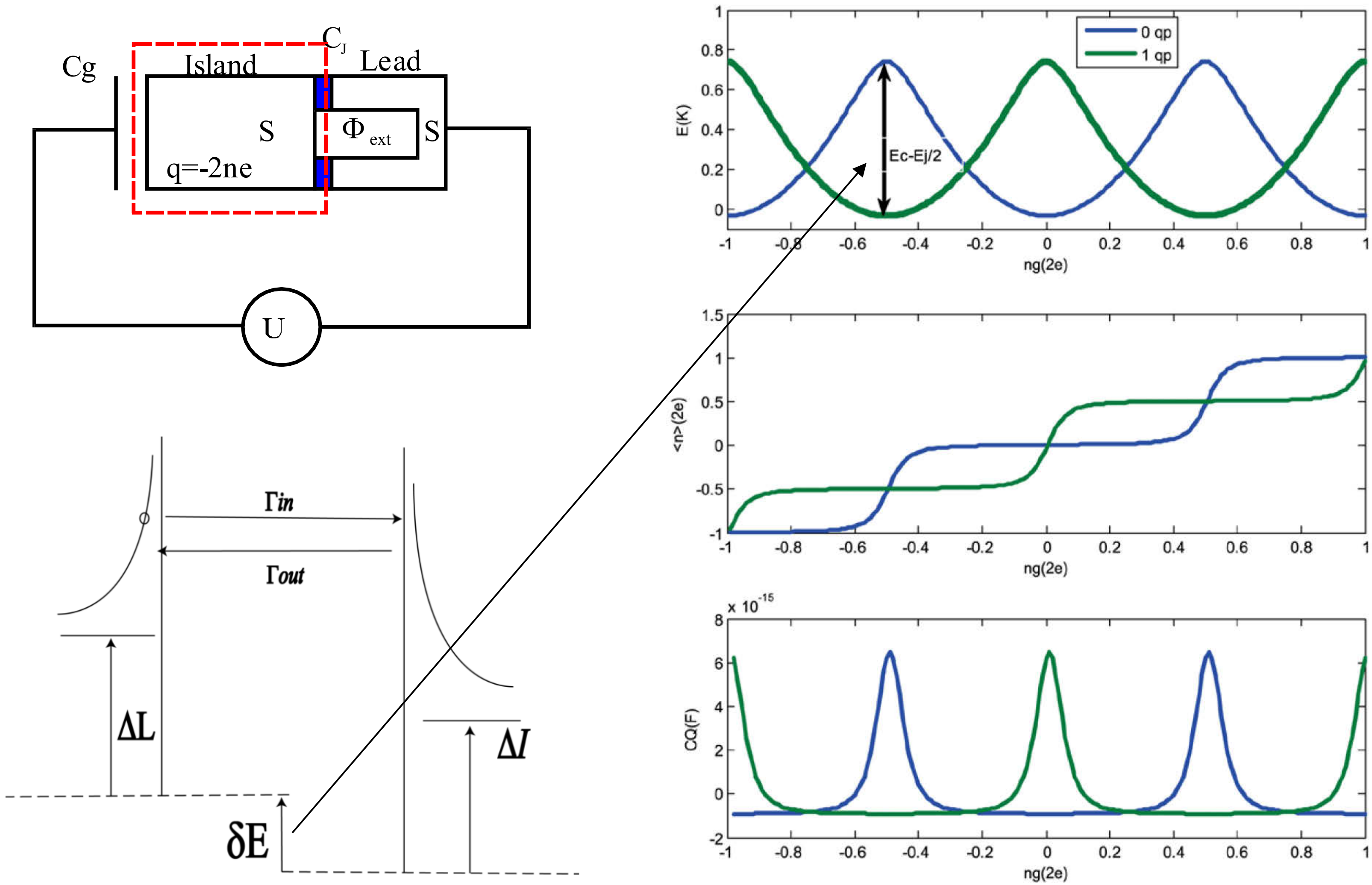
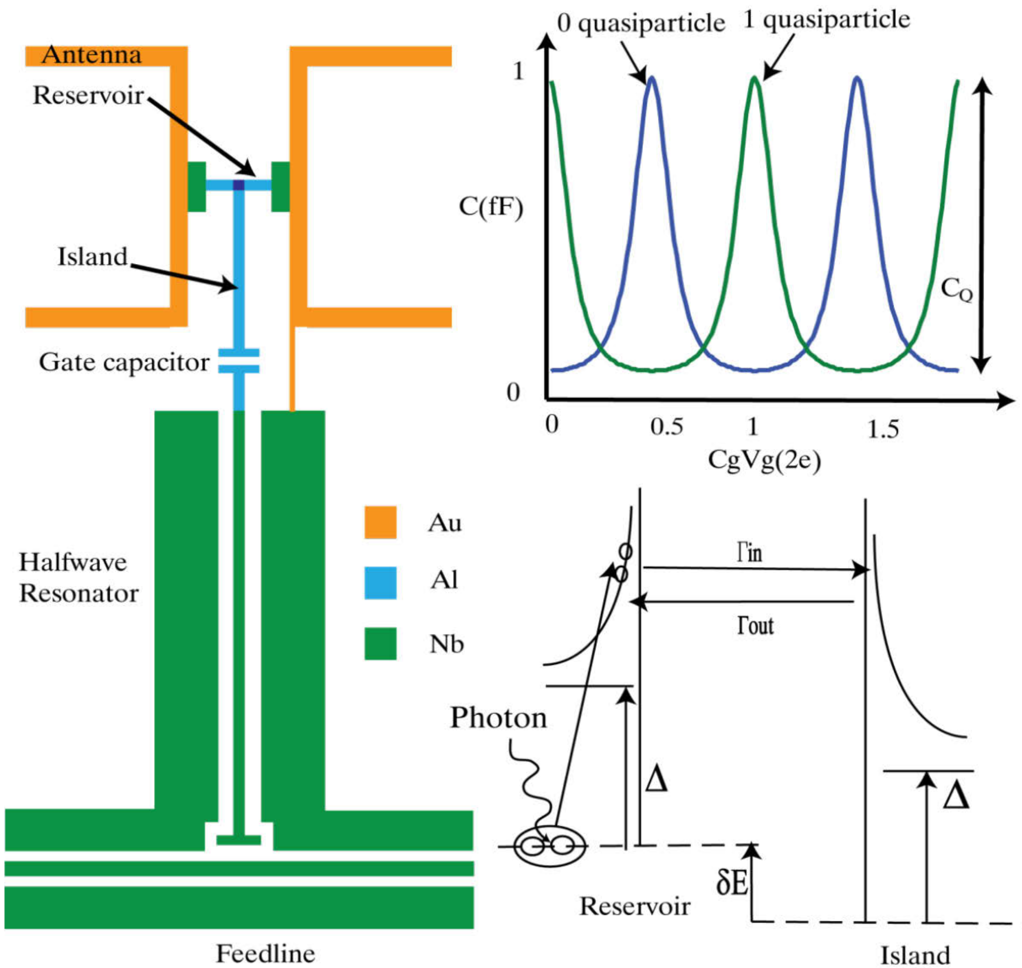
# Single Cooper-pair Box (SCB)

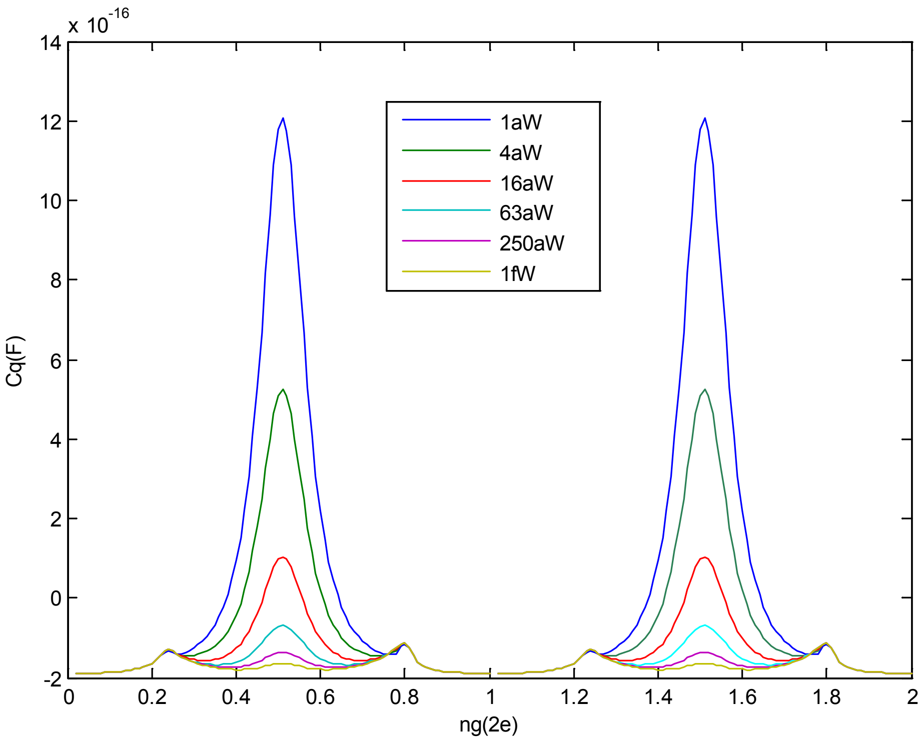


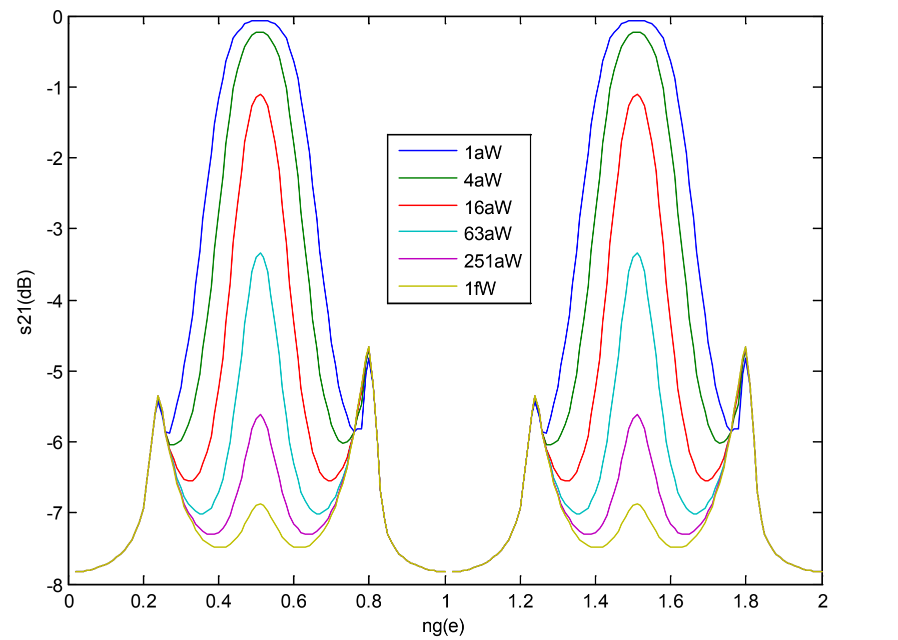
# The Quantum Capacitance Detector




- Radiation coupled by an antenna breaks Cooper pairs in the reservoir (absorber)
- Quasiparticles tunnel onto the island with a rate $\Gamma_{in}$ proportional to the quasiparticle density in the reservoir
- Quasiparticles tunnel out of the island with a rate $\Gamma_{out}$ independent of the number of quasiparticles in the reservoir
- At steady state the probability of a quasiparticle being present in the island is given by $Po(Nqp)=\Gamma in/(\Gamma in+\Gamma out,)$
- The resulting change in the average capacitance will be $C_Q=(4E_C/E_J)(C_g^2/C_\Sigma)Po(Nqp)$
- *This change in capacitance will produce a phase shift* $\delta\Phi\sim 2C_Q/(\omega_o Z_o C_C^2)$

# Simulated response

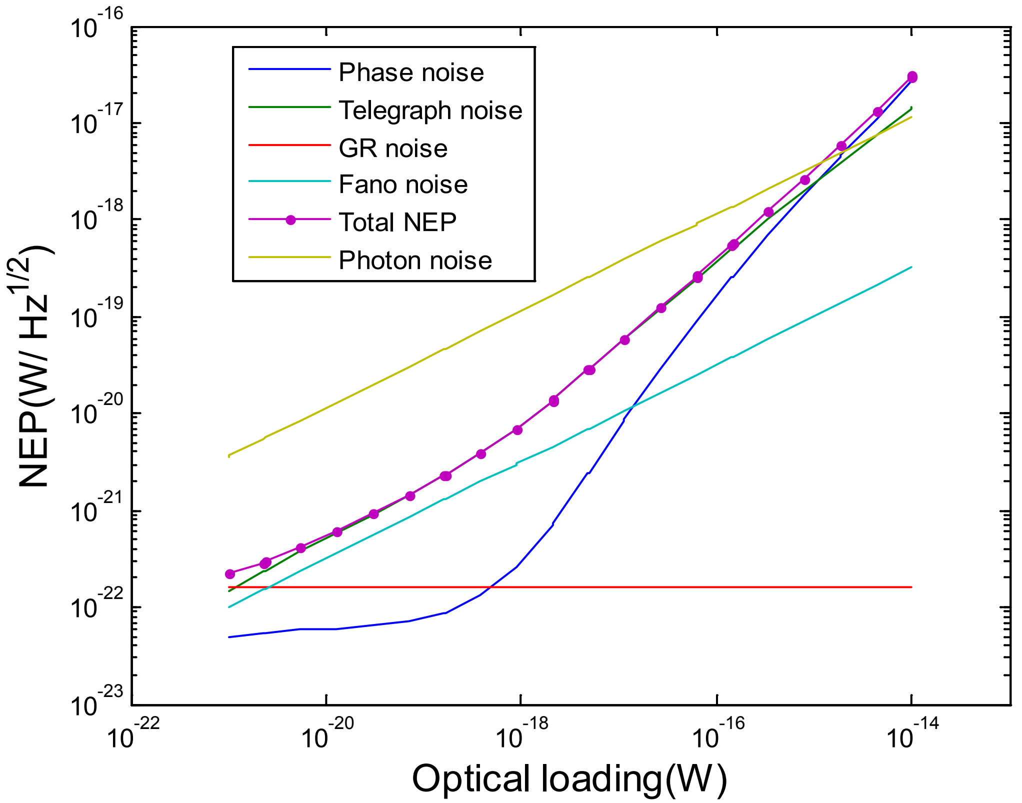



- SCB capacitance x gate voltage (in units of Cooper Pair charge) for different coupled optical signal power

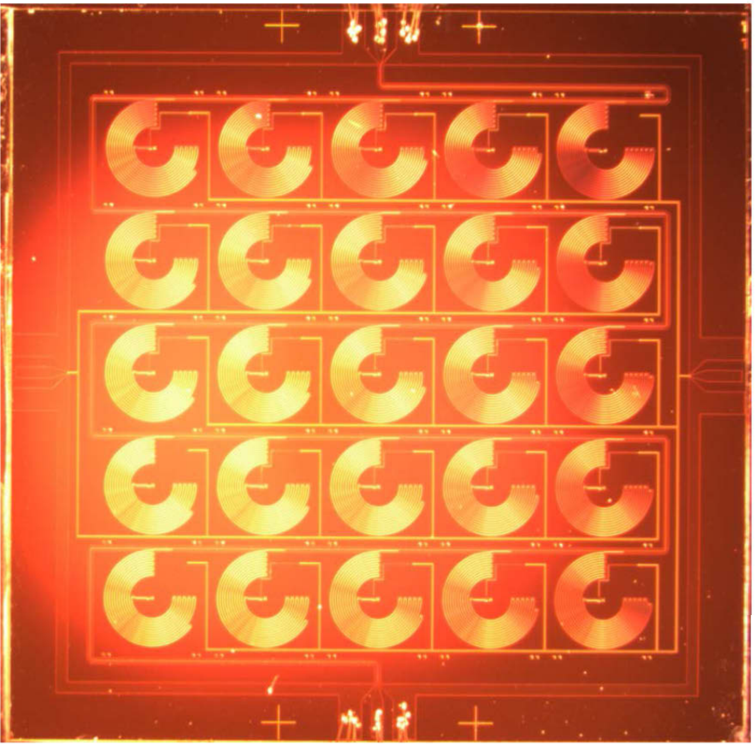
- transmission through feedline x gate voltage (in units of Cooper Pair charge) for different coupled optical signal power

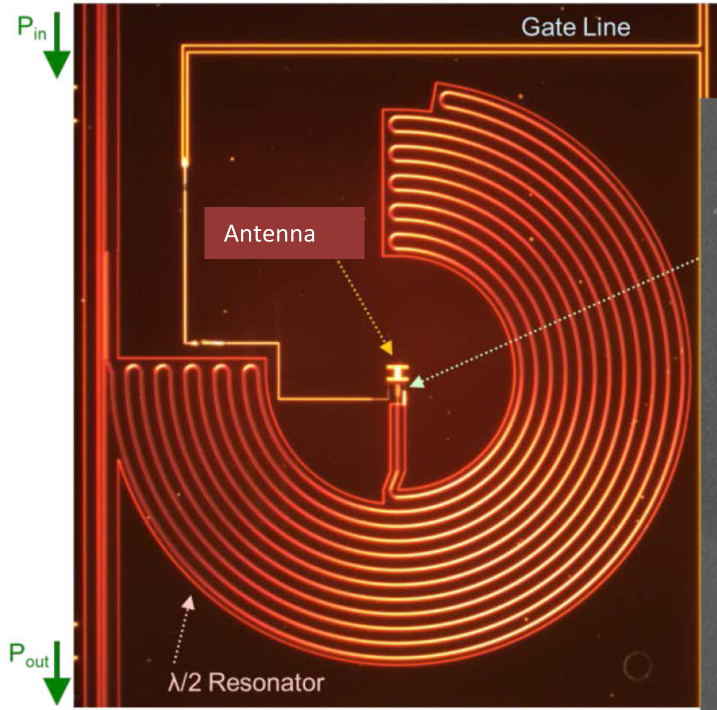
# Theoretical Sensitivity vs. Signal Power

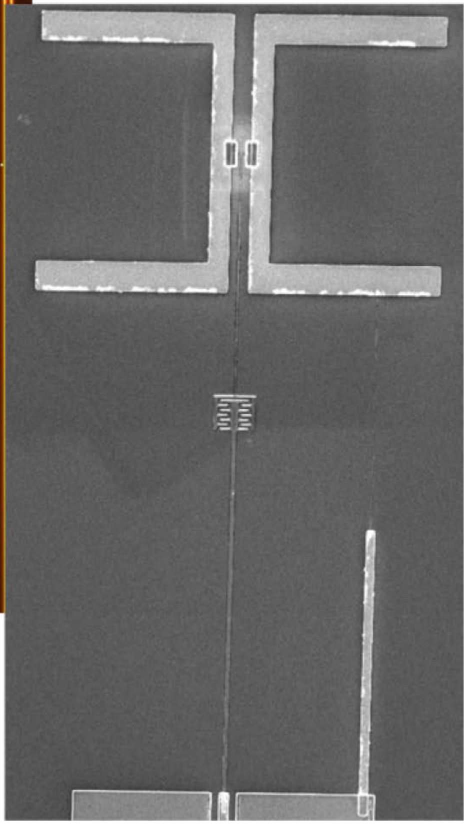


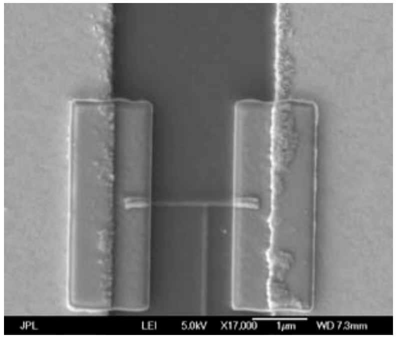

- *Detector is background limited over a wide range of operation*

# Quantum Capacitance Detector: 5x5 Array





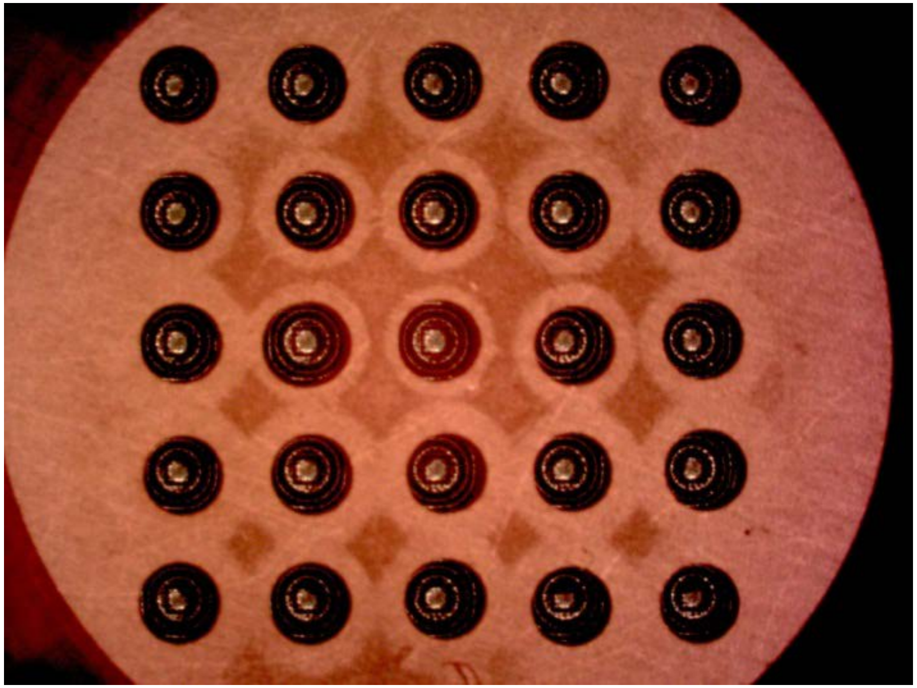



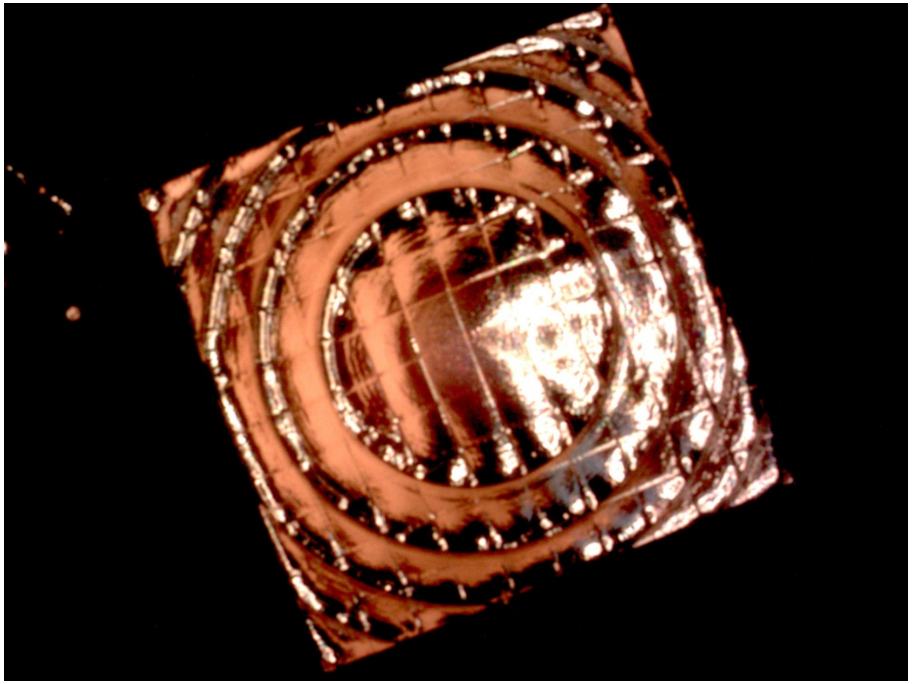



Only center device
Illuminated by lens.
Each device has a slightly
Different resonance frequency.

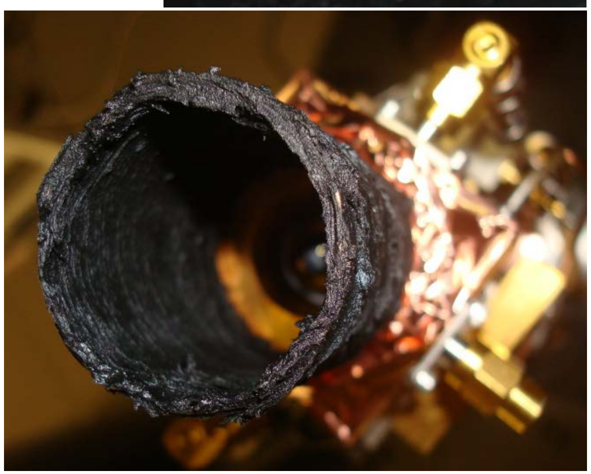
# Fresnel lens array

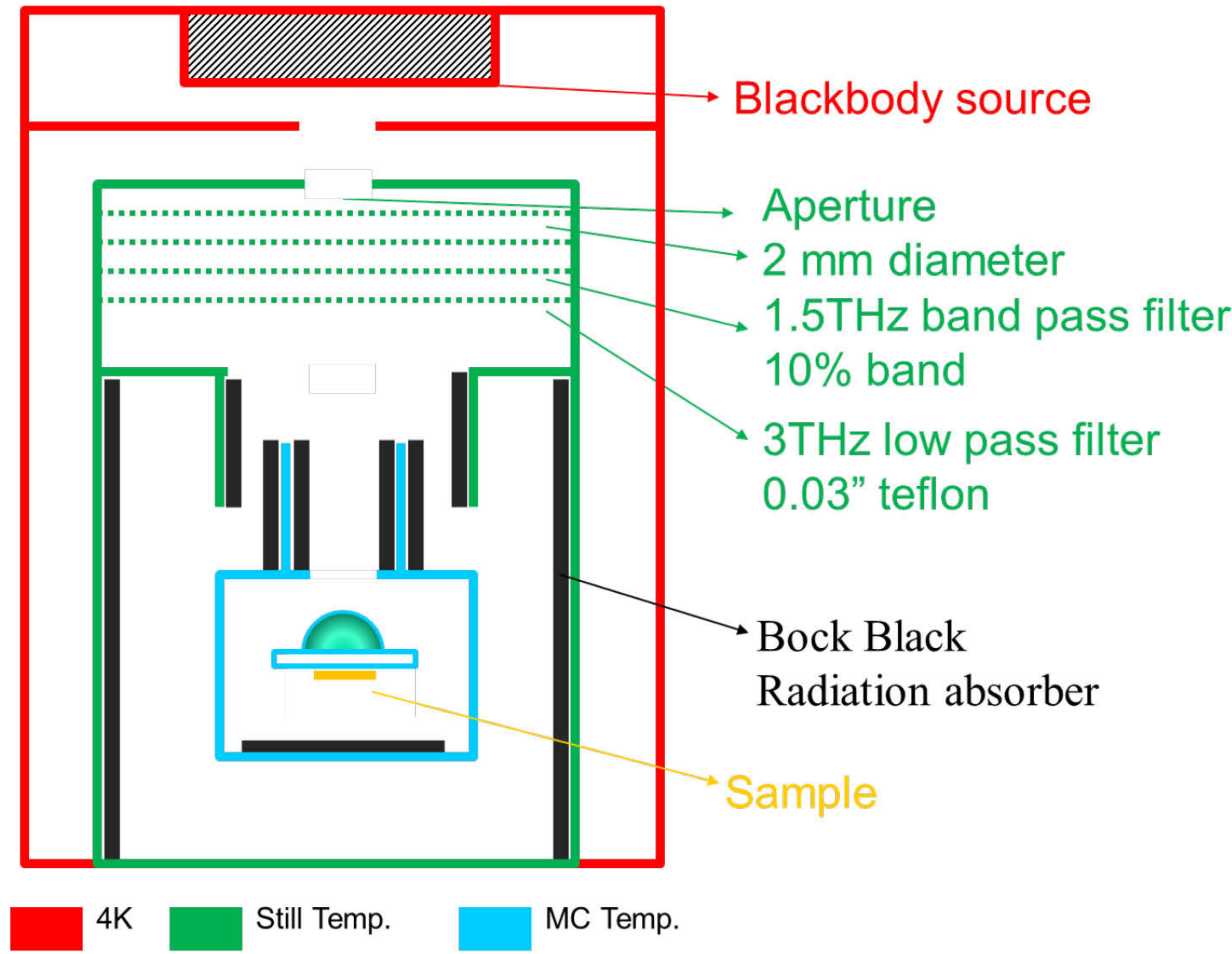
Lens array made by Dan Wilson using an electron beam lithography technique developed by Paul Maker, Dan Wilson and Rich Muller at JPL





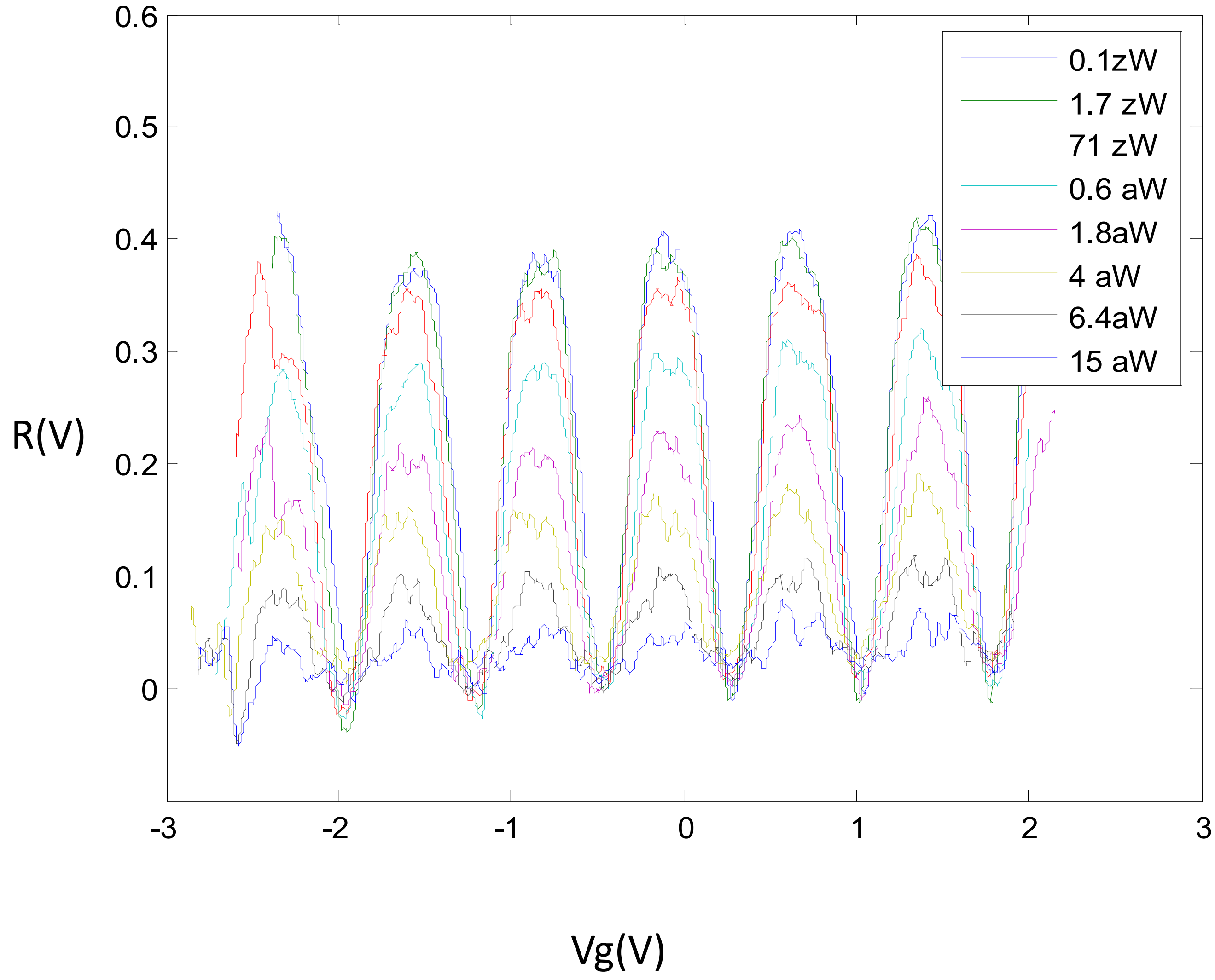
# Experimental Setup



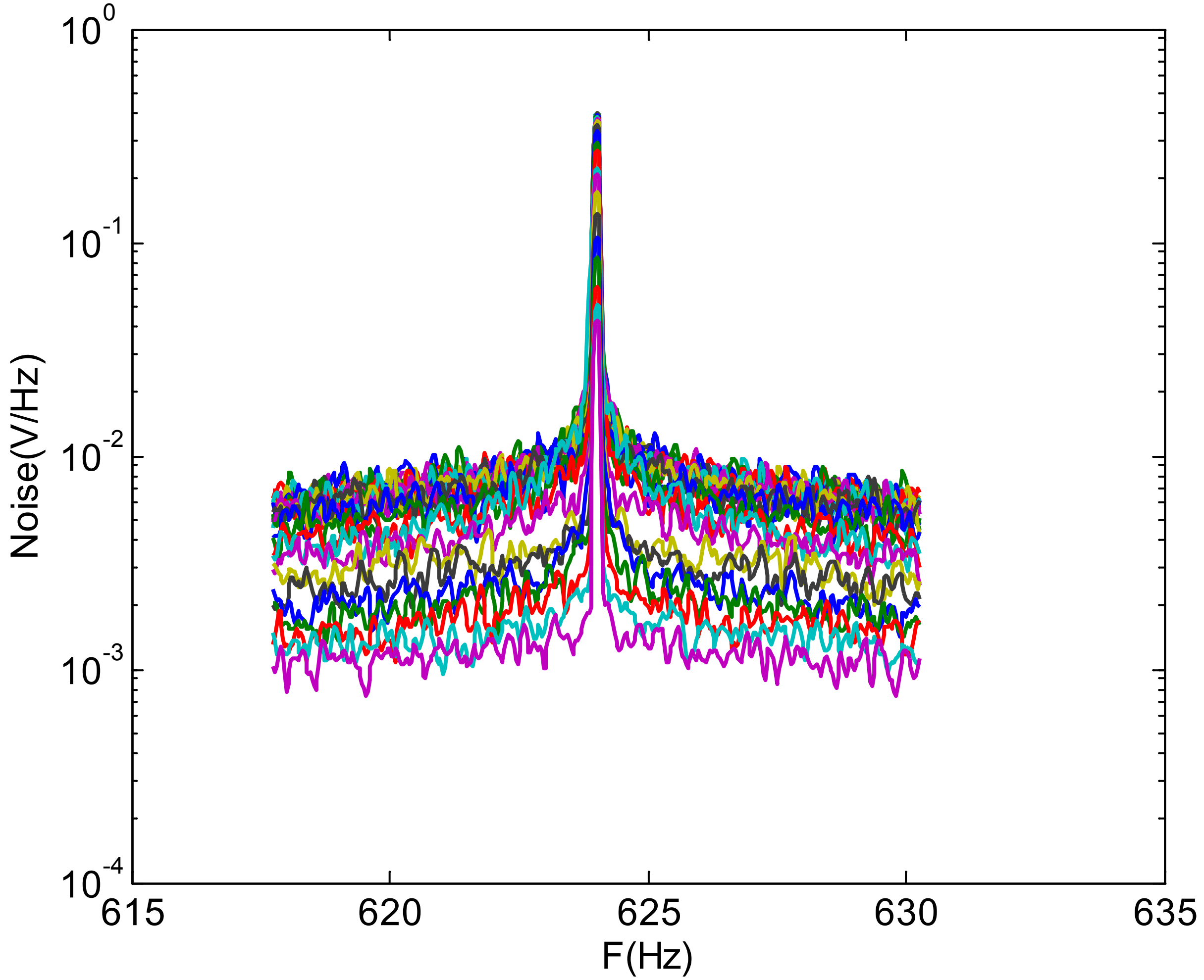



- Black body source and filters provide 1.5THz radiation from 4.2 – 40 K. Bock Black absorbs stray 4K radiation

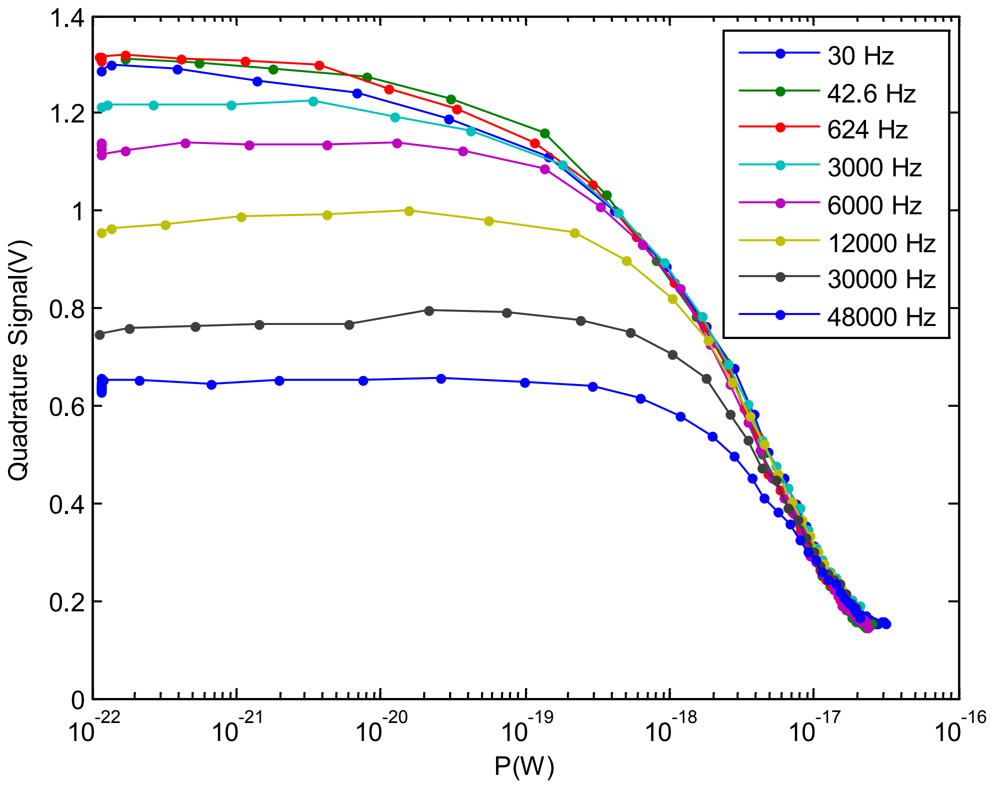
# Response x gate voltage as a function of black body source temperature



# Noise measurements

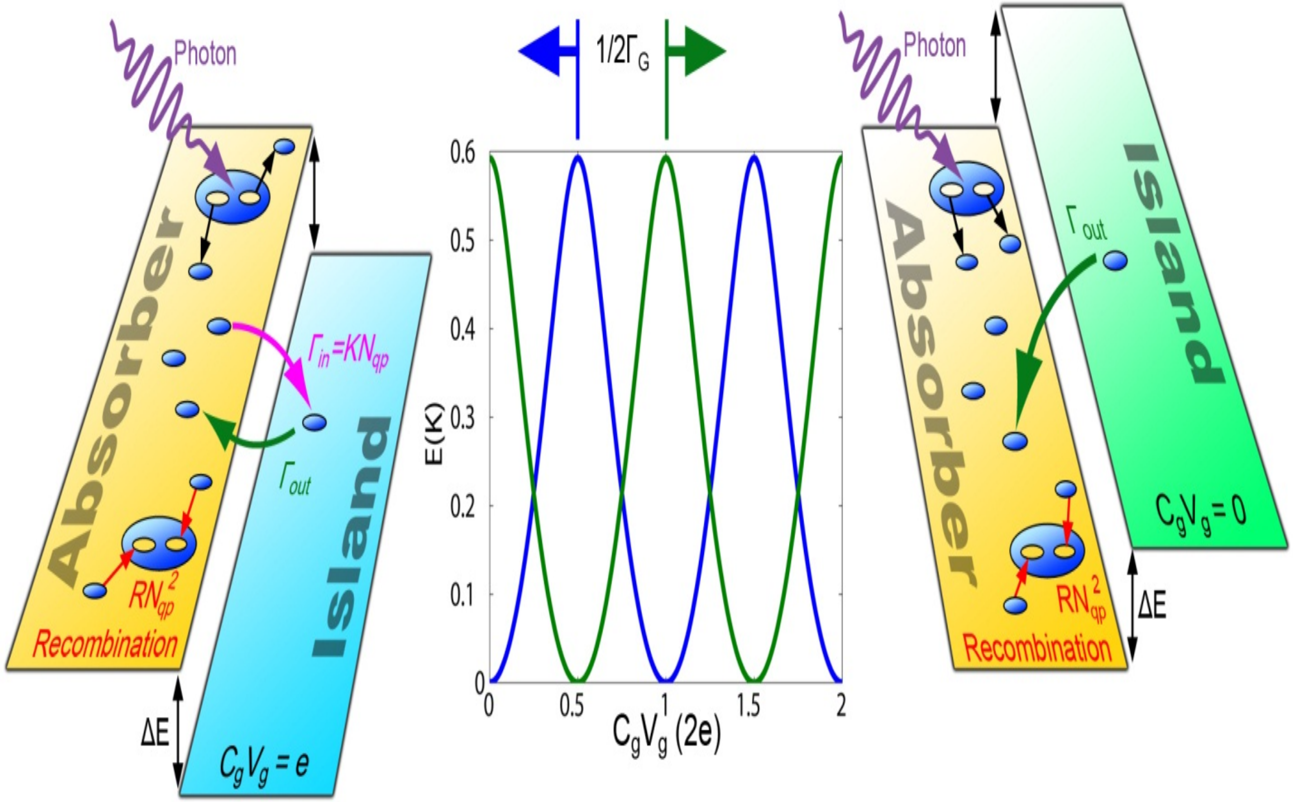


# Measurements of Response versus optical power for various gate sweep rates




- Aperture 500um
- Diffraction causes illumination to be about the same for all pixels
- Response similar from pixel to pixel
- What causes sweep rate dependence?

# Sweep rate dependence model



# Sweep rate dependence model

Detailed balance equation

$$dN_{qp}/dt = \eta P_S/\Delta - RN_{qp}(N_{qp}-1) - \Gamma_{in}N_{qp} + \Gamma_{eff} = \eta P_S/\Delta - (R+K)N_{qp}^2 + RN_{qp} + \Gamma_{eff}$$

Nqp = number of quasiparticles
Δ = superconducting gap energy
P= optical signal power
η = conversion efficiency from photon energy to quasiparticles ~ 0.57
R= recombination rate
Γin= tunneling rate from absorber to island = KNqp
Γeff= effective tunneling rate from island to absorber

Model for Γeff -> $\Gamma_{eff} = \sqrt{\Gamma_{out}^2 + SR^2}$

At the end of each sweep quasiparticles are dumped back into reservoir. If the sweep rate (SR) is faster than the intrinsic tunneling out time Γout, then $\Gamma_{eff}$~ SR. If SR is much slower, $\Gamma_{eff}$~ $\Gamma_{out}$

# Sweep rate dependence

Steady state solution

$$N_{qp} = (R + \sqrt{R^2 + 4(\eta P_S / \Delta + \Gamma_{eff})(R+K)} / 2(R+K)$$

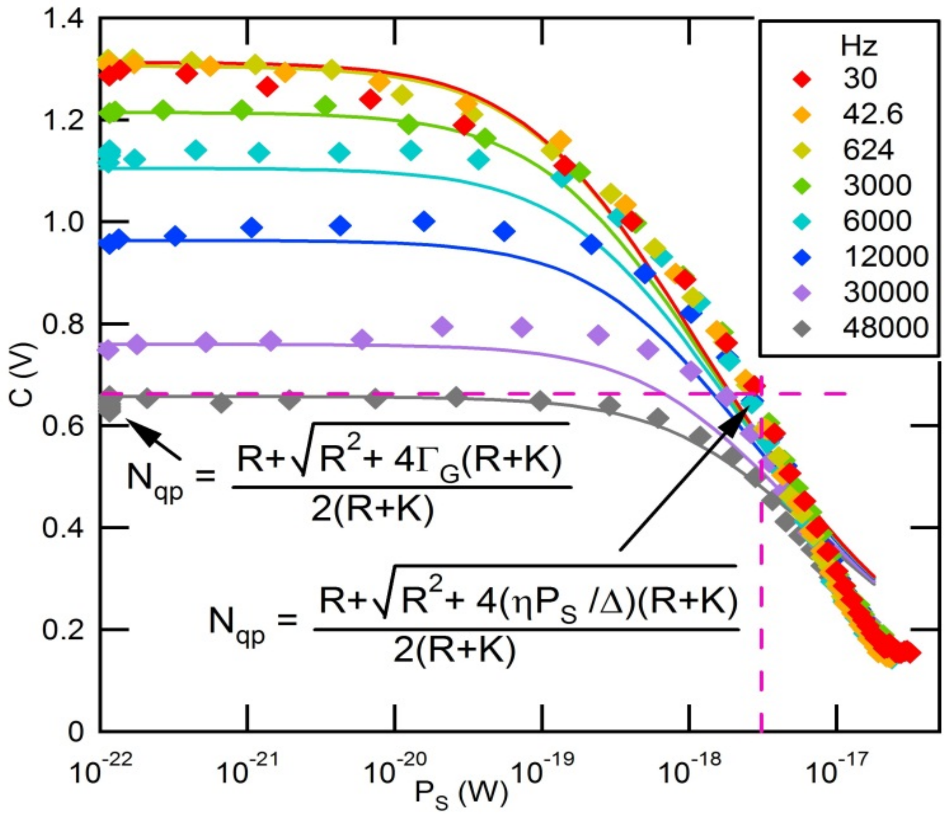
PR is the photon arrival rate, hυ the photon energy, Δ the absorber superconducting gate

Response is a single value function of Nqp

$$C = A\Gamma_{out} / (\Gamma_{out} + \Gamma_{in}) = A / (1 + KN_{qp} / \Gamma_{out})$$

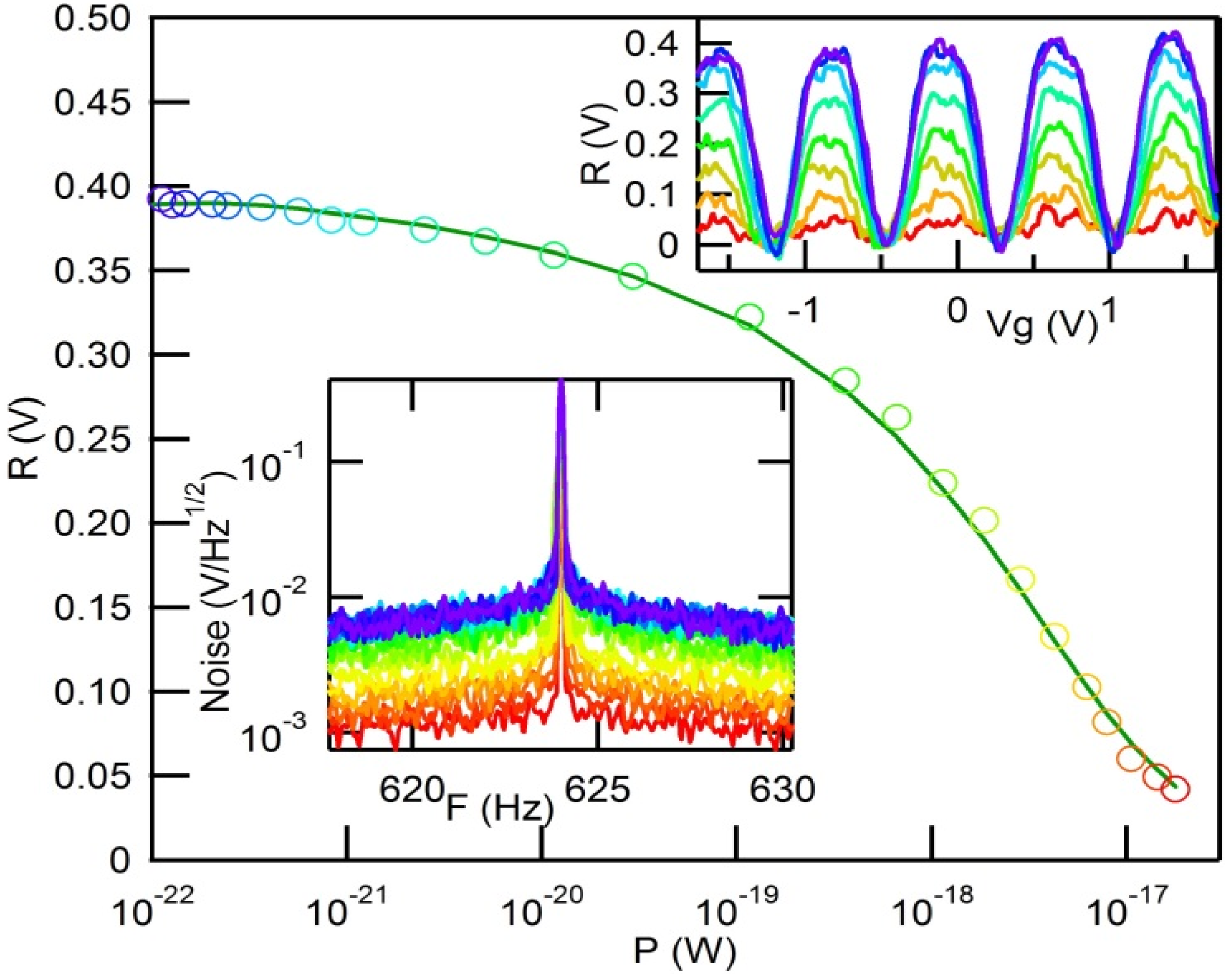
A is a constant (depending on the electronics)

# Sweep rate dependence = calibration of photon arrival rate!




By comparing the response at low power and high sweep rate with the same response at high power and low sweep rate we arrive at $Ps=\Gamma_G\Delta/\eta$

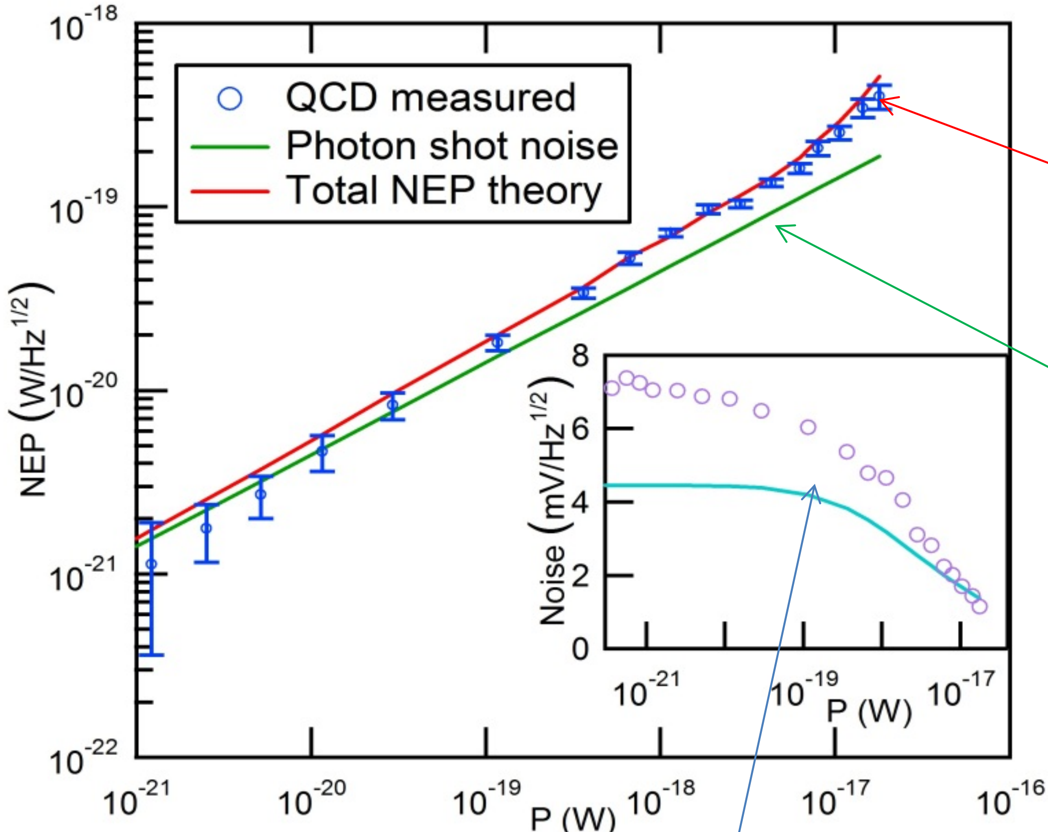
# Response



0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
R (V)
$10^{-22}$
$10^{-21}$
$10^{-20}$
$10^{-19}$
$10^{-18}$
$10^{-17}$
P (W)
0.4
0.3
0.2
0.1
0
R (V)
-1
0
1
Vg (V)
$10^{-1}$
$10^{-2}$
$10^{-3}$
Noise (V/Hz$^{1/2}$)
620
625
630
F (Hz)

# NEP measured with power calibration

Photon shot noise limited!




$$NEP_{tot} = \sqrt{NEP_{ph}^2 + NEP_{sn}^2}$$

$$NEP_{ph} = \sqrt{2h\nu P_s}$$

$$NEP_{sn} = S_{sn}(f)/(dC/dP)$$

$$S_{sn}(f) = \sqrt{2A^2(\Gamma_{in}\Gamma_{out}/\Gamma_{\Sigma})/(\Gamma_{\Sigma}^2 + (2\pi f)^2)}$$

# Conclusion

- Achieved photon shot noise limited NEP at 200µm wavelength in a 5x5 array
- Novel way of calibrating absorbed optical power
- Fresnel lenses working
- Introduced special filters to cut down noise through coaxes
- Next
  - Redesign antenna for better efficiency
  - Tweak Fresnel lens fabrication for better lens profile

# Noise Equivalent Power