Small Array of Low Frequency Readout Quantum Capacitance Detectors

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Electron Beam Lithography by Richard E.Muller
Fresnel lens array by Daniel Wilson

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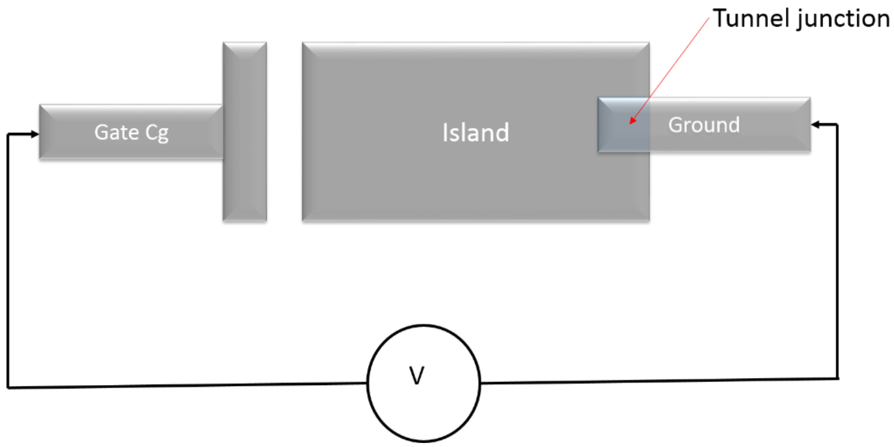
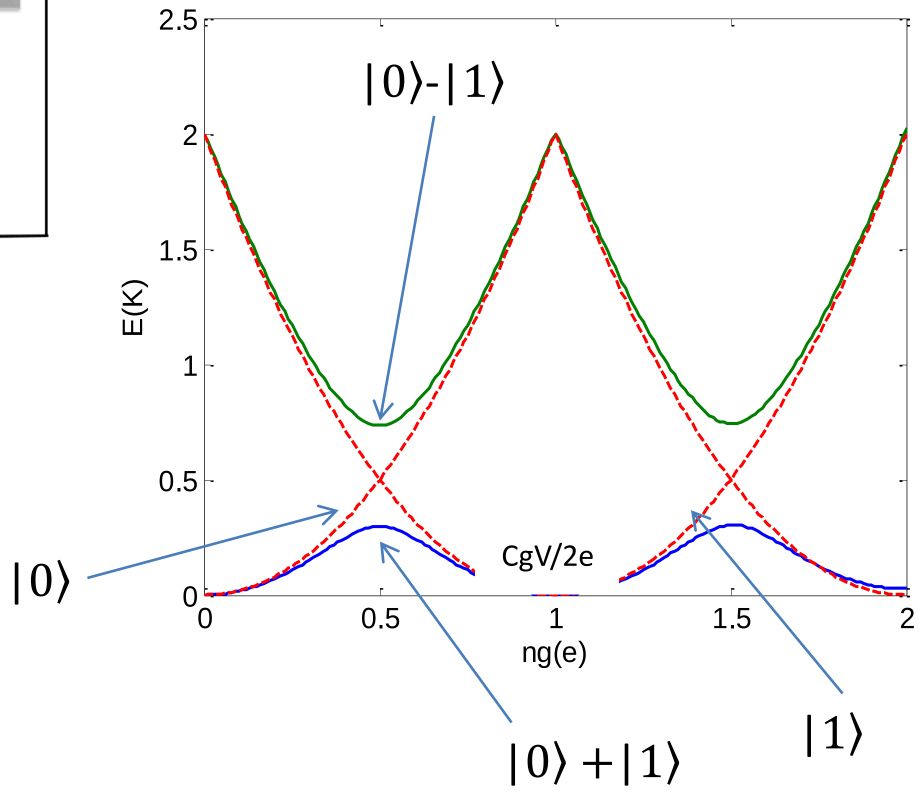
Single Cooper-pair Box (SCB) – developed as a Qubit

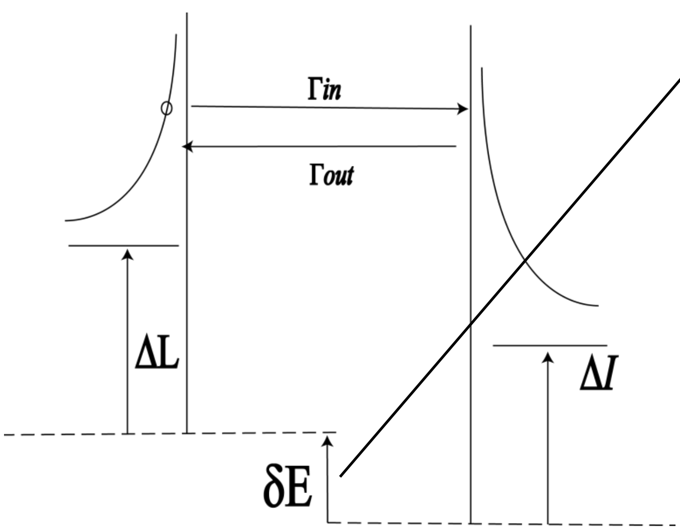


- Small island of superconducting material connected to a ground electrode via a tunnel junction
- Cooper pairs (two paired electrons) can tunnel into the island
- Island can be biased with a voltage via gate capacitance Cg
- Energy states are parabolas corresponding to 0, 1, 2 excess Cooper-pairs in island
- Superconductivity introduces coupling between charge states, creating an avoided crossing and mixing the charge states
- Basis for a Quantum Bit

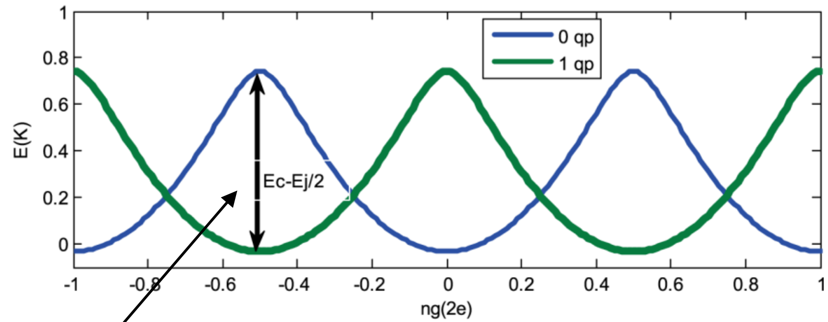


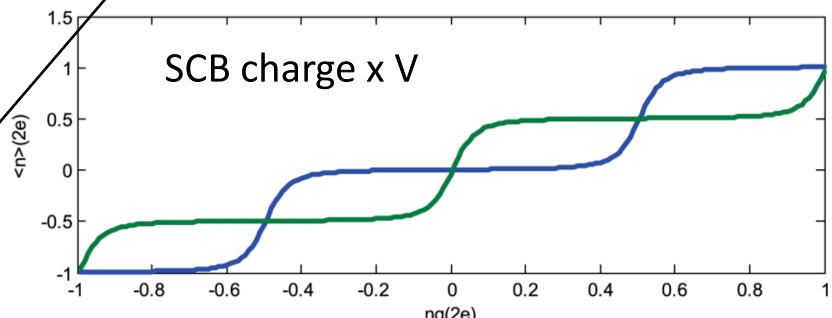
Single Cooper-pair Box (SCB)

- Unpaired electrons can which may exist above the superconducting gap can also tunnel to the island shifting the graphs between blue and green (even and odd state)
- By biasing the device at one of the capacitance peaks, one can observe a large capacitance shift when a quasiparticle (unpaired electron) tunnels into the island

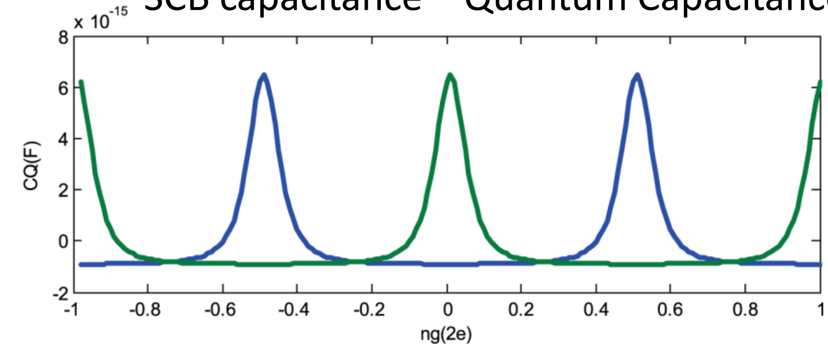


SCB ground state energy x V



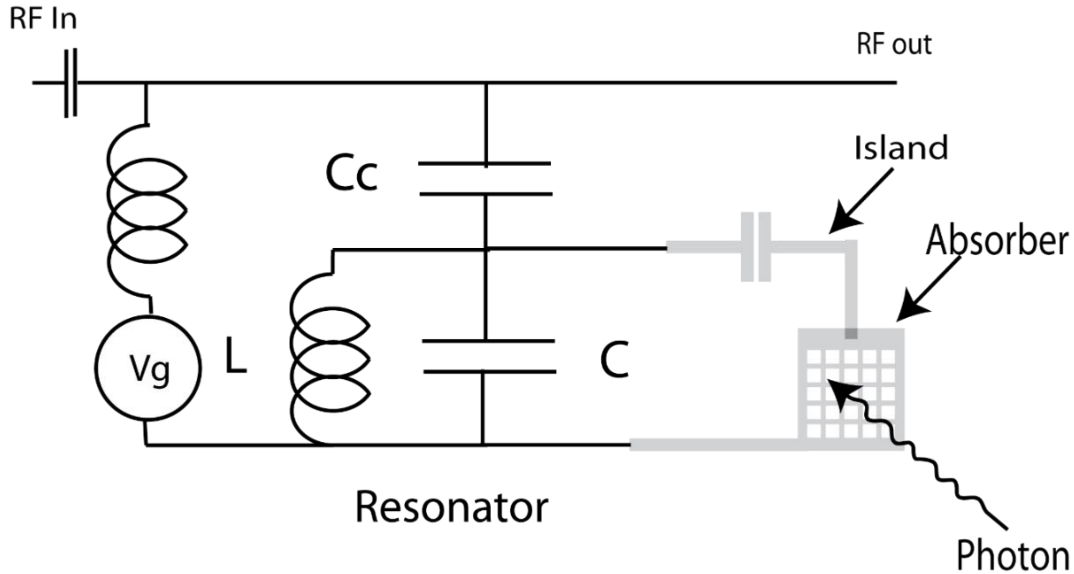


SCB capacitance – Quantum Capacitance



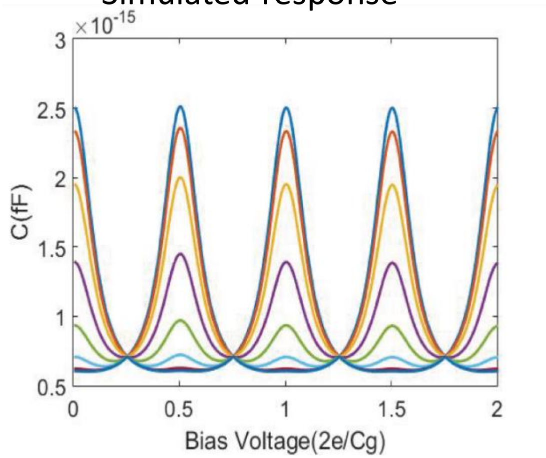
M. D. Shaw, J. Bueno, P. K. Day, C. M. Bradford, and P. M. Echternach, Phys. Rev. B **79**, 144511 2009.

Quantum Capacitance Detector Concept

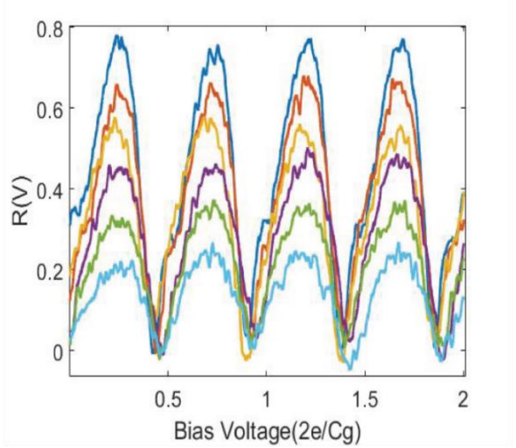


- Make the ground a photon absorbing structure (antenna or metal mesh)
- Insert the SCB in a resonating circuit
- A photon strikes, generating unpaired electrons
- Electrons tunnel to the island, changing its capacitance
- The change in capacitance shifts the resonator frequency

Simulated response



Actual response



- 2×10^{-20}W
- 2×10^{-19}W
- 5×10^{-19}W
- 2×10^{-18}W
- 5×10^{-18}W
- 2×10^{-17}W

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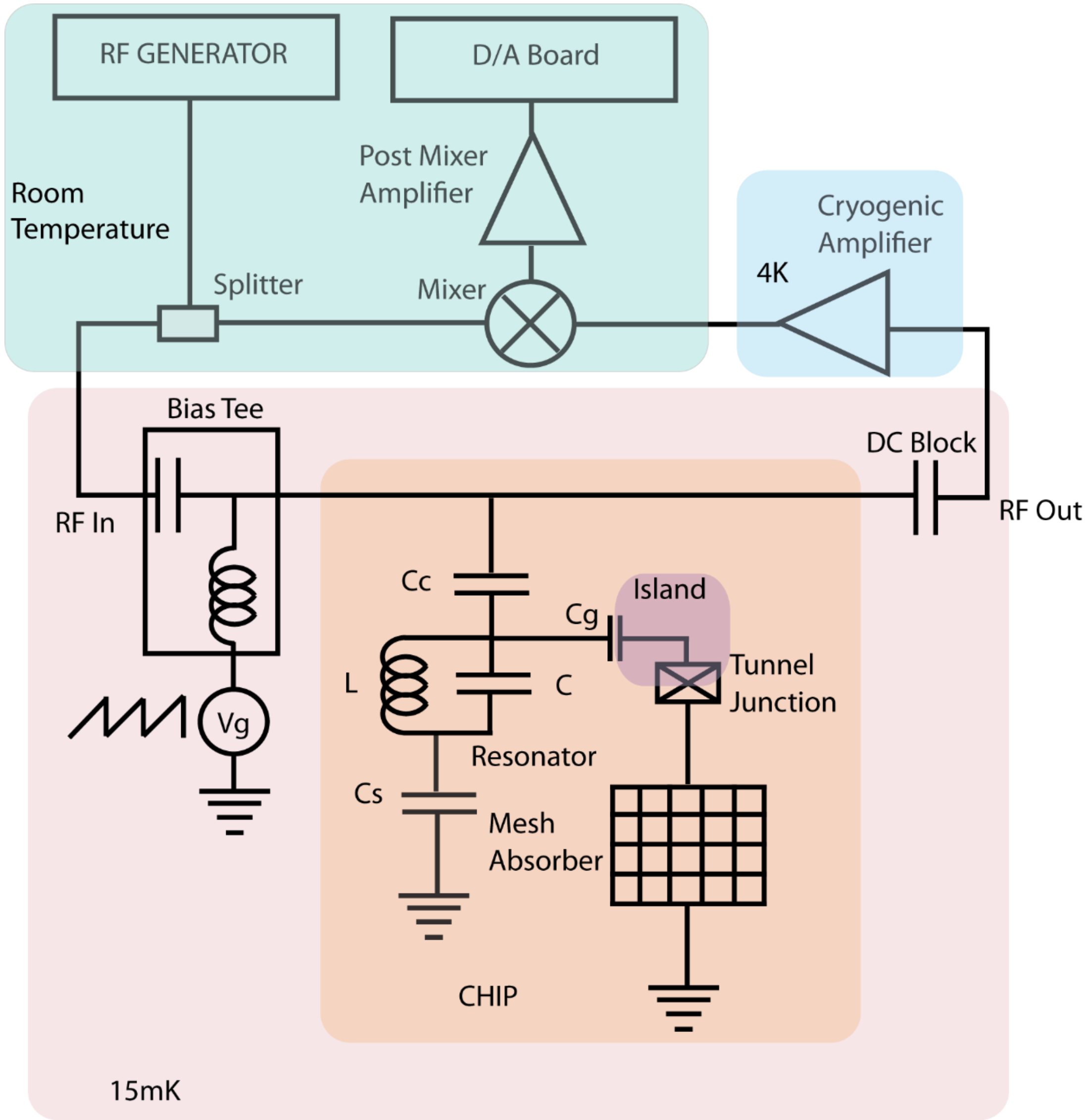
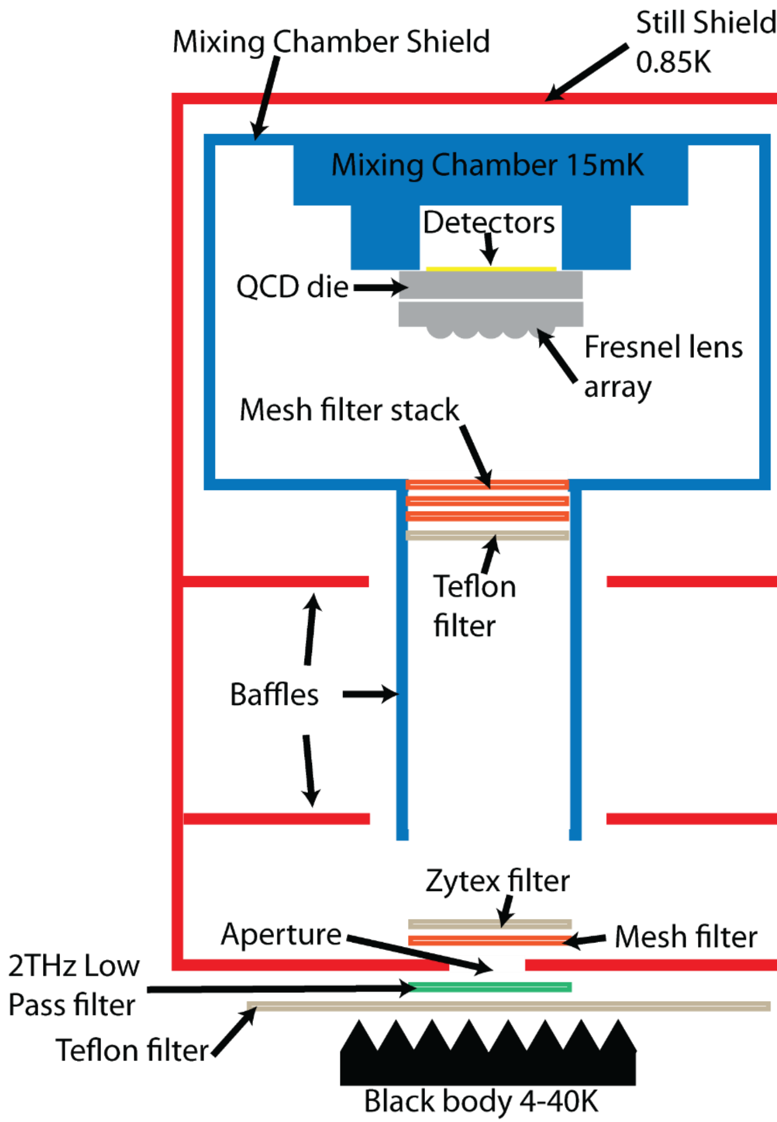
Measurement setup

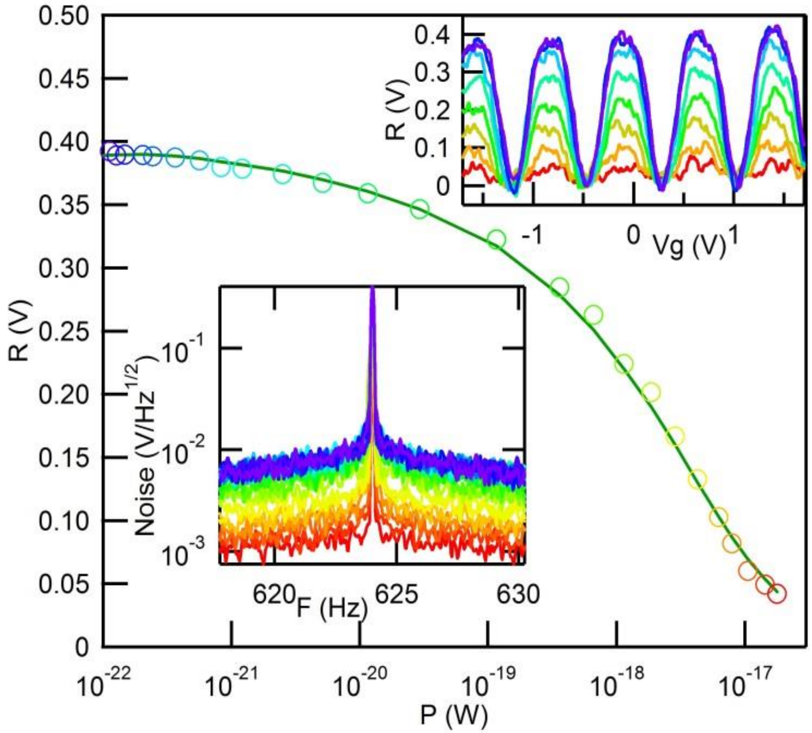


Measurement setup



The Quantum Capacitance Detector

Response and noise as a function of optical signal

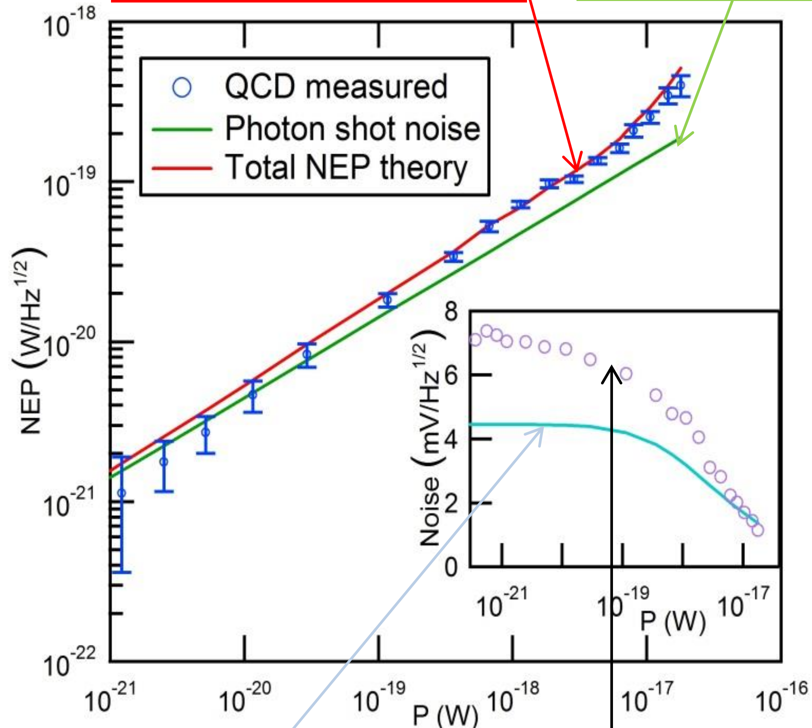


NEP as a function of optical signal

Photon shot noise limited!

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

$$NEP_{ph} = \sqrt{2hnP_s}$$



Total measured noise

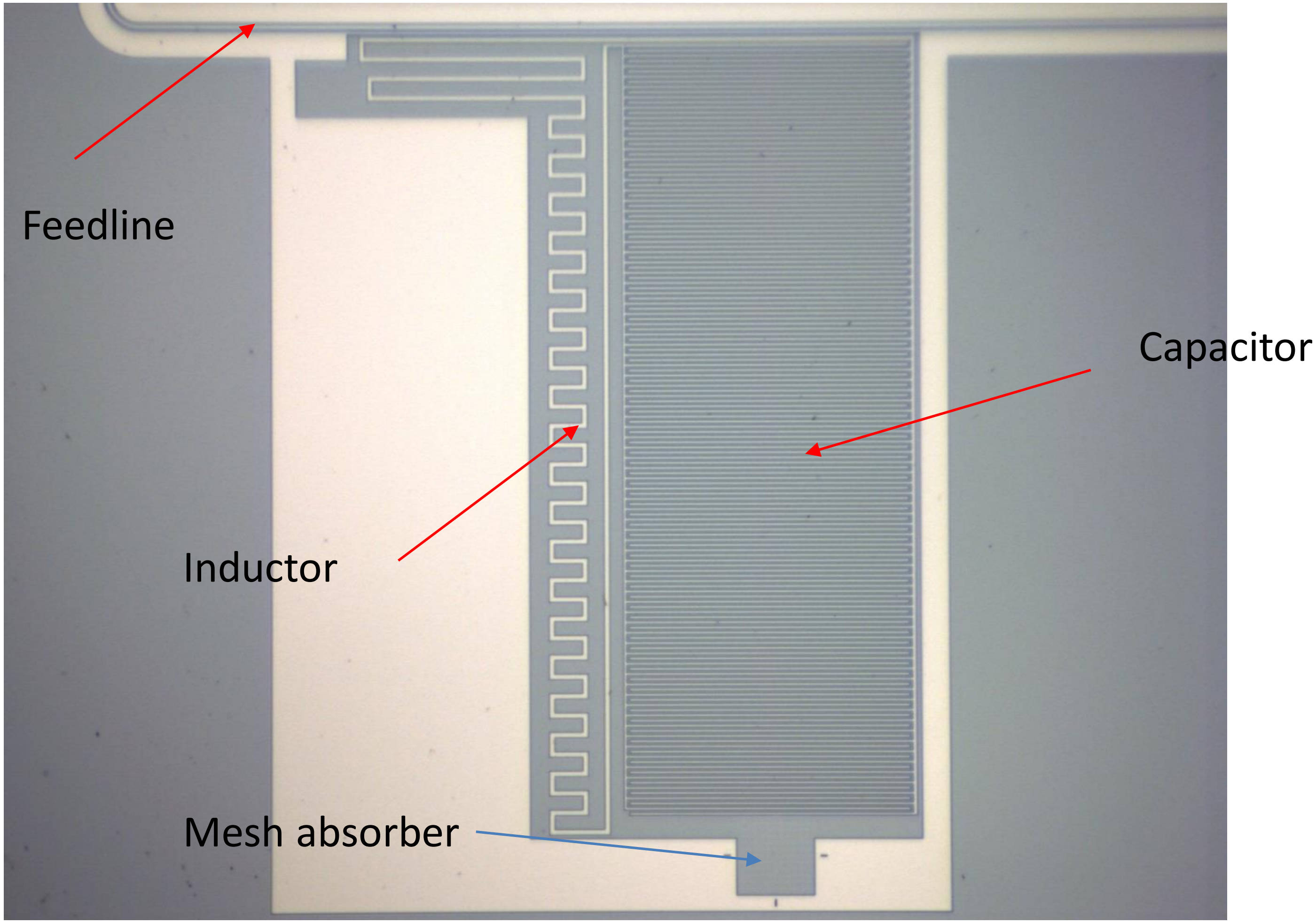
$$NEP_{SN} = S_{SN}(f)/(\frac{dR}{dP})$$

Shot noise of electron tunneling

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

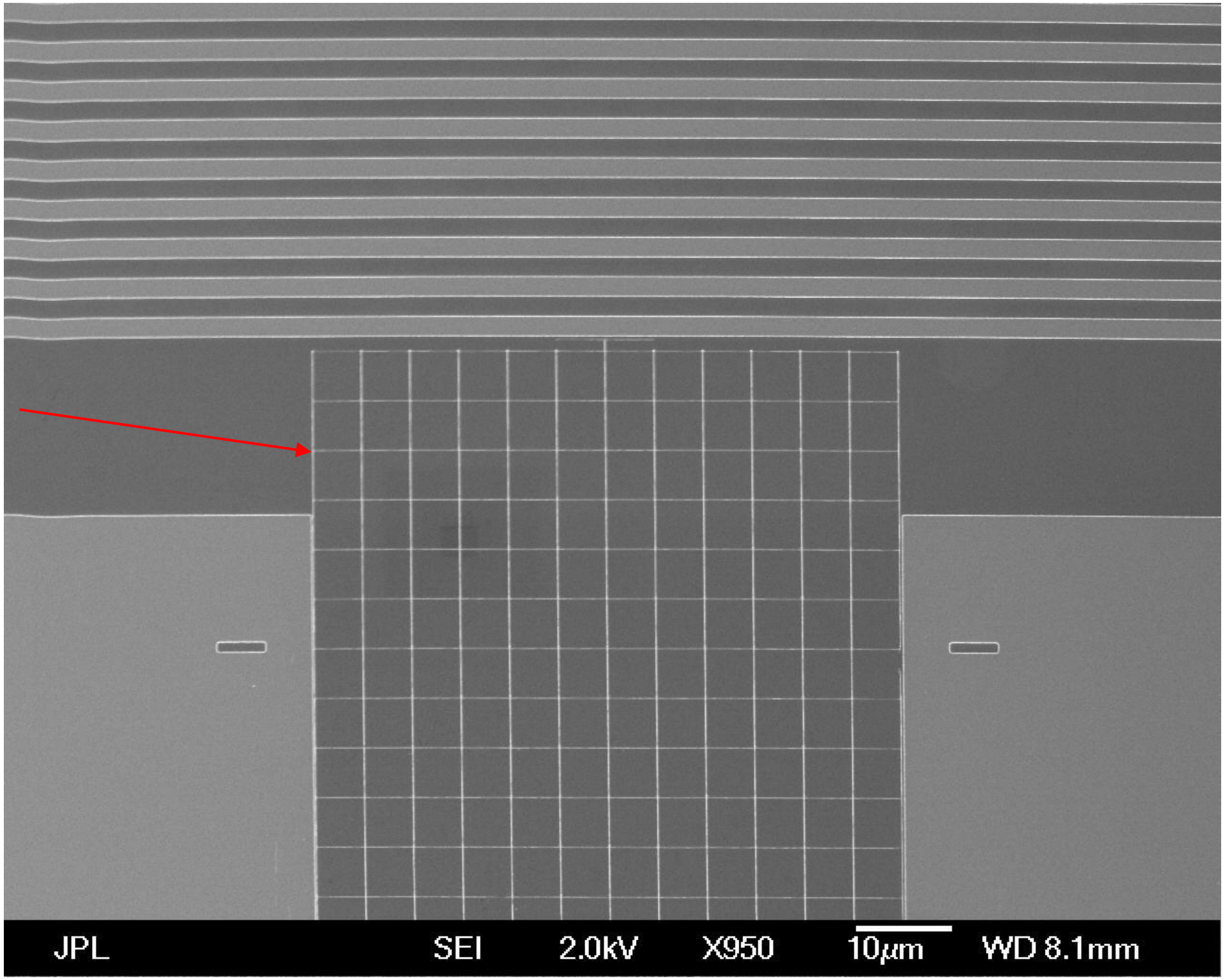
Lens coupled mesh absorber LEQCD

- Need mesh absorber instead of antenna to better couple to spectrometer modes
- Lumped element resonator saves space and has better characteristics than CPW half wave resonator

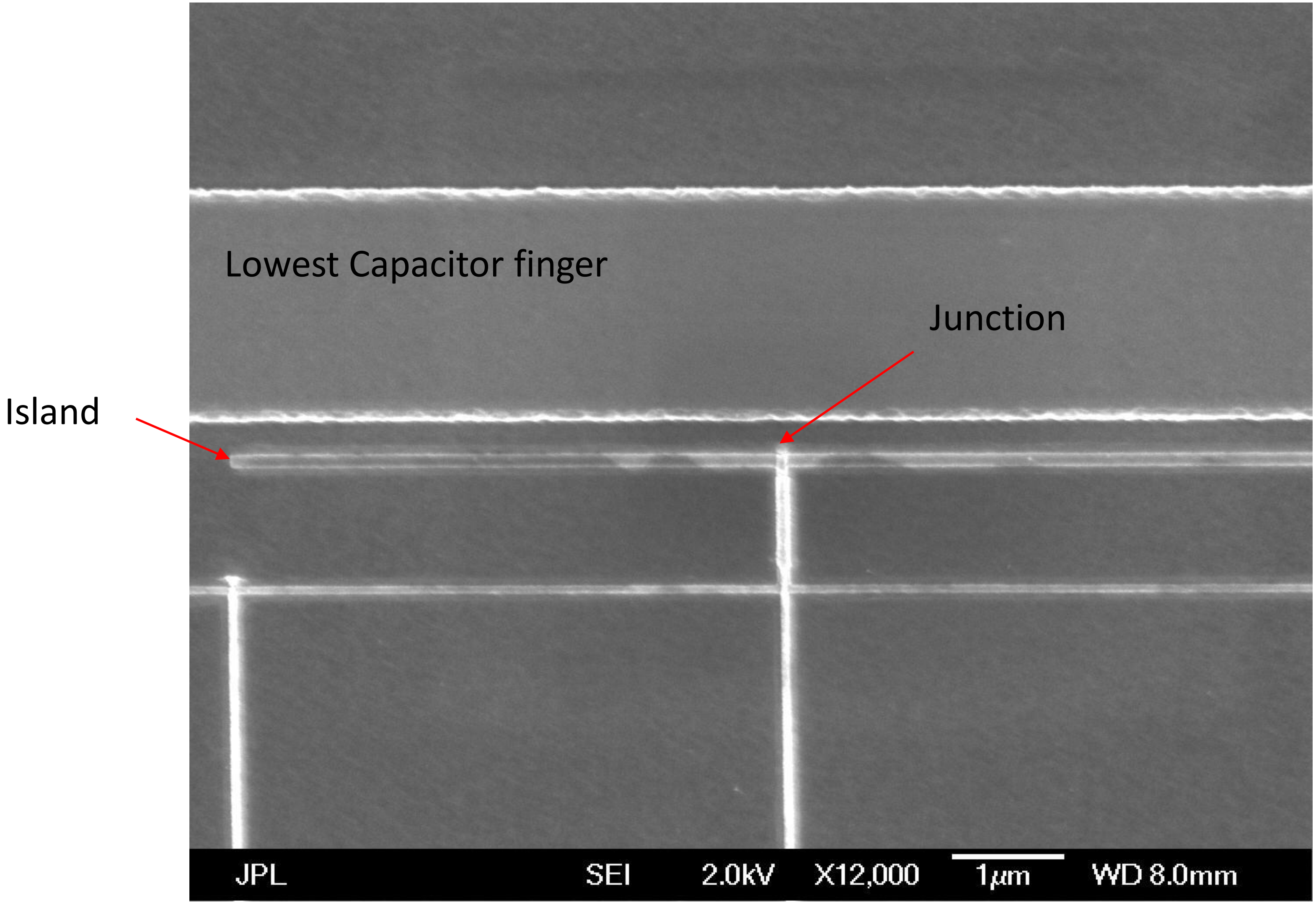


Lens coupled mesh absorber LEQCD

Mesh absorber

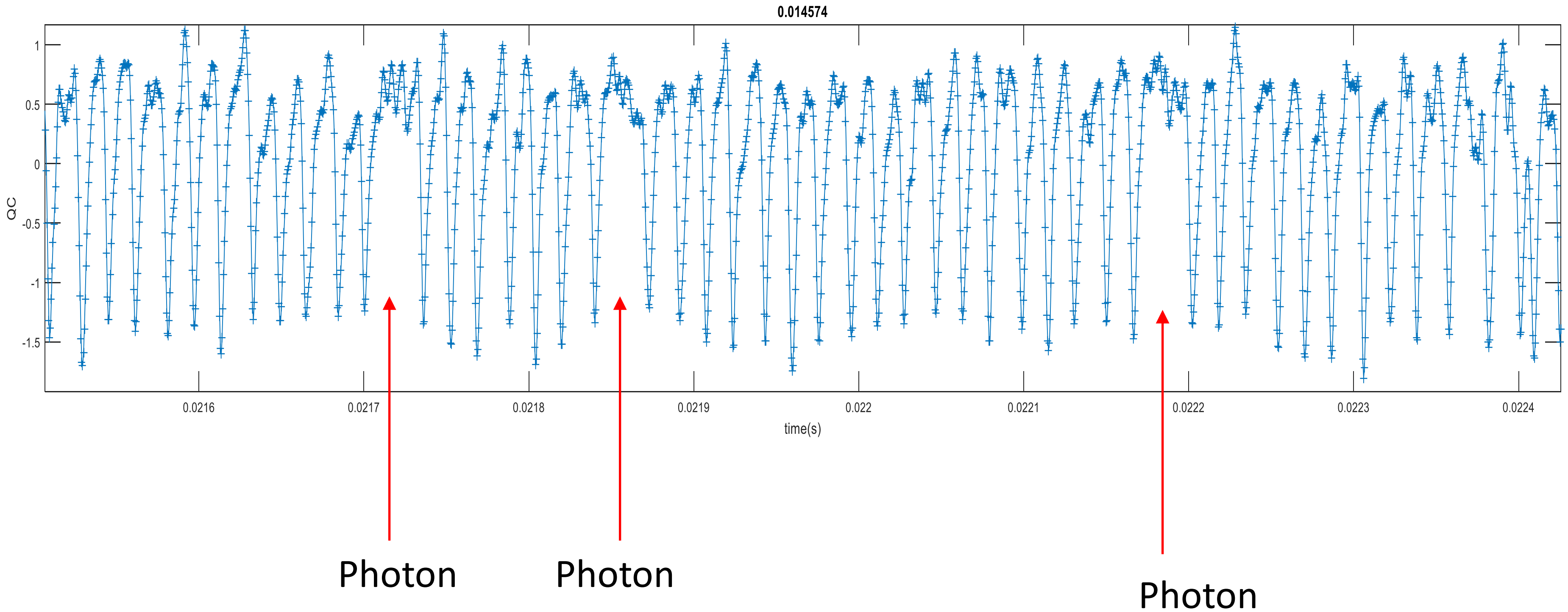


Lens coupled mesh absorber LEQCD



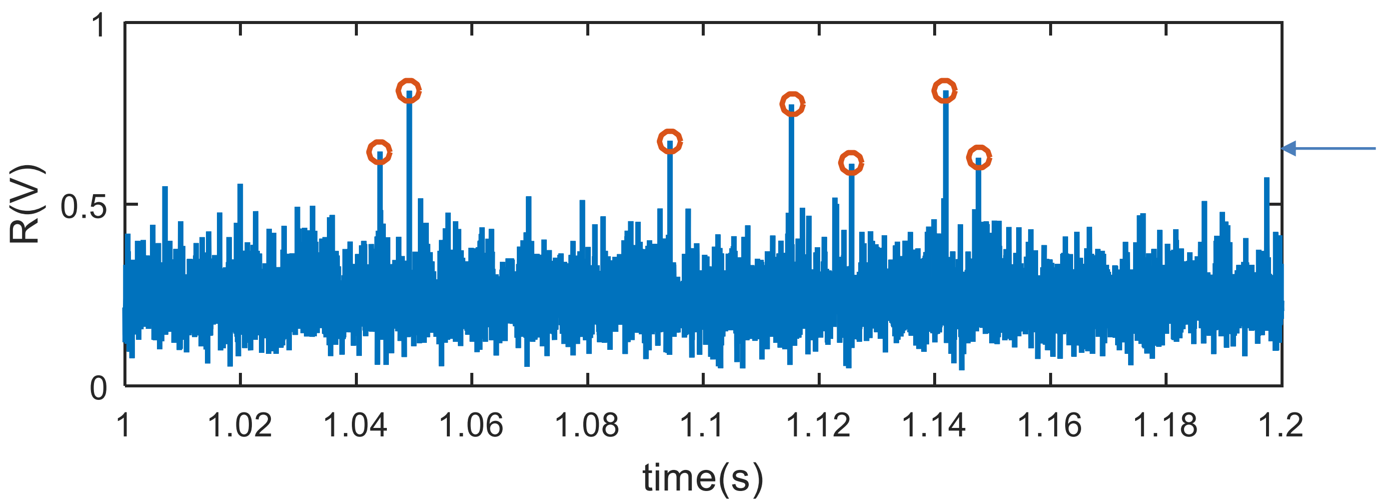
“ Fast sweep reveals single photon events spoiling QC signal

- Sweep rate ~ 22kHz spanning 3 Quantum Capacitance Peaks => effective sweep rate ~ 66kHz
- Should block background tunneling while still allowing tunneling due to single photon absorption
- Raw QC time trace should be absolutely periodic
- Gaps are due to high tunneling suppressing the Quantum Capacitance signal
- Therefore Gaps should be due to single photon absorption

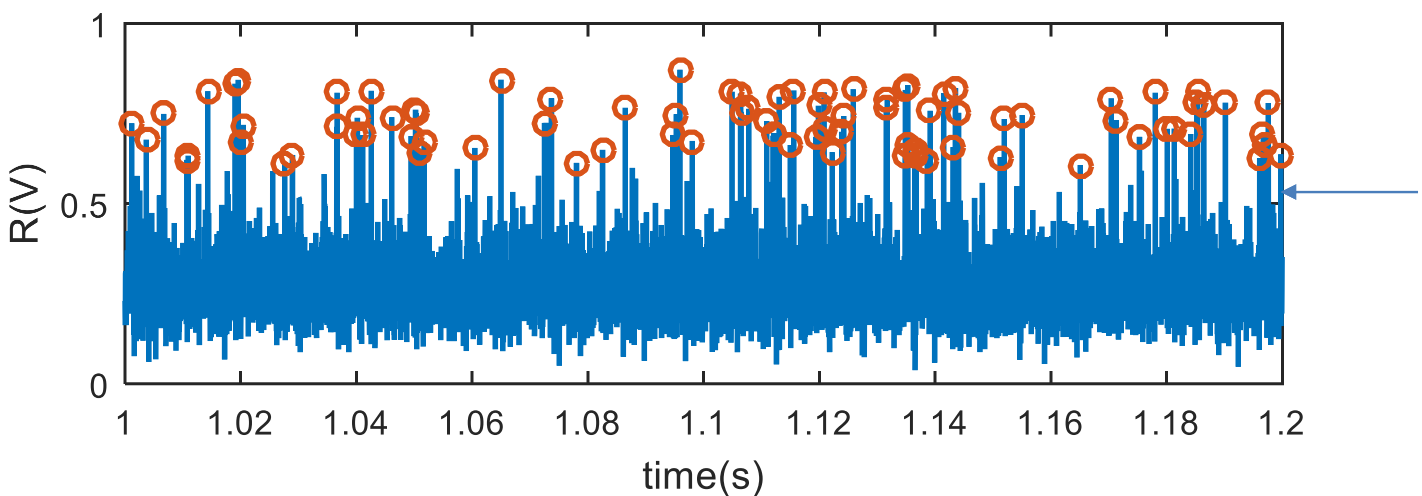


Variance evaluated in 30 us bins shows photon events

- From time traces calculated variance of slices corresponding to 2 QC peaks (to avoid problems at the edge of sweep with e-shifts) – slices are 30μs long
- Subtracted this trace from the maximum of the traces
- Gaps in the Quantum Capacitance trace will show up as peaks
- Repeat for different black body source temperatures



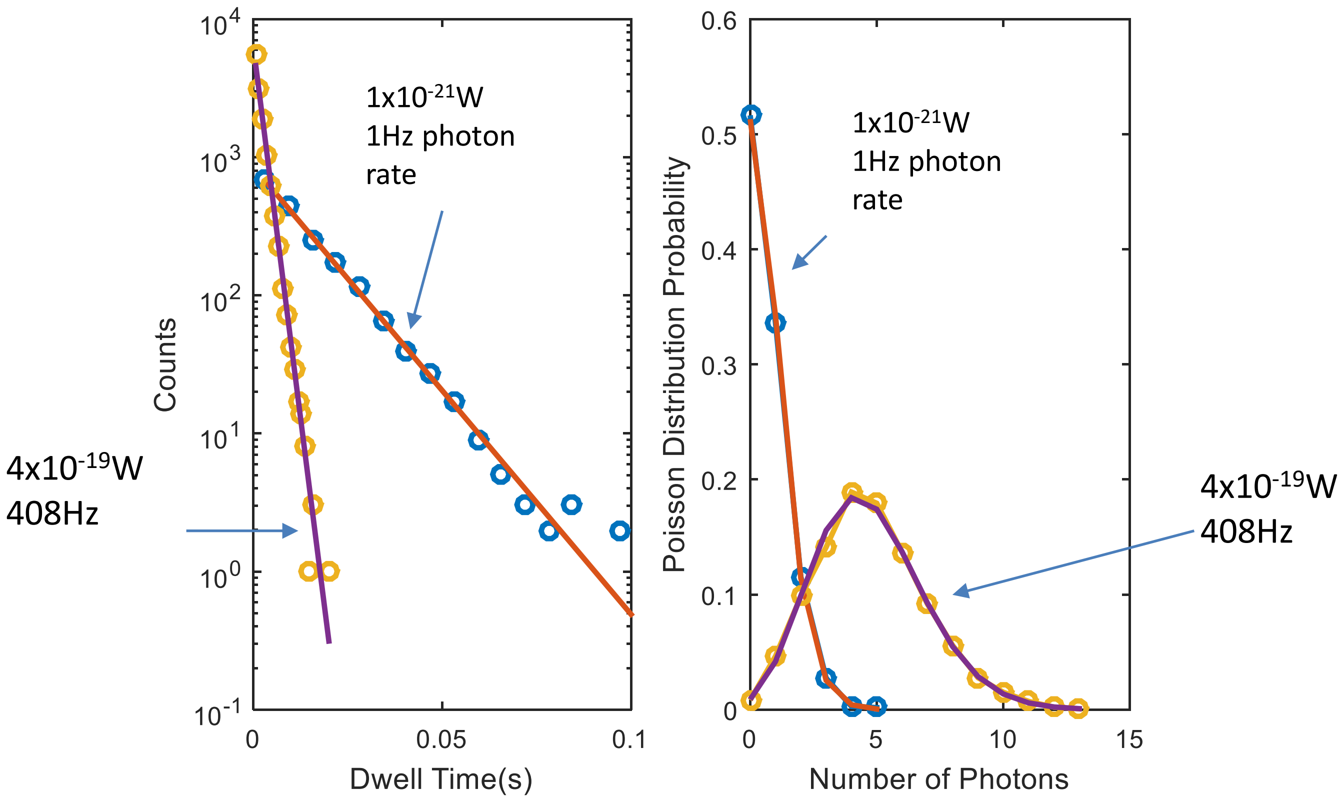
$1x10^{-21}$W
1Hz photon rate



$4x10^{-19}$W
408Hz

Photon arrival intervals follow Poisson statistics

- From the photon time traces, extract dwell time histograms – exponential decay corresponds to Poisson statistics
- Calculate probability of having N photons within a time interval 36ms (Arbitrarily picked)
- Plot probability x number of photons; blue circles is measured, lines are calculated Poisson distribution probability (no fit, just using measured average number of photons)



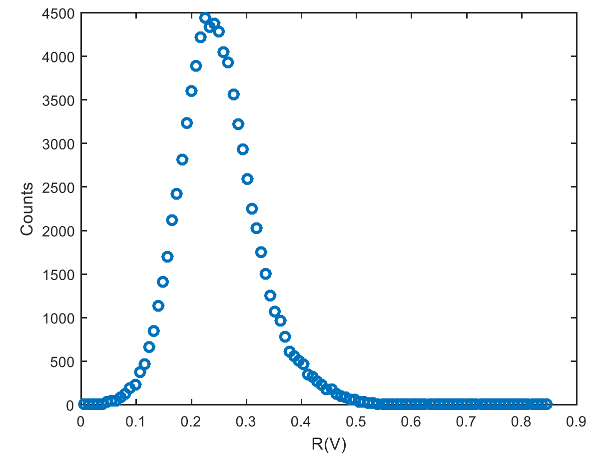
Photon arrival statistics

Histogram of response for various black body temperatures

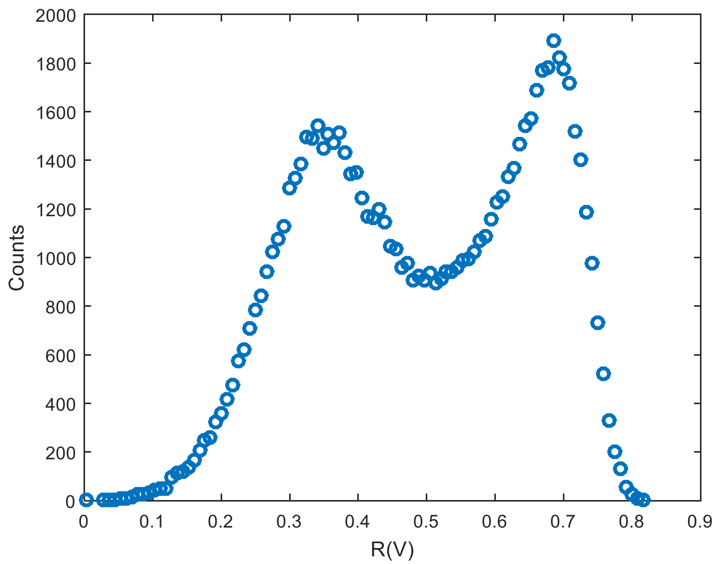
For cold black body only peak around 0.25 exists

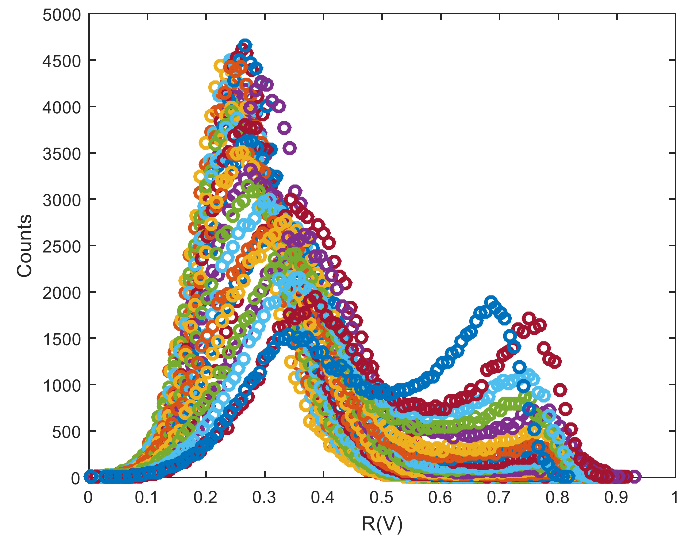
For hot black body peak around 0.6-0.7 is larger than peak at 0.25

Cold black body



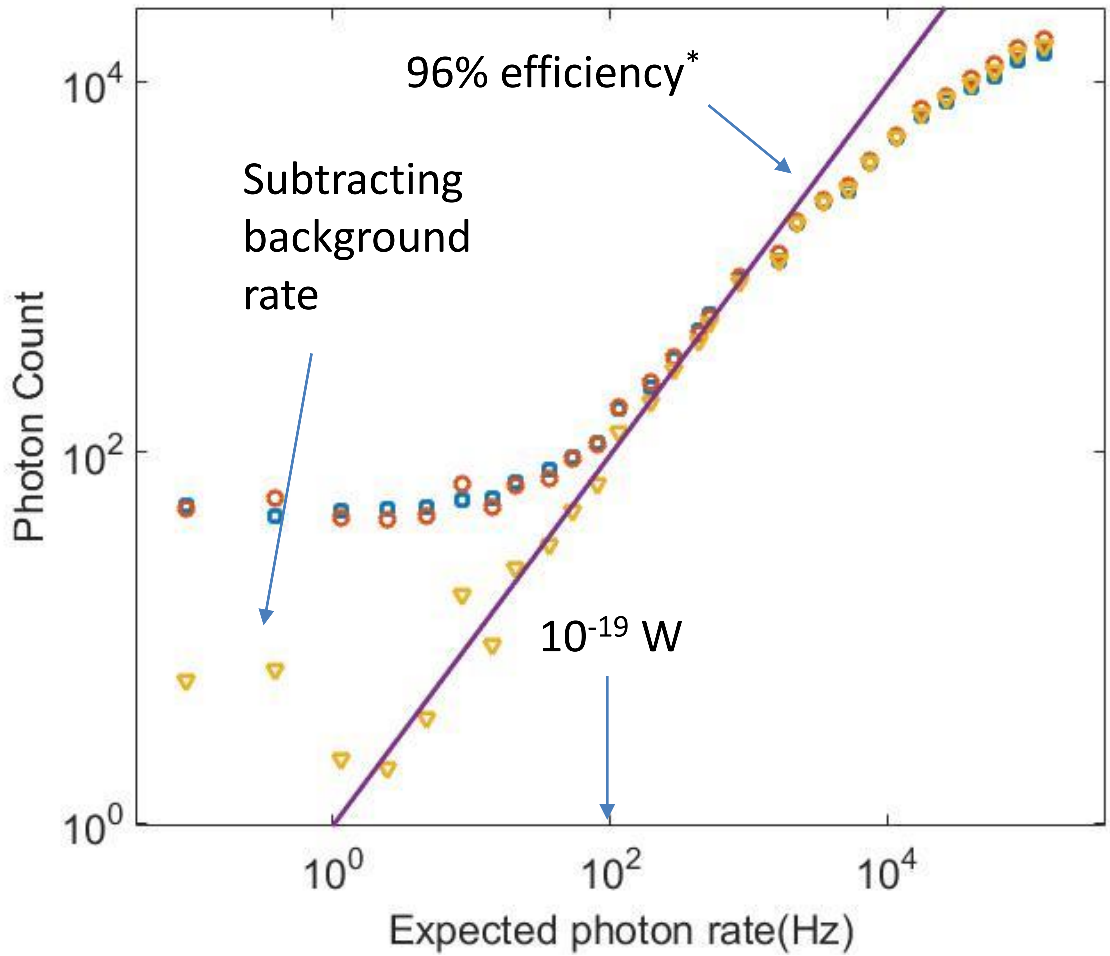
Hot black body





- Peaks get closer together at high black body temperatures due to filtering by the resonator of the high frequency stream
- Could lower resonator Q by stronger coupling at the expense of fewer channels

Counts of response between 0.6 and 0.9 versus number of expected photons



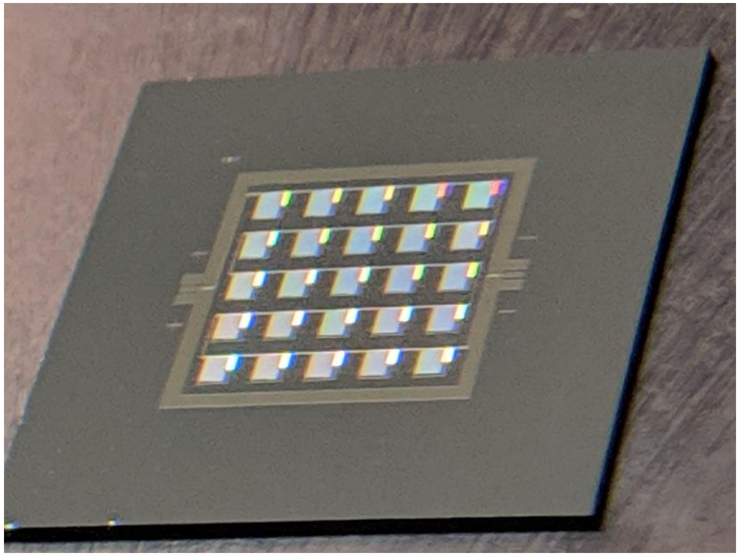
- Efficiency will decrease with when time intervals between photons become comparable to the time separation of two Quantum Capacitance Peaks

* With respect to absorbed power

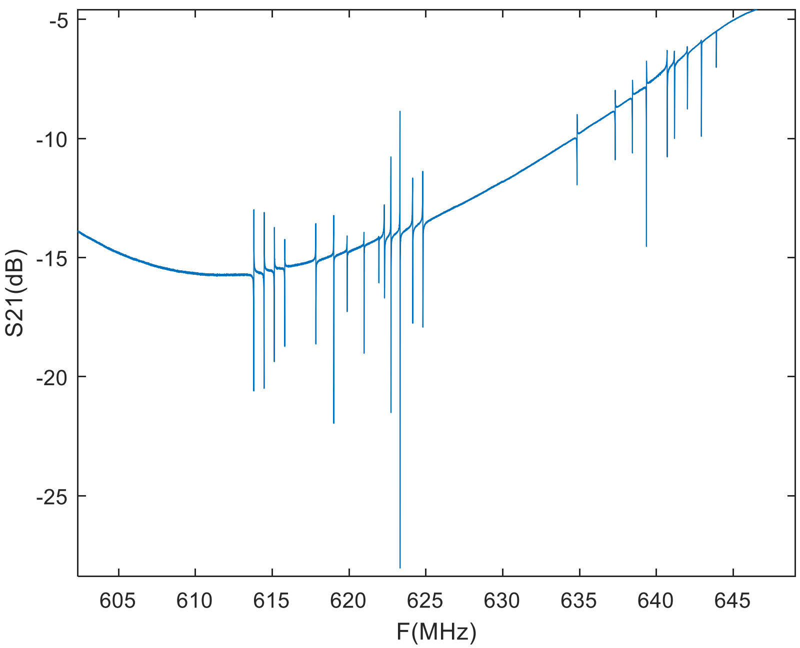
Results published in Nature Astronomy, volume 2, issue 1, pp 90-97, Jan 2018

5x5 array of low frequency readout QCDs

Device fabrication by Andrew Beyer

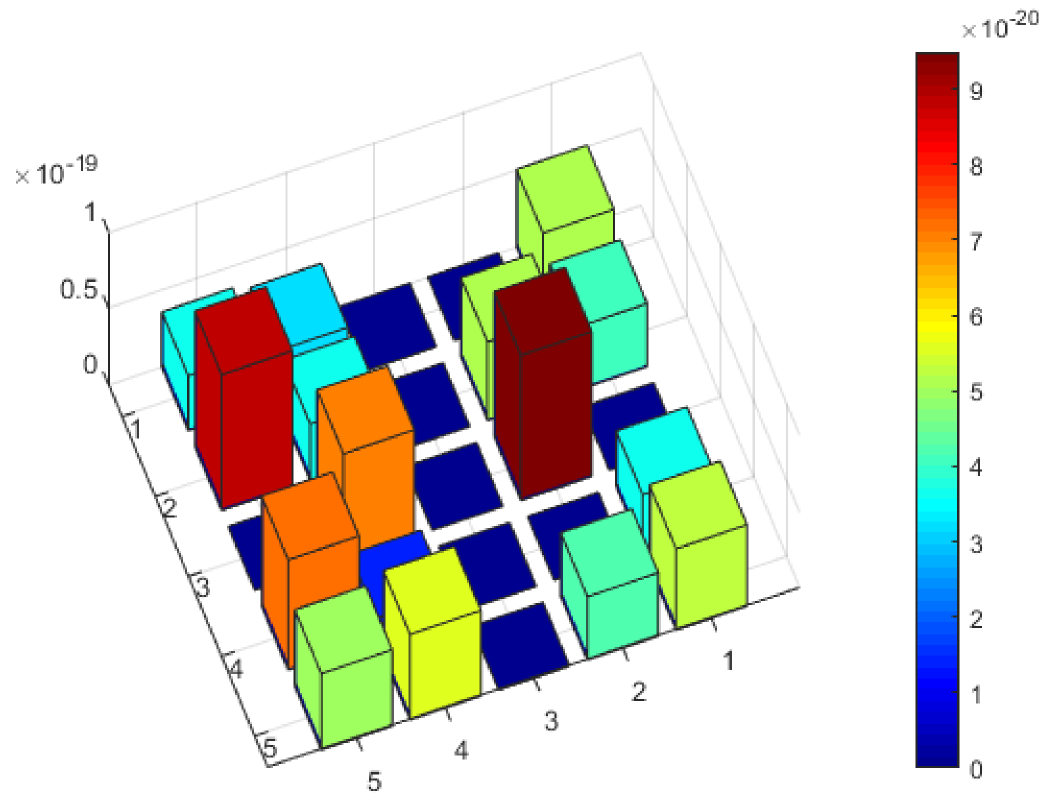


- 614 to 644 MHz
- Consume less power
- Higher Q resonators
- Smaller frequency spacing

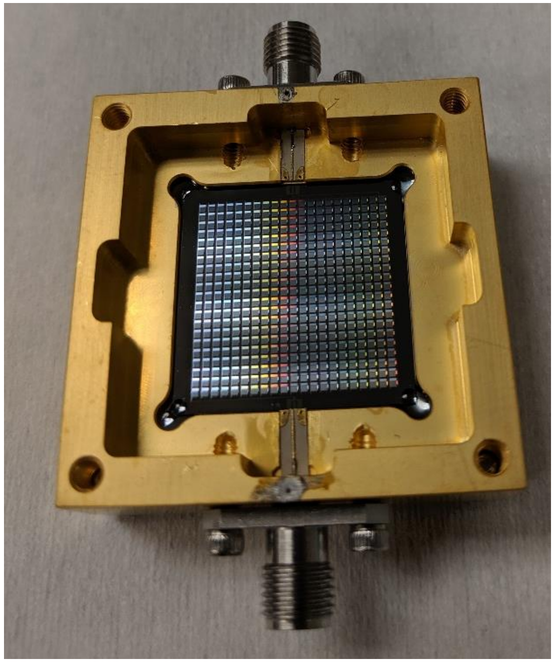


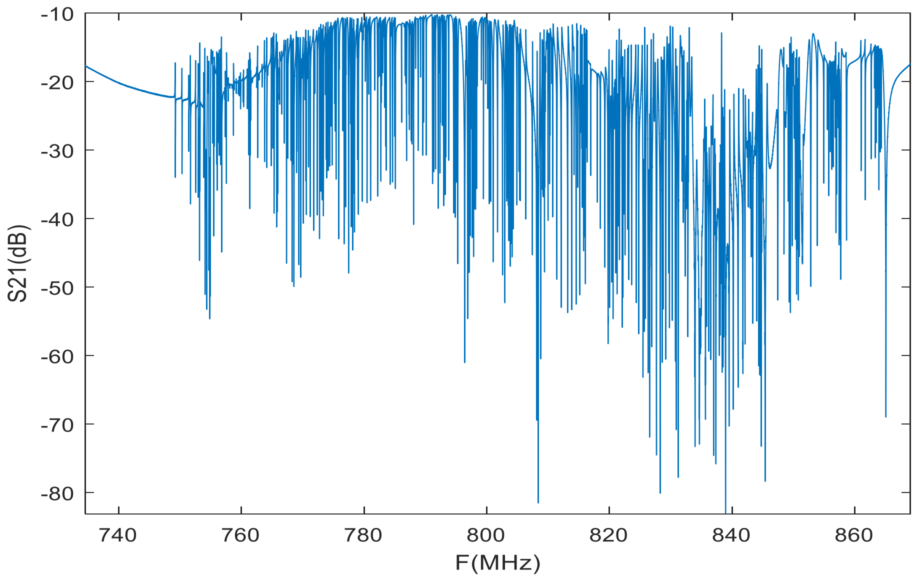
5x5 array of low frequency readout QCDs

- Plot of NEP x pixel location for pixels with NEP < $10^{-19}W/Hz^{1/2}$
- Pixels with NEP > $10^{-19}W/Hz^{1/2}$ are plotted as zero
- Center column had pixels without mesh absorbers by design
- Measurements performed sequentially on individual pixels
- Multiplexed readout of all pixels performed by Lorenzo Minutolo. Please visit poster Session A 139- 49. A flexible GPU-accelerated radio-frequency readout



21x21 array of low frequency readout QCDs

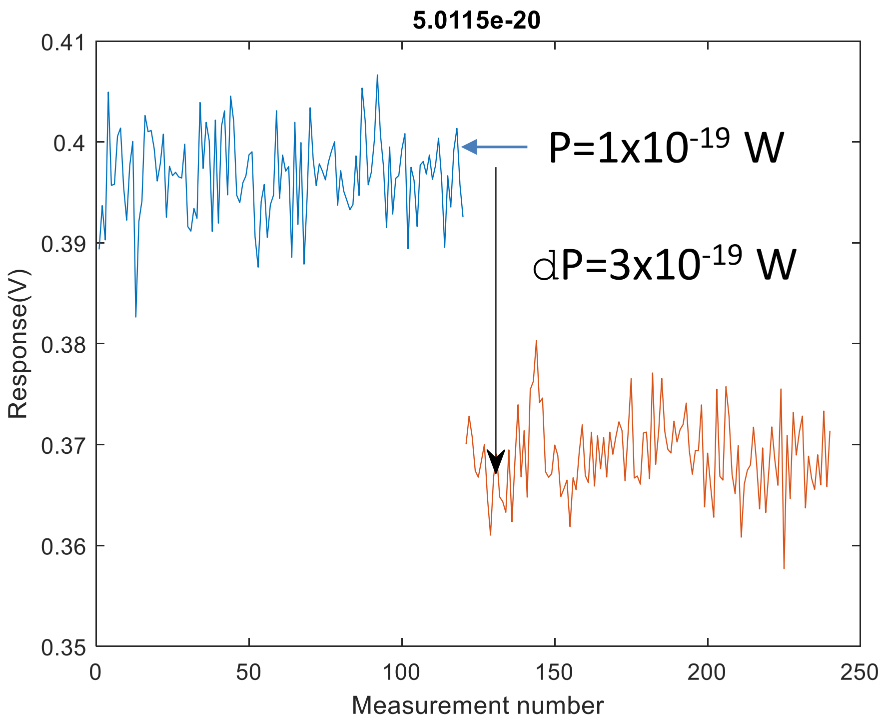




Device fabrication by Andrew Beyer

- 4 designs – mesh absorber galvanically or capacitively coupled to ground plane; island length 10 or 15 um
- 63 pixels with no mesh absorber

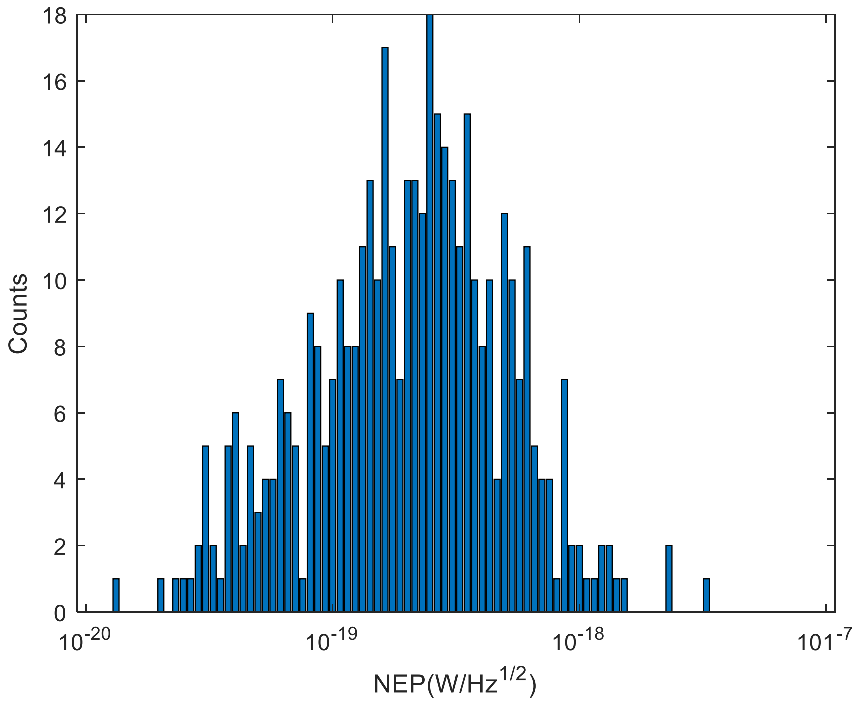
21x21 array of low frequency readout QCDs



- No lens array, but can get up to 10^{-18} W of optical power
- Each point corresponds to a measurement 0.5s long (measurement bandwidth 1Hz)
- Power is stepped
- NEP is the power step divided by the signal to noise ratio

21x21 array of low frequency readout QCDs

NEP histogram



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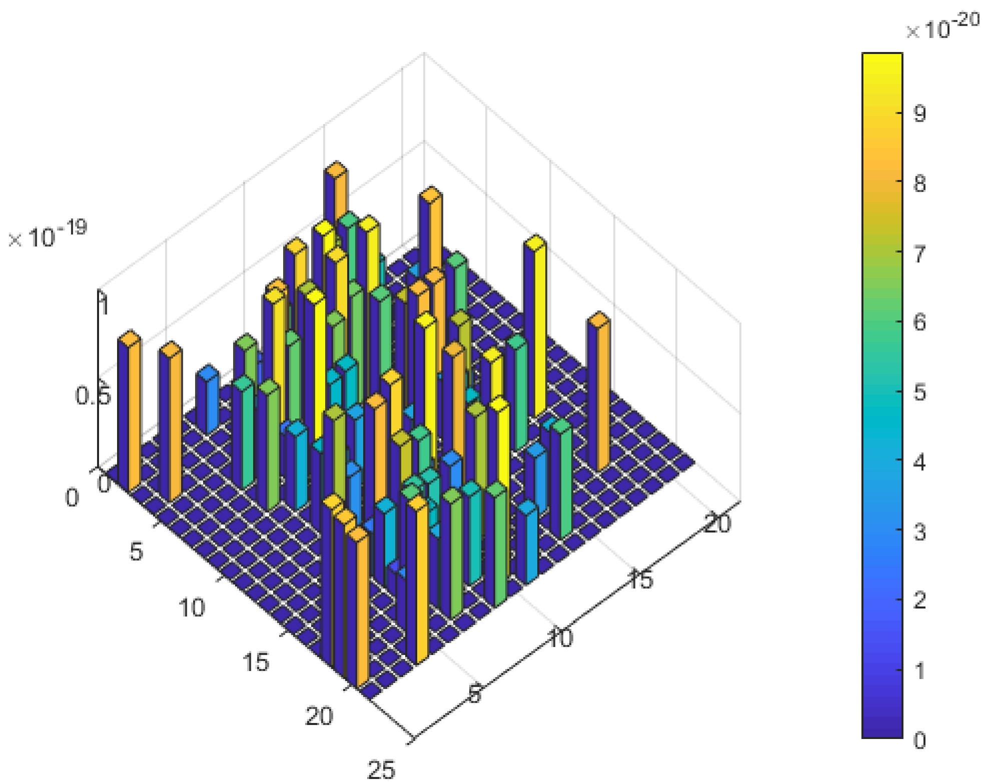
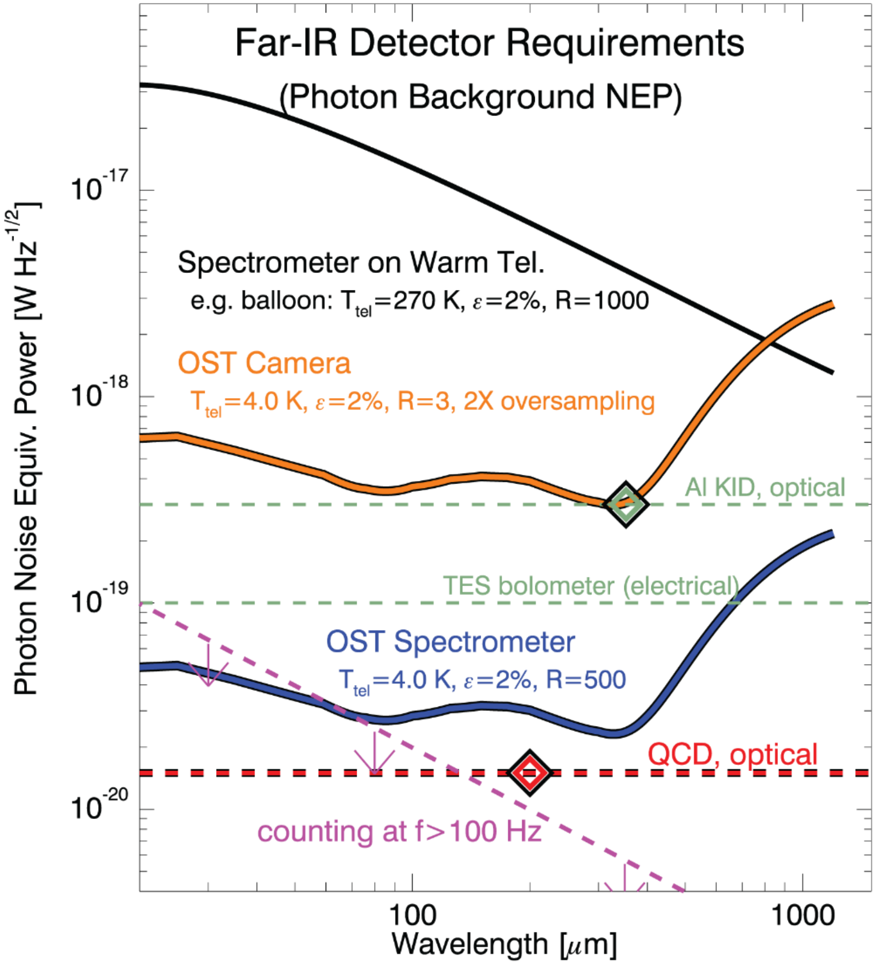


- NEPs of pixels better than $1x10^{-19}$ $W/Hz^{1/2}$
- NEPs of other pixels displayed as zero
- 419 resonators found (out of 441 – locations on chip might not be accurate)
- Devices with isolated (capacitively coupled) mesh perform the best

Conclusion

- QCDs shot are noise limited at 10^{-19}W of optical loading
- Single Photon Counting at 1.5THz from 10^{-19} to 10^{-17}W demonstrated
- Large format arrays possible with frequency multiplexing
- Good candidate for a detector array in a cold far-IR spaceborne telescope



Post-doctoral position available

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