The Quantum Capacitor Detector – counting single photons in the far-infrared

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Electron Beam Lithography by Richard E.Muller

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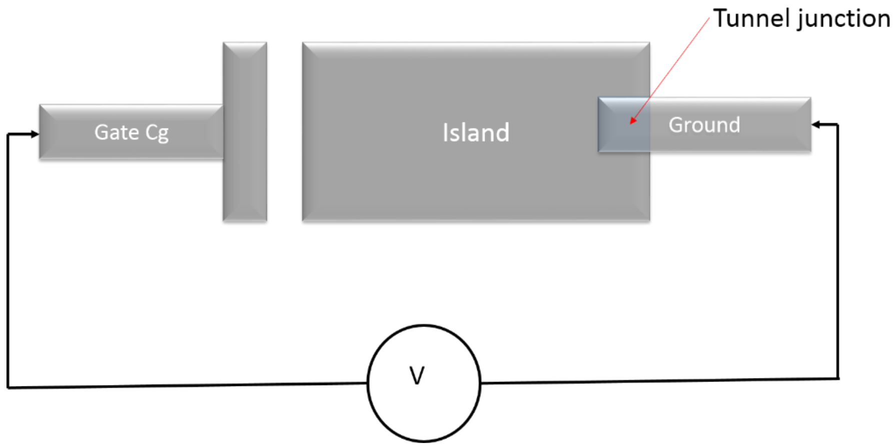
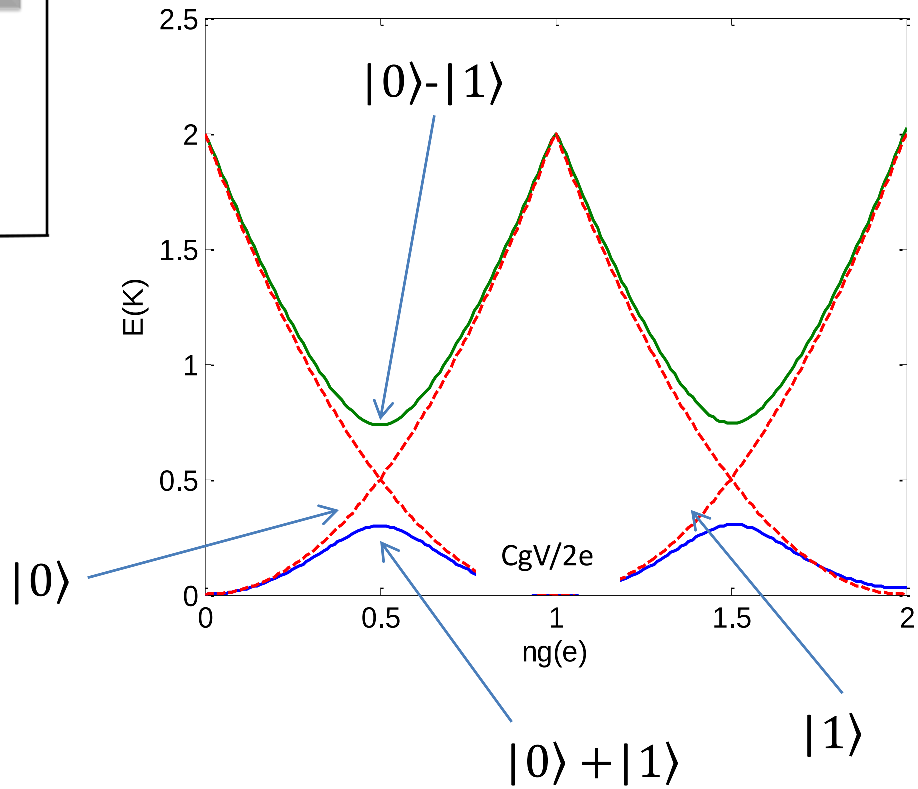
Single Cooper-pair Box (SCB) – developed as a Qubit

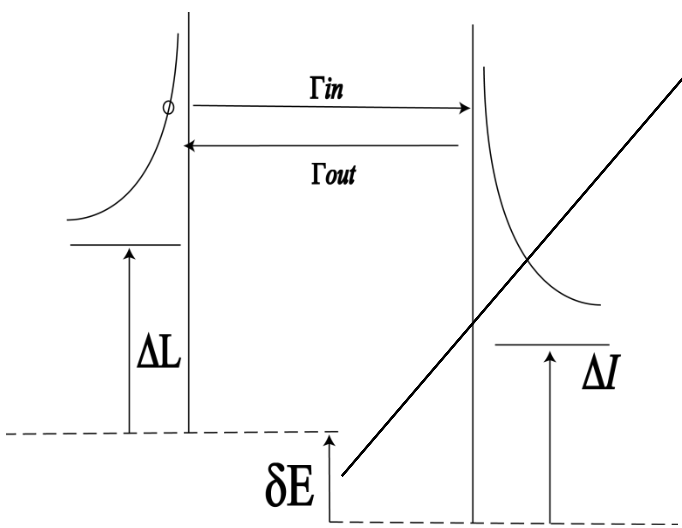


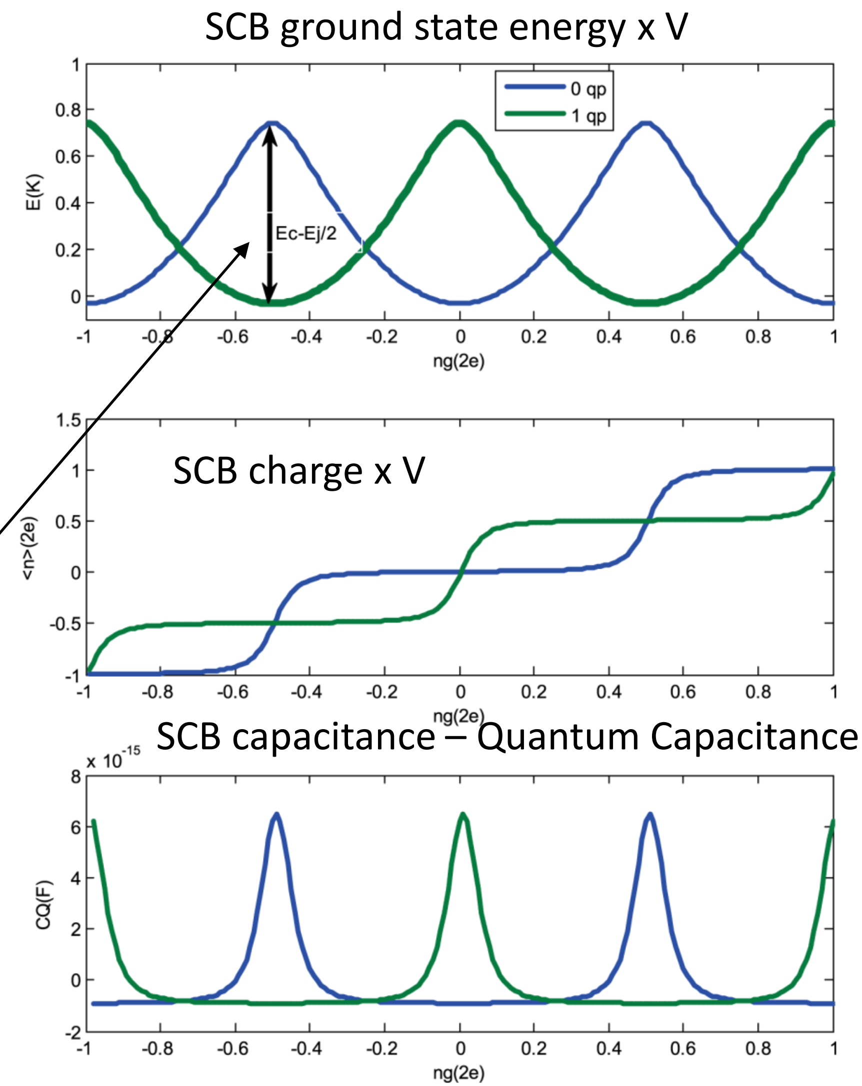


- Small island of superconducting material connected to a ground electrode via a tunnel junction
- Cooper pairs (two paired electrons) can tunnel into the island
- Island can be biased with a voltage via gate capacitance Cg
- Energy states are parabolas corresponding to 0, 1, 2 excess Cooper-pairs in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





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

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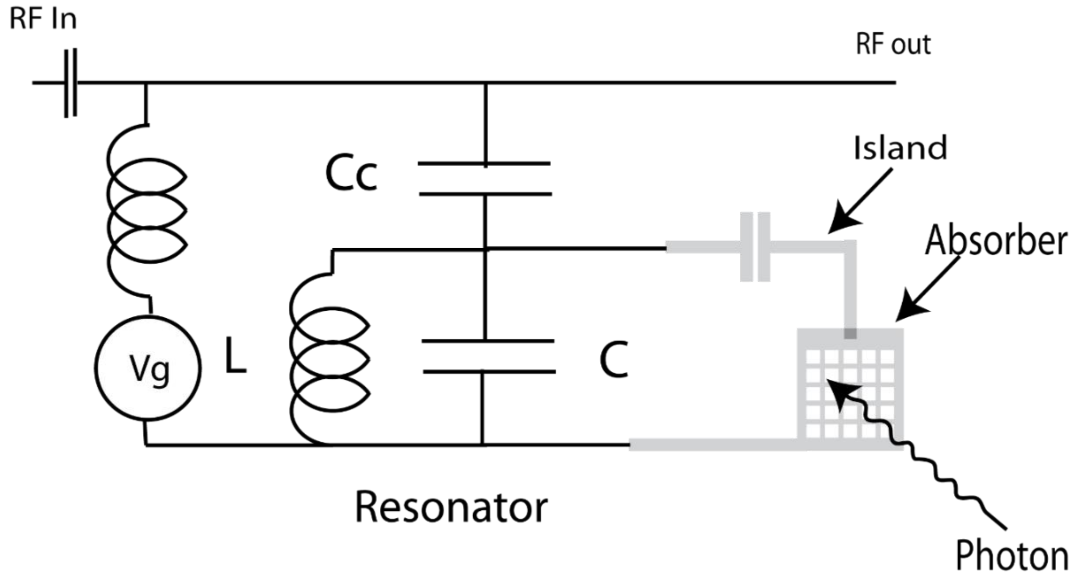
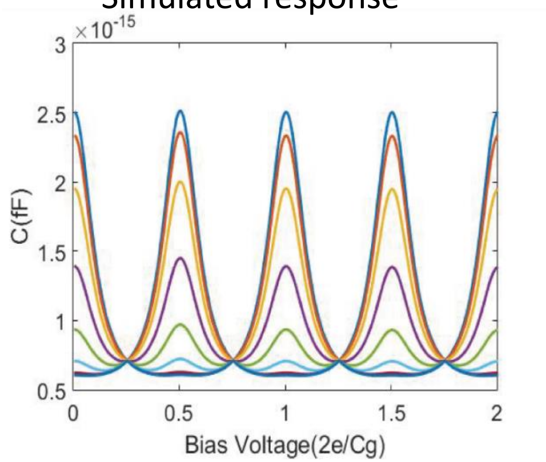
Quantum Capacitance Detector Concept

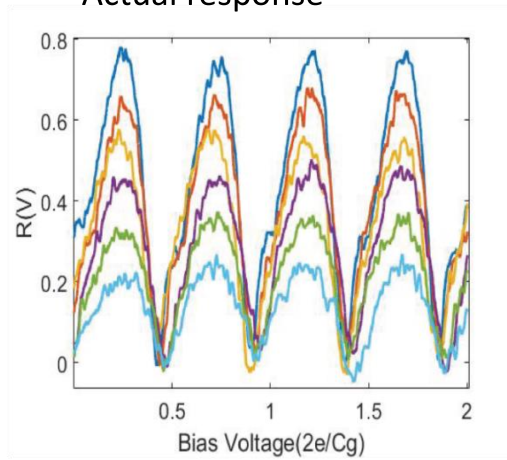


- Make the ground a photon absorbing structure (antenna or metal mesh)
- Insert the SCB in a resonating circuit
- A photon strikes, generating unpaired electrons
- Electrons tunnel to the island, changing its capacitance
- The change in capacitance shifts the resonator frequency

Simulated response



Actual response



M. D. Shaw, J. Bueno, P. K. Day, C. M. Bradford, and P. M. Echternach,
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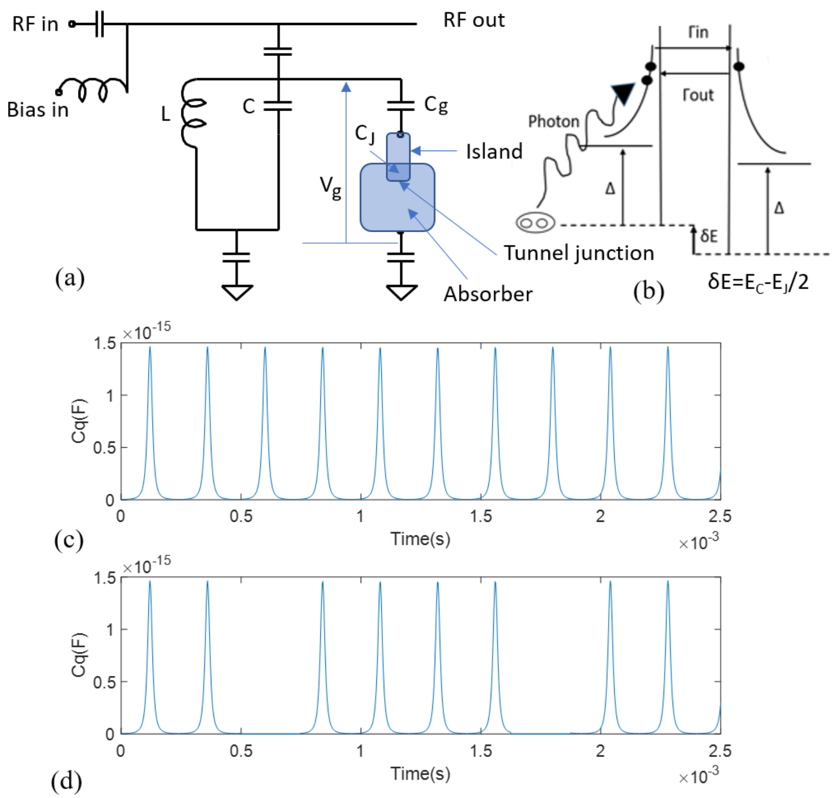
Quantum Capacitance Detector Single Photon Detection

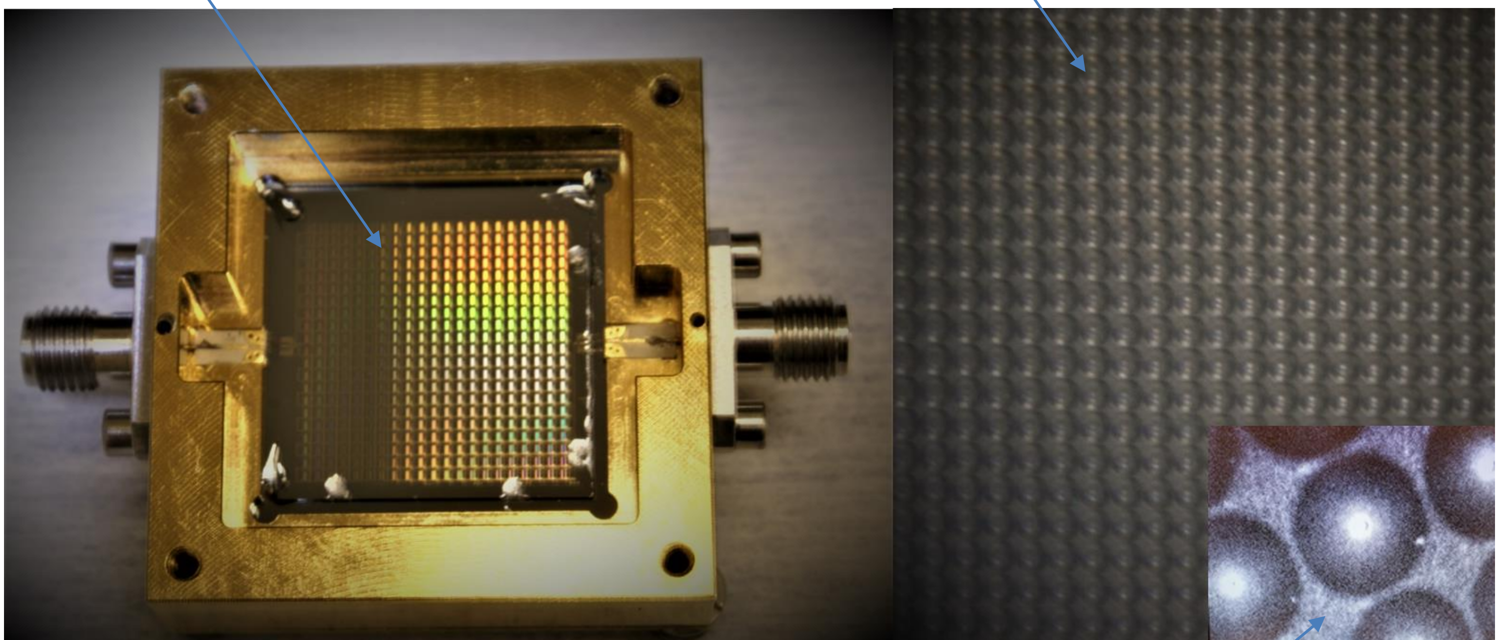


Quantum Capacitance Detector concept. (a) An island of superconducting material is connected to an absorber via a small tunnel junction and biased by a gate capacitor with a linear voltage ramp in a sawtooth format. (b) A photon absorbed breaks a Cooper-pair causing quasiparticles to tunnel onto the island with a rate Γin and out of the island with a rate Γout (c) The capacitance of the island displays a periodic stream of peaks. The device is embedded in a resonator, and the capacitance change is detected by the change in resonance frequency. (d) A photon striking the absorber breaks Cooper pairs creating a population of quasiparticles which tunnel onto the island, destroying a peak.

21x21 Array

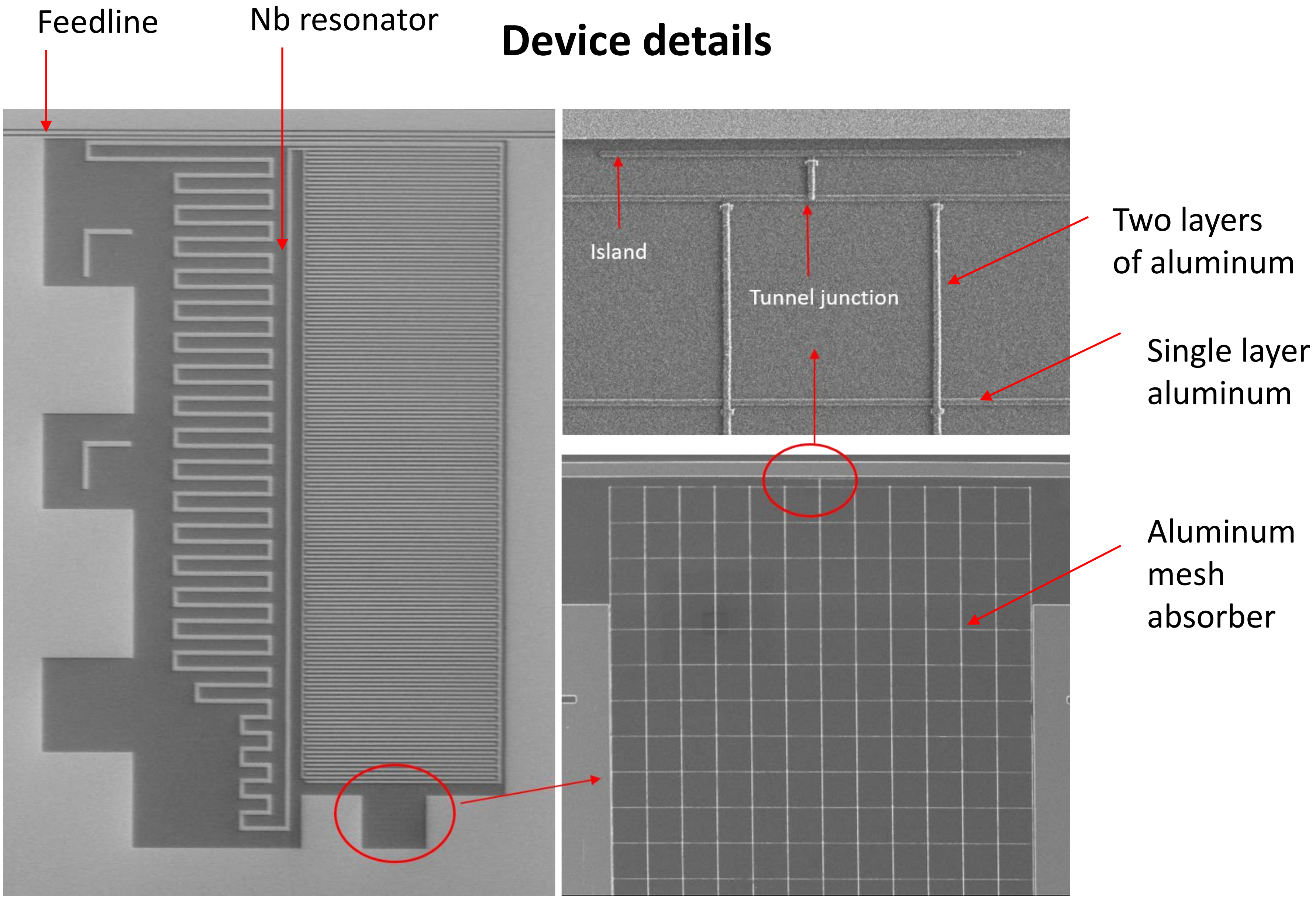
Devices on front side

Lens array on the back side

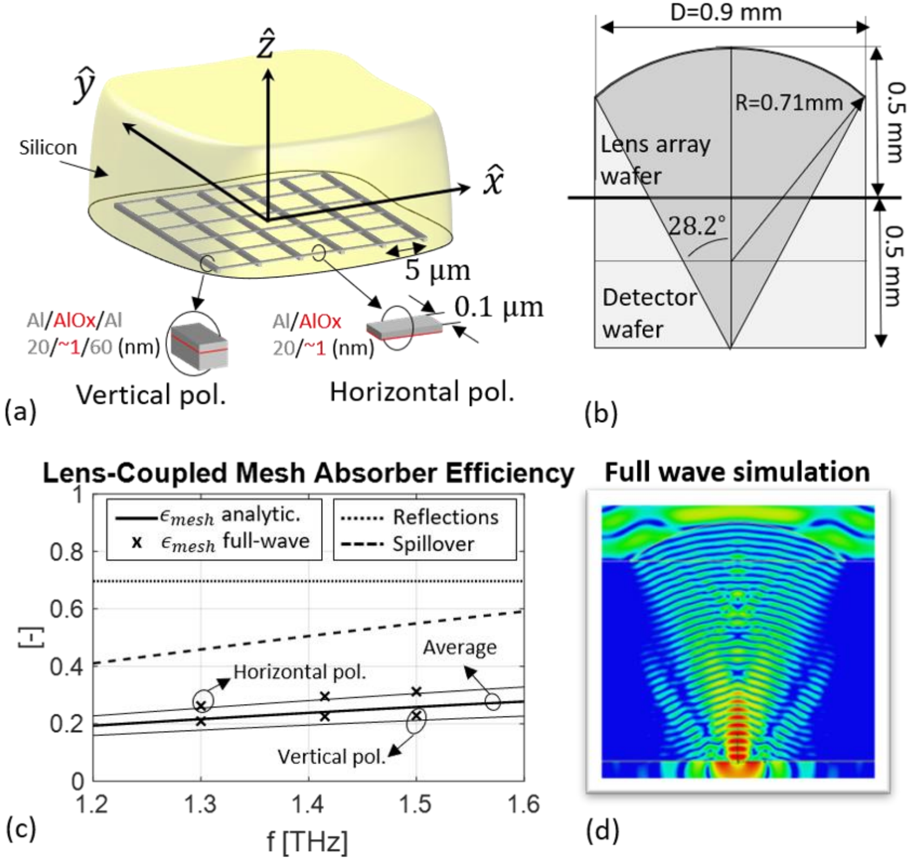


Lens array detail

Device details



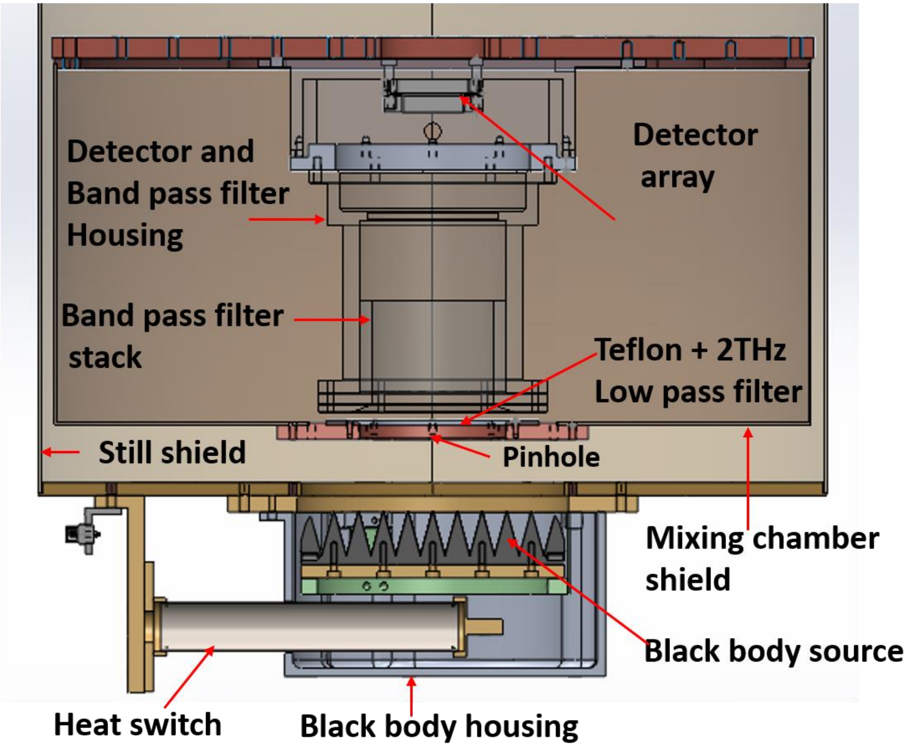
Expected optical performance



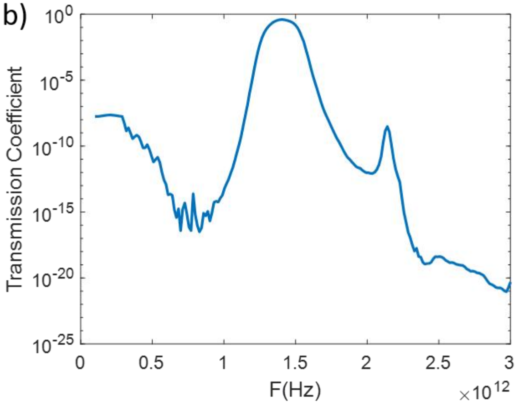
- Hi F# lens (1.06) makes spot comparable to mesh size causing spillover losses
- No antireflection coating
- Second layer in one direction of absorber causes less than idela impedance matching in one polarization
- Expected end to end efficiency ~ 25%

Optical and measurement setup

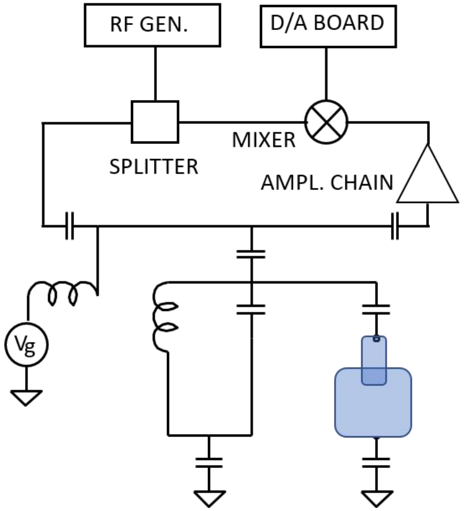
a)



b)

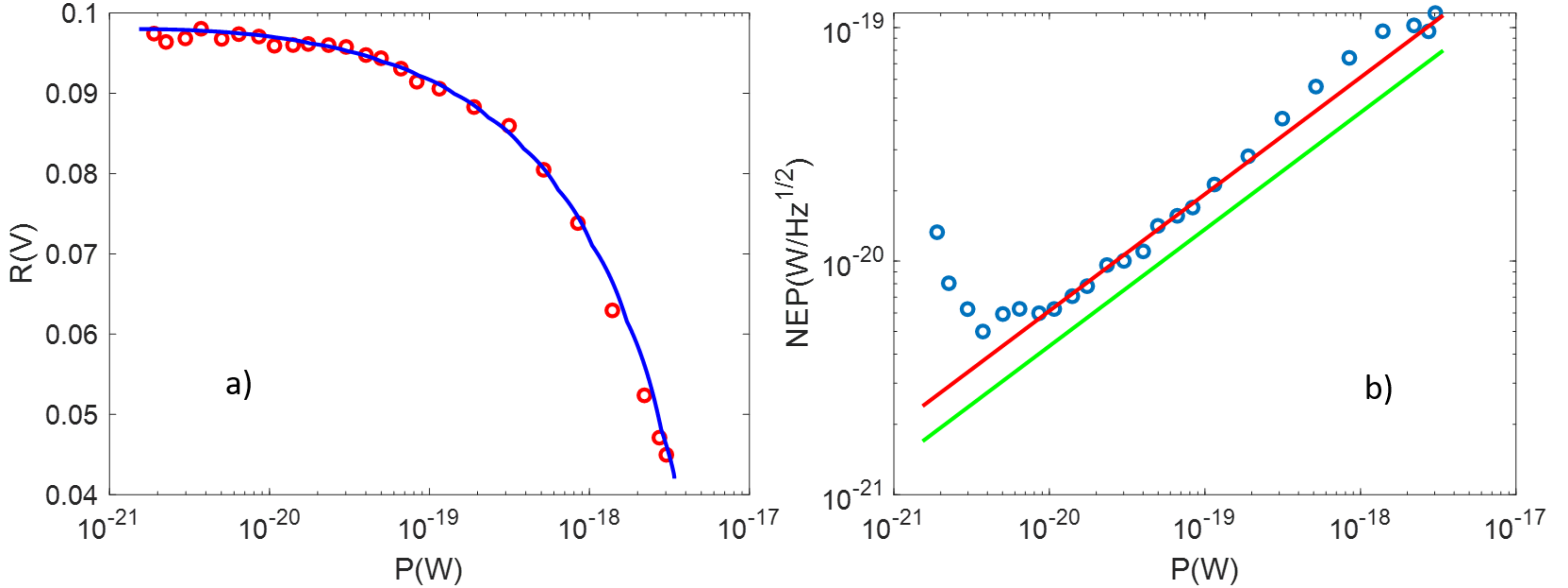


c)



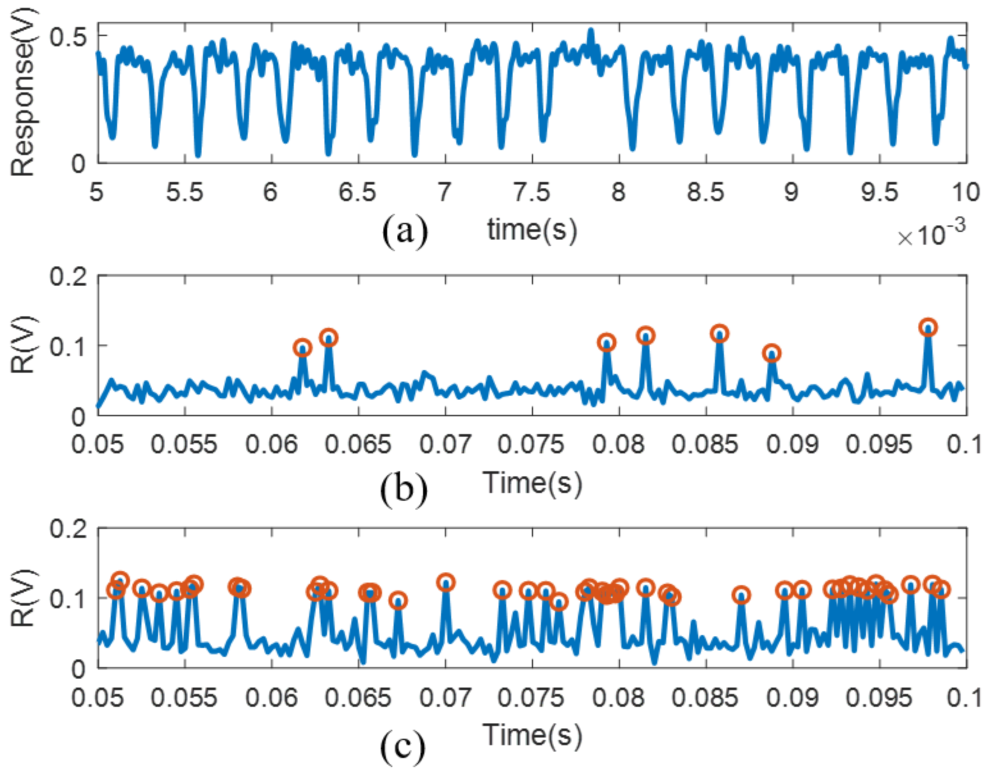
$$Ps = \Omega_M A_A \int_{\nu_l}^{\nu_h} \epsilon_{mesh}(\nu) \frac{T(\nu) 2h\, \nu^3 / c^3}{e^{\frac{h\nu}{k_B T}} - 1} d\nu$$

Single pixel “average” QC measurements



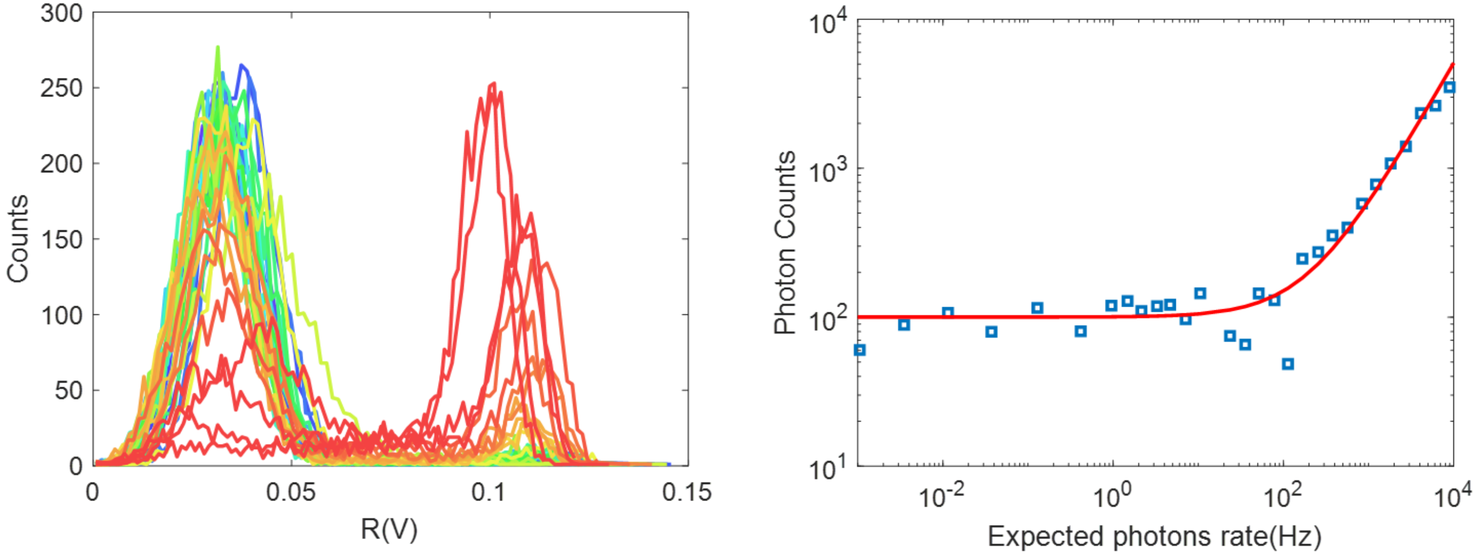
(a) Response of a single pixel as a function of optical illumination power. The circles are the experimental data and the blue line a fit used to calculate the device responsivity. (b) Noise Equivalent Power for a single pixel (circles). The green curve is the photon NEP assuming 100% efficiency, and the red curve assuming 50% efficiency.

Single pixel single photon QC measurements



Raw quadrature response with a cold black body source showing a single photon detection event characterized by the gap in the periodic trace. (b) Processed data for a cold black body source. Each point corresponds to a 250μs interval. A peak highlighted by a circle represents a single photon detection event. (c) Same process as the center plot but for a warmer black body source, showing an increased frequency of single photon detection events.

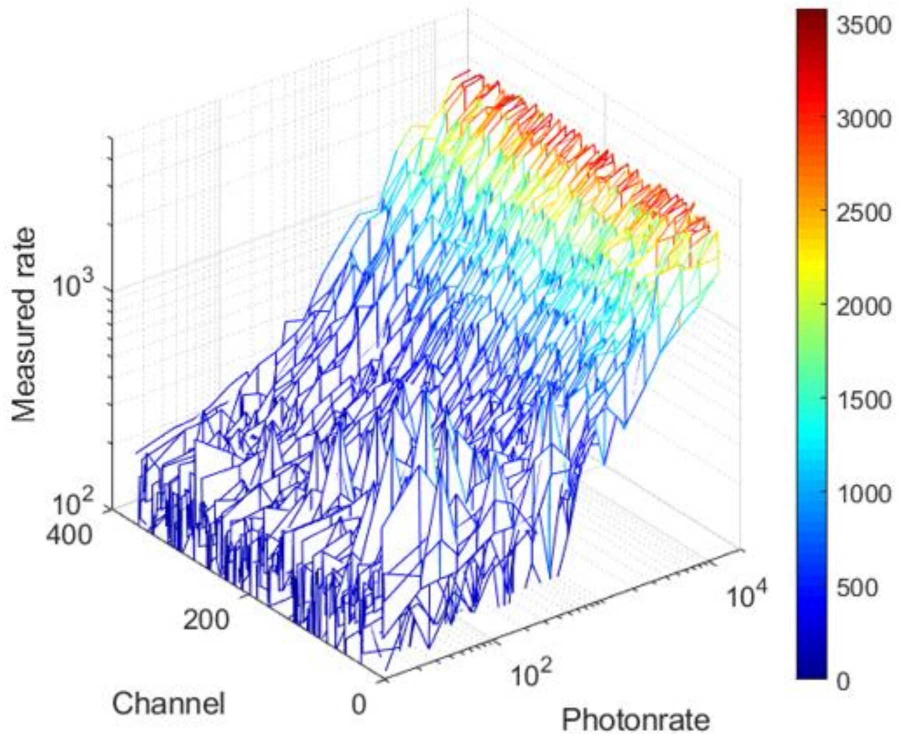
Single pixel single photon QC measurements



(a) (b)

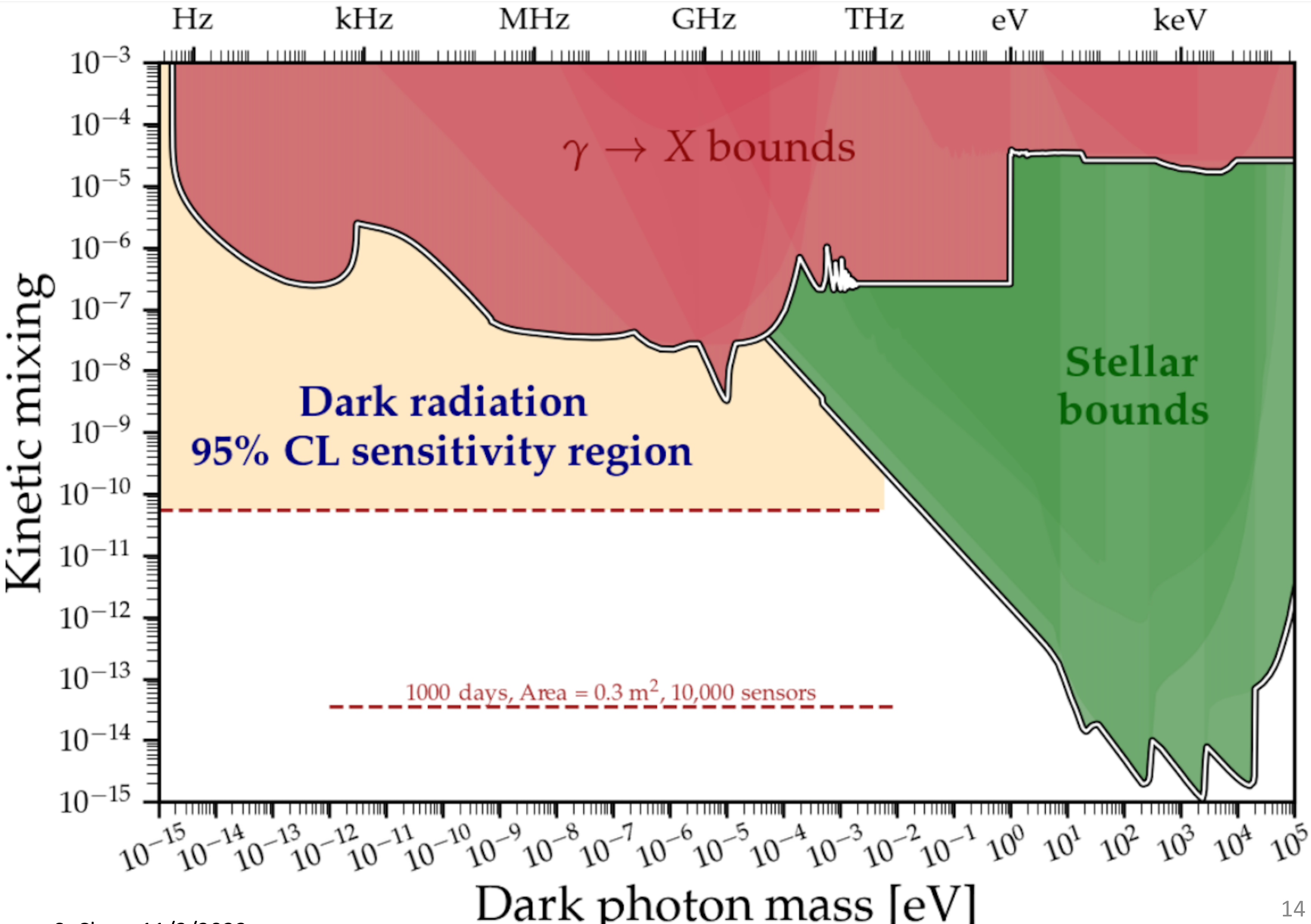
Histogram of counts in one second traces similar to those shown in Fig 8 (b) and (c) for all black body temperatures. The left peak represents absence of photons while the right peak represents photon detection events. Black body temperatures are color coded, with blue being cold and red hot. (b) Sum of photon detection events as a function of expected photon rate.

Multipixel pixel single photon QC measurements



Measured photon rate as a function of expected photon arrival rate for the 21x21 array of quantum capacitance detectors.

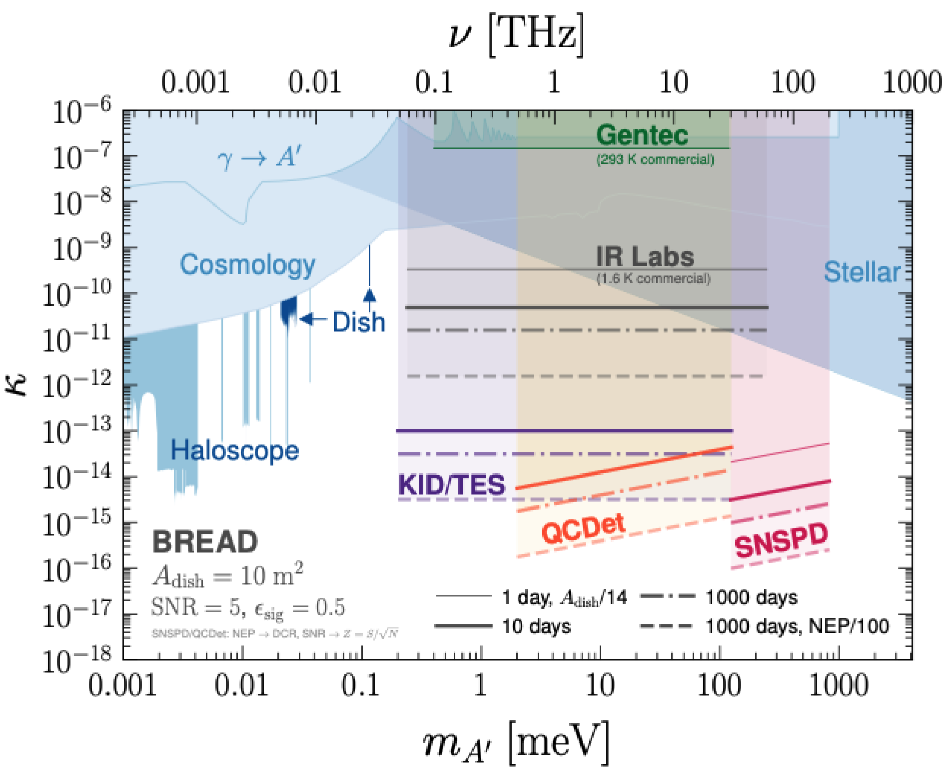
Sensitivity projection Dark Radiation

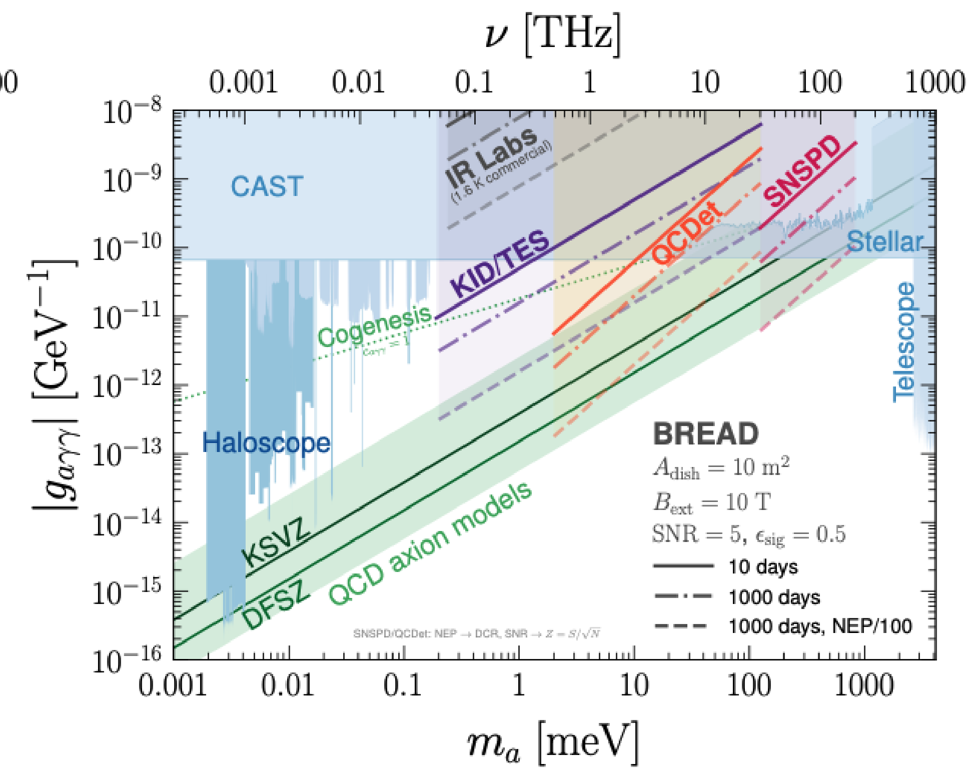


Aaron S. Chou, 11/2/2022

Dark photons might also be the dark matter: BREAD projections

J. Liu et al., Phys.Rev.Lett. 128 (2022) 13, 131801





- The dark matter signal can be focused and so BREAD uses novel optical elements.
- The dark radiation signal is homogeneous and isotropic, and so the experimental design requires large collection area and solid angle (etendue).

Conclusion

- QCDs are exquisitely sensitive far infrared detectors
- Working on reducing dark counts
- Applications include hidden photon and dark radiation detection