Itinerant Single Microwave Photon Detection

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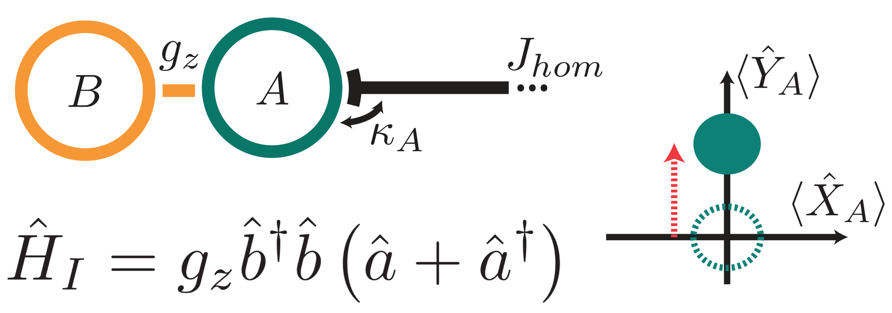
Objective Develop a high-fidelity detector for traveling single microwave photons which operates continuously without active reset or prior information about the photon's arrival time.

Optical photons, which can be detected with commercially available SPDs, have ~10^4 times more energy than microwave photons, illustrated by the difference in area of the red and blue circles. Measuring single microwave photons is challenging due to their small energies compared to room temperature noise.

Detector theory

Toy model

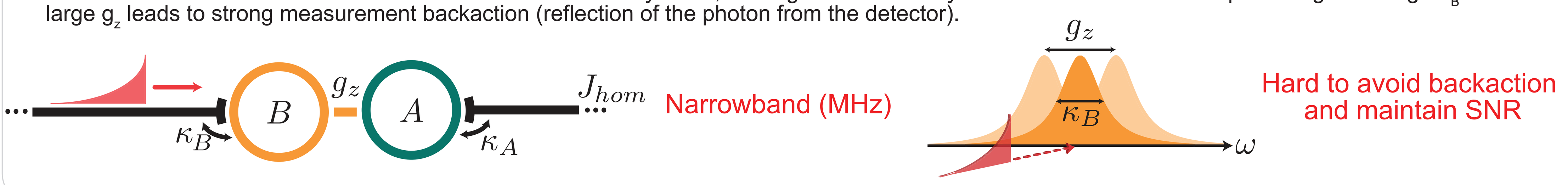
A probe cavity (A) which is measured continuously in time, is coupled with strength g_z to an absorber cavity (B). Assuming an ideal interaction Hamiltonian, the presence of a photon in mode B creates a longitudinal displacement of A which can be measured with a homodyne setup.



$$\hat{H}_I = g_z \hat{b}^\dagger \hat{b} \left(\hat{a} + \hat{a}^\dagger\right)$$

Shortcomings of toy model

Problems arise when trying to use the toy model to detect flying photons. To get a long interaction time with the absorbed photon, the coupling (κ_B) between the absorber mode and the environment has to be very small, leading to an inherently narrowband detector. Compensating for a large κ_B with a large g_z leads to strong measurement backaction (reflection of the photon from the detector).



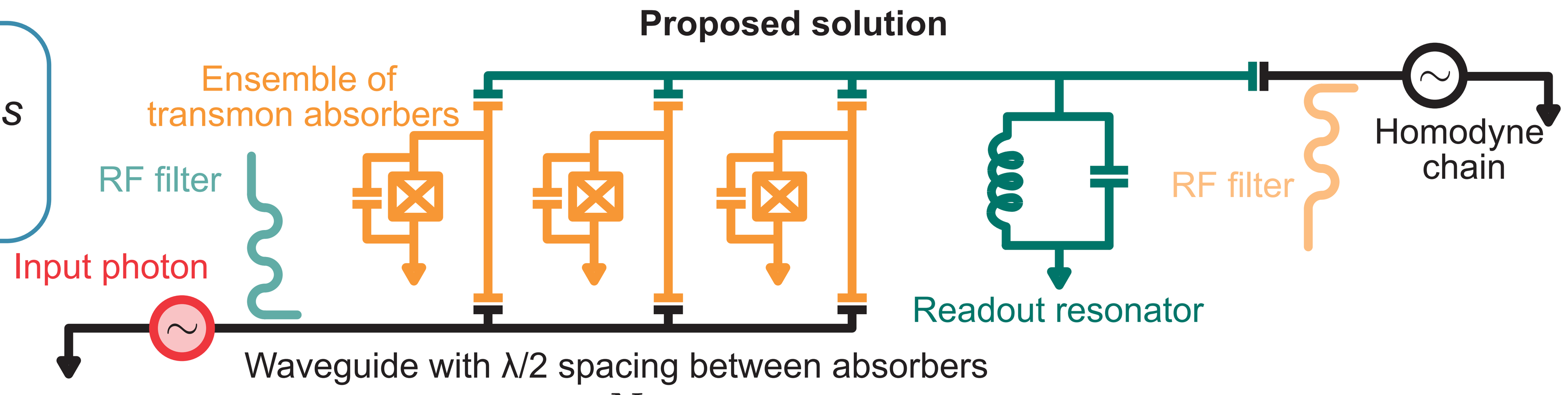
Waveguide quantum electrodynamics (wQED)

Placing a section of lossless waveguide λ/2 long between absorbers allows for photon mediated interactions to occur causing correlated decay. In such a system with two absorbers, one mode will have a linewidth twice the bare linewidth of the absorber (forming a superradiant **'bright'** state) and the other mode will have a linewidth approaching zero (forming a sub-radiant **'dark'** state).

Details: B. Royer, et al., PRL 120, 203602 (2018)

Need to exploit methods to increase photon interaction times without imposing additional bandwidth restrictions.

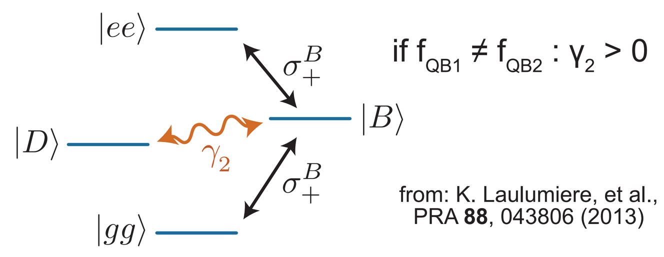
Proposed solution



$$\hat{H}^D_\chi = g_z \hat{N}_B \hat{X}_A + \sum_{i=1}^{N} \Delta_i \hat{b}_i^\dagger \hat{b}_i + 2\chi \hat{N}_B \hat{a}^\dagger \hat{a} + \Delta_+ \hat{b}_+^\dagger \hat{b}_+$$

Using wQED to improve the toy model

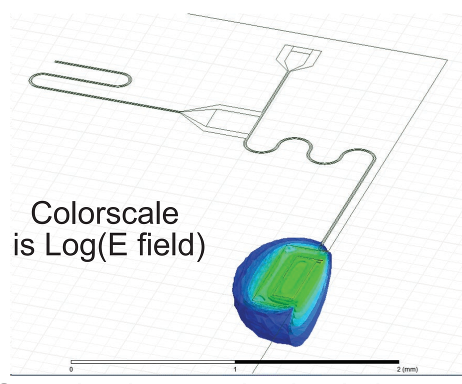
If slight detunings between the absorbers are introduced, coherent exchange between the bright and dark state occurs **allowing for photons to be trapped for longer than the inverse of the detector's absorption bandwidth.**



from: K. Laulumiere, et al., PRA **88**, 043806 (2013)

RF design and fabrication

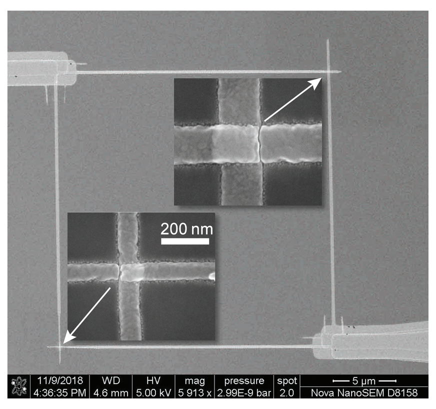
RF simulations ensure design parameters are met



Sample eigenmode simulation performed in Ansys HFSS. Here the effectiveness of the bandstop filter to reduce energy relaxation through the on-chip DC bias line is verified.

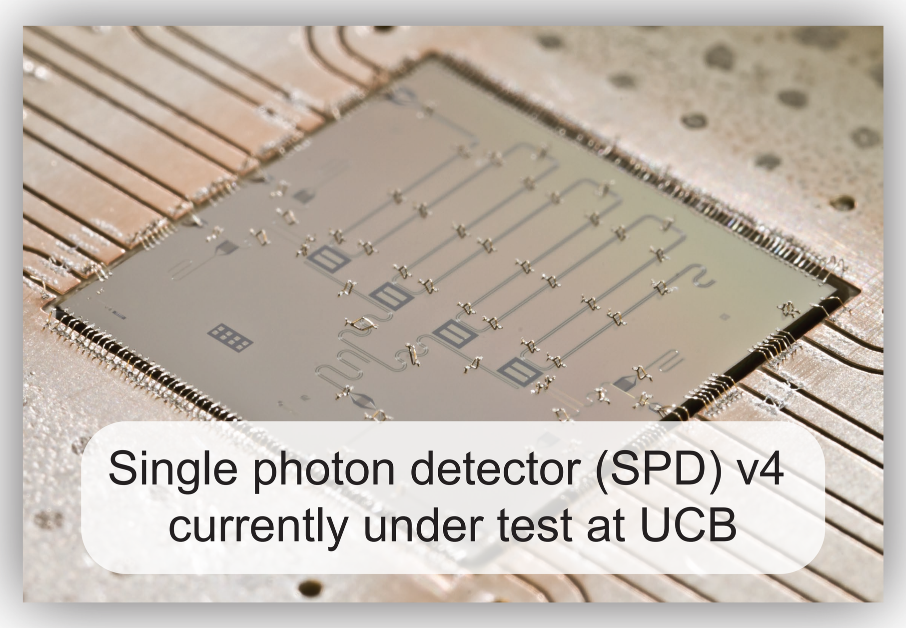
SPDv4 parameters (MHz)

	Target	Actual
ω_{RO}	6500	6394
κ_{RO}	0.8	0.775
ω_{01}	5600	5600
χ	0.11	0.11-0.15
κ_{Bright}	4	2.8
T_1	> 30 µs	37-47 µs
T_2	> 30 µs	40-50 µs



8:1 asymmetric squids were used to provide tunable non-linear inductance with reduced susceptibility to flux noise[1]. Shunting this squid with a capacitor forms a transmon qubit.

[1]Hutchings et al. PRA 8,044003 (2017)



Single photon detector (SPD) v4 currently under test at UCB

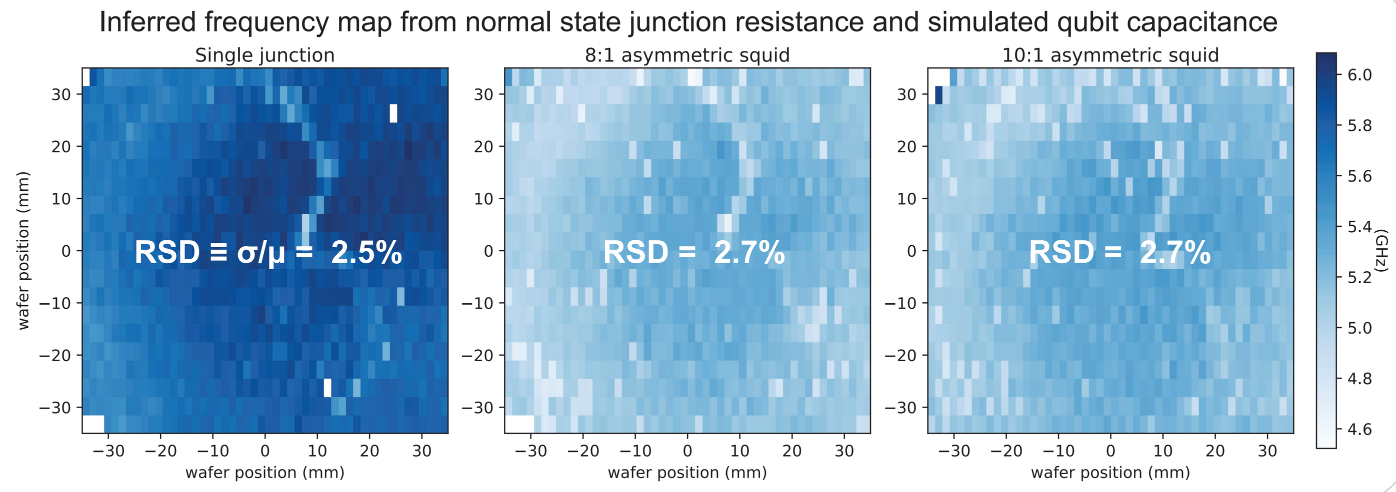
Processing details: 6" wafer yields 64 devices in 3 days.

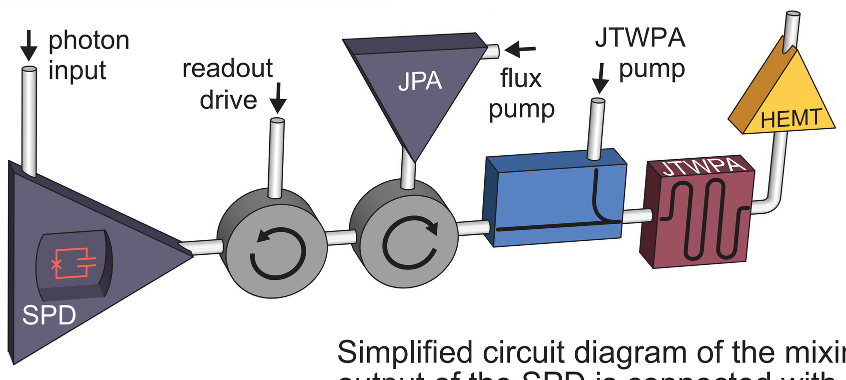
- Design layout with GDS-py
- Clean high resistivity intrinsic Si with piranha and BOE
- Sputter 200 nm Nb, spin MMA, e-beam pattern Nb features
- Develop (3:1 IPA:MIBK)
- ICP-RIE etch Nb (BCl_3/Cl_2), strip resist (NMP)
- HF clean, spin e-beam resist bilayer (MMA/AR-P 6200.9)
- E-beam write Manhattan style junctions
- Cold develop AR-P with NAA
- Develop MMA with ultrasonically assisted 3:1 IPA:H_2O
- Al evap, in situ oxidation, Al evap, liftoff
- Spin, write junction contact pieces
- Ion mill, normal angle Al evap, liftoff
- Probe junction resistances, dice
- Post-process cleaning, wire bond

Josephson junction uniformity

The next generation SPD (shown at right) will require thousands of Josephson junctions to operate. Although simulations show that the detector will work in the presence of moderate disorder (~ 10%), minimizing global variations will lead to higher yield and benefit concurrent fabrication efforts of ever-larger quantum processors. Results below are on test wafers containing 3000 ~ 200 x 200 nm junctions after 34 iterations of improvements.

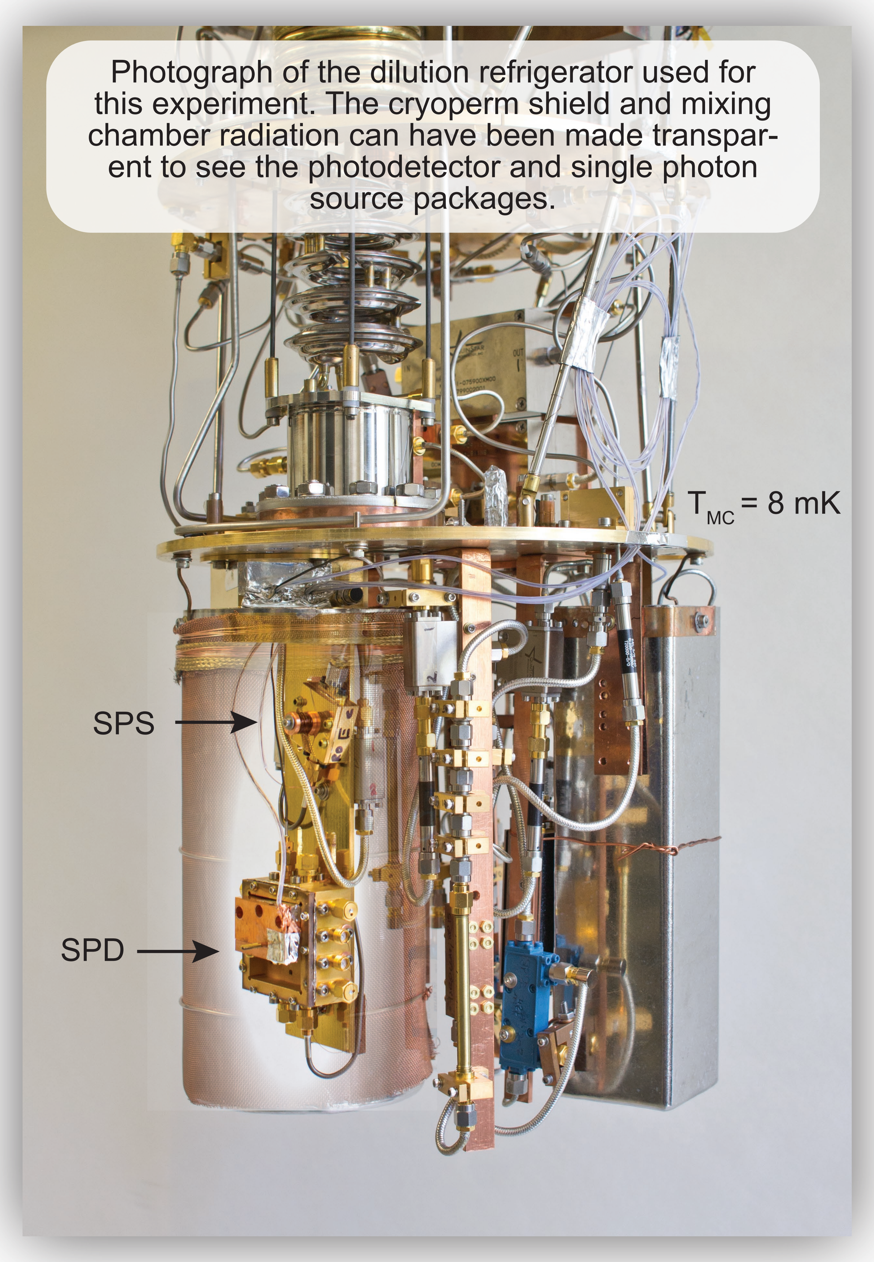
Inferred frequency map from normal state junction resistance and simulated qubit capacitance





Simplified circuit diagram of the mixing chamber RF components. The output of the SPD is connected with Nb-Ti coax to a phase-sensitive JPA acting as a low noise preamplifier before a Josephson Traveling Wave Parametric Amplifier (JTWPA) since it has, combined with its required microwave components, ~ 3 dB of insertion loss.

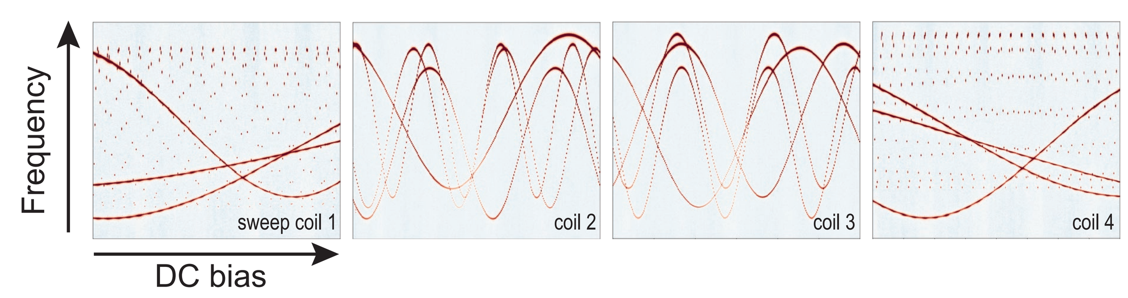
Detector characterization

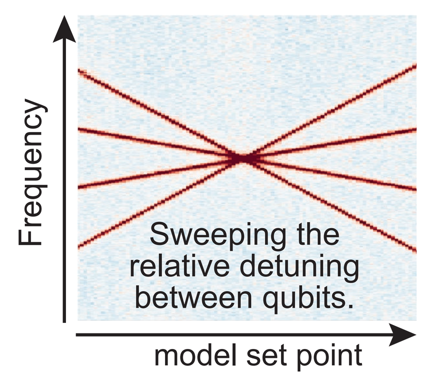


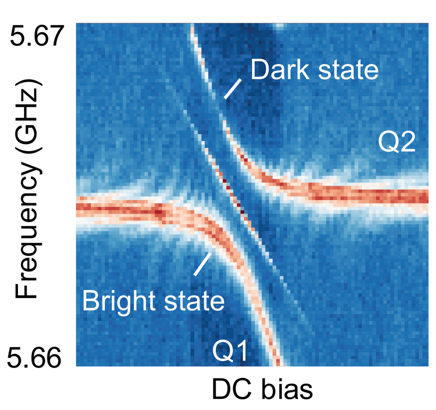
Photograph of the dilution refrigerator used for this experiment. The cryoperm shield and mixing chamber radiation can have been made transparent to see the photodetector and single photon source packages.

Calibrating eigencoils

Measuring the frequency response of each qubit from each coil with 2-tone spectroscopy, the mutual inductance matrix can be reconstructed, enabling independent tuning to arbitrary frequencies.

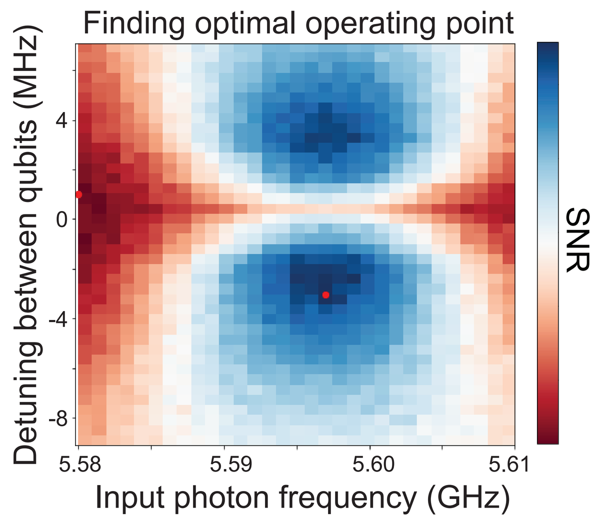




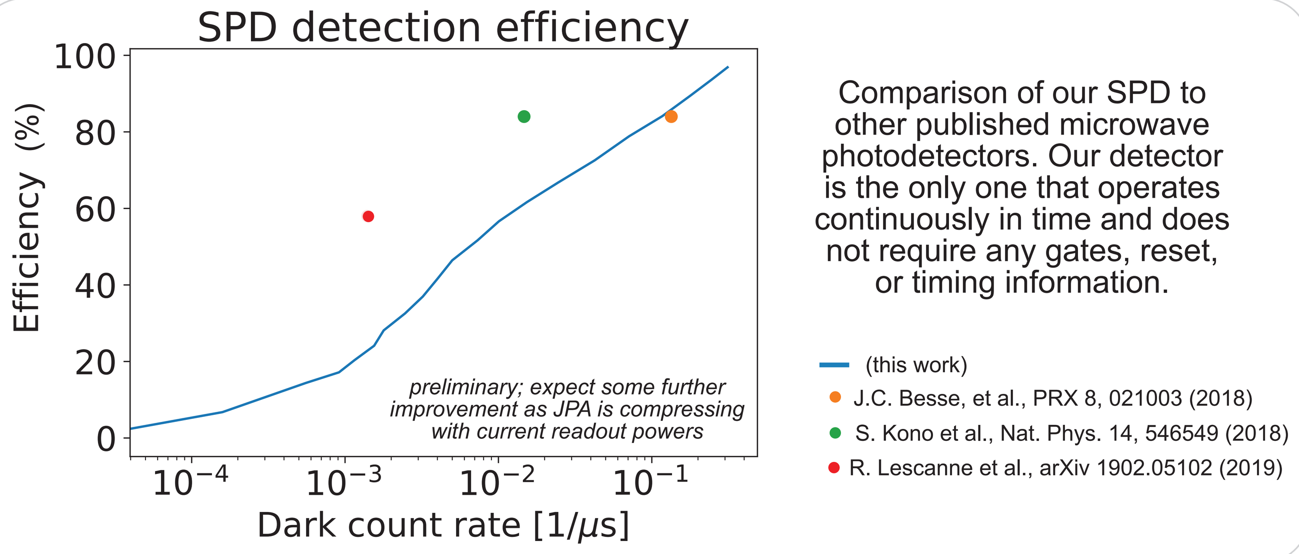


Evidence of photon mediated interactions sweeping one qubit through another in SPDv1

Integrating over the window where we expect to see a signal, we can form histograms from the values obtained by repeating the 2 element pulse sequence many times. Fitting a Gaussian to the distributions, we can determine an 'SNR' for that operating point, then map the effect of sweeping the relative detunings between qubits and the input photon frequency.

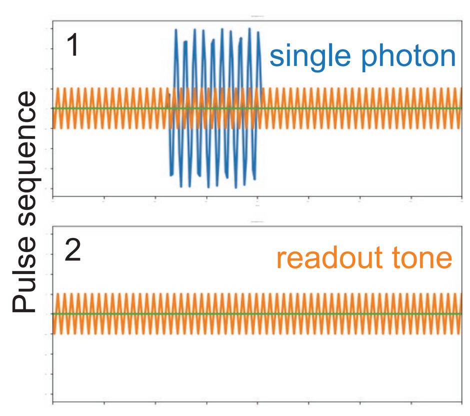


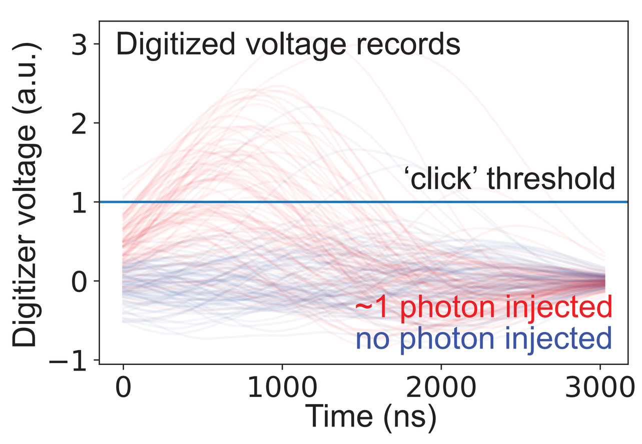
SPD detection efficiency



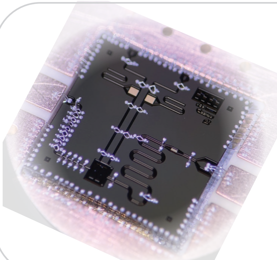
Comparison of our SPD to other published microwave photodetectors. Our detector is the only one that operates continuously in time and does not require any gates, reset, or timing information.

Calibrations with weak coherent tone





Next step: benchmark performance with single photon source (SPS)



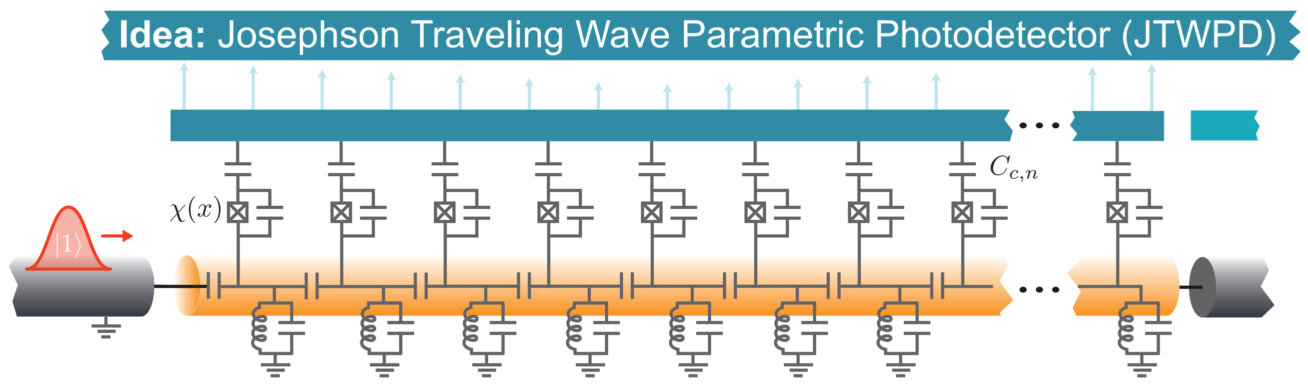
Finally, we can repeat the experiment with our off-chip single photon source chip: a transmon qubit strongly coupled to a port leading to the detector. A separate line is used to excite the qubit without spurious detector excitation. The linewidth of the source is optimally matched to the detector bandwidth.

Outlook: next generation SPD

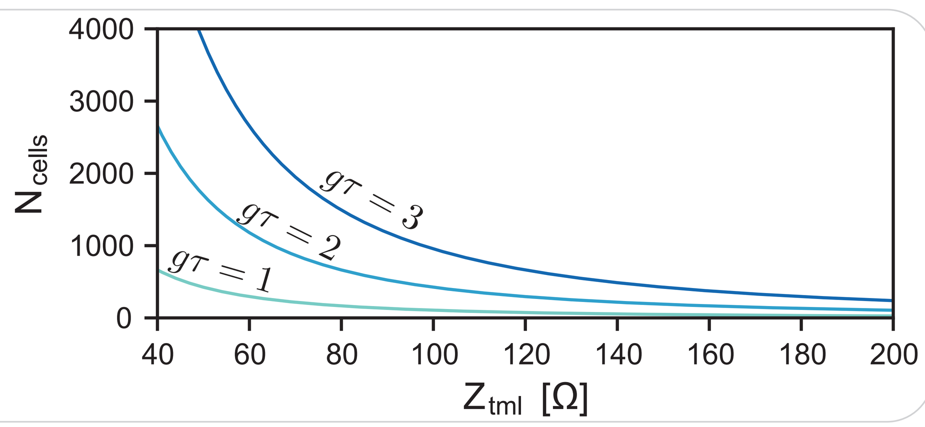
What if we could:

- Improve bandwidth by designing a device with a long interaction time without conversion into a local mode?
- Minimize measurement induced reflections by limiting information gathered about $\hat{x}$ to limit backaction in $\hat{p}$?

Idea: Josephson Traveling Wave Parametric Photodetector (JTWPD)



Number of unit cells required to achieve different values of gτ, a key figure of merit for this detector, where g indicates the strength of the cross-Kerr coupling and τ is the amount of time the photon is in the detector as a function of transmission line impedance. We intend to achieve gτ = 3 using a 100 Ω transmission line and ~1000 unit cells.



Theory: The ensemble of absorbers in SPDv4 is replaced with a metamaterial transmission line referred to as a composite right/left-handed (CRLH) transmission line which is attractive due to its potential for dispersion and band-structure engineering. For a specific choice of parameters, you get an upper and lower frequency cutoff (good for limiting dark counts and readout resonator decay!), frequency independent characteristic impedance, and slow light propagation. Distributed coupling and long physical length of the detector (>>1 wavelength) limits information gathered about the photon's position to minimize momentum backaction. A klopfenstein impedance transformer directs photons into the device with minimal loss from conventional 50 Ω microwave hardware.

LTD-18 Milan, Italy
July 22-26, 2019