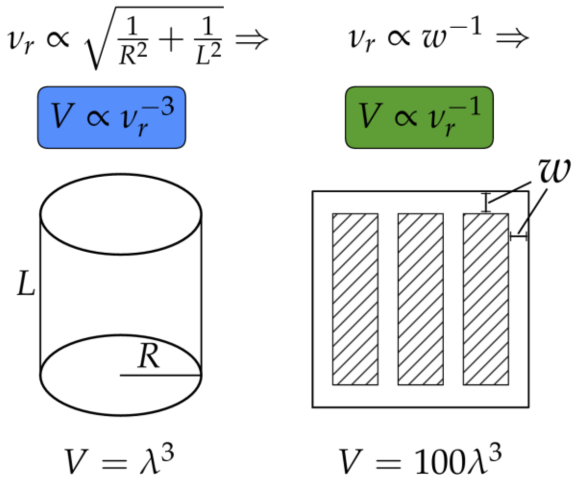
Transmon-based single microwave photon detectors for QCD axion searches in the classical window

Osmond Wen

A next-generation axion haloscope

Volume-enhanced resonators

- standard cavity geometry suffers at higher frequencies
- solutions: volume-enhanced resonant axions (ADMX-VERA)
  - thin-shell resonators
  - coupled-cavity resonators



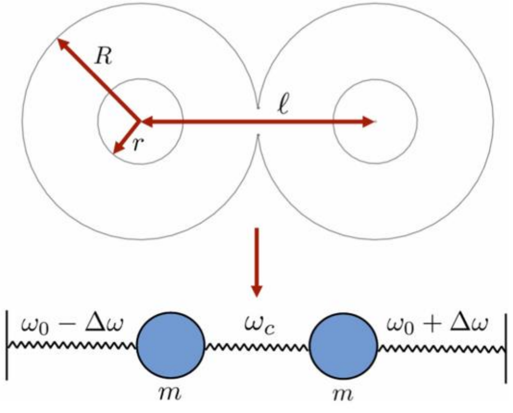


FIG. 1. Spring model for two strongly-coupled coaxial cavities.

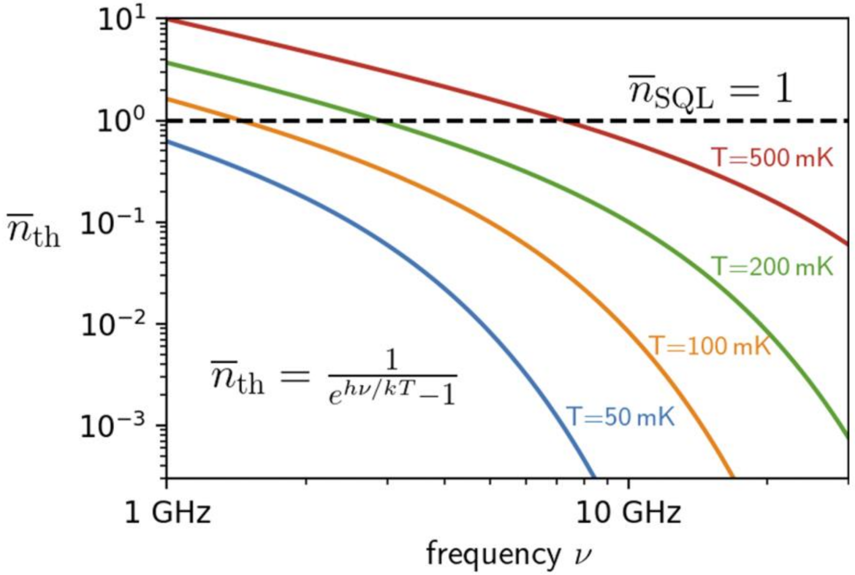
Photon-counting receiver

- phase-sensitive measurement: standard quantum limit

$$\delta P = kT_{\text{sys}}\Delta\nu \geq \bar{n}_{\text{SQL}} h\nu\Delta\nu$$

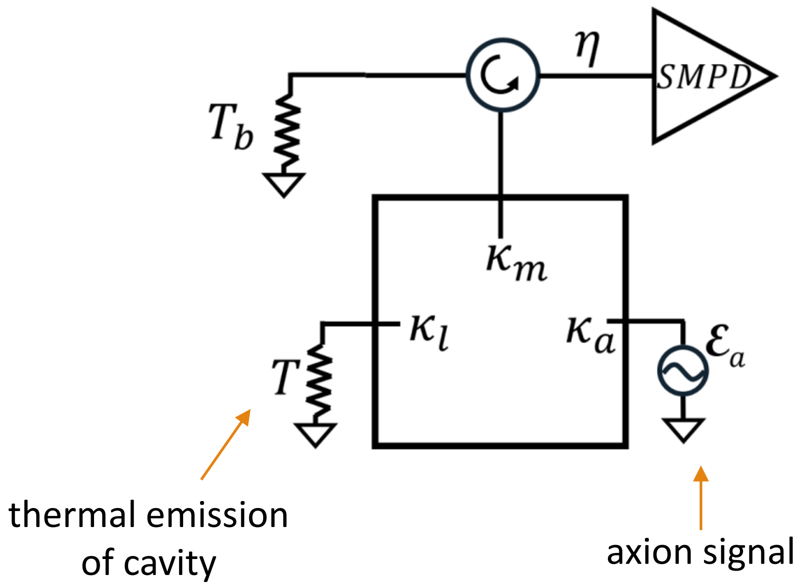
- calorimetric, phase-insensitive: thermal photons

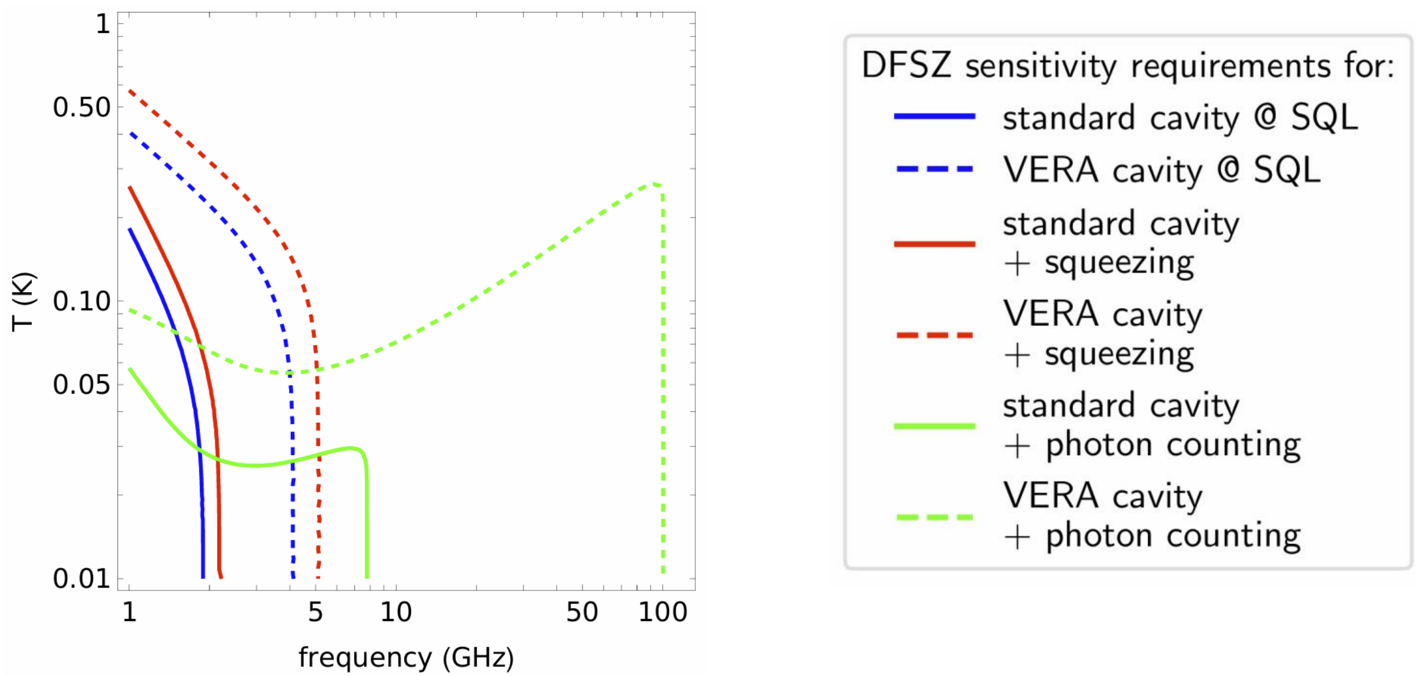
$$\delta P \geq \bar{n}_{\text{th}} h\nu\Delta\nu = \frac{1}{e^{h\nu/kT}-1} h\nu\Delta\nu$$



A next-generation axion haloscope

- in-depth study of vacuum squeezing vs photon counting with volume-enhanced cavities:
  - [Maximizing quantum enhancement in axion dark matter experiments | Phys. Rev. D]
  - SMPD = single microwave photon detector
- each curve assumes 100 search days over 5% bandwidth
- photon-counting is key for higher frequencies!





A next-generation axion haloscope

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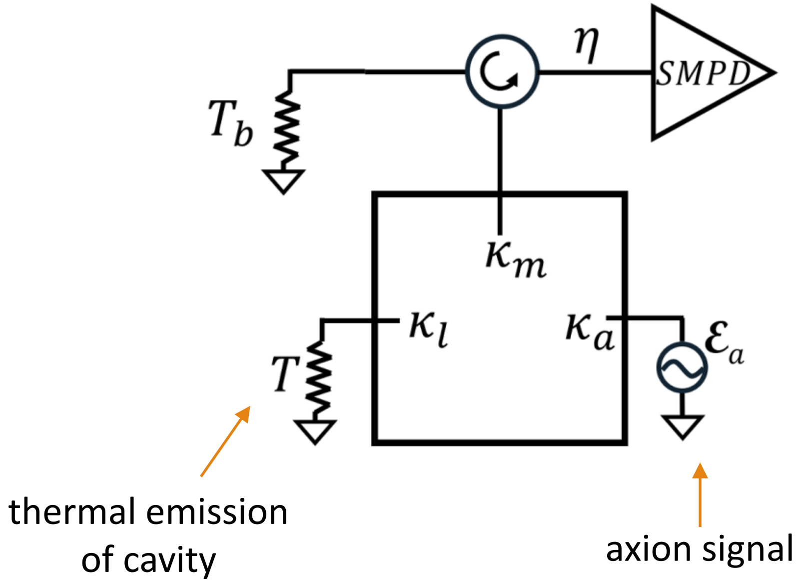
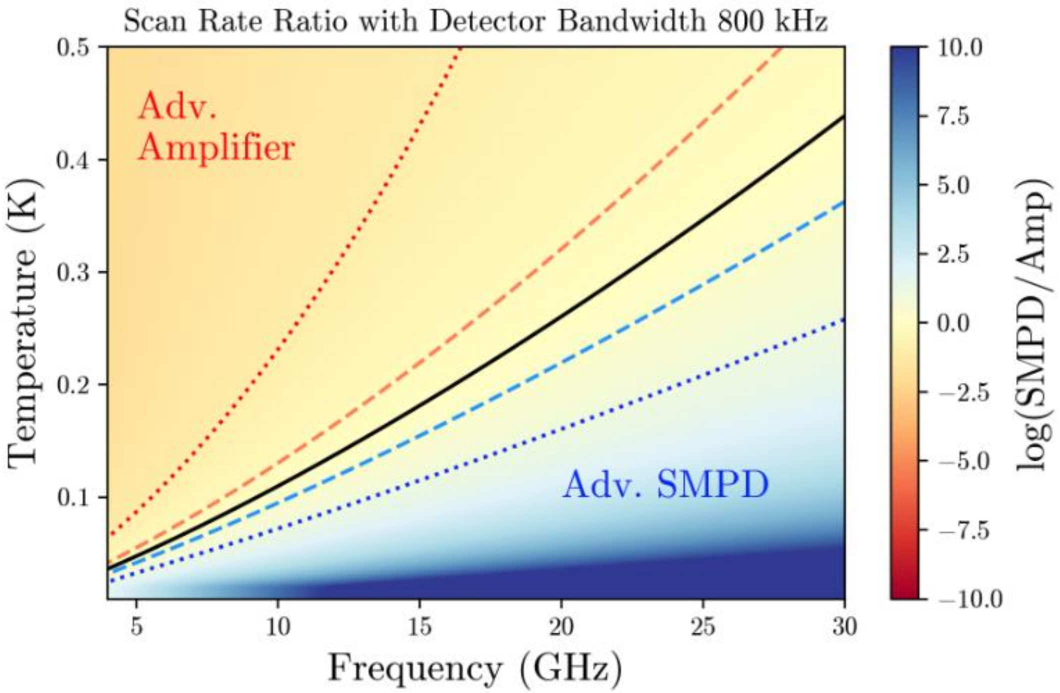
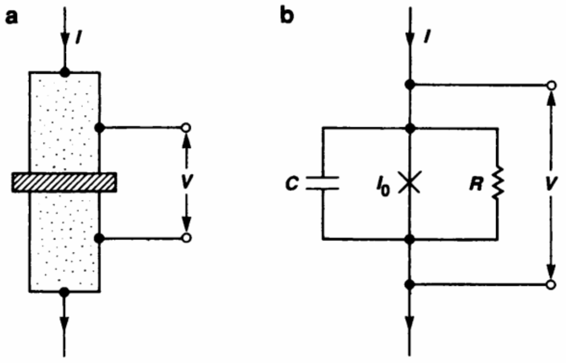
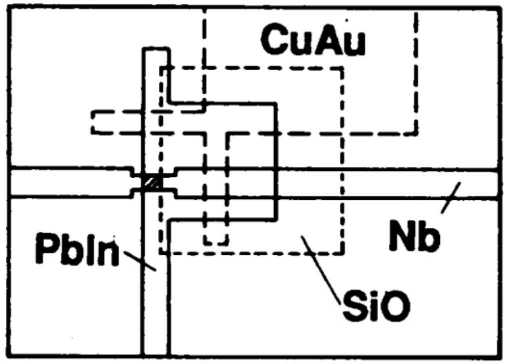


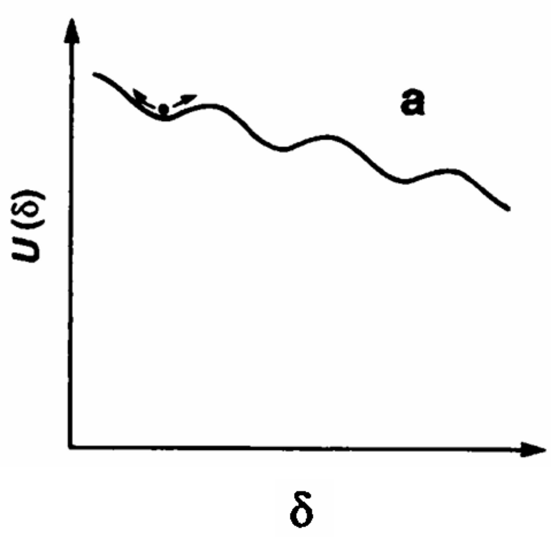


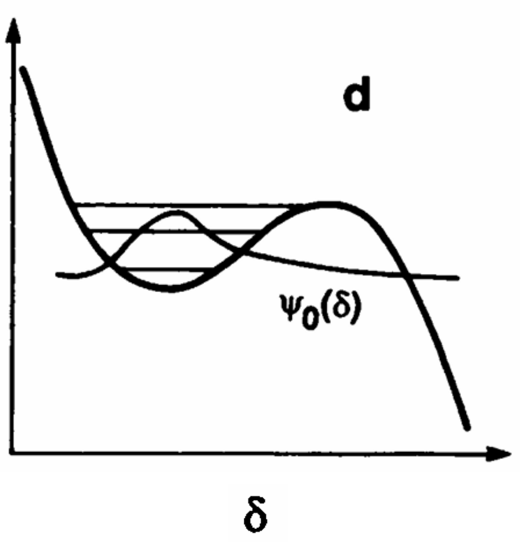
Nobel Prize in Physics 2025

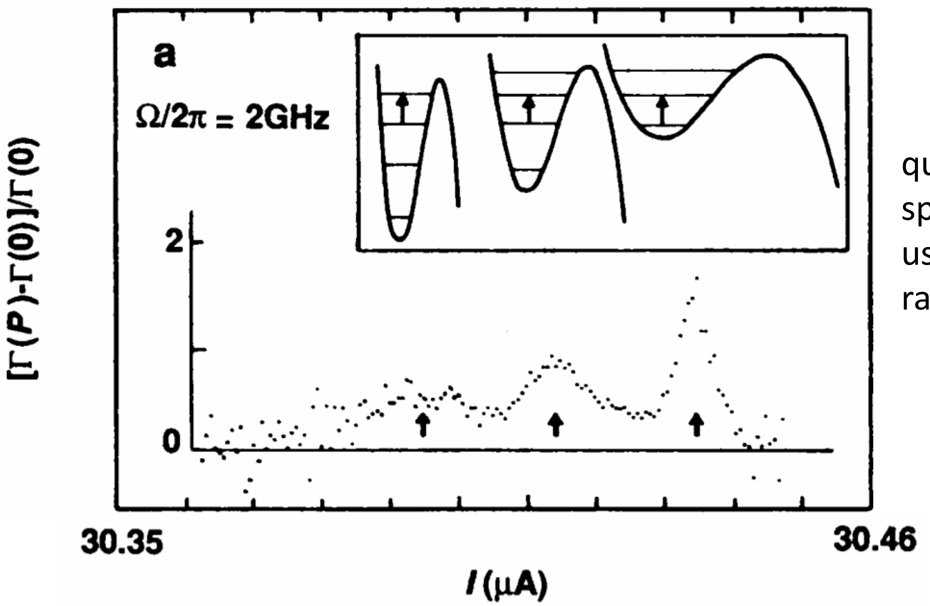
- “for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit.”







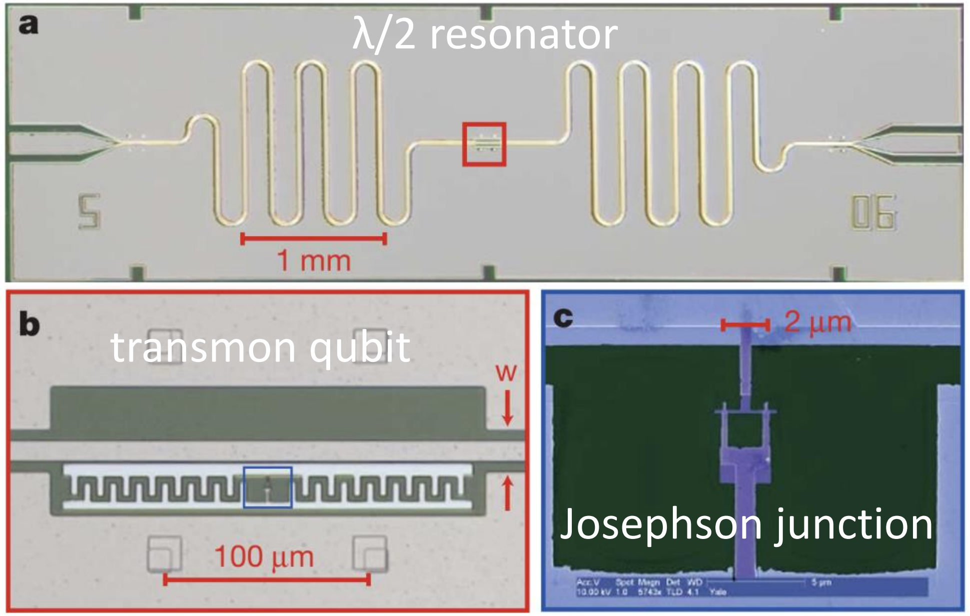




qubit spectroscopy using tunneling rates

Microwave readout of qubits

- Superconducting circuits: circuit QED (Schuster 2007)
  - Transmon qubit + **dispersive coupling** to CPW resonator
  - monitor CPW transmission while sweeping qubit frequency

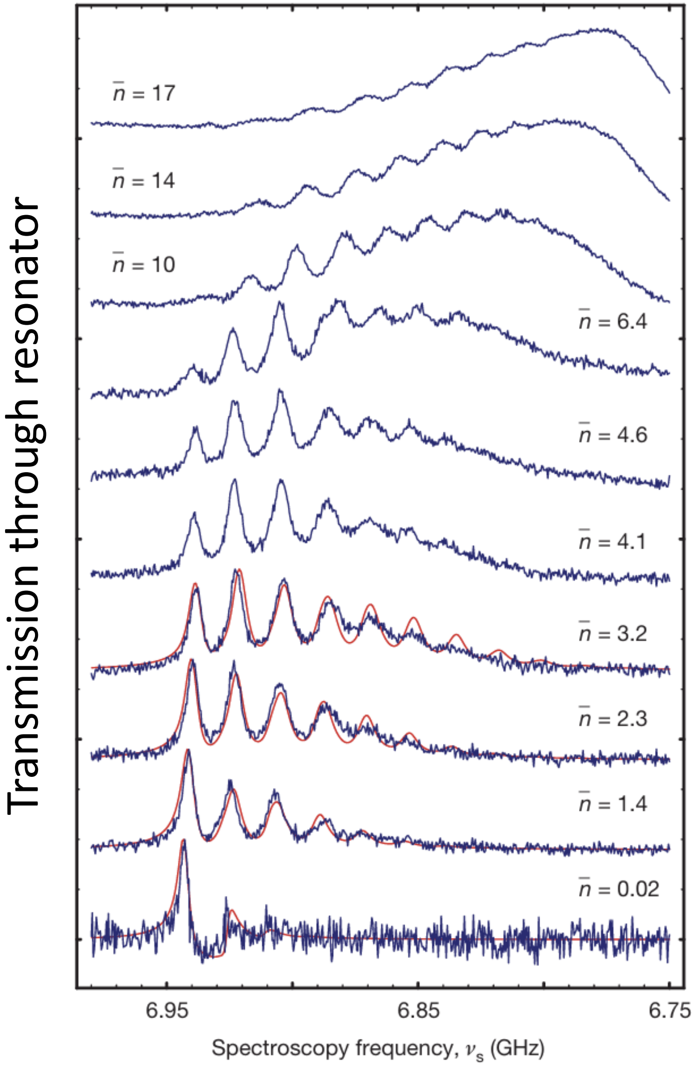


$$H_{\text{Stark}} \supset (\omega - \chi\sigma^\dagger\sigma)a^\dagger a$$

← resonator mode

Stark shift

qubit mode

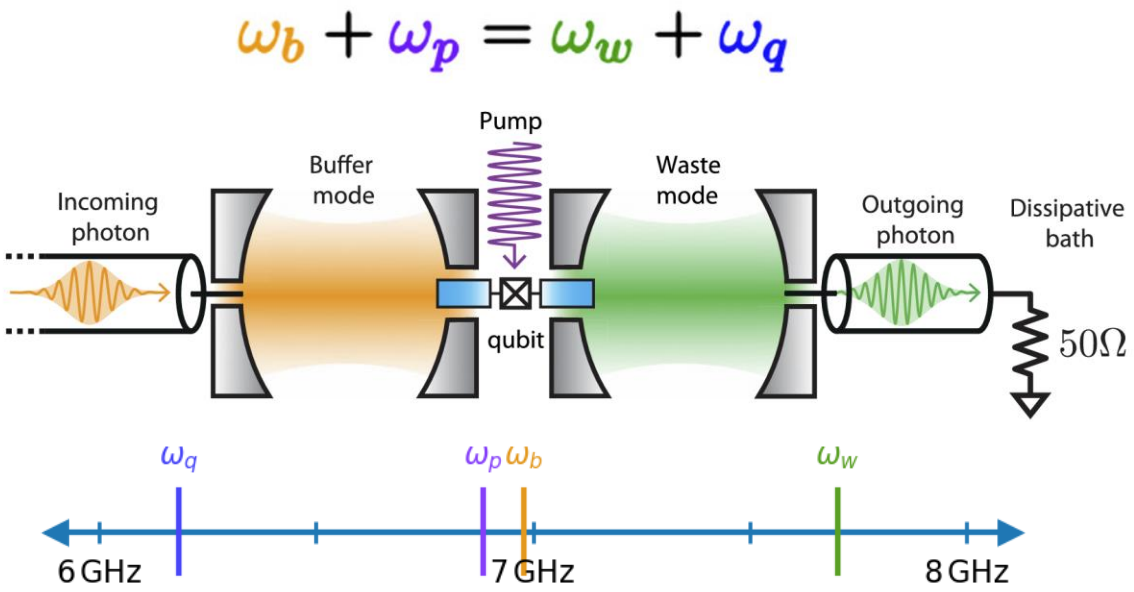


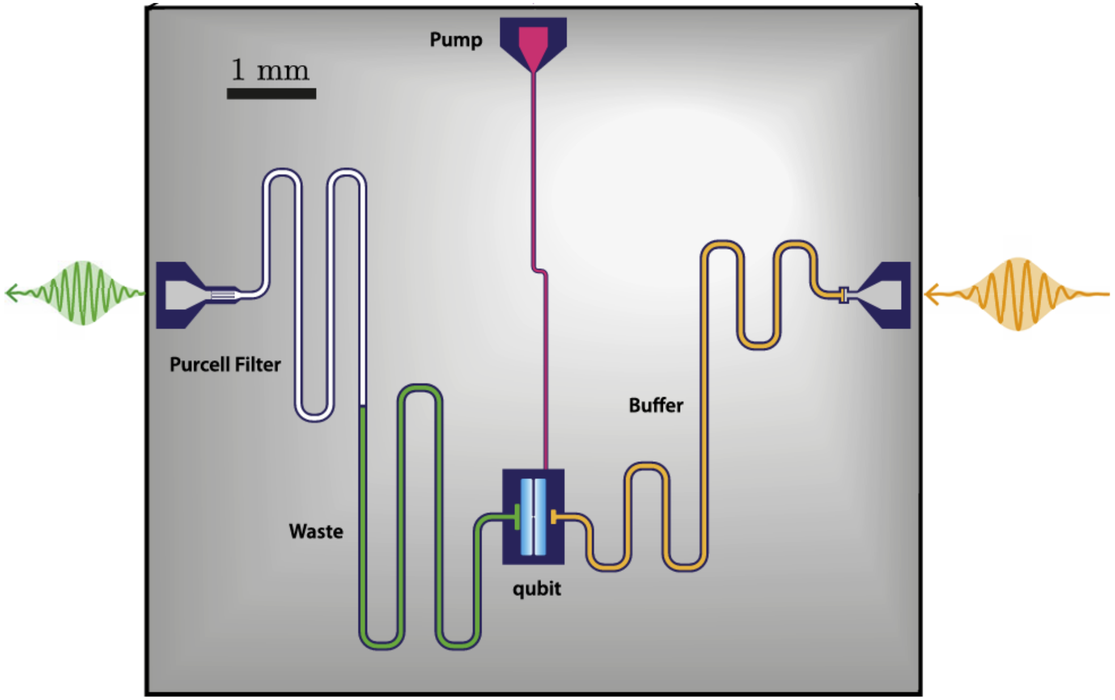
qubit spectroscopy using microwave readout

increasing CPW RF power

Transmon-based SMPD

- Single microwave photon detector (SMPD)
- Quantronics group at Paris-Saclay University: Quantronics group - GQ
- Qubit coupled to two resonators: one input, one output
- **Four-wave mixing,** actuated by a pump tone: Irreversible Qubit-Photon Coupling for the Detection of Itinerant Microwave Photons | Phys. Rev. X



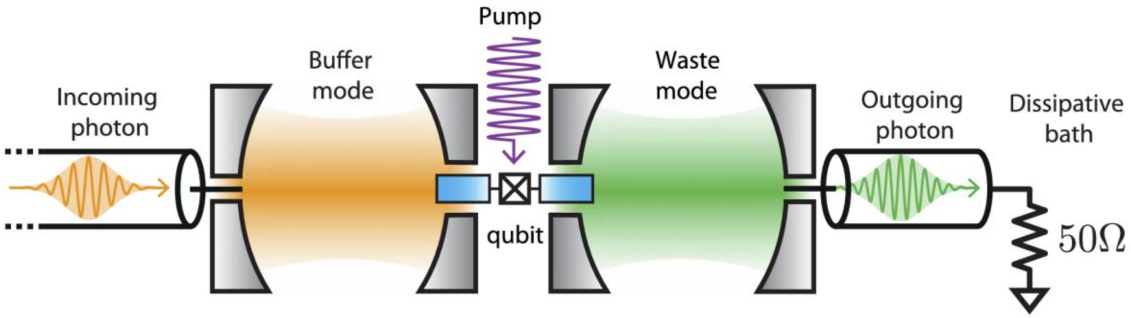


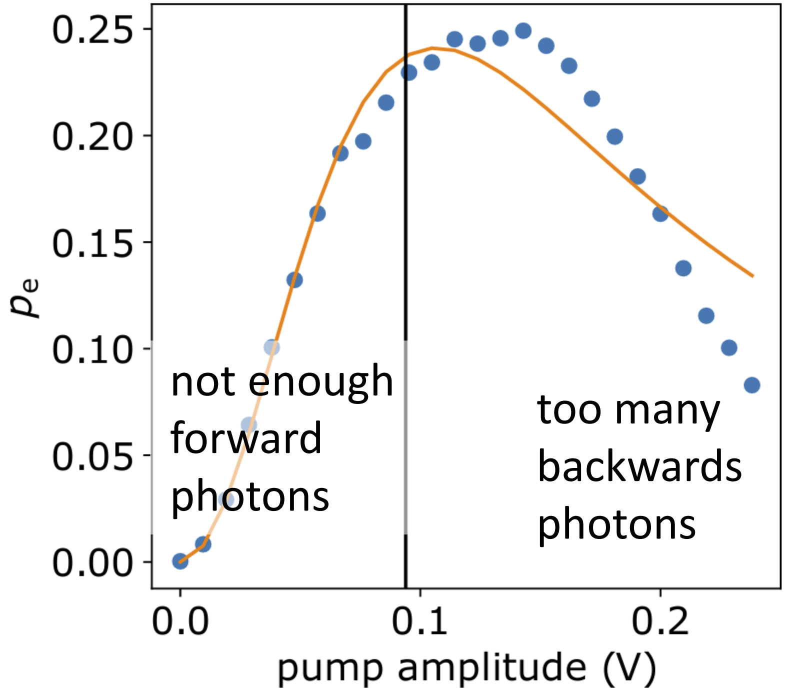
Irreversibility for photon detection

- There are both forward and reverse processes

$$H_{4\mathrm{wm}} \supset g_3 \hat{b} \hat{\sigma}^\dagger \hat{w}^\dagger + g_3 \hat{b}^\dagger \hat{\sigma} \hat{w}$$

- The reverse process can be suppressed with **dissipation engineering**, i.e., the Lindblad equation
  - want $g_3 \ll \kappa_{\mathrm{waste}}$, aka you want waste photons to leave ASAP
  - tune g_3 with the pump amplitude
  - optimize g_3 for the best cavity cooperativity

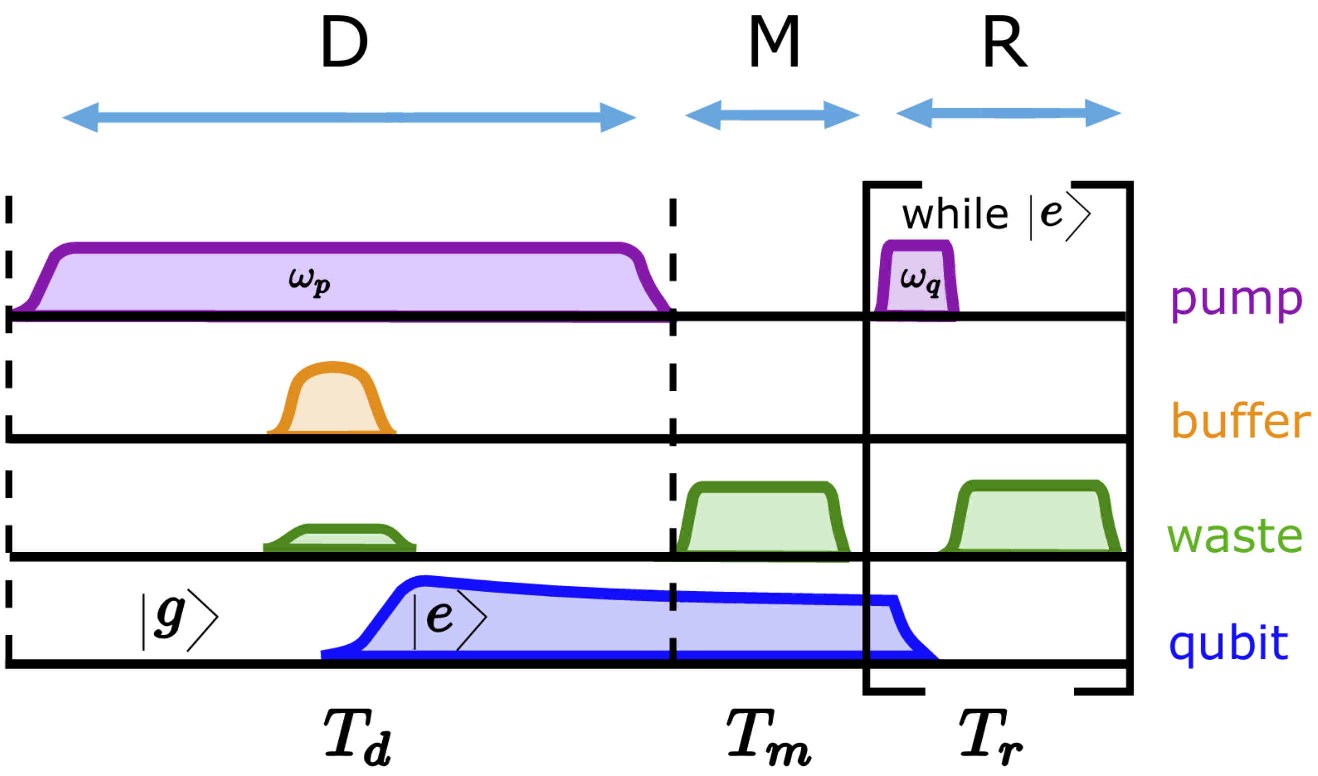




- [Magnetic resonance of a single electron spin and its magnetic environment by photon counting - TEL - Thèses en ligne]

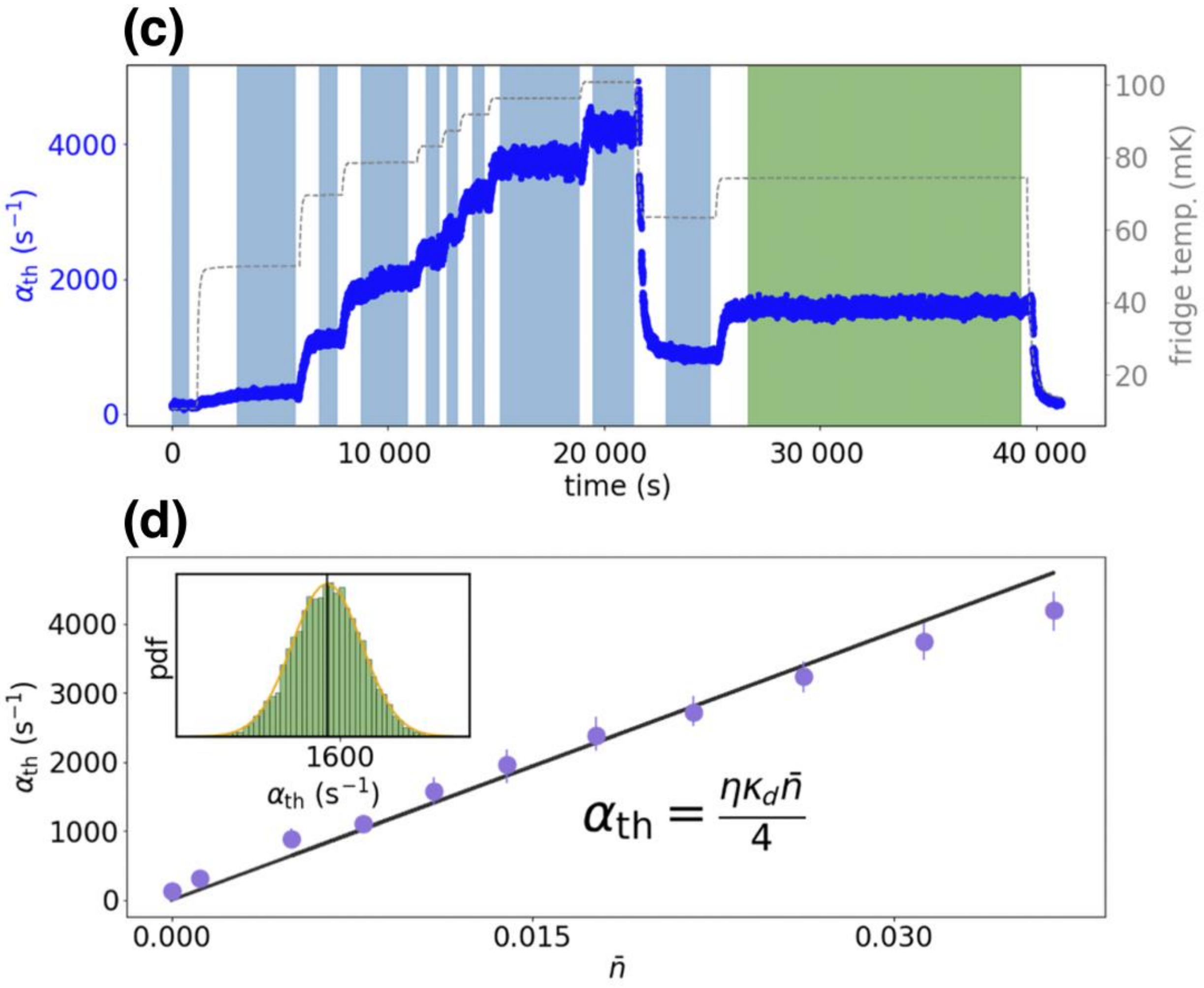
SMPD cyclic operation

- D = detection
  - pump power on
  - ~10 us, determined by T_1
- M = measurement
  - measure the waste resonator for a dispersive shift
  - Duration determined by waste resonator bandwidth
- R = reset
  - prepare the qubit in the ground state wih a pi pulse for the next detection phase
  - check that the qubit is in the ground state with the waste resonator
- [Cyclically Operated Microwave Single-Photon Counter with Sensitivity of | Phys. Rev. Applied]



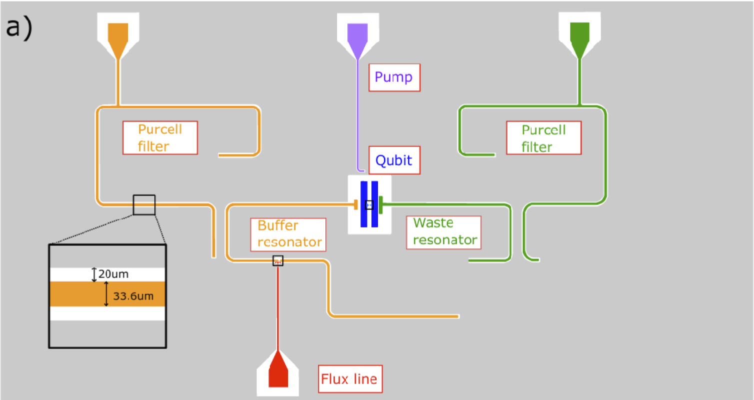
SMPD dark counts

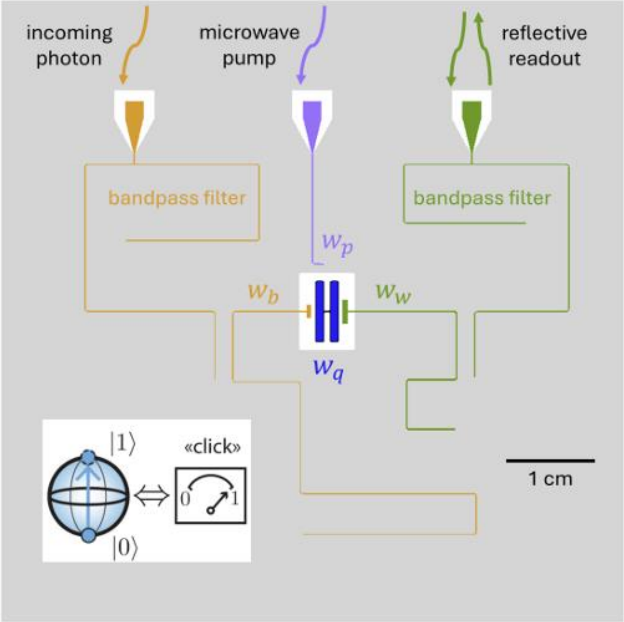
- Saclay measured temperature dependent dark counts
- 80 Hz dark count corresponds to 35 mK electromagnetic temperature
- [Cyclically Operated Microwave Single-Photon Counter with Sensitivity of | Phys. Rev. Applied]



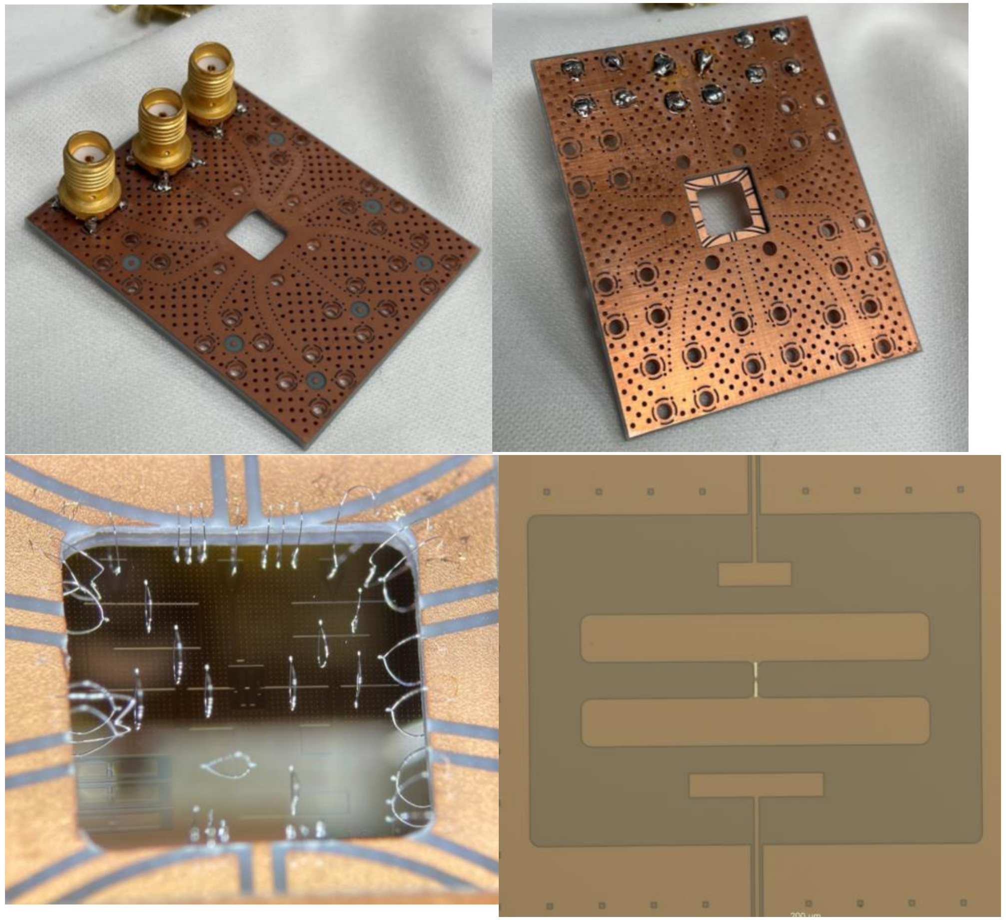
First SMPD device: Spheal

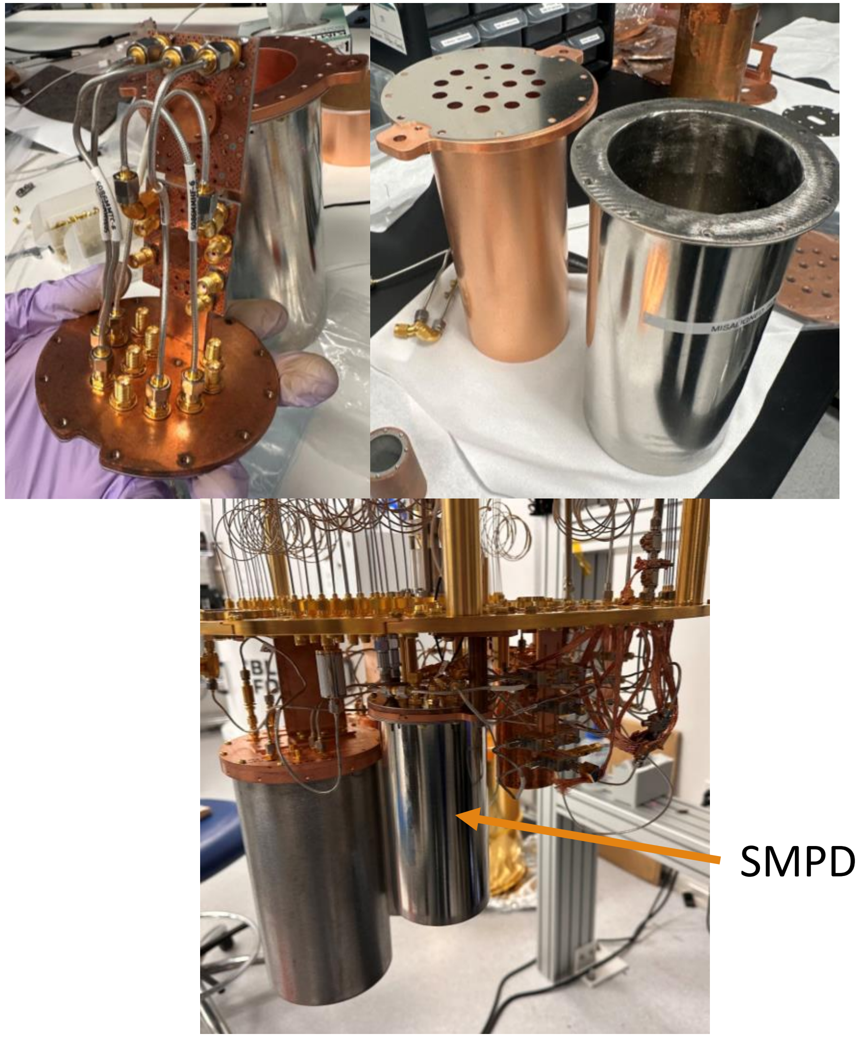
- Goal: recreate a Saclay device
- Schuster Lab fabrication resources
- Materials
  - Saclay: sapphire substrate, tantalum resonators, aluminum junctions
  - Spheal: silicon substrate, tantalum resonators, aluminum junctions
- Chip size:
  - Saclay: 6 mm x 11 mm
  - Spheal: 7 mm x 7 mm
- CPW geometry
  - Saclay: signal = 33.6 um, gap = 20 um
  - Spheal: signal = 10 um, gap = 6 um





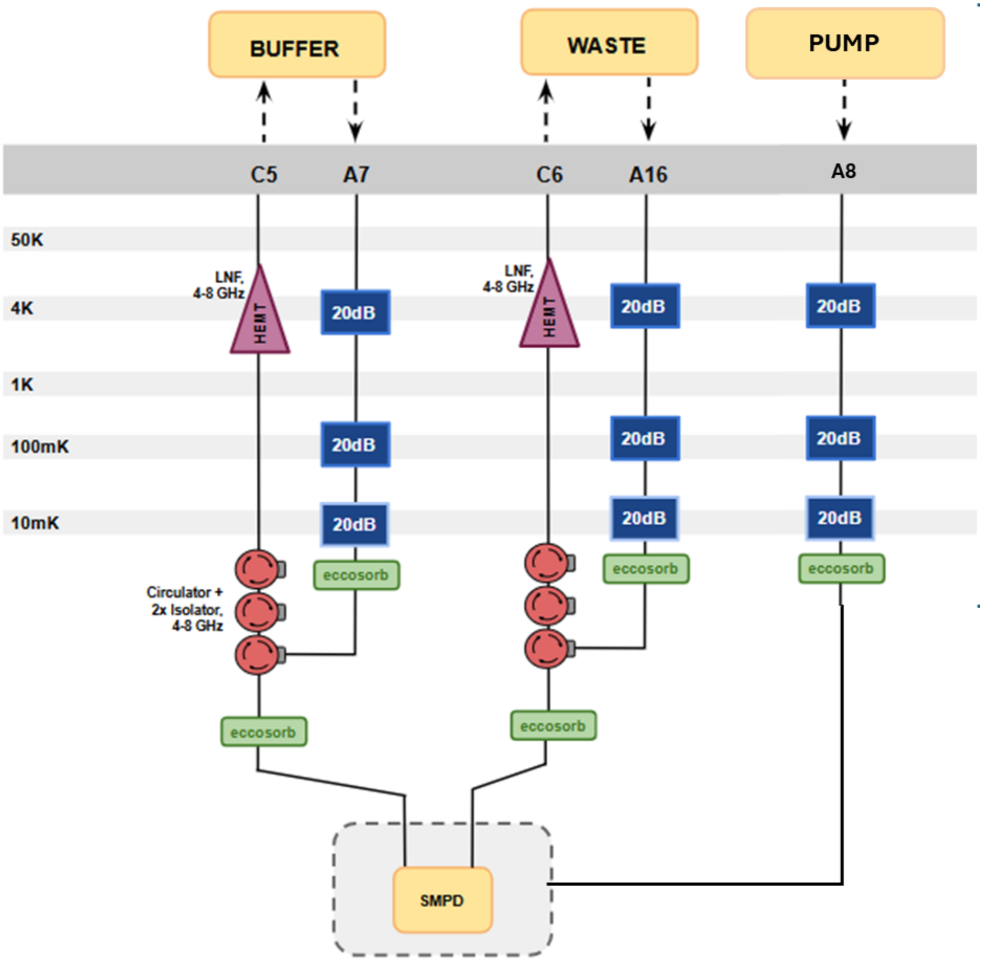
Device housing and shielding





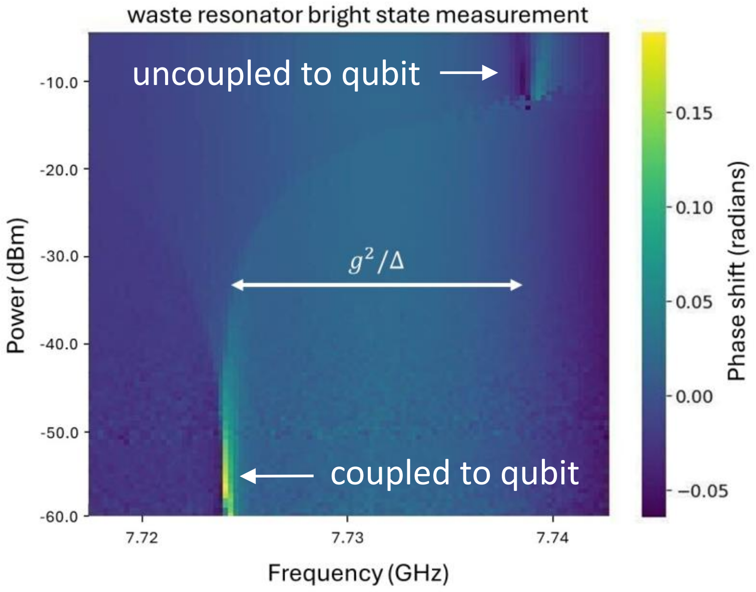
Circuitry and readout

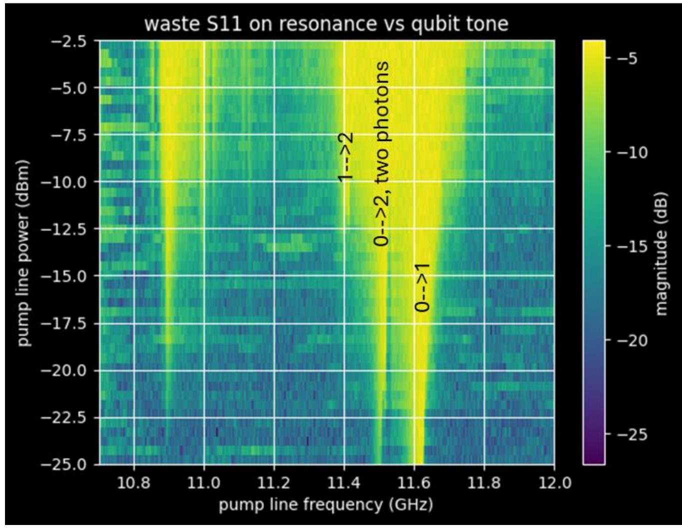
- Reflective measurement off the buffer and waste resonators
  - No SQL amplifiers
- quantum instrumentation control kit (QICK)
  - SLAC Scientist Shannon Harvey

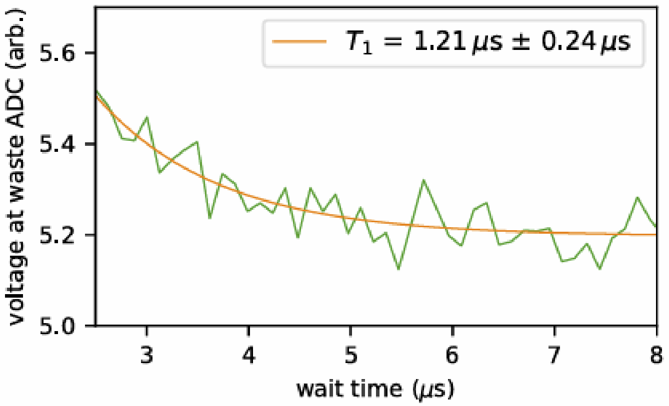


Qubit dispersive readout

- The good: waste resonator dispersive readout
  - Bright state measurement: qubit-resonator coupled system
  - Qubit spectroscopy: measure change to waste S11 as a function of pump line frequency
- The bad: qubit frequency 2x higher than designed for
  - Room temperature resistance measurements prepared us for this issue
- The bad: 1.2 us T1 time
  - More radiation at higher frequency
- The ugly: buffer resonator was not coupled to qubit

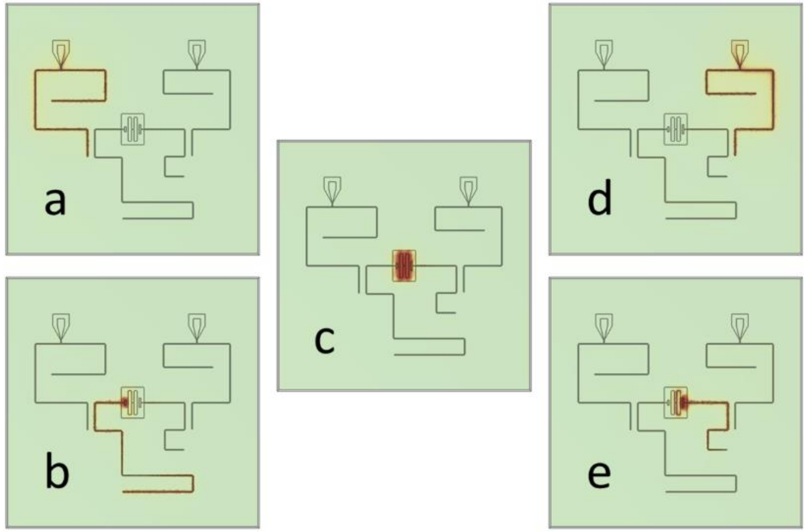






Comparison with simulation

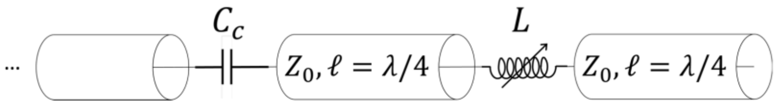
- Naïve eigenmode analysis in COMSOL did not indicate the buffer resonator issue
- Developing Microwave Office and Amazon Web Services (AWS) Palace pipelines



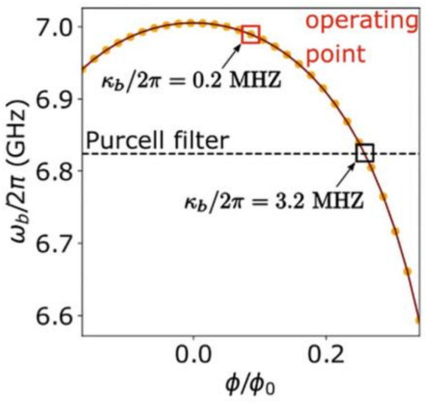
Parameter	Spheal	COMSOL sim.
waste		
$\omega_w/2\pi$	7.724 GHz	7.52 GHz
$\kappa_w/2\pi$	0.2 MHz	1.9 MHz
buffer		
$\omega_b/2\pi$	6.902 GHz	7.16 GHz
$\kappa_b/2\pi$	1 MHz	3.8 MHz
qubit		
$\omega_q/2\pi$	11.6 GHz	6 GHz
α	210 MHz	240 MHz
T_1 time	1.2 μs	$\lesssim$ 30 μs
couplings		
g_w^2/Δ_w	15 MHz	–
$\chi_{qw}/2\pi$	1.8 MHz	–

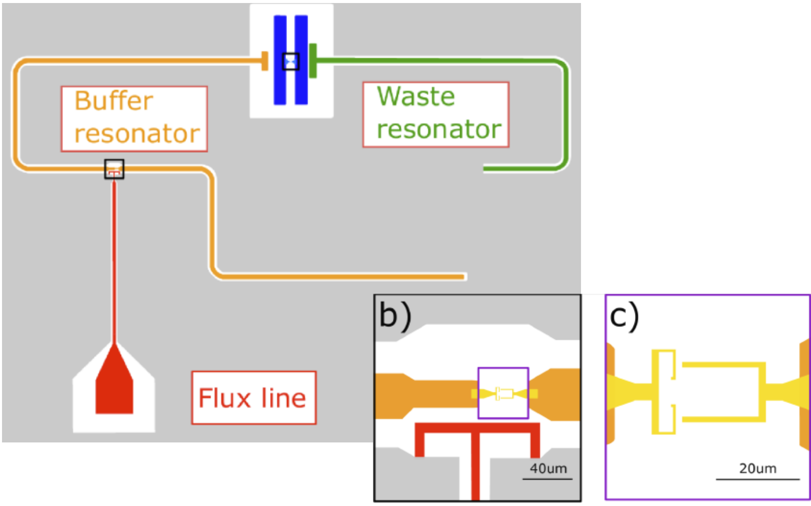
SMPD tunability

- want 5-7 GHz to match with a VERA cavity
  - current tunability at the 1-3% level
- dc SQUID + CPW resonator

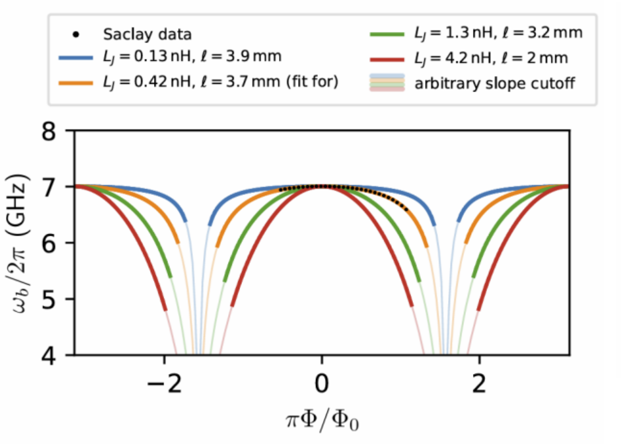


- other options? rf SQUID, SNAIL, KI-tunable

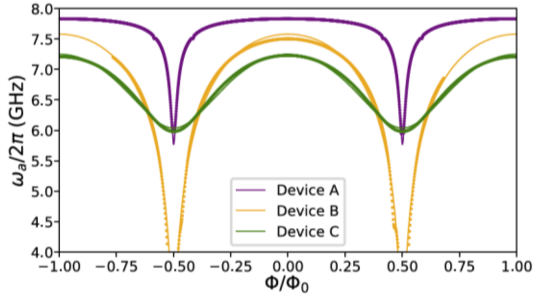


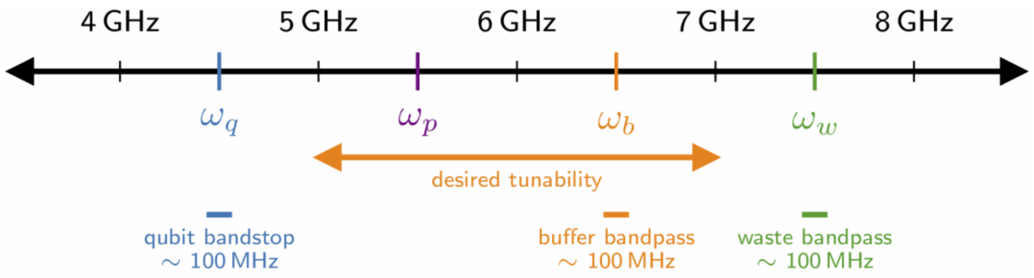


CPW + dc SQUID tunability (Saclay design)



CPW + SNAIL tunability



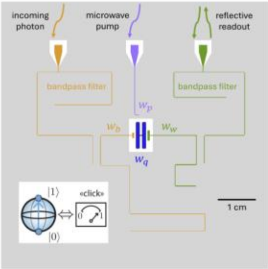


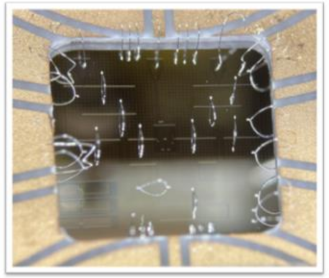
SMPD current status

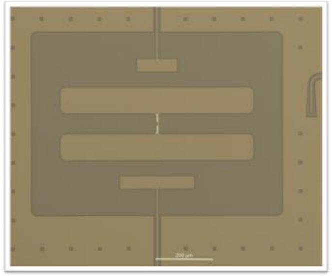
- Three objectives:

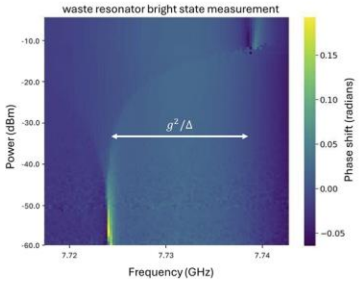
1. Re-produce an SMPD with the base Saclay design and limited design tweaks.
2. Increase the tunability of the Saclay design to match that of VERA cavities [24]: 5 to 7 GHz.
3. Perform a cryogenic dark photon search with a VERA cavity.

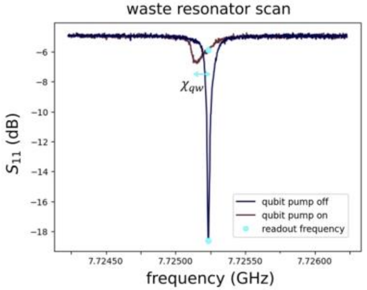
- Objective 1:
  - made a non-tunable version
  - qubit frequency was 2x higher than designed for
  - waste resonator coupled to qubit but buffer resonator did not

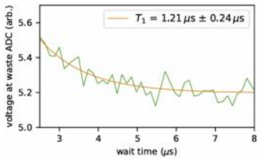






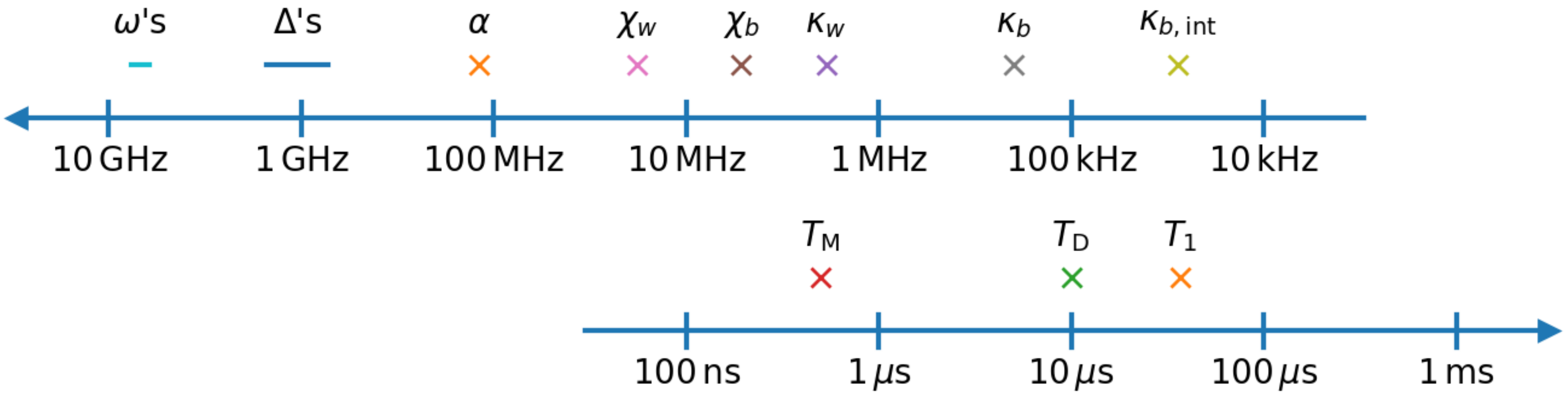






The SMPD hierarchy (backup)

- Want T_1 to be long and T_M to be short
- Always need $\chi_w \chi_b \gg \kappa_w \kappa_b$
- Want ω_b to be tunable – how will that impact χ_b?



SMPD hierarchy

$\chi_w \chi_b \gg \kappa_w \kappa_b$

$\kappa_w \gg \kappa_b$

$T_D = \sqrt{2(T_M + T_R)T_1}$

$T_M \gtrsim 1/\kappa_w$

SMPD efficiency (backup)

- total efficiency has four components

$$\eta_{\text{total}} = \eta_{4\text{wm}} \cdot \eta_{\text{ro}} \cdot \eta_{\text{duty}} \cdot \eta_{\text{qubit}}$$

  - 4wm: transfer efficiency, determined by cavity cooperativity and internal losses in the buffer
  - ro: readout efficiency; fidelity with which the waste resonator state can be identified; depends on T_1 and cryogenic amplifier noise
  - duty: T_d / (T_d + T_m + T_r)
  - qubit: T_1 decay will limit readout fidelity

$$\eta_{\text{qubit}} = \frac{T_1}{T_\text{d}}(1 - e^{-T_\text{d}/T_1})$$

- Saclay: η_{theory} = 0.46 η_{meas} = 0.43

$$\eta_{4\text{wm}} = \frac{4\mathcal{C}}{(\frac{\kappa_{\text{bint}}}{\kappa_{\text{bext}}} + 1 + \mathcal{C})^2}$$