Josephson Parametric Amplifiers: Theory and Application

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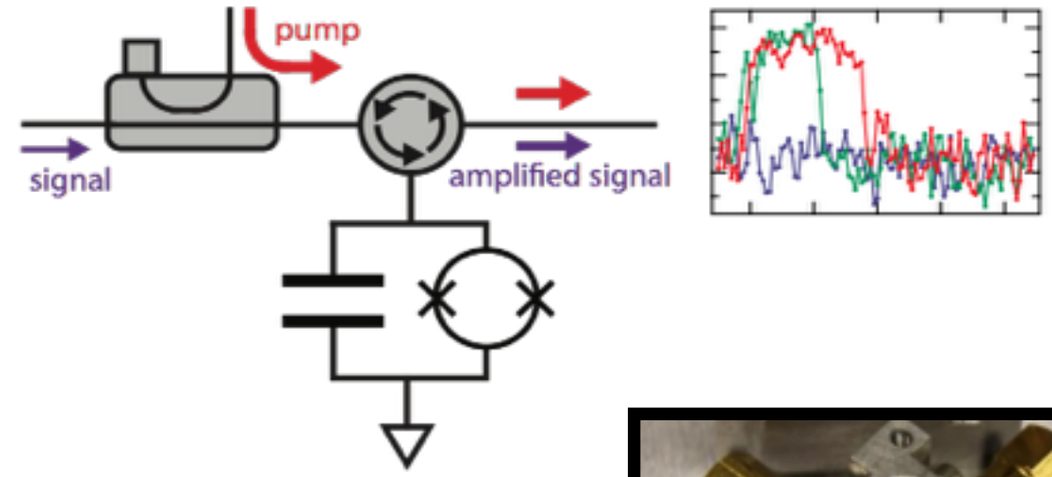
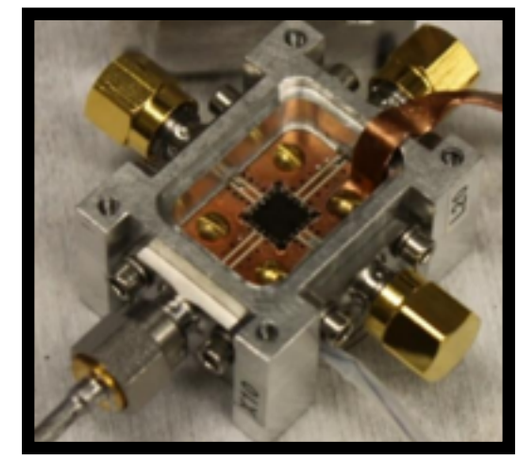
Outline

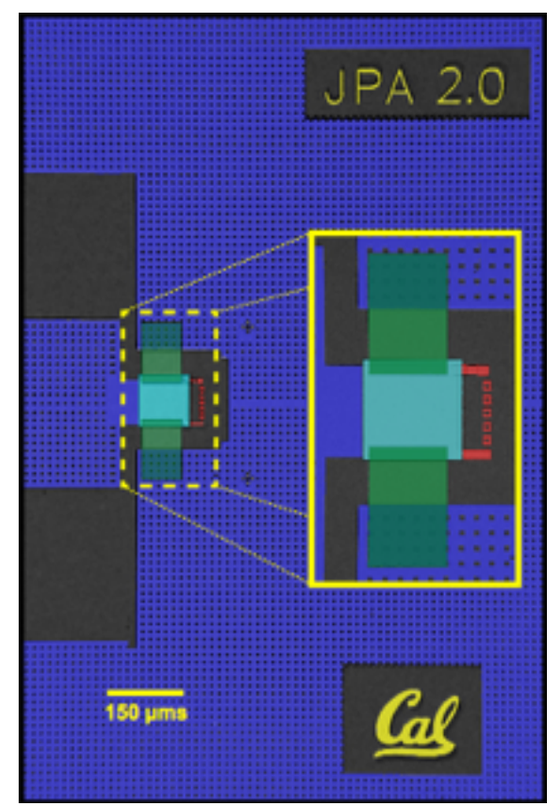
- Introduction
  - JPAs in cQED
  - Amplification and SNR
  - Parametric Amplification



- Standard 4-8 GHz JPAs
  - Basic design
  - Characterization and performance



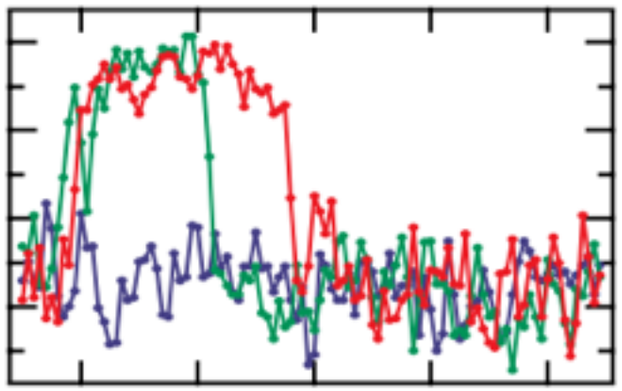
- Lower frequency JPAs
  - Cryo-housing
  - Dynamic range
  - ~1-2 GHz device (L-band)
  - ~500-700 MHz device



Josephson Parametric Amplifiers

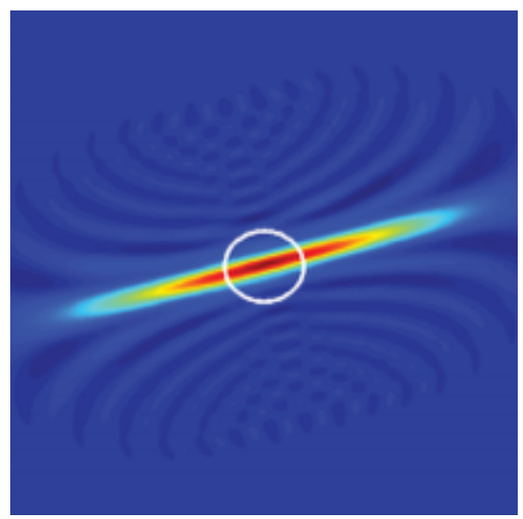
Josephson parametric amplifiers (JPA) are an enabling technology for superconducting qubit measurement

Quantum Jumps



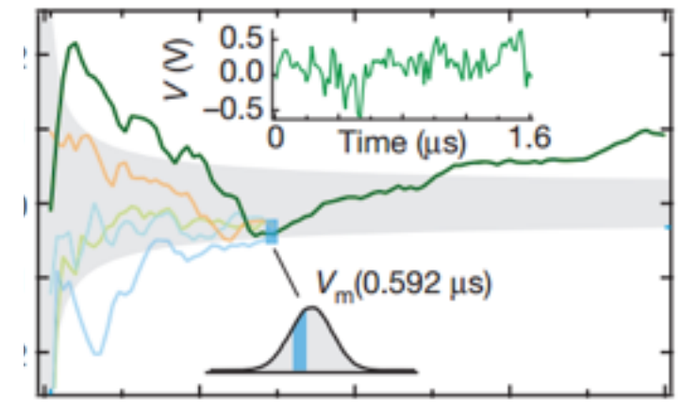
R. Vijay *et al.*, *PRL* (2011)

Squeezed microwaves



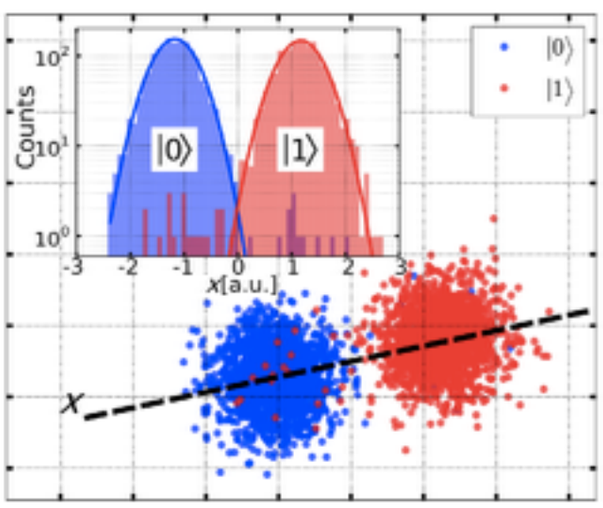
F. Mallet *et al.*, *PRL* (2011);
C. Eichler *et al.*, *PRL* (2011);
E.P. Menzel *et al.*, *PRL* (2012);
K.W. Murch *et al.*, *Nature* (2013)

Weak measurements



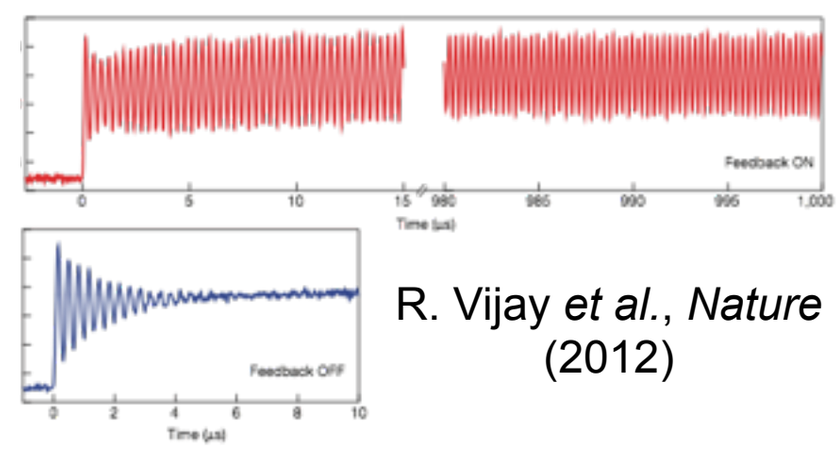
M. Hatridge, *et al.*, *Science* (2013);
K.W. Murch *et al.*, *Nature* (2013);
S. Weber *et al.*, *Nature* (2014);

High-Fidelity Readout



E. Jeffrey *et al.*, *PRL* (2014)

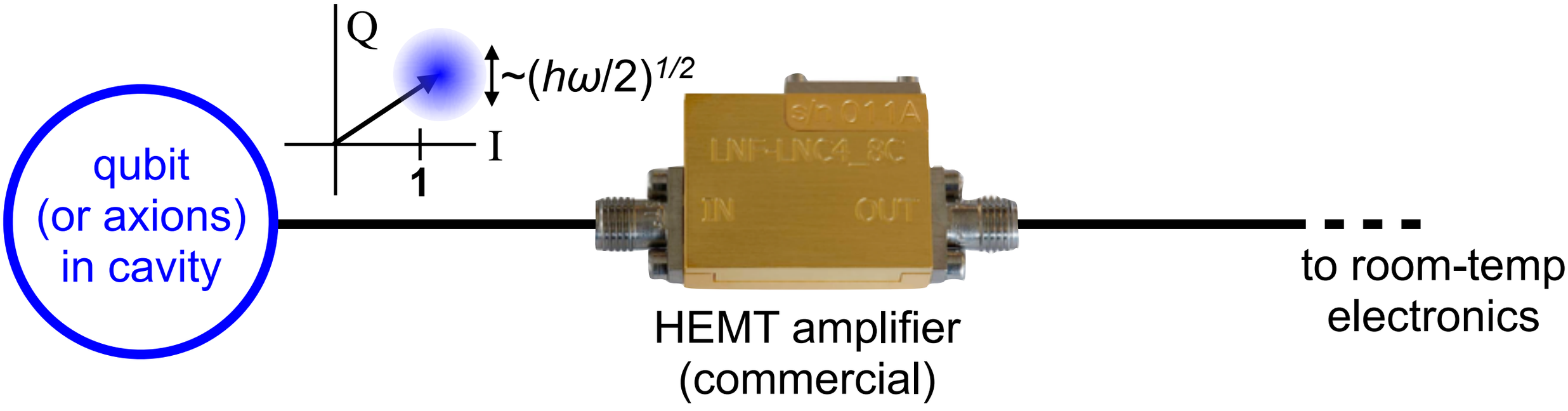
Quantum Feedback



R. Vijay *et al.*, *Nature* (2012)

Seminal work on parametric amplifiers: B. Yurke
Many related approaches: Yale, JILA, Saclay, UCSB, and others…

Amplification and SNR



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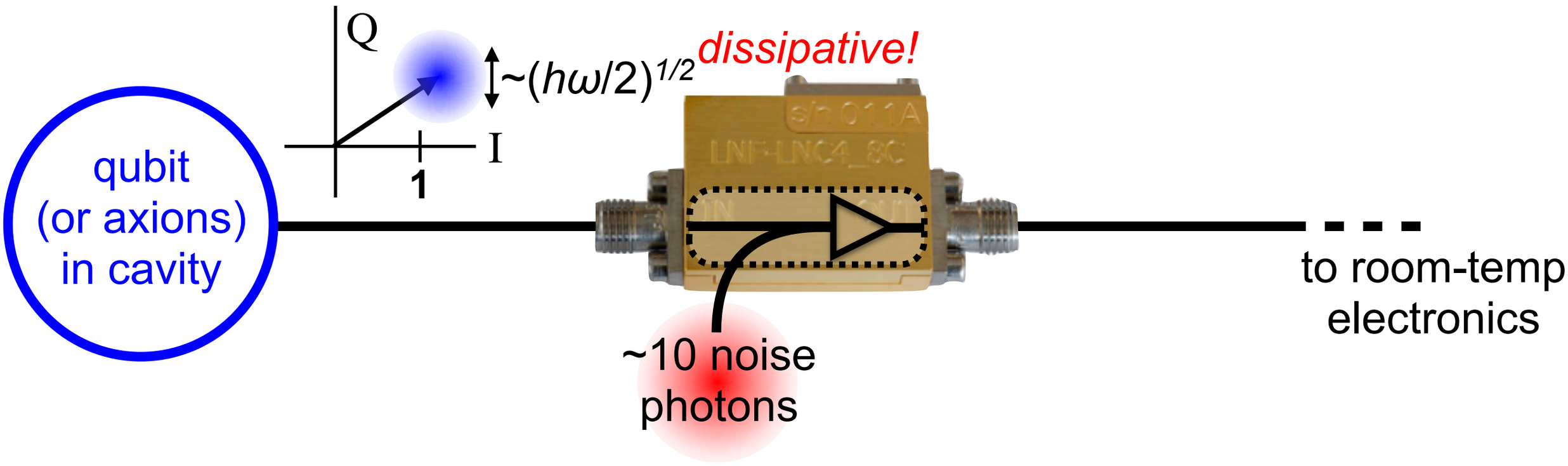

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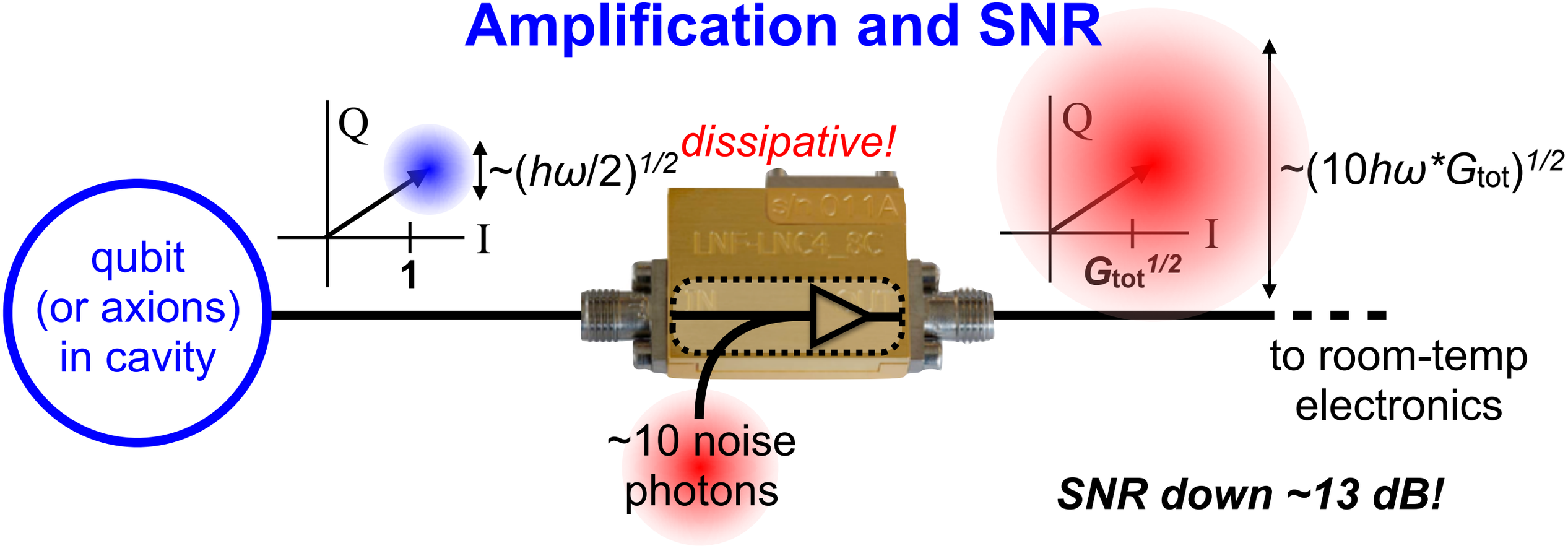

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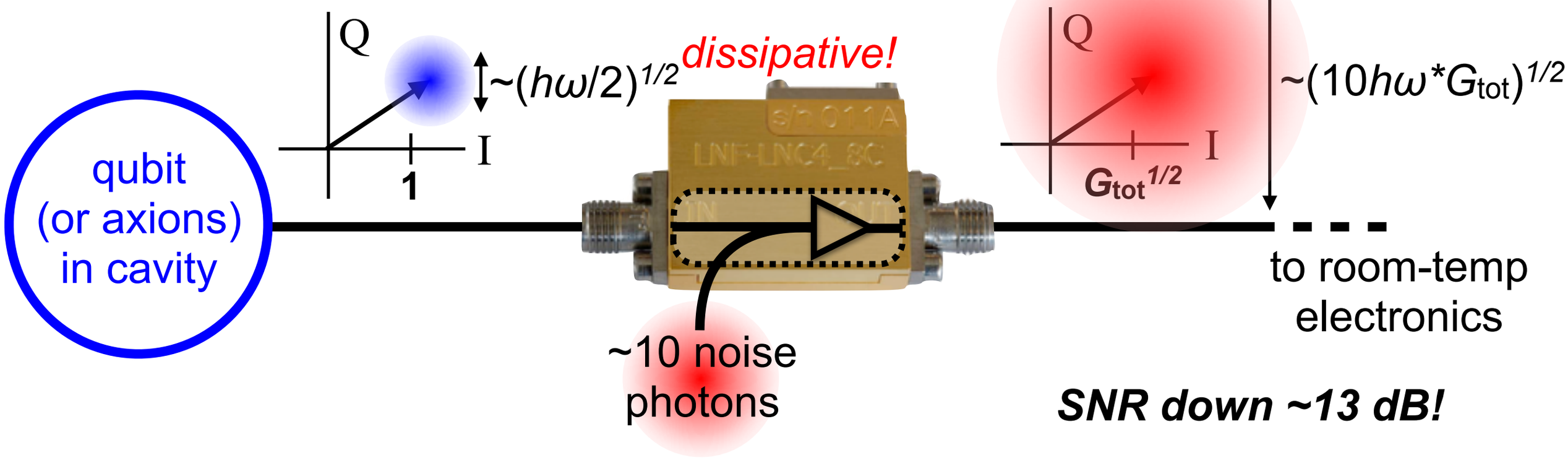

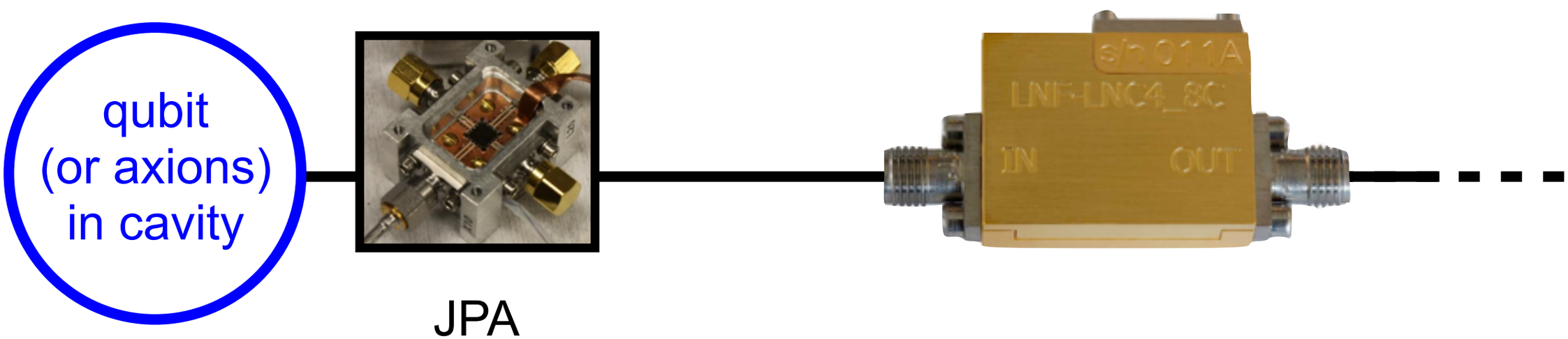

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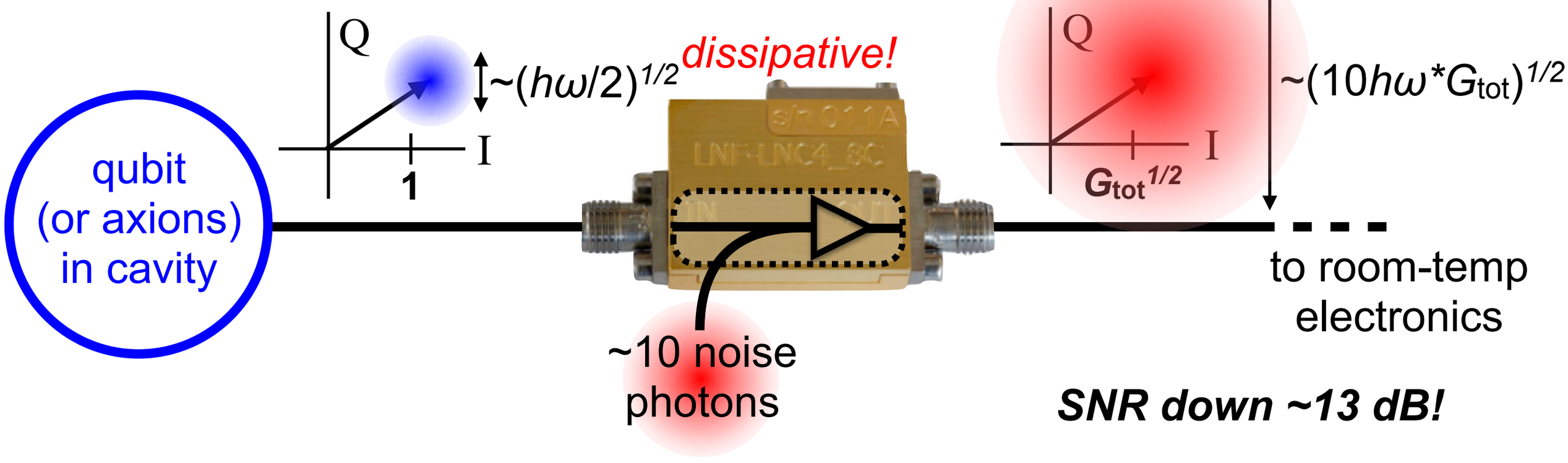

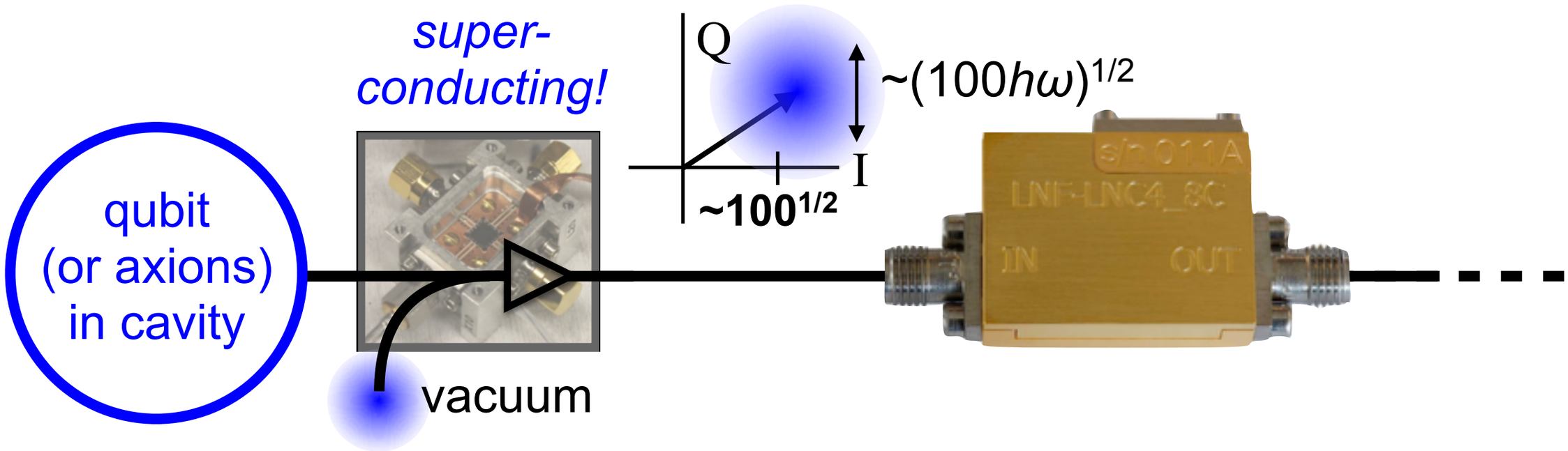

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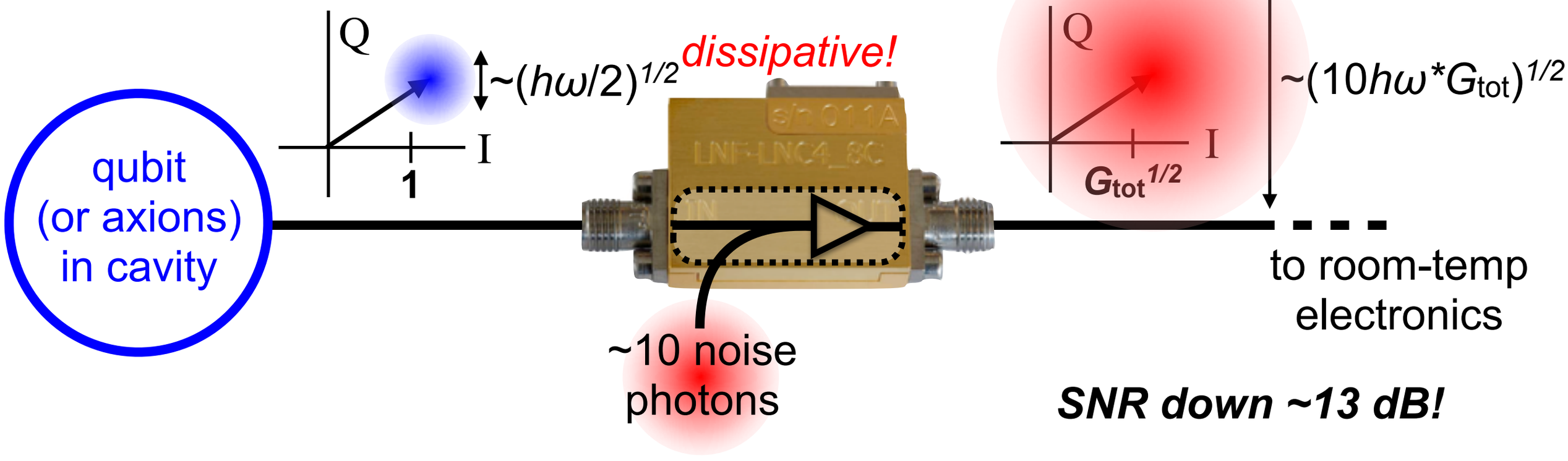

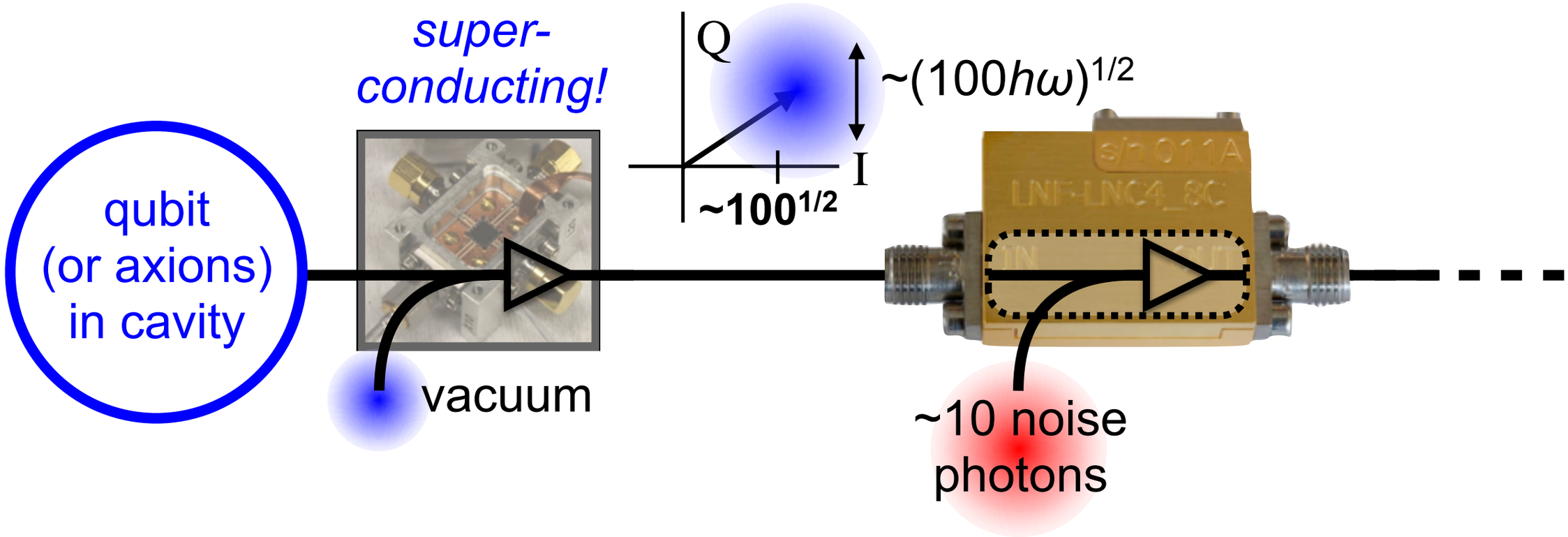

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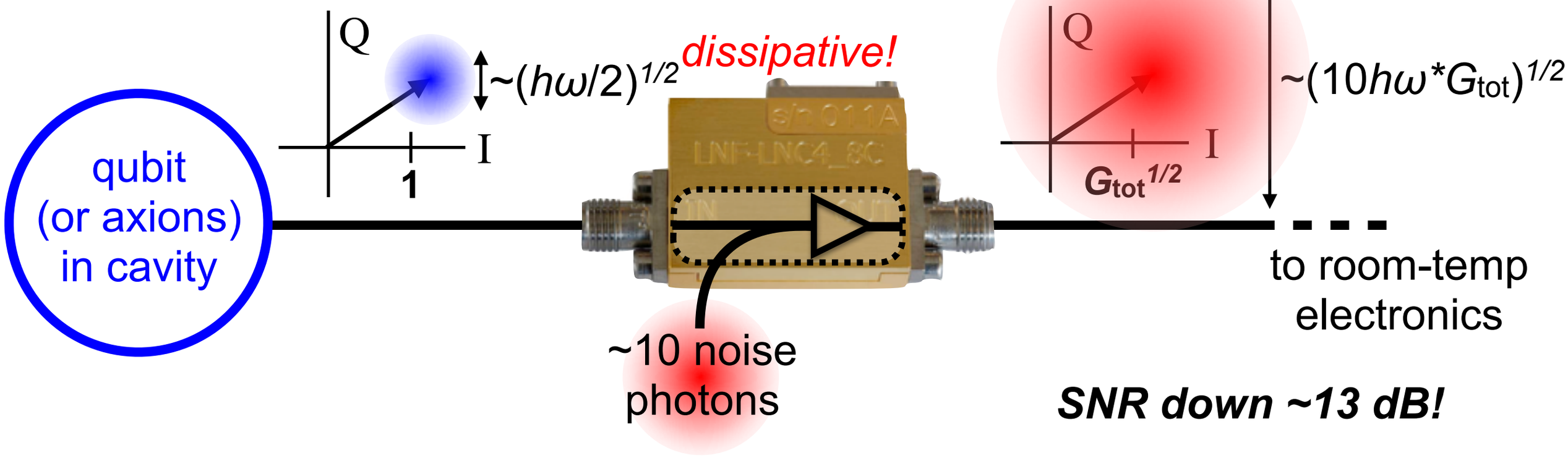

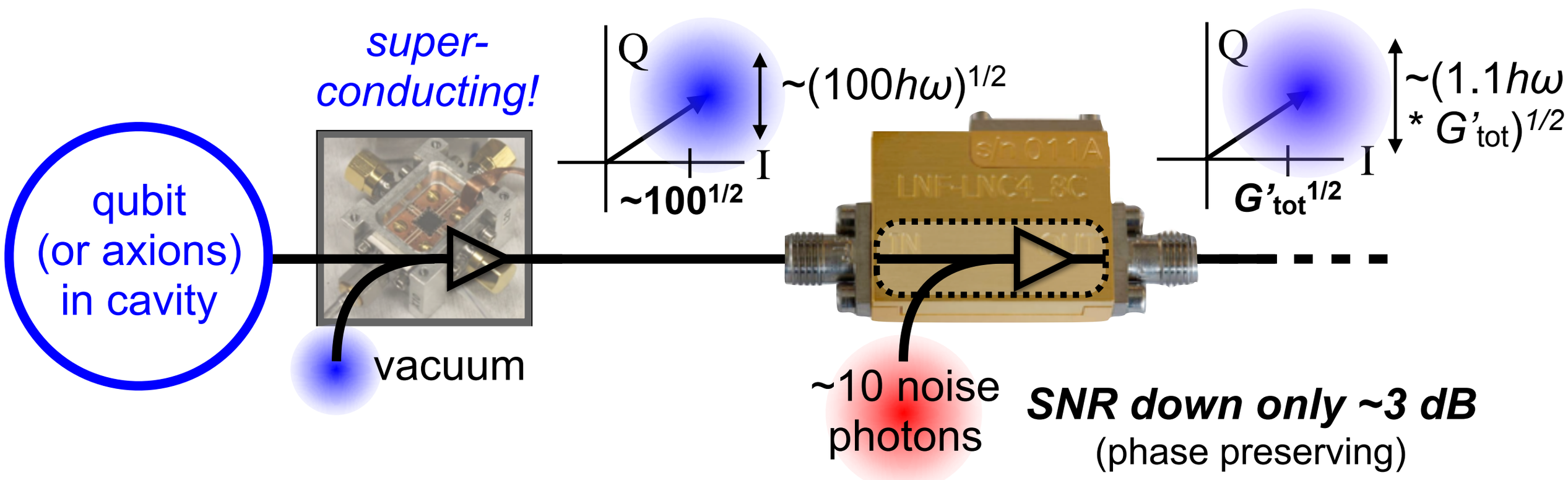

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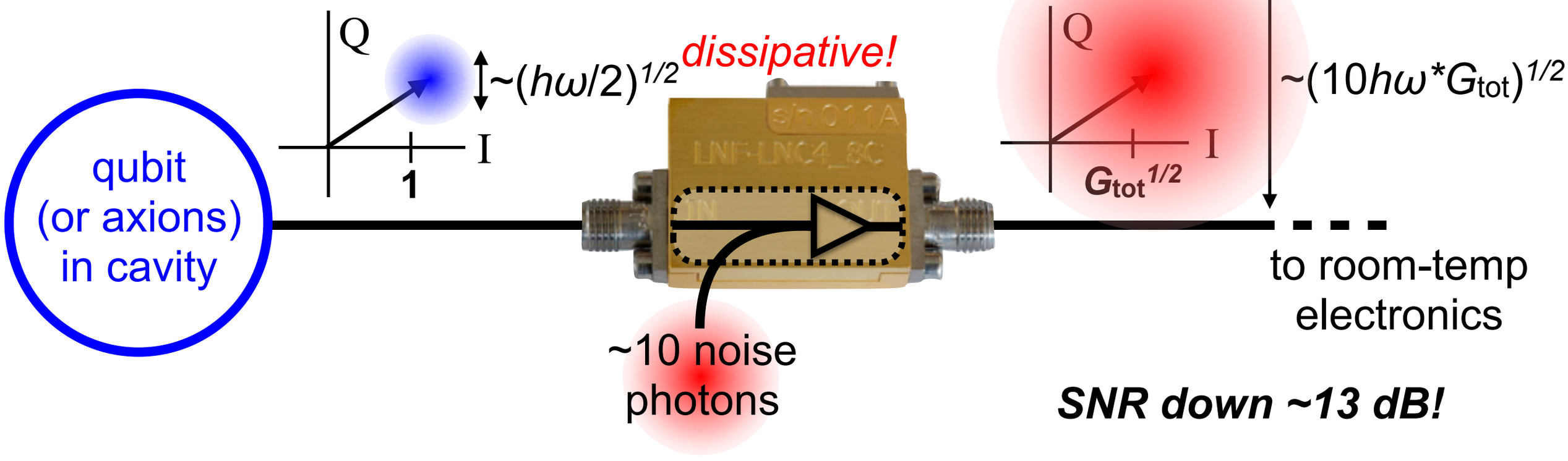
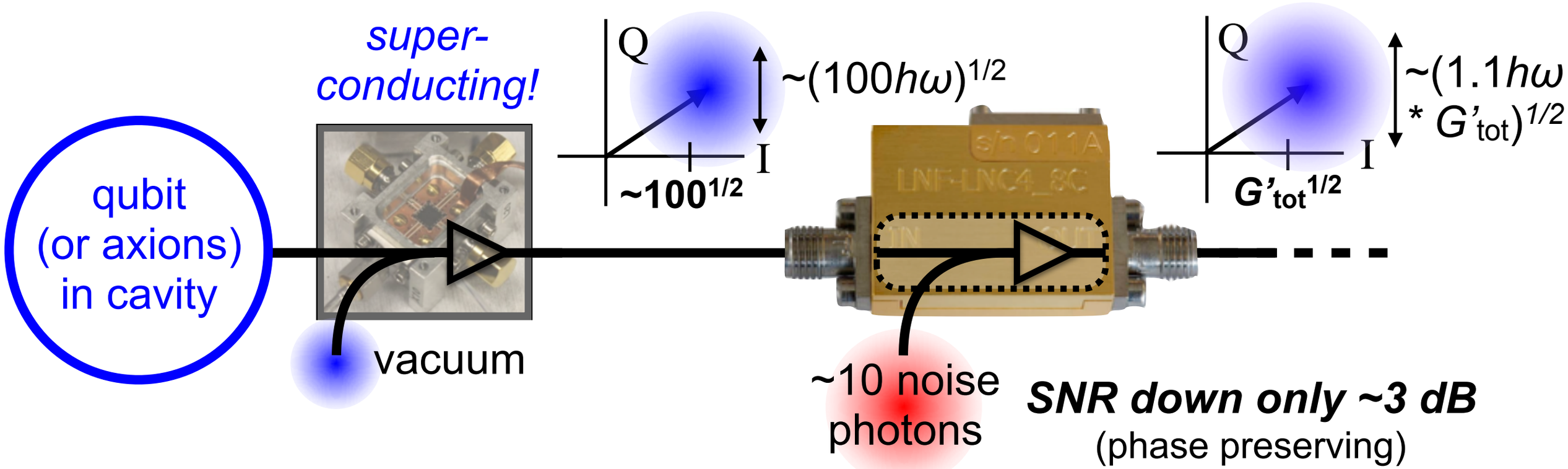
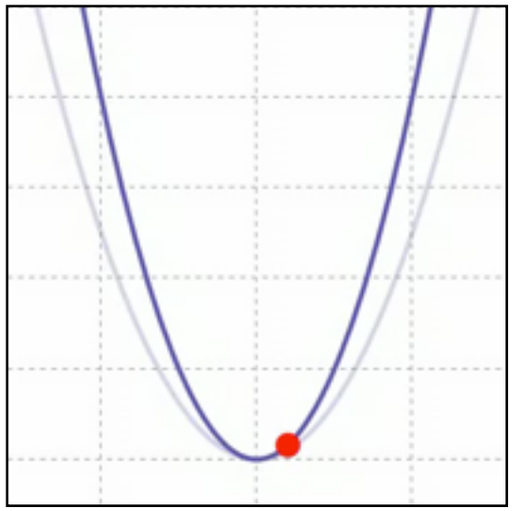




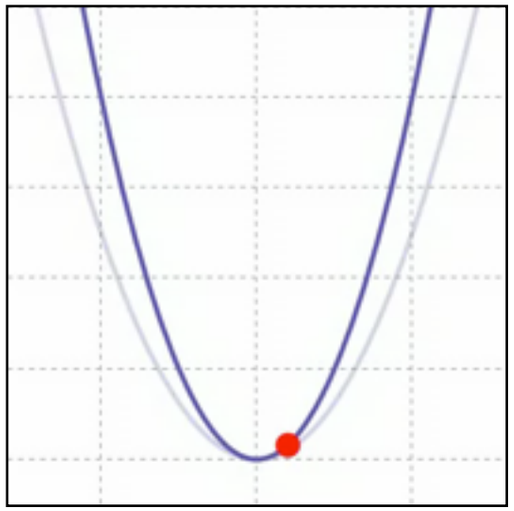
- **JPA improves SNR ~10dB** → **Averaging time reduced ~100x !**

Parametric Amplification



- Resonance frequency ω_0 modulated at ~$2\omega_0$
- Work done on in-phase field quadrature (phase-sensitive amplification)
- Detune pump ➡ work done on both quadratures (phase-preserving amplification)

Parametric Amplification



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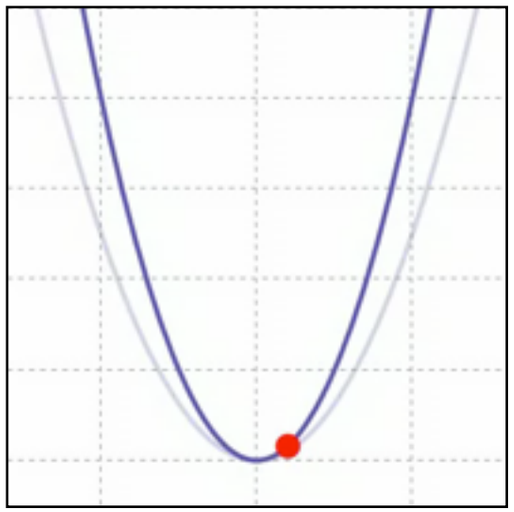

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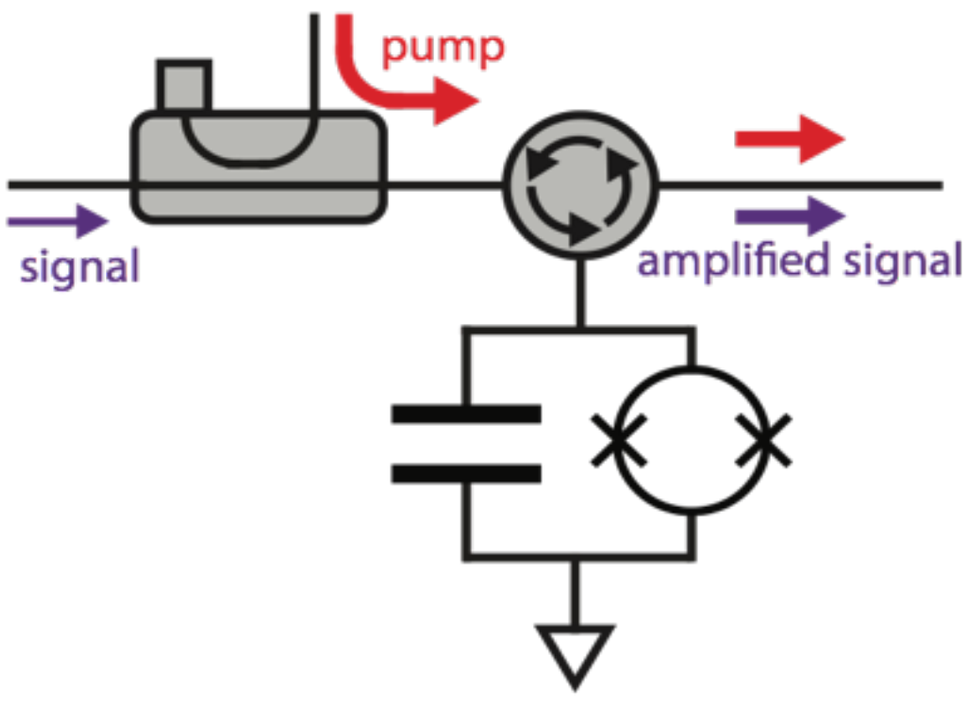
- **Josephson junction = nonlinear inductor**

$$L_J(I) = (\varphi_0 / I_0)\,(1 + I^2/I_0^2 + \ldots)$$

$\omega_r \approx \omega_0 + \Delta\omega(I_{pump})\cos(2\omega_{pump}t)$ → **"Current-pump" at ~ω_0**



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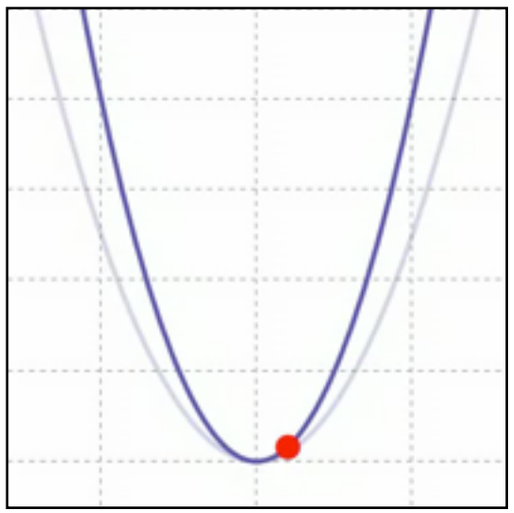

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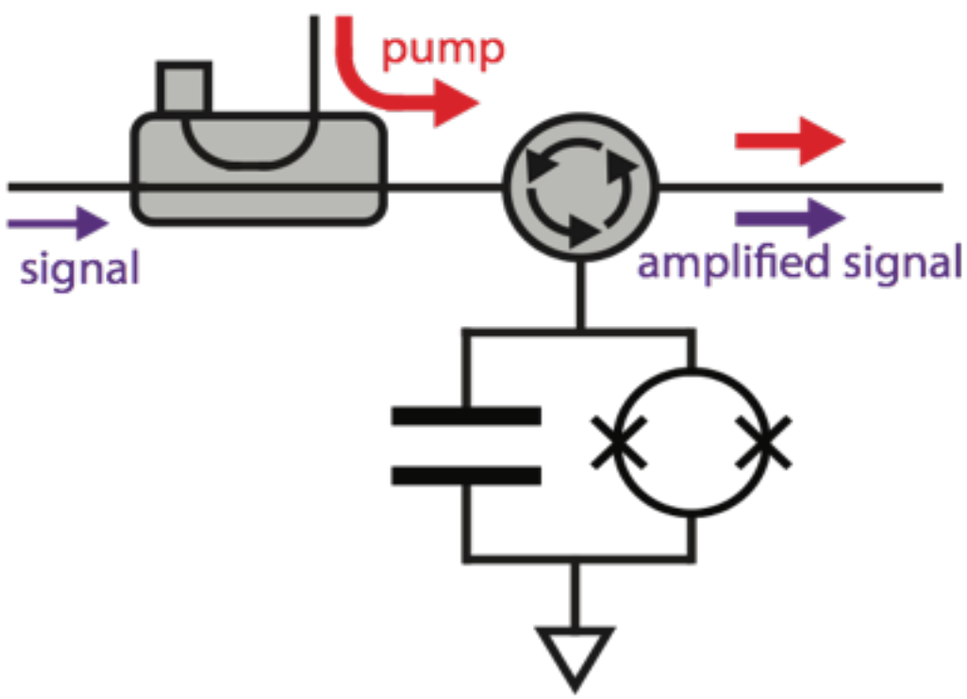
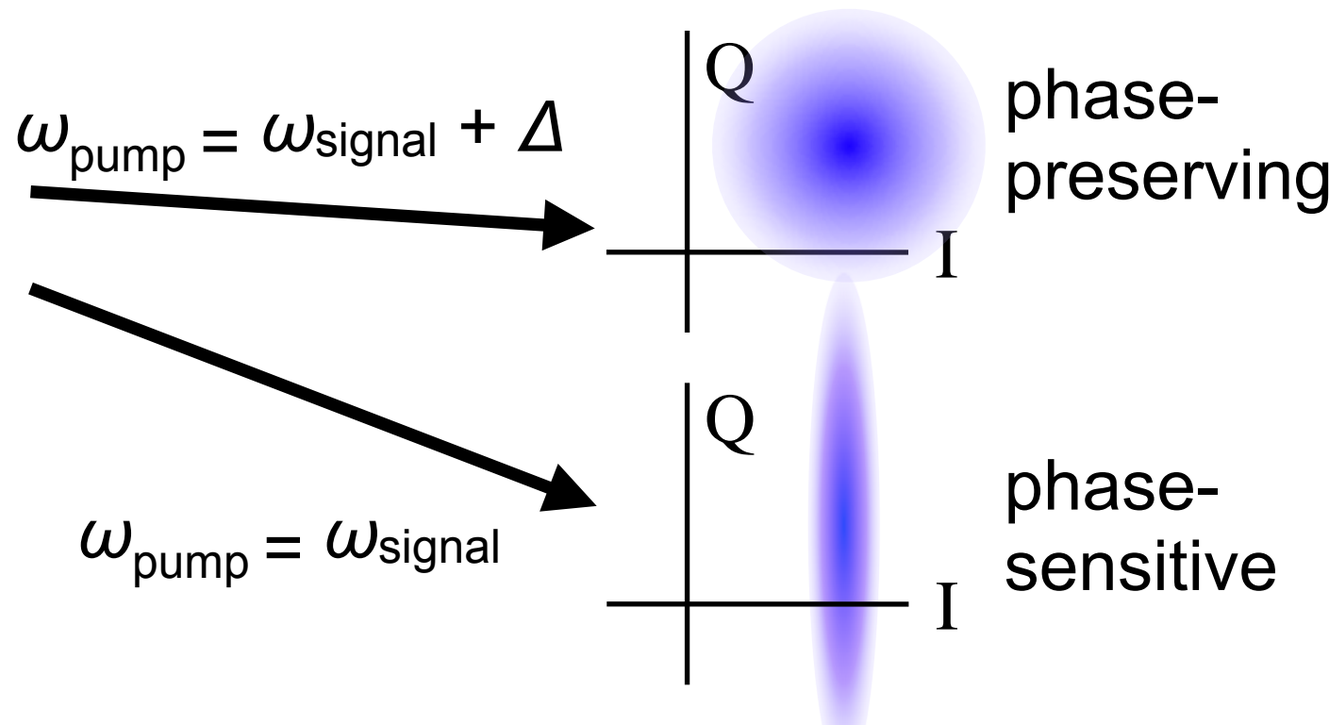
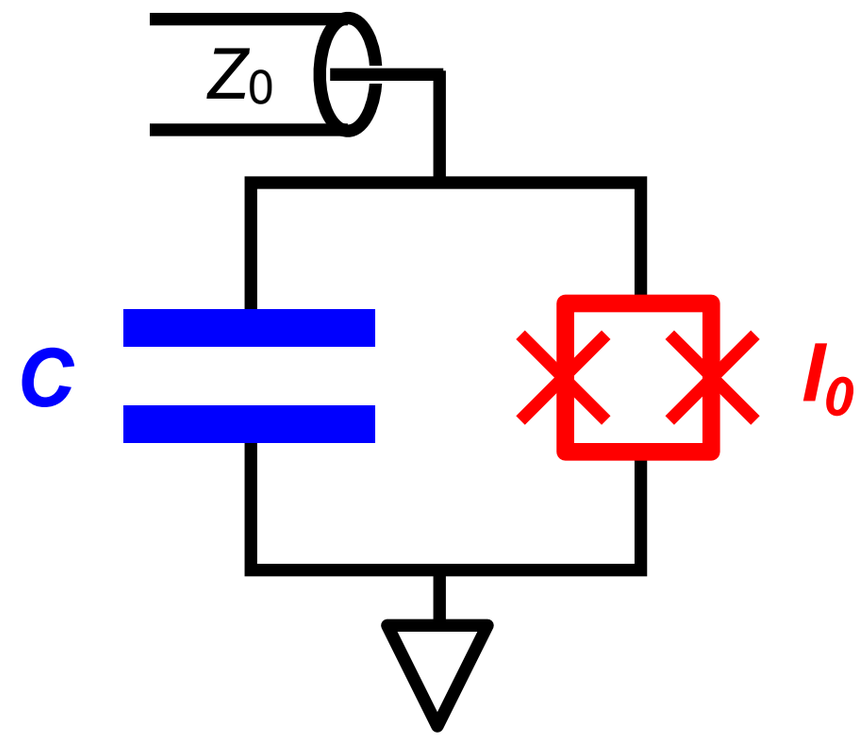




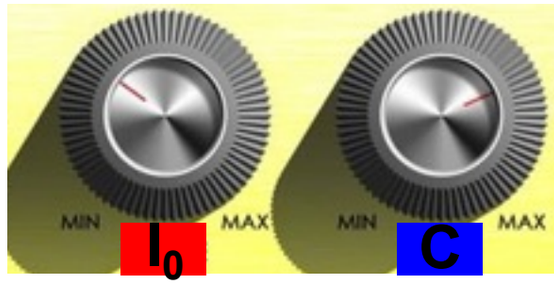
Standard JPA Design

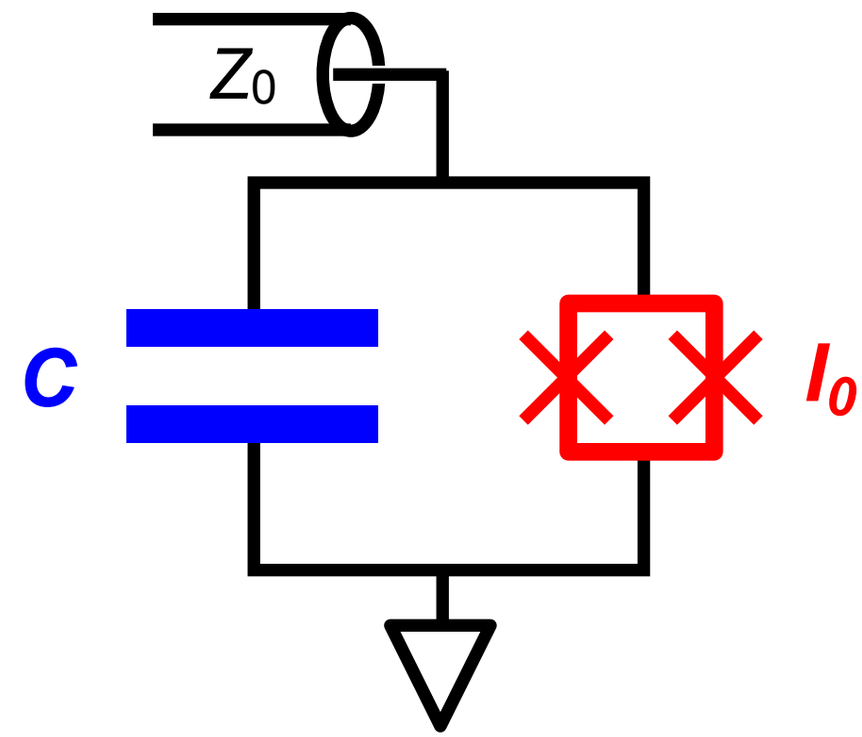


Resonant Frequency

Bandwidth (Q)

Standard JPA Design





Resonant Frequency

Bandwidth (*Q*)

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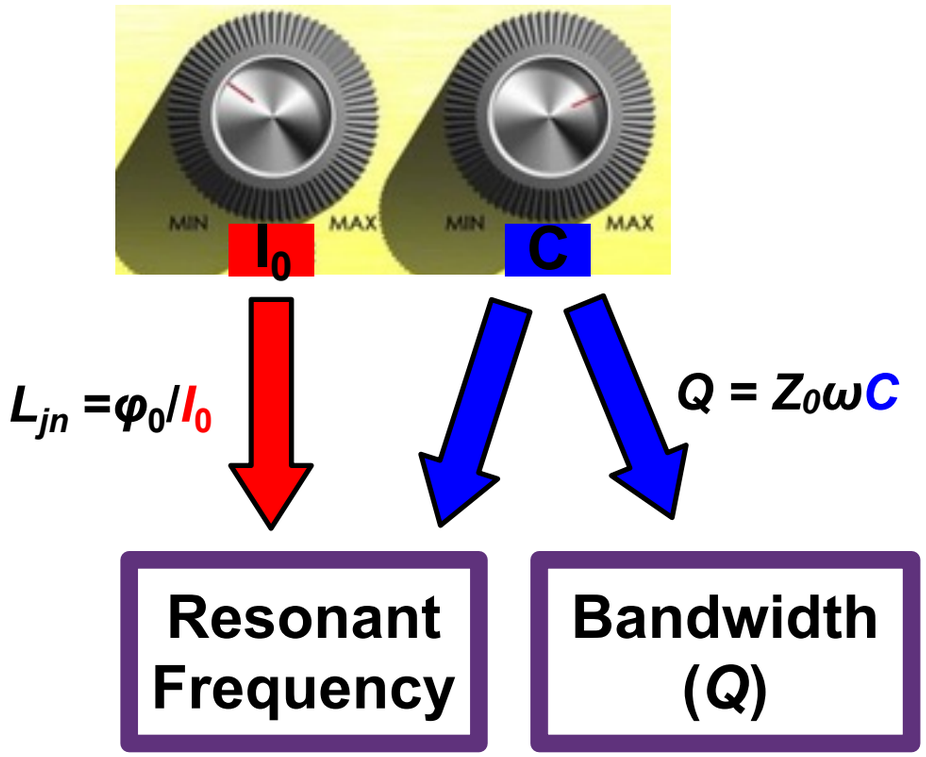

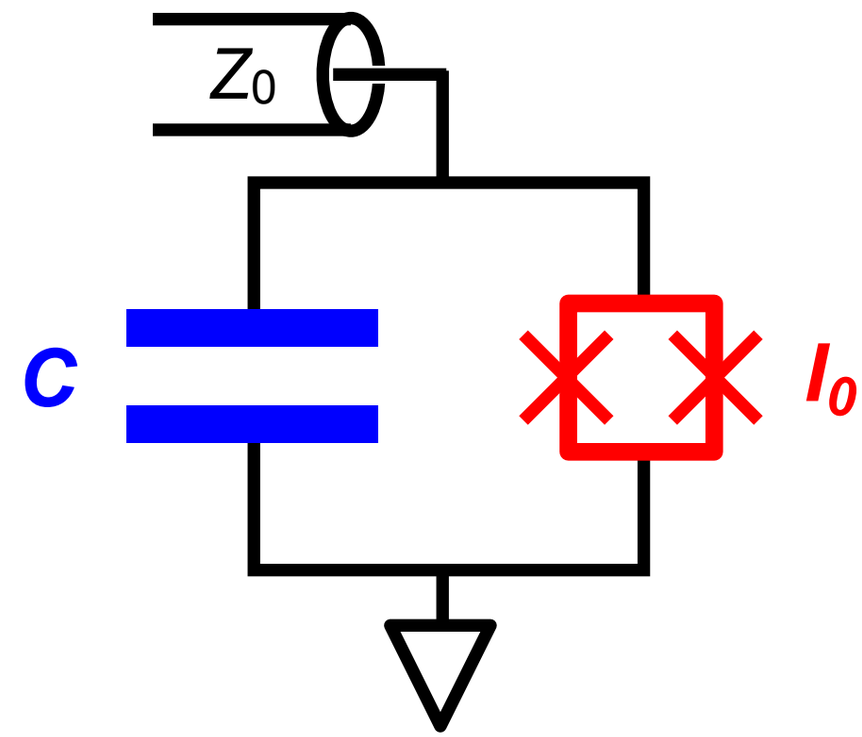

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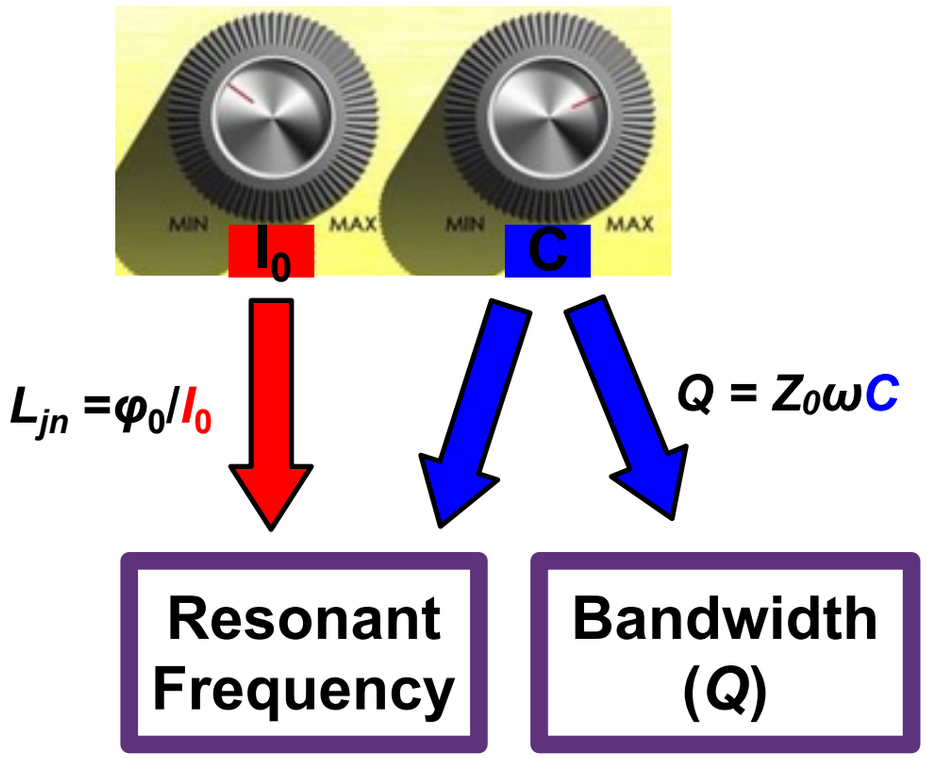
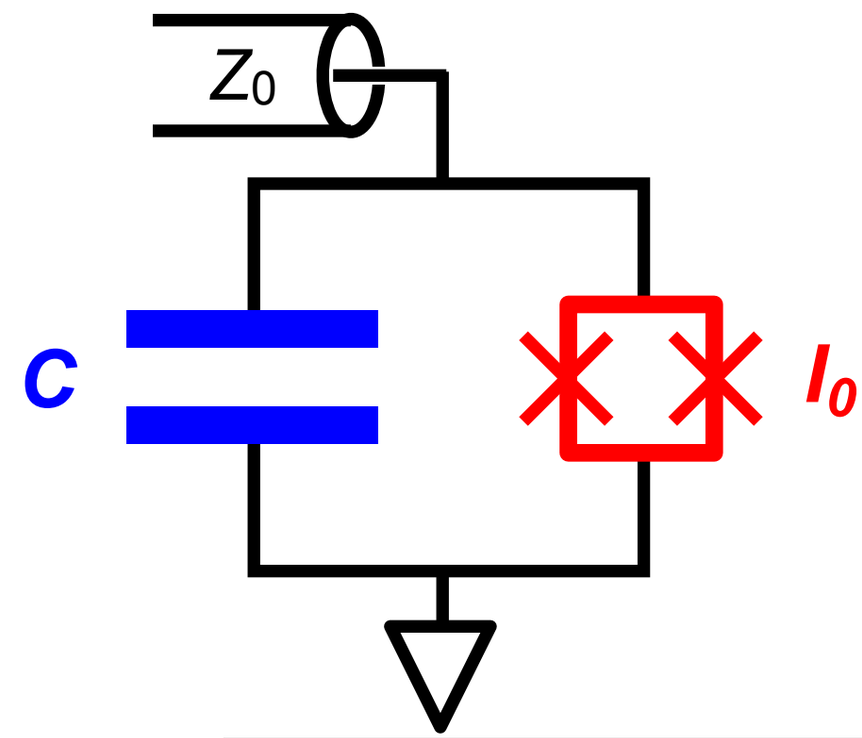
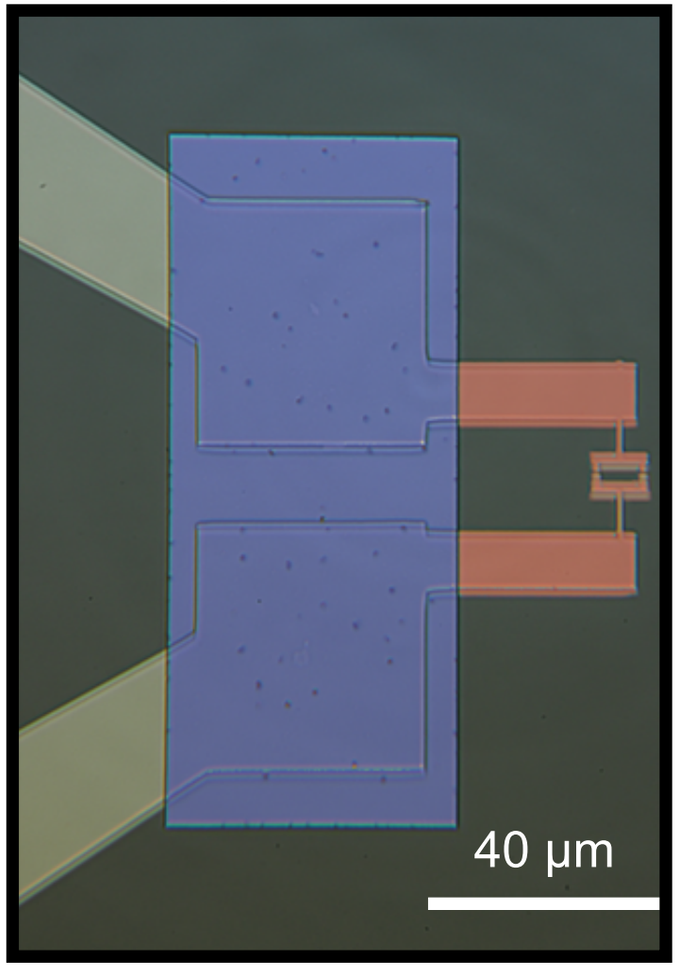




- **Aluminum device**
  BW ~ 20 MHz @ G ~ 20dB
  tunes over 4-8 GHz
- ***C* ~ 3.2 pF**
  Parallel plates with 16nm AlO_x dielectric
- **L_J ~ 140 pH**



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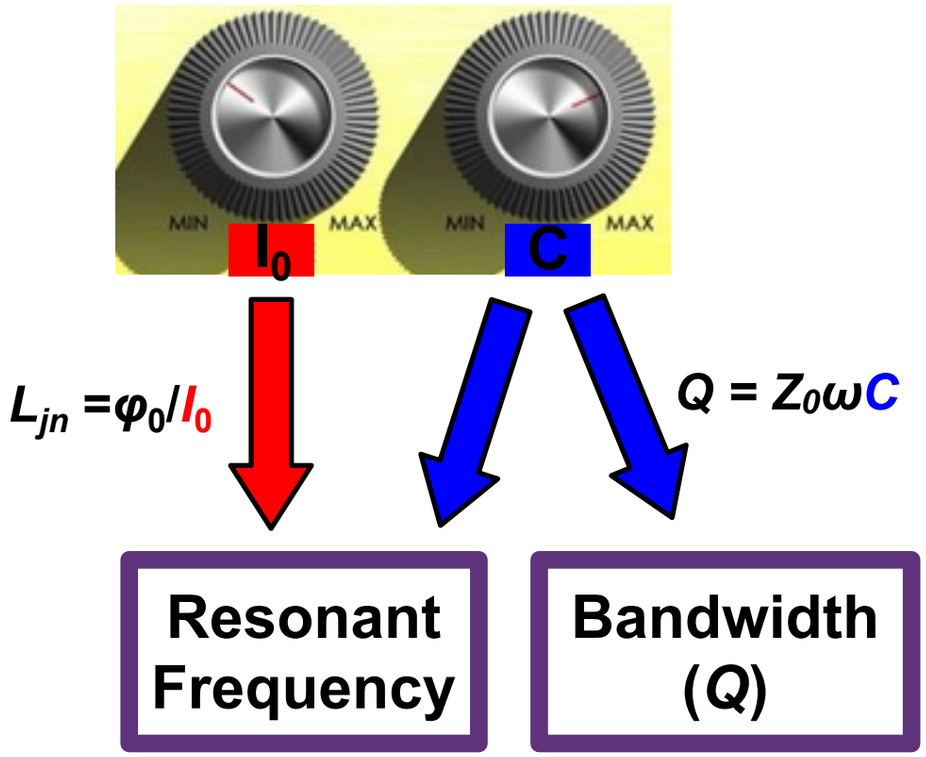

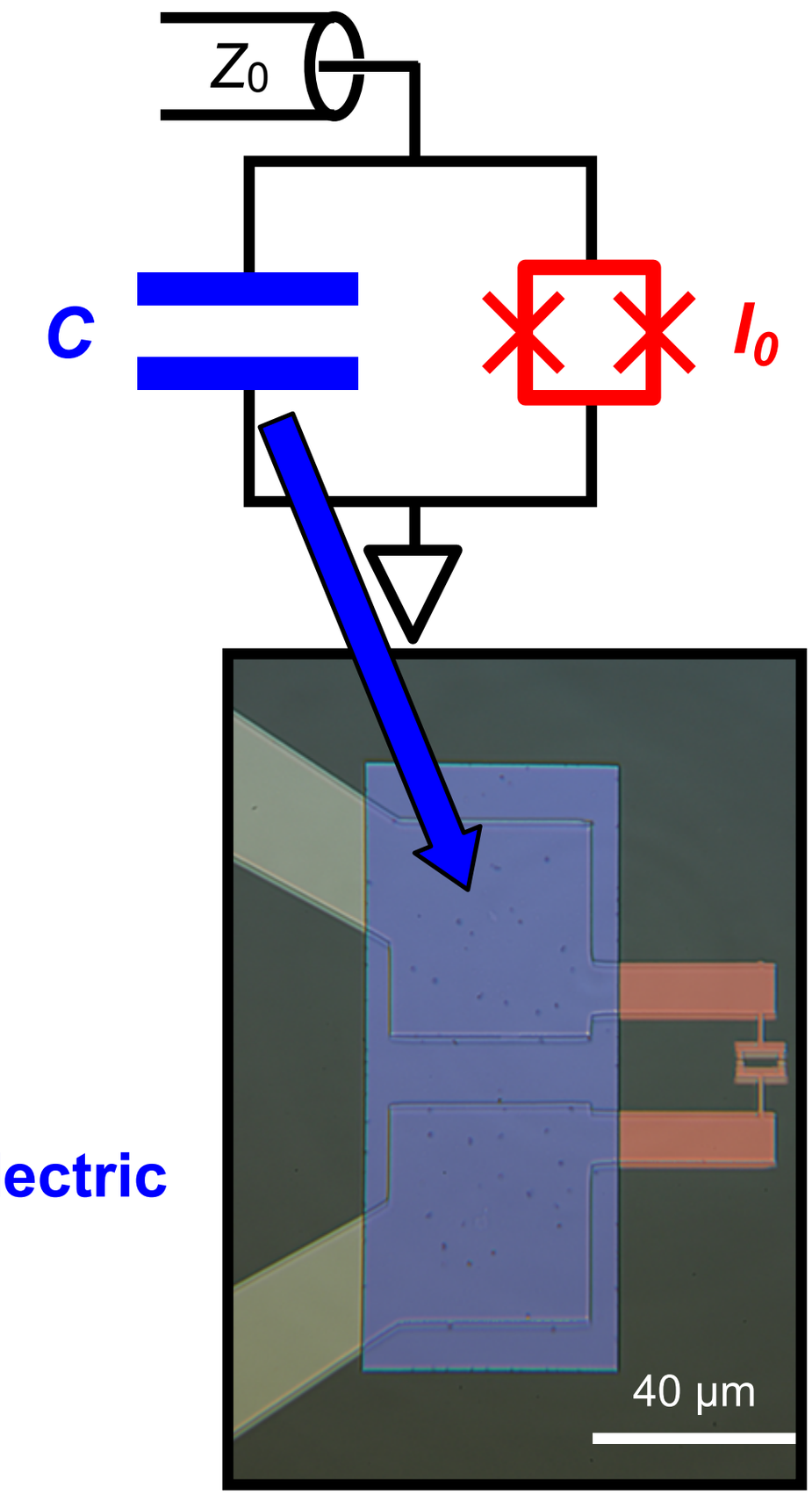

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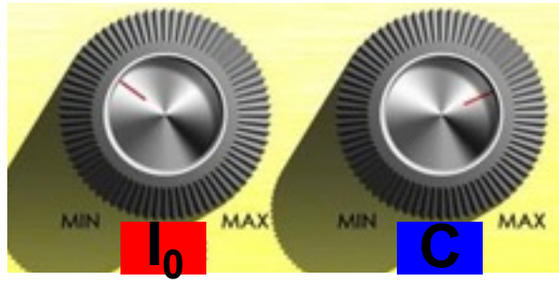
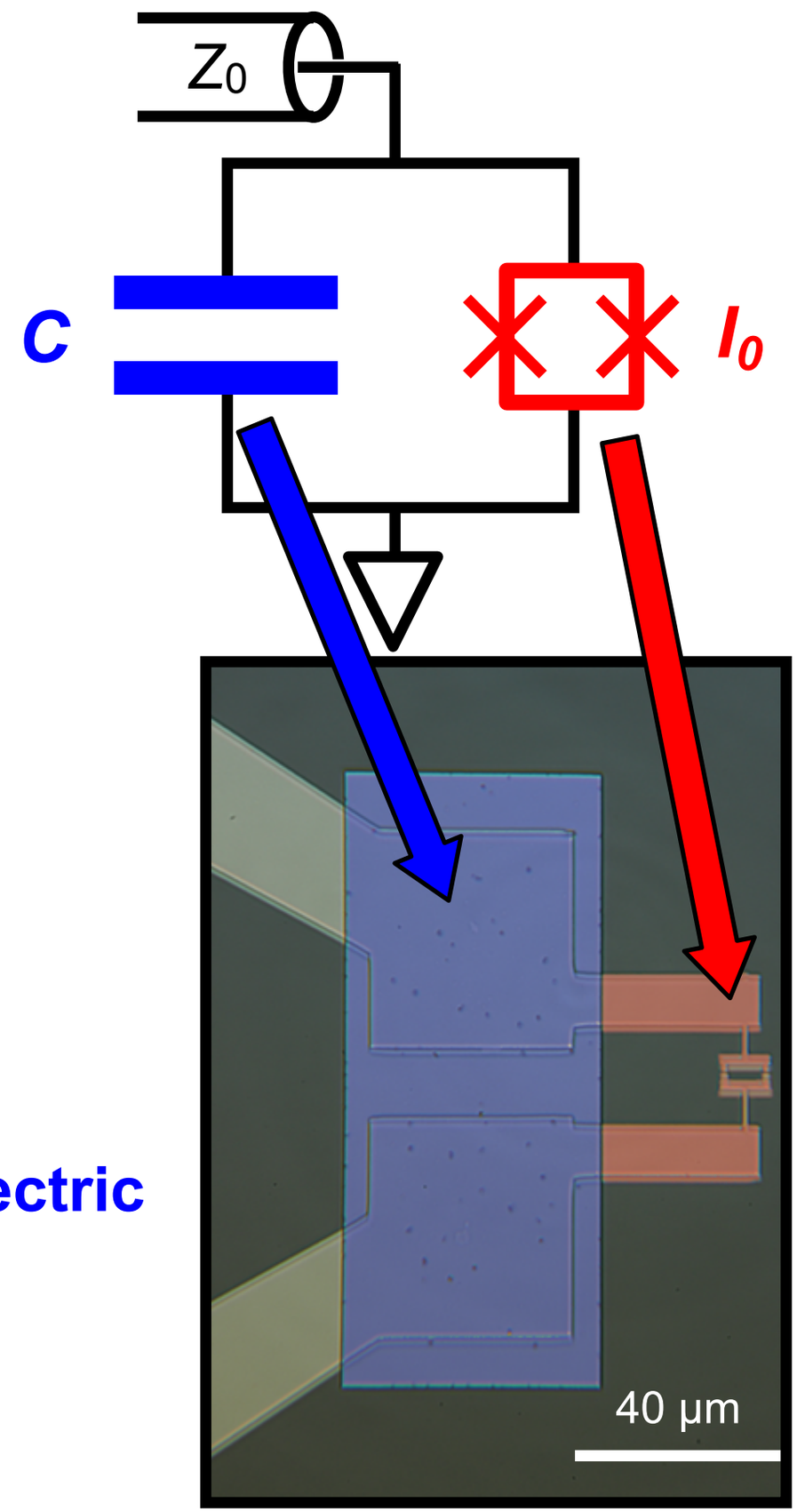


$L_{jn} = \varphi_0 / I_0$

$Q = Z_0 \omega C$

Resonant Frequency

Bandwidth (*Q*)



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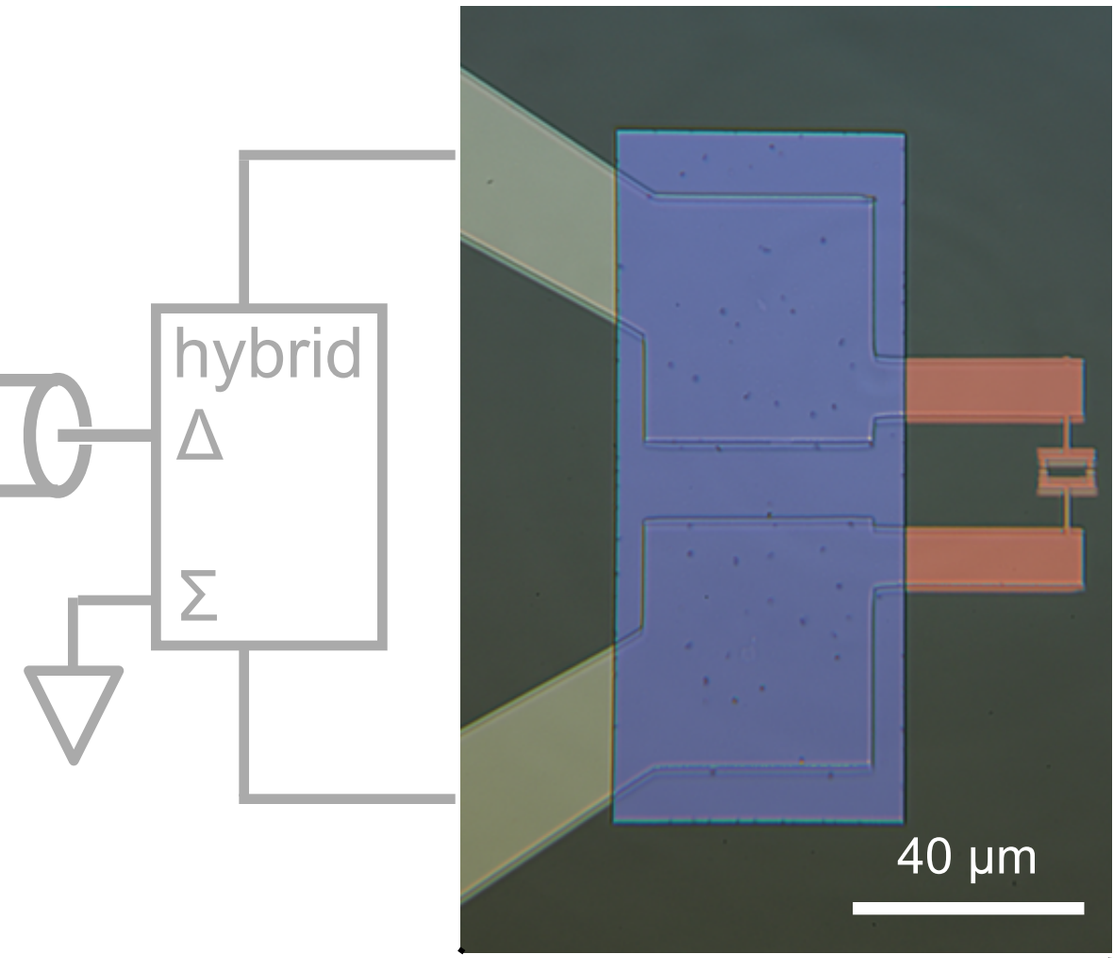
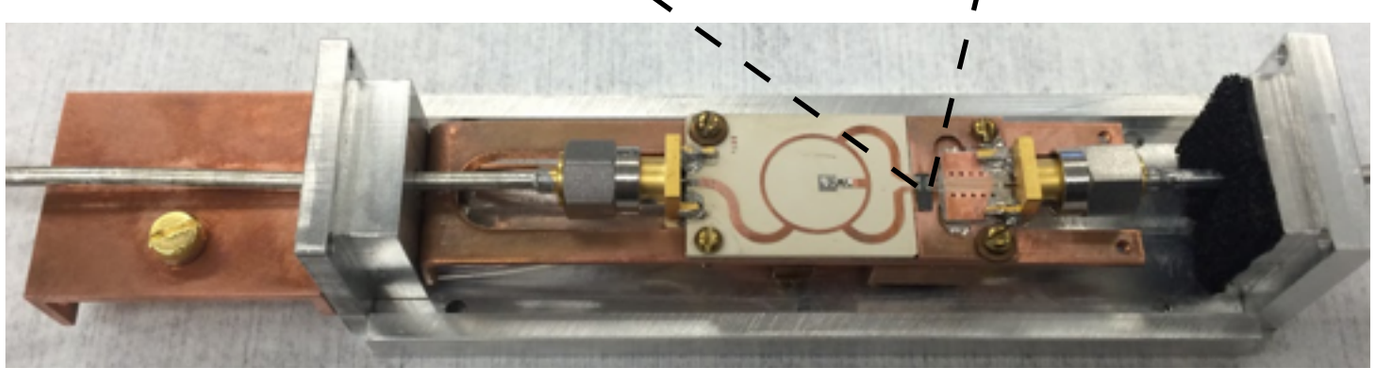
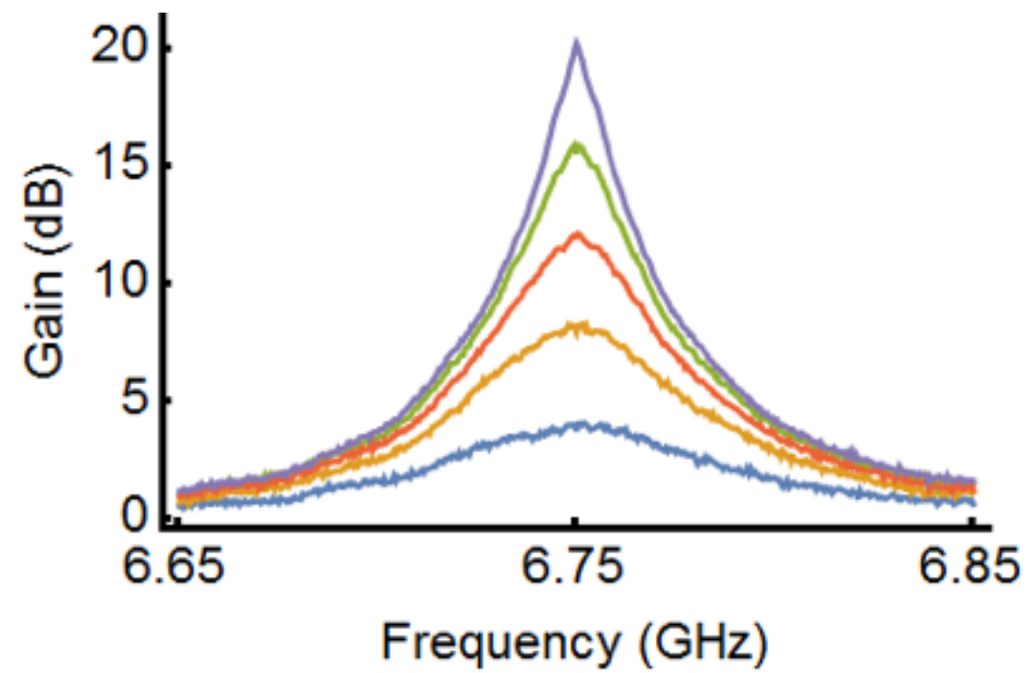
Device Characterization

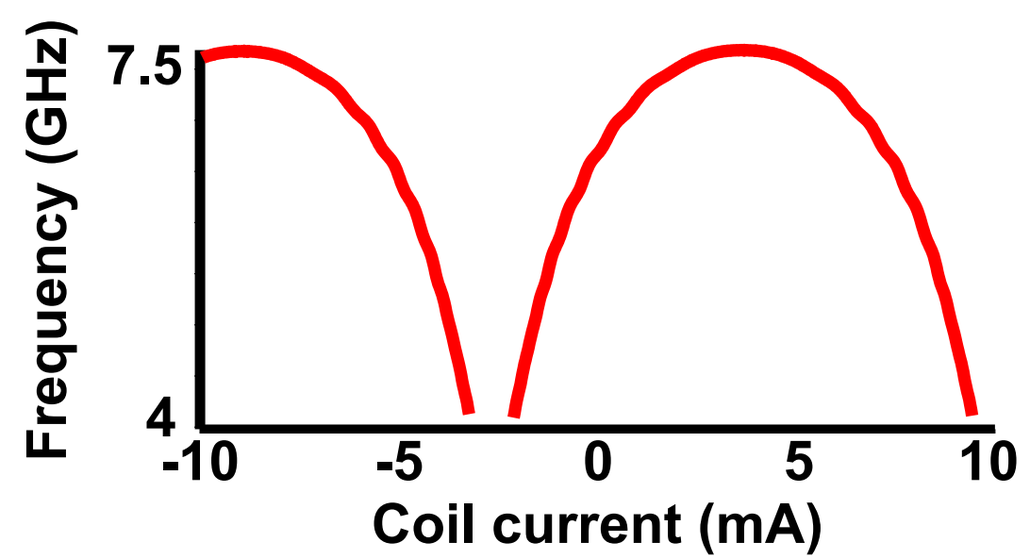




Typical performance (C-band)

- G x BW ~ 200 MHz
- P_{1dB} ~ -130 dBm



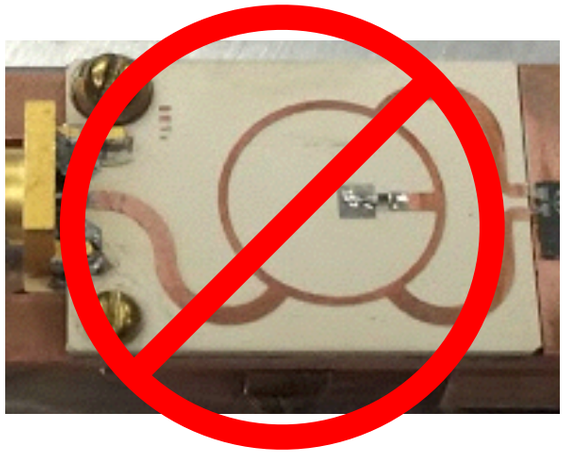


(offset due to no cryoperm shield)

Designing for Lower Frequencies

I. Device must be **single-ended** (vs. differential)

- 180° hybrid too big at low frequencies!



II. Device needs sufficient **dynamic range**

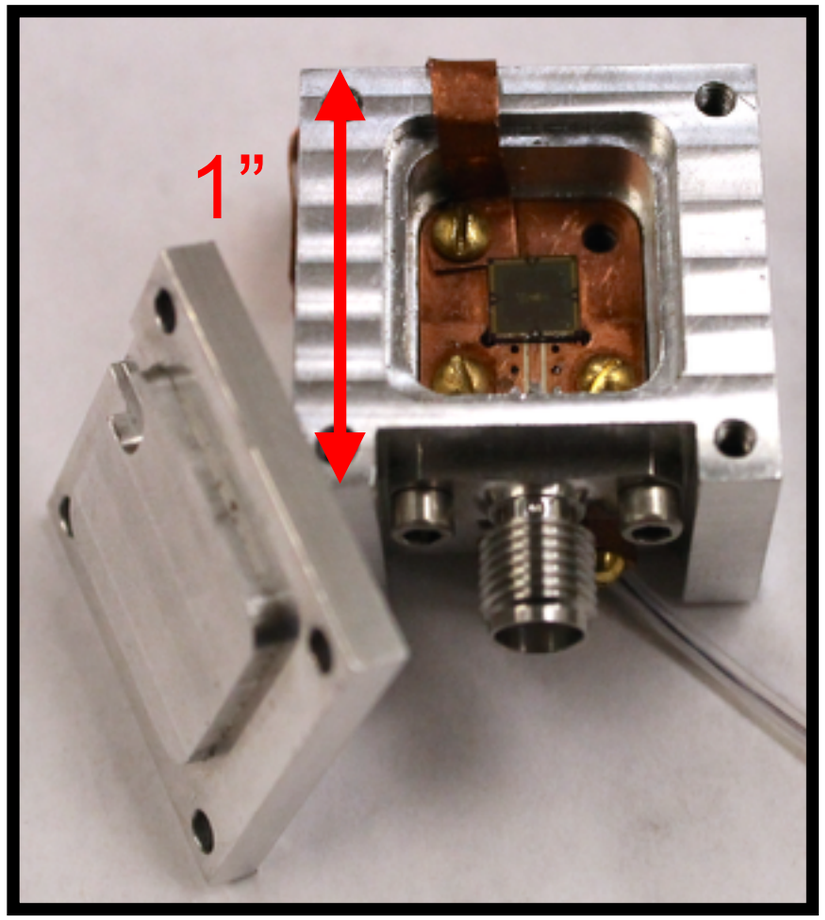
- Low frequency/bandwidth JPAs saturate at lower powers
- Saturation from incident quantum/thermal noise can degrade performance

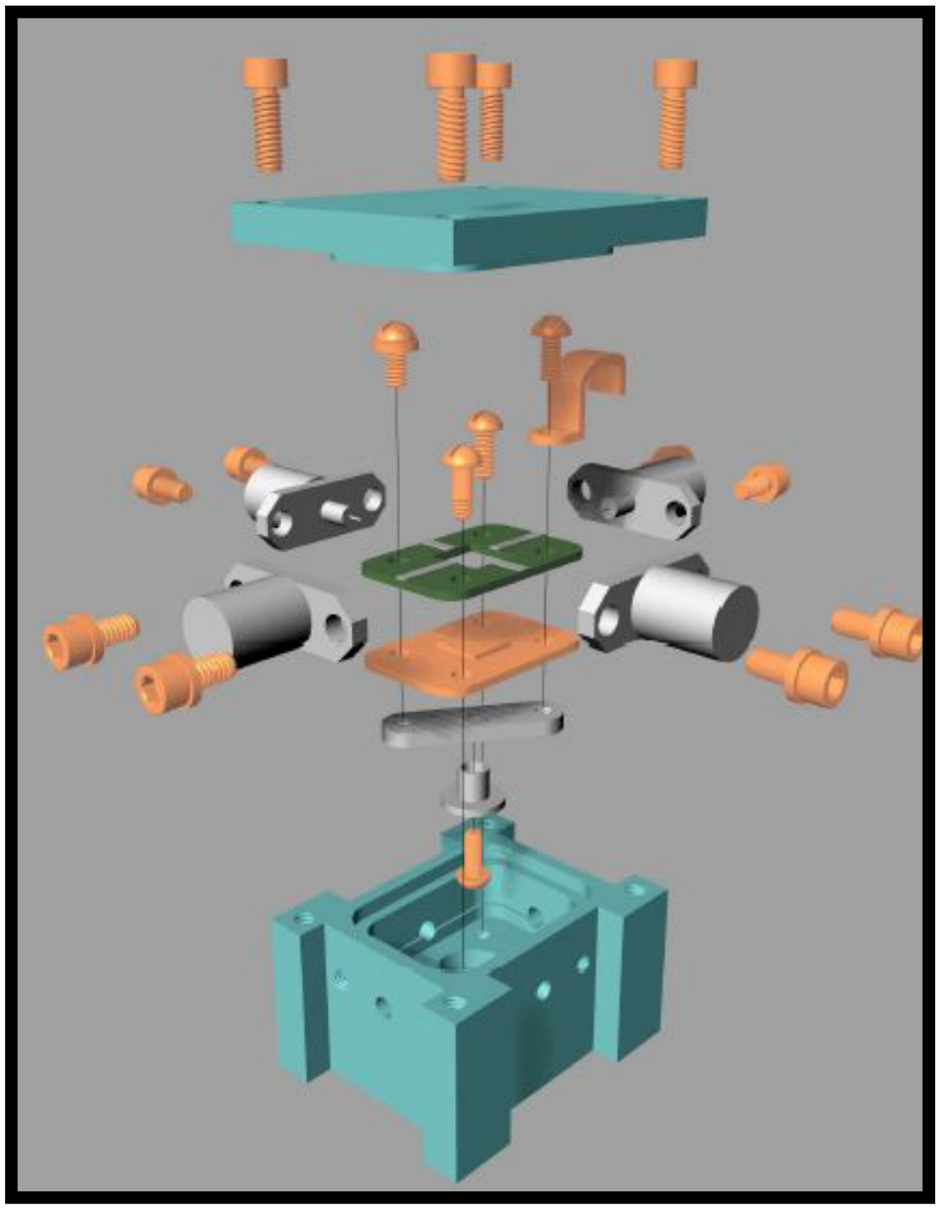
III. Need large capacitance in **compact design**

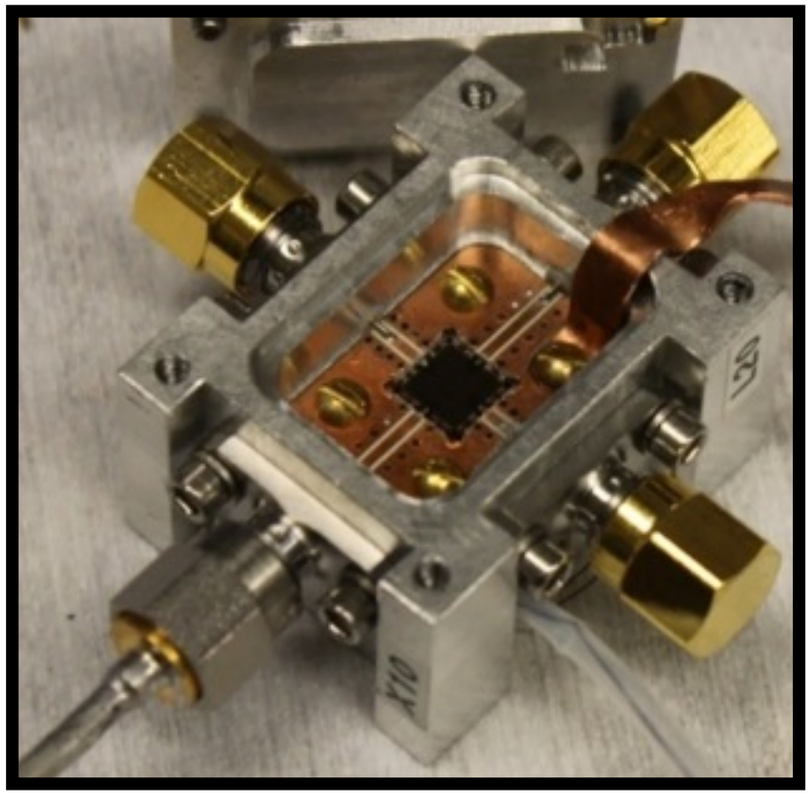
- Excess geometric inductance can cause device instabilities

Single-Ended JPA Housing

- Aluminum magnetic shield
- Near light-tight enclosure
- 1”x1”x0.8” (1-port box)
- Cu thermalization strap
- Superconducting coil (flux-bias)

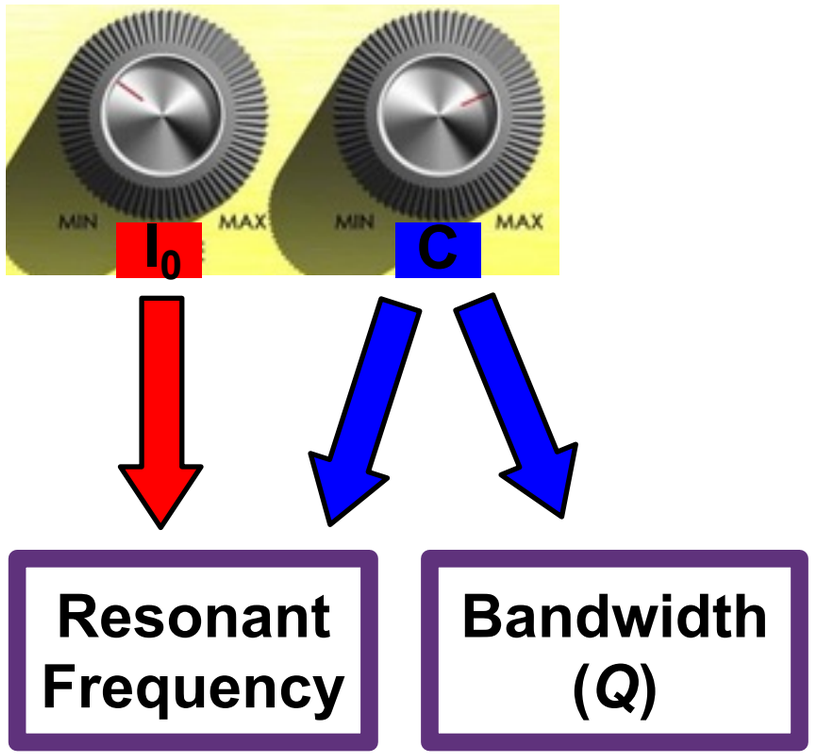


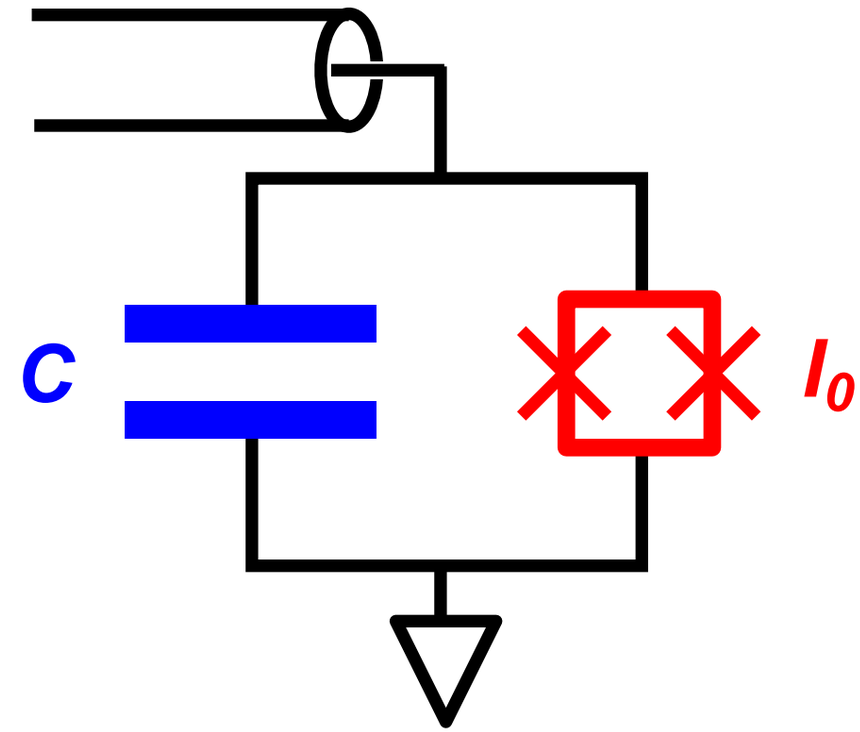




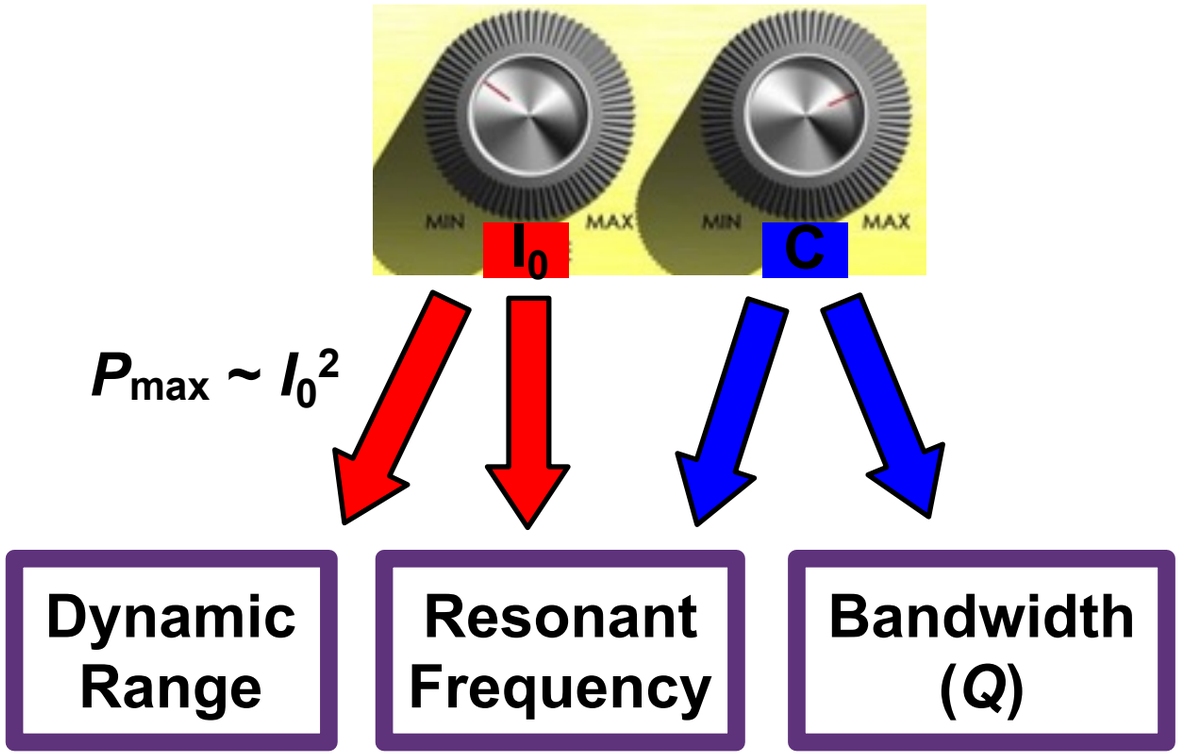
Designers:
D. Wright
R. Lolowang

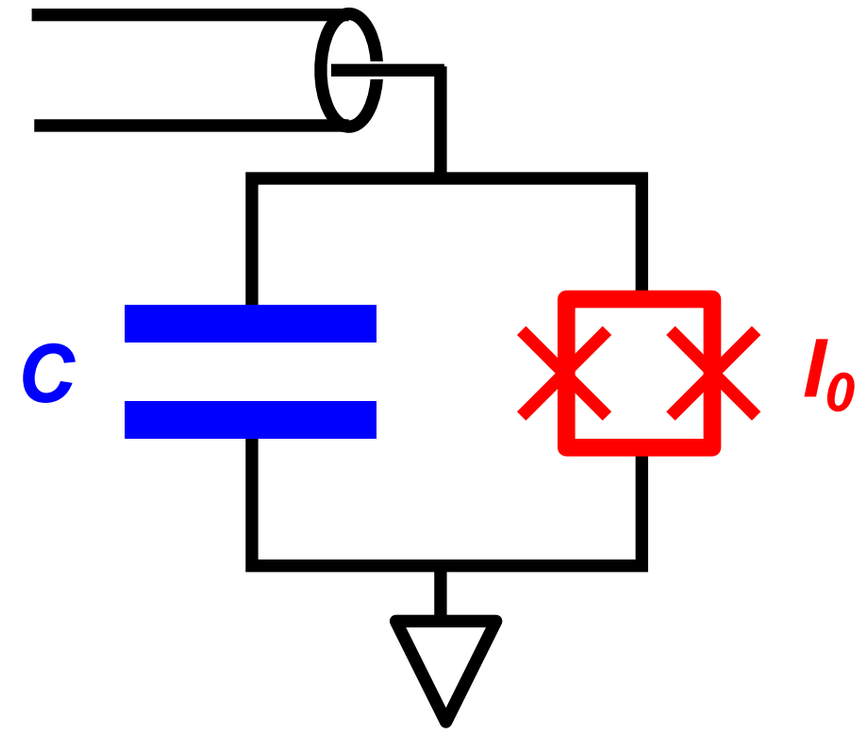
Dynamic Range and Nonlinearity



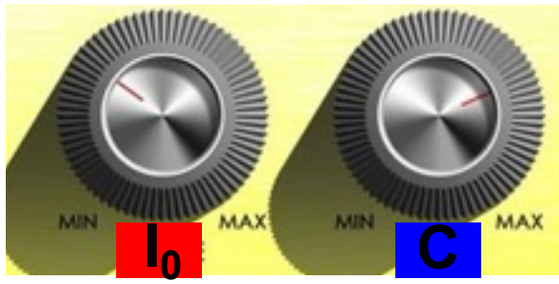


Dynamic Range and Nonlinearity





Dynamic Range and Nonlinearity

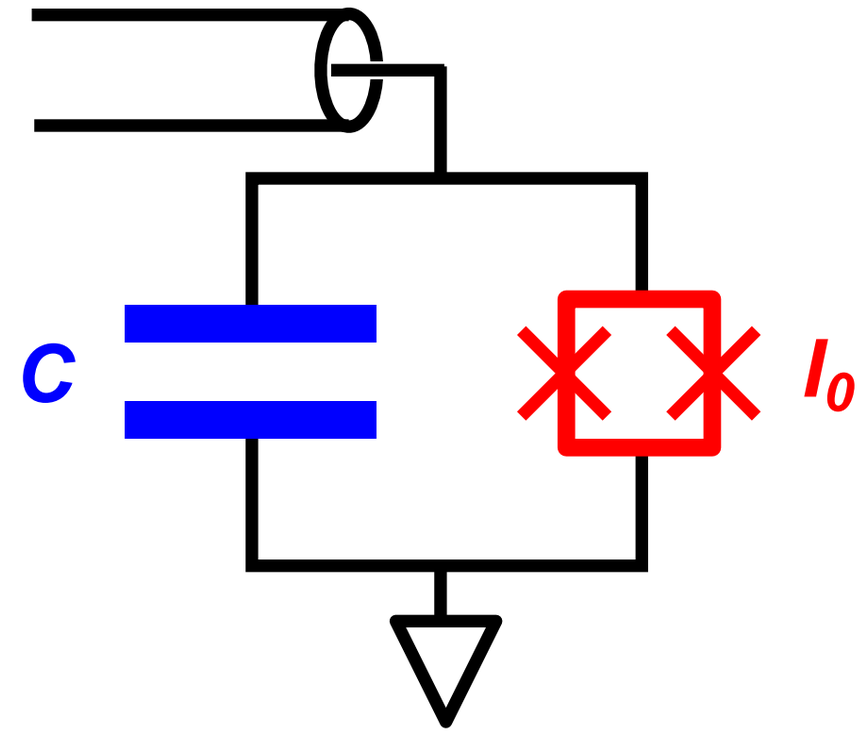


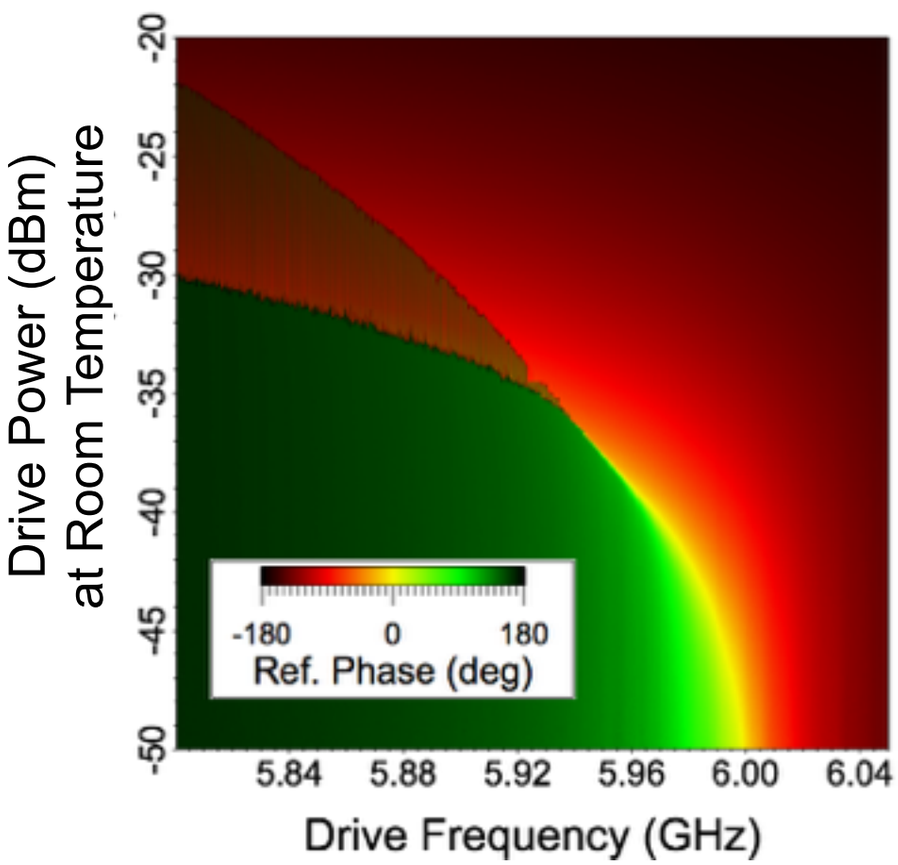
$P_{max} \sim I_0^2$

Dynamic Range

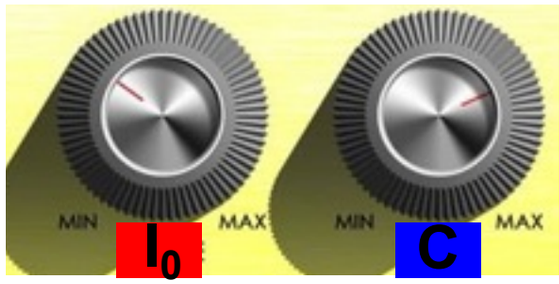
Resonant Frequency

Bandwidth (*Q*)





Dynamic Range and Nonlinearity



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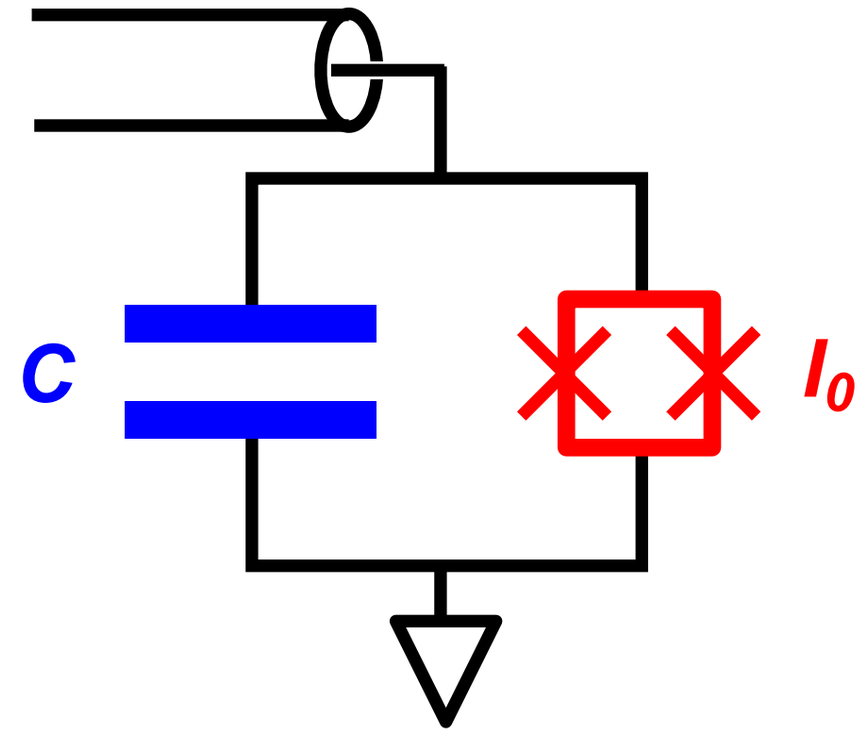
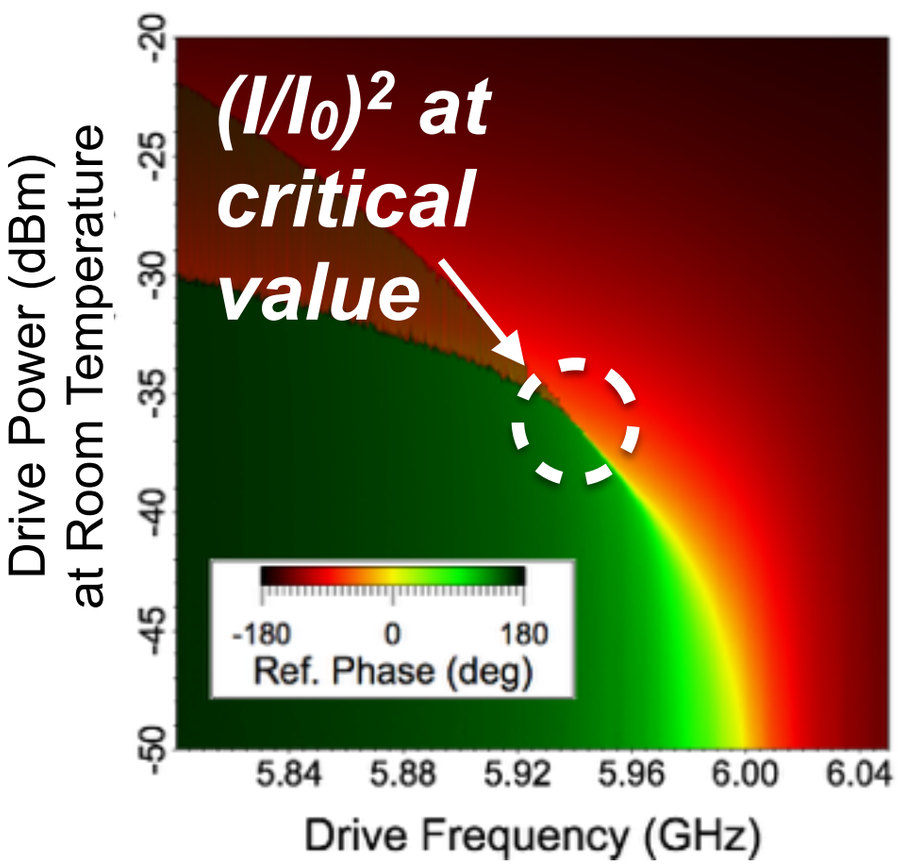
Dynamic Range

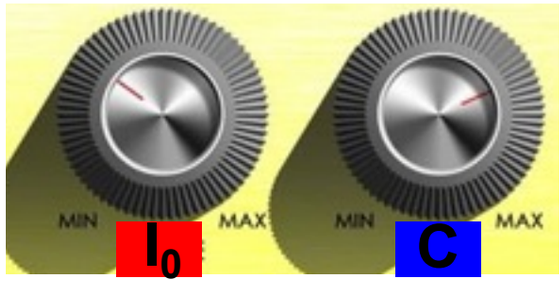
Resonant Frequency

Bandwidth (*Q*)



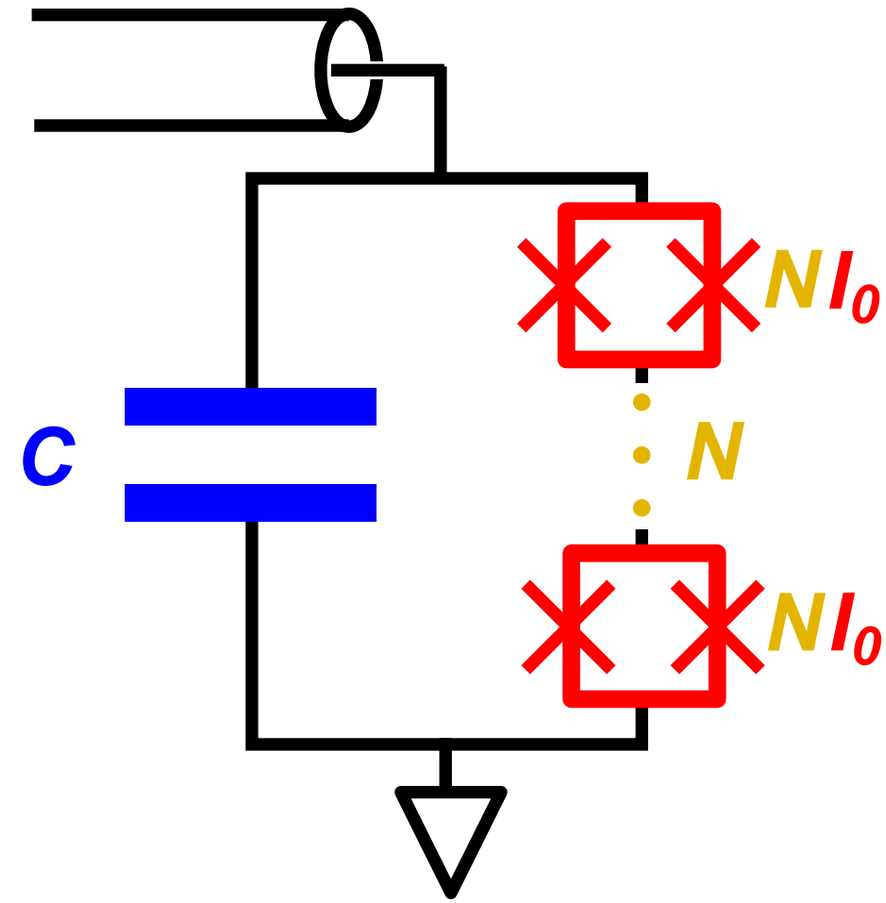


Dynamic Range and Nonlinearity

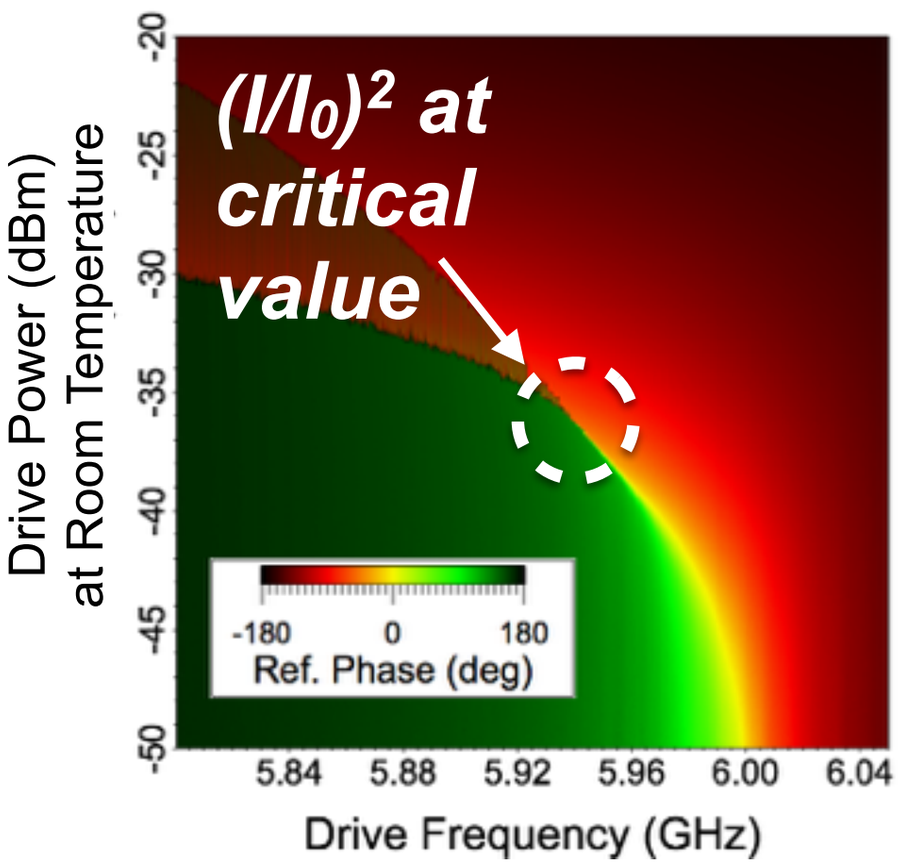


$P_{max} \sim I_0^2$

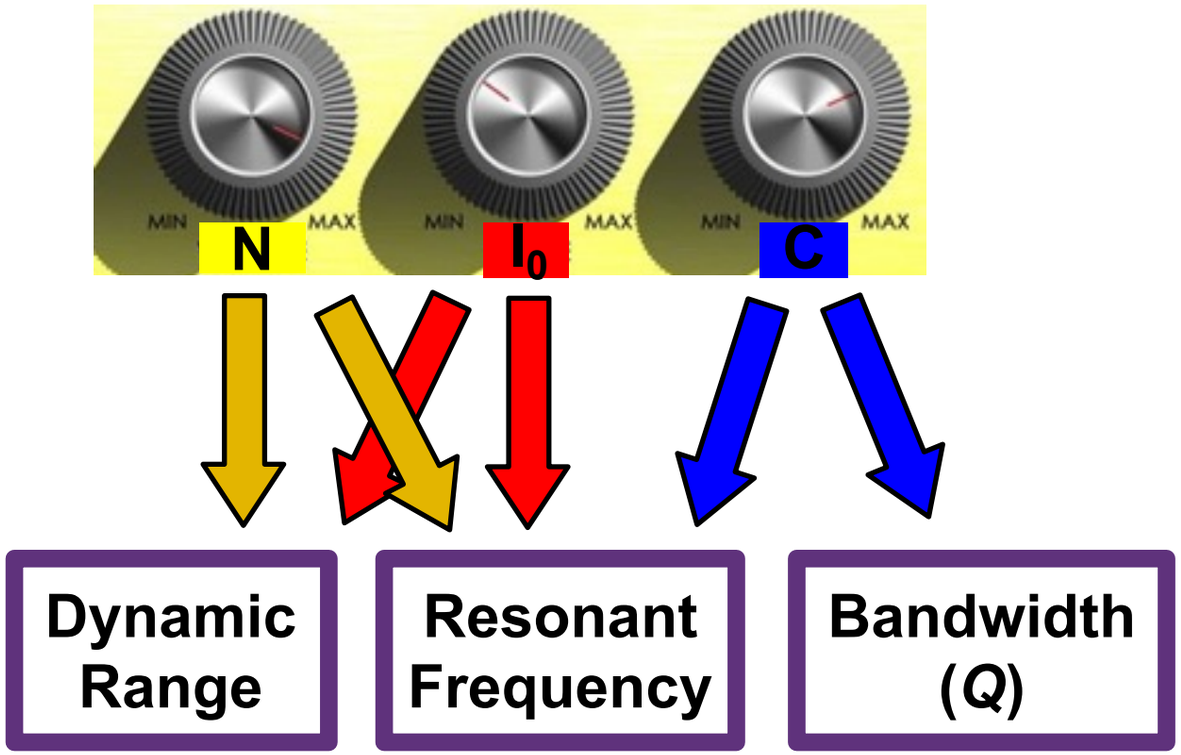
Dynamic Range | **Resonant Frequency** | **Bandwidth (*Q*)**

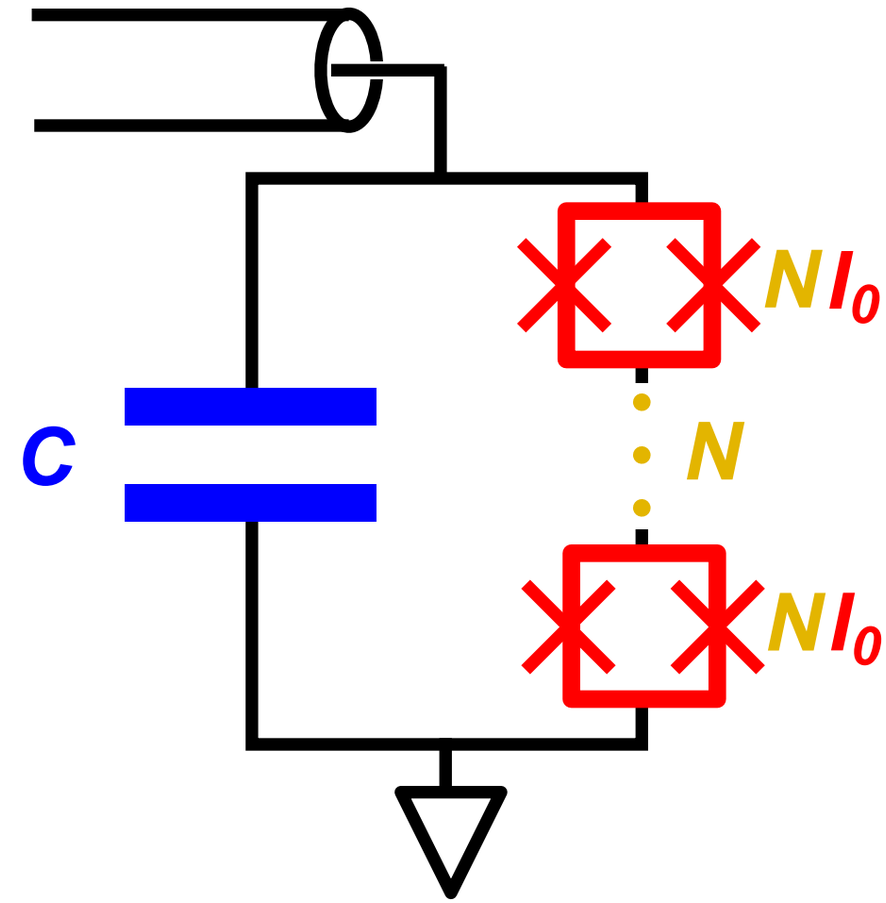


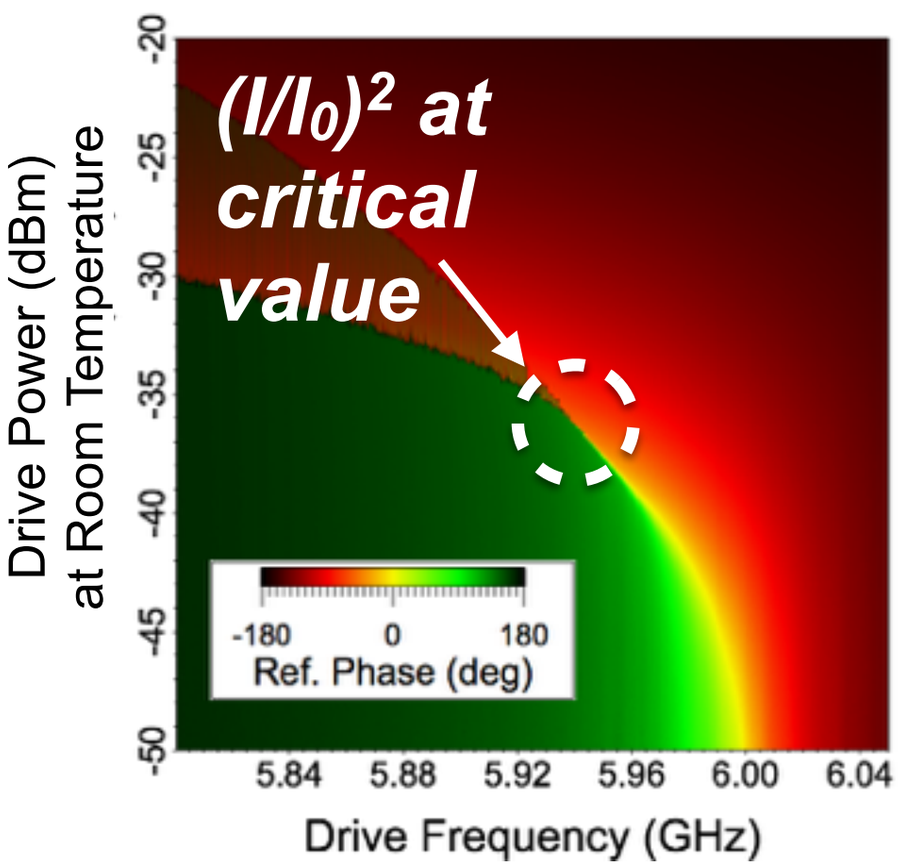
- **Josephson inductance unchanged**
- **Critical current scaled by *N***



Dynamic Range and Nonlinearity

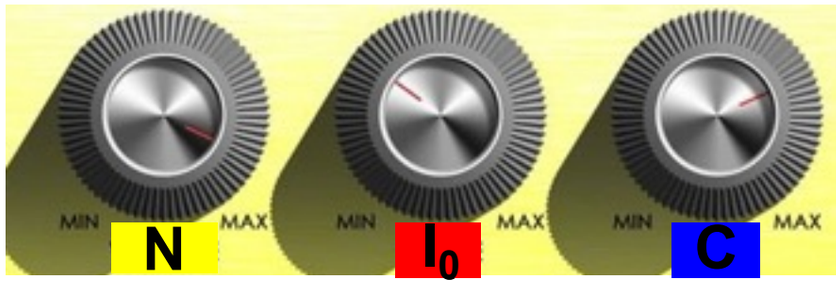


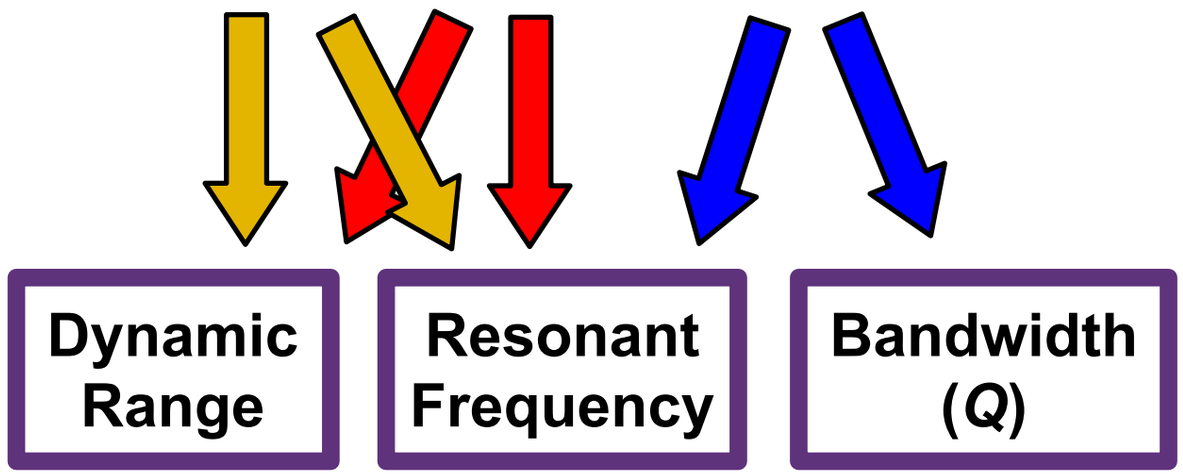


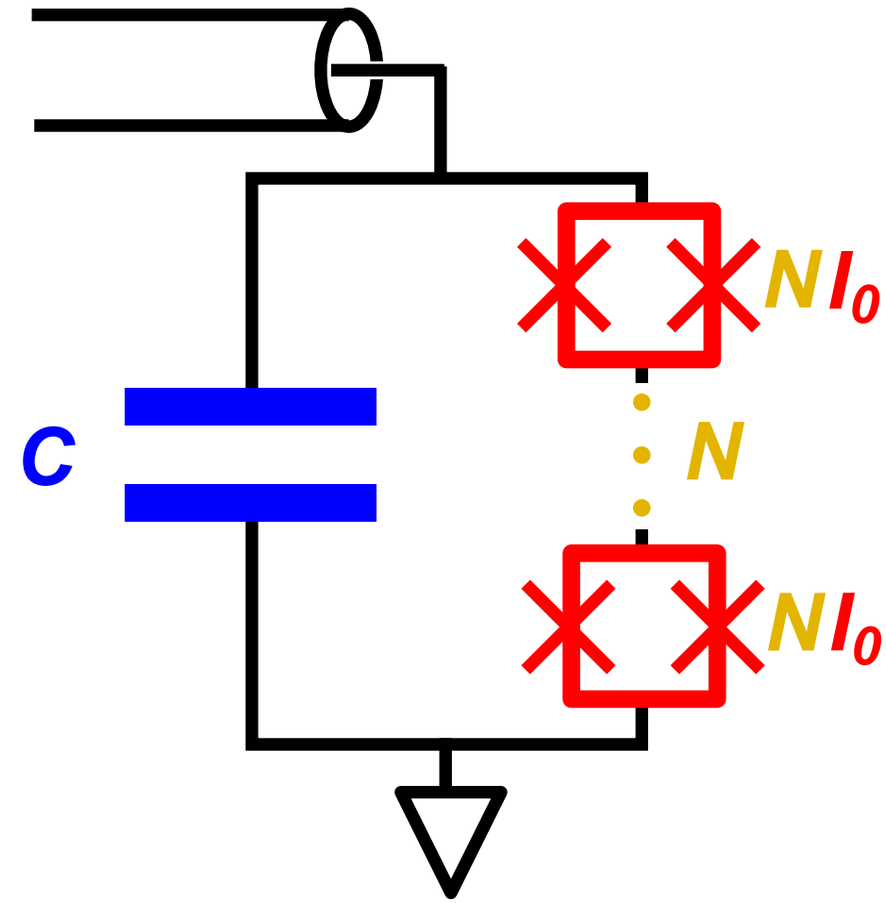


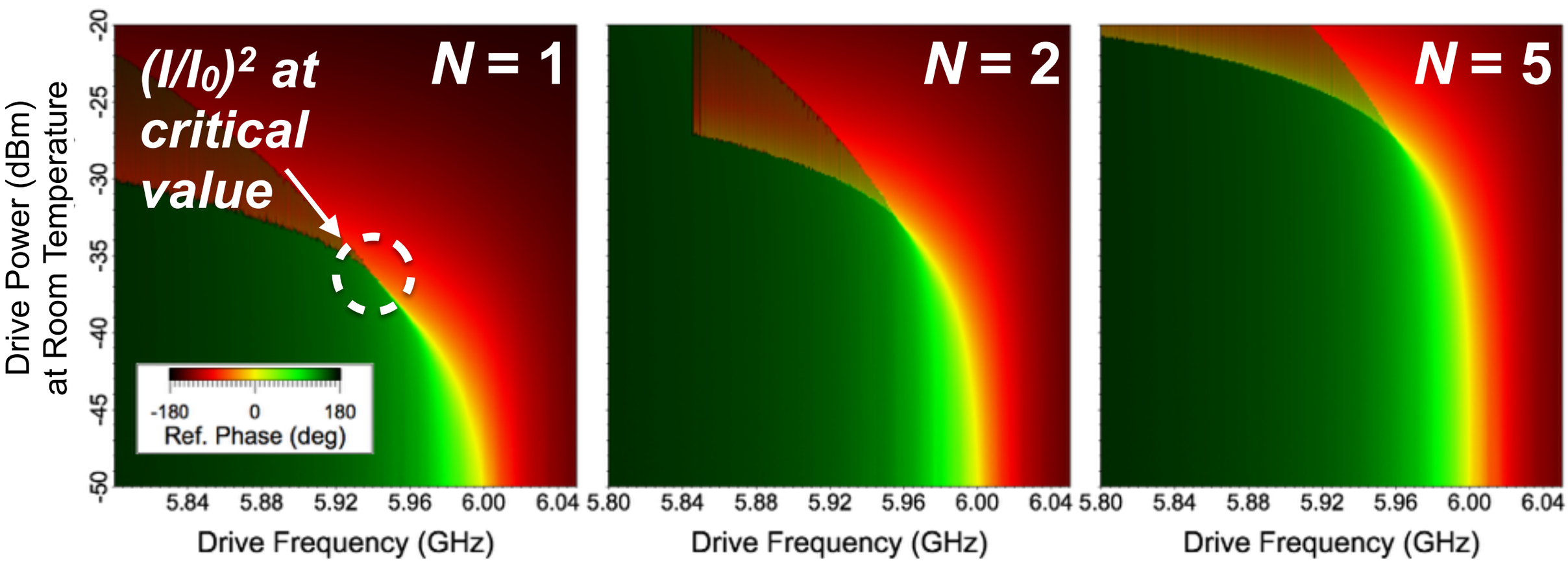
- Josephson inductance unchanged
- Critical current scaled by *N*

Dynamic Range and Nonlinearity

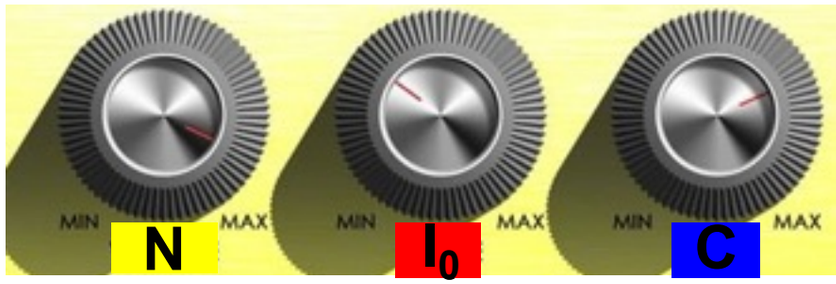


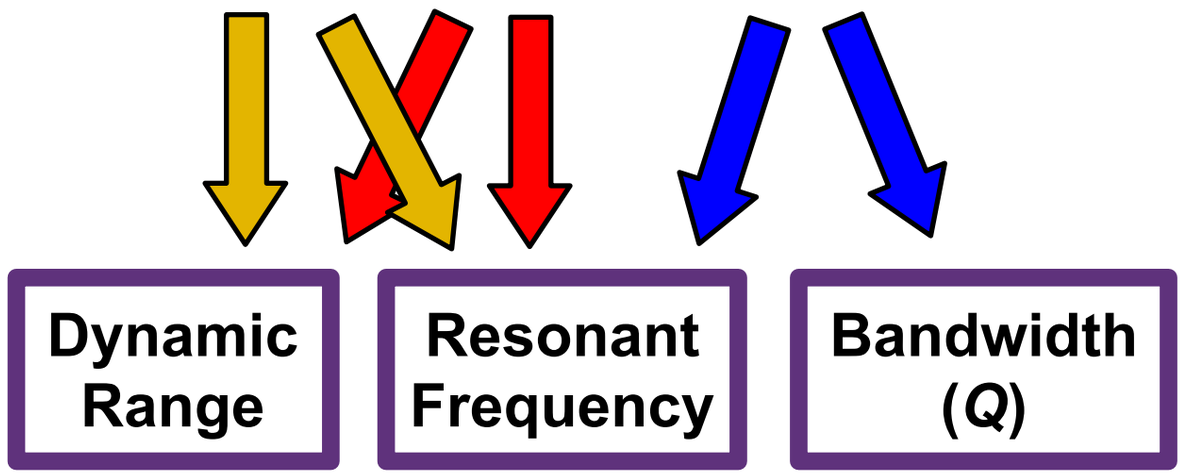


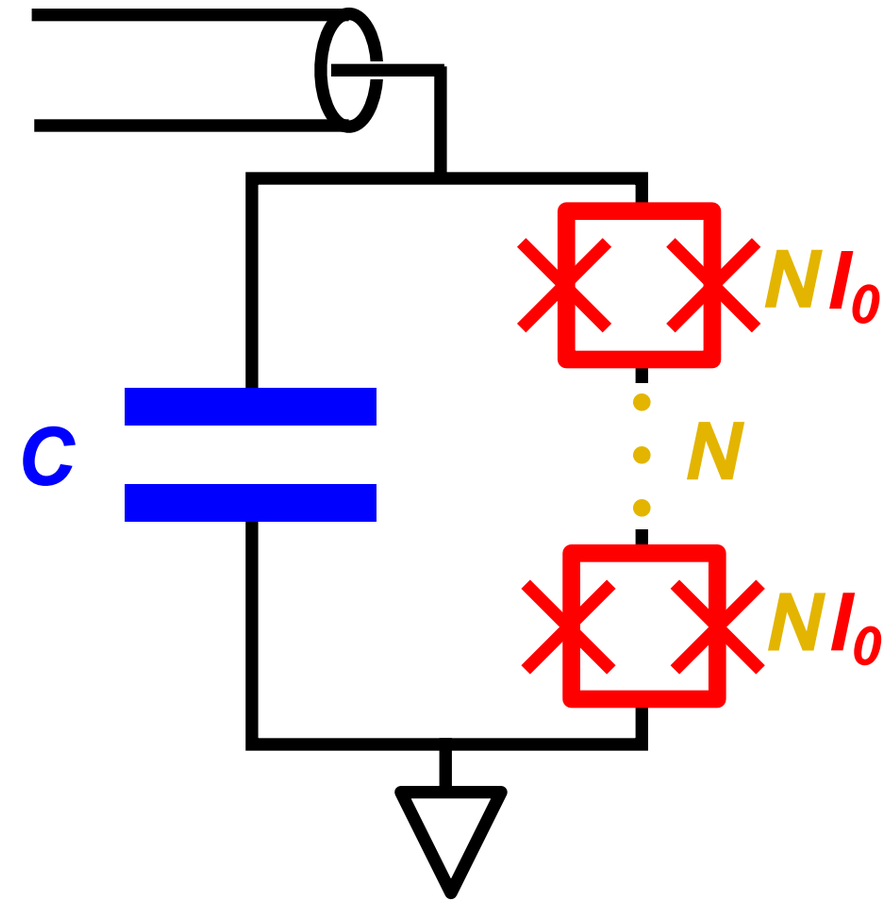


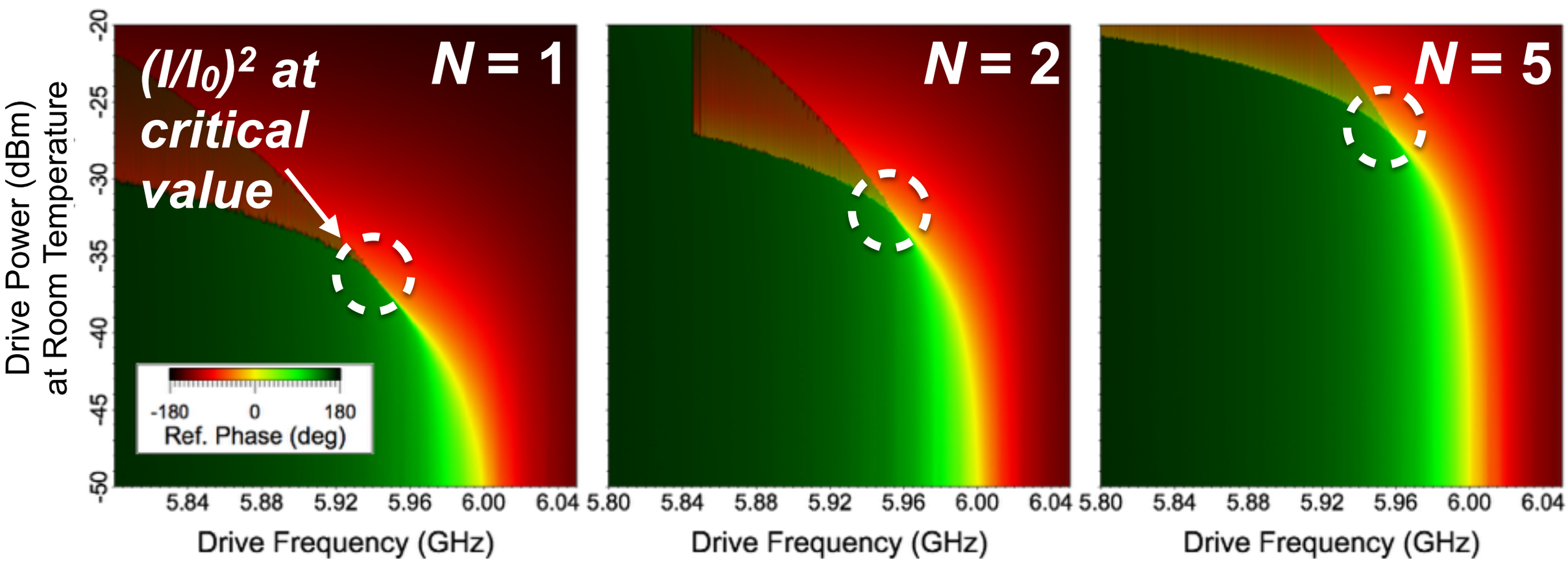


Dynamic Range and Nonlinearity



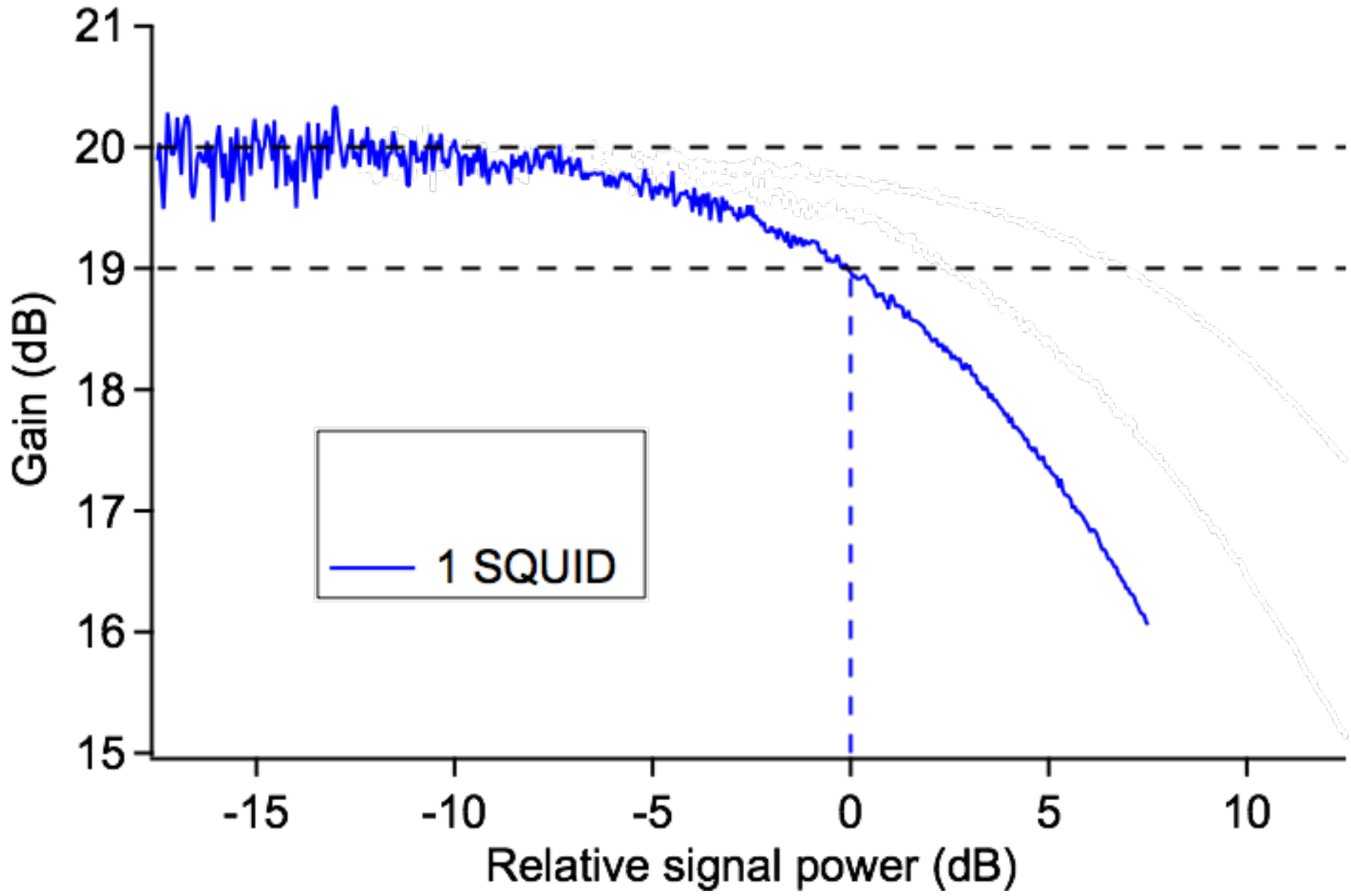






Dynamic Range and Nonlinearity

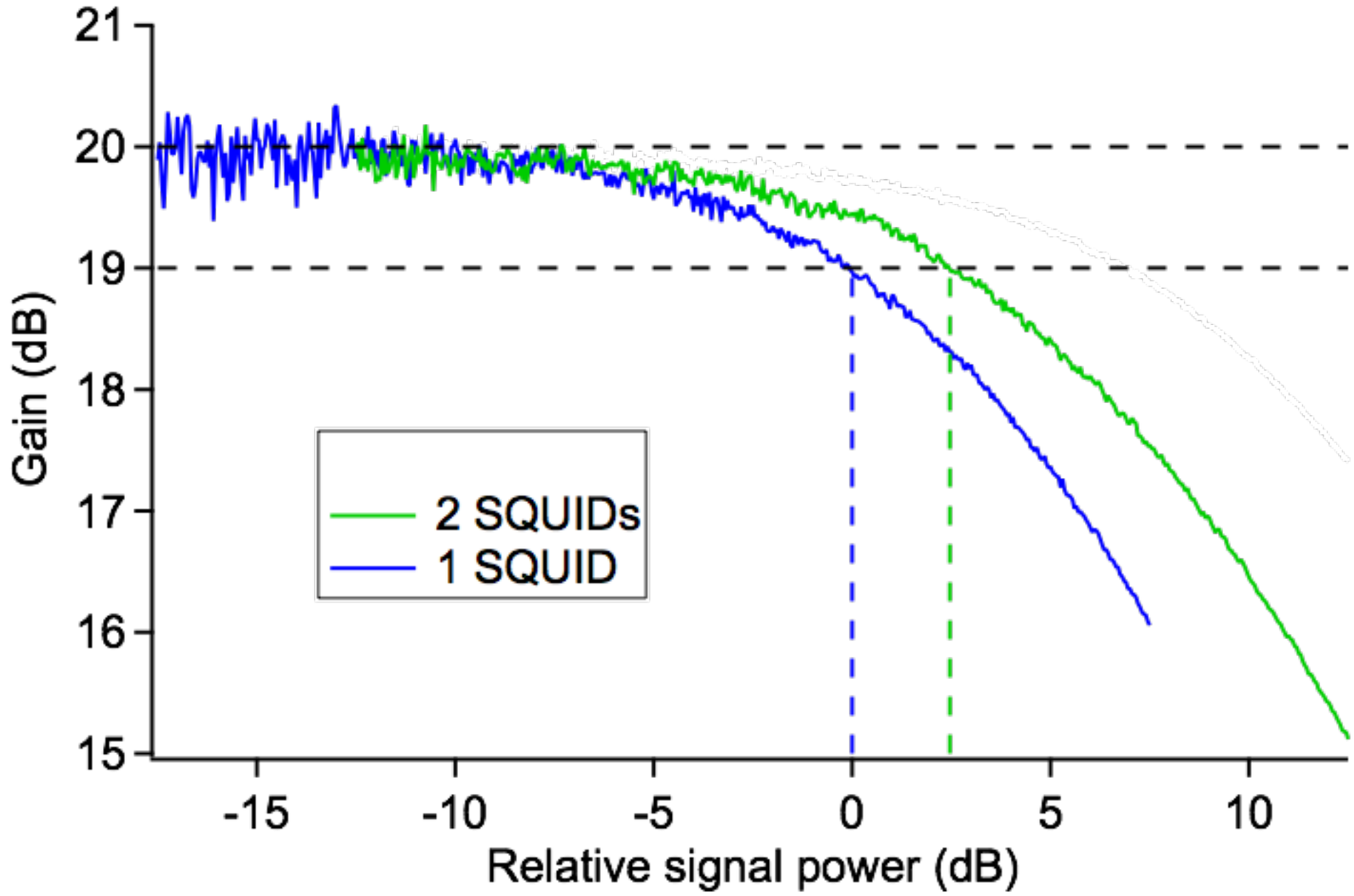
Compression at 6 GHz:



Normalized to *N*=1 device performance

Dynamic Range and Nonlinearity

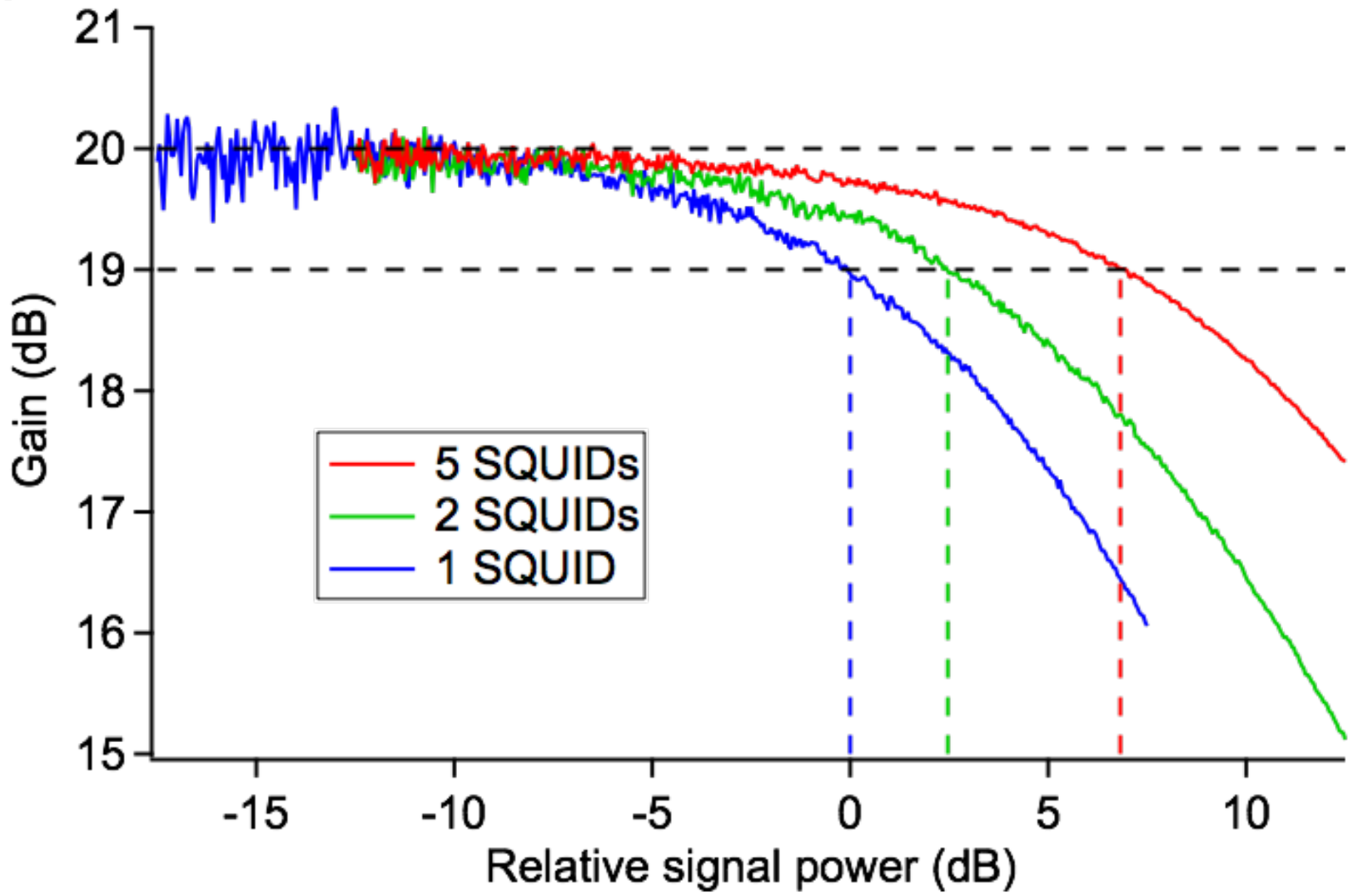
Compression at 6 GHz:



Normalized to *N*=1 device performance

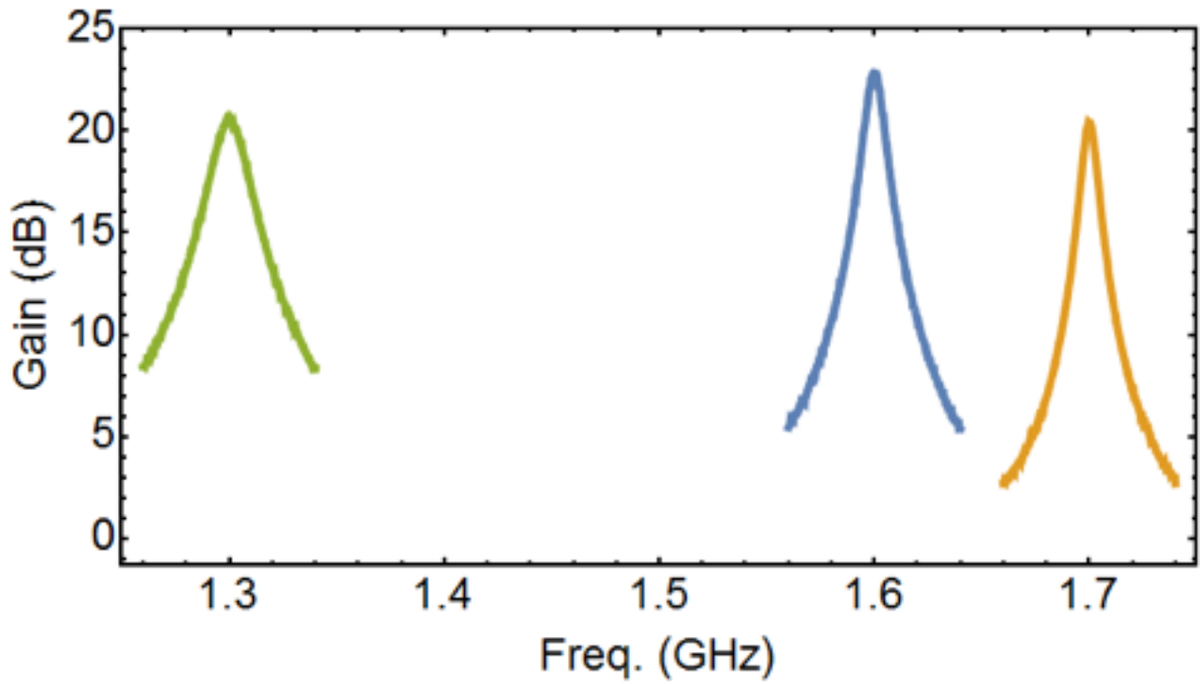
Dynamic Range and Nonlinearity

Compression at 6 GHz:

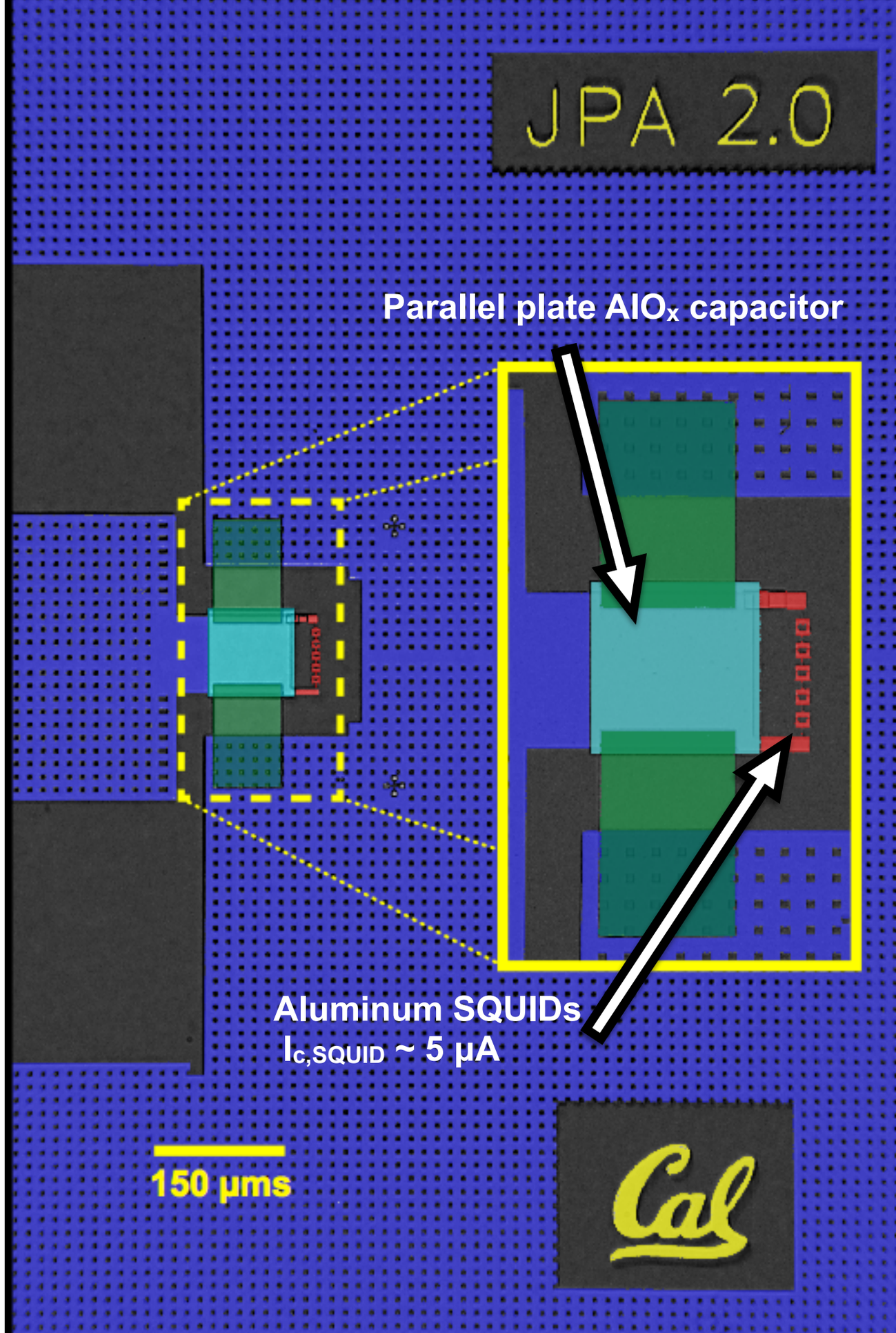


Normalized to *N*=1 device performance

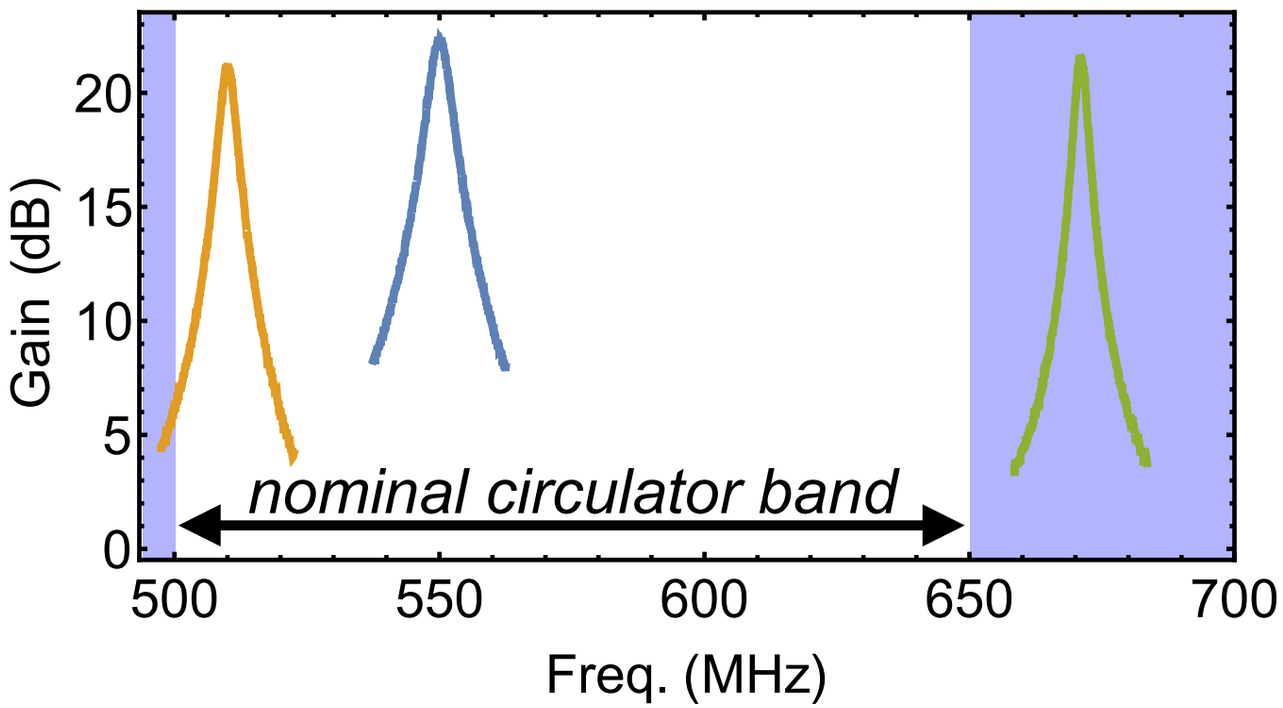
L-Band JPA



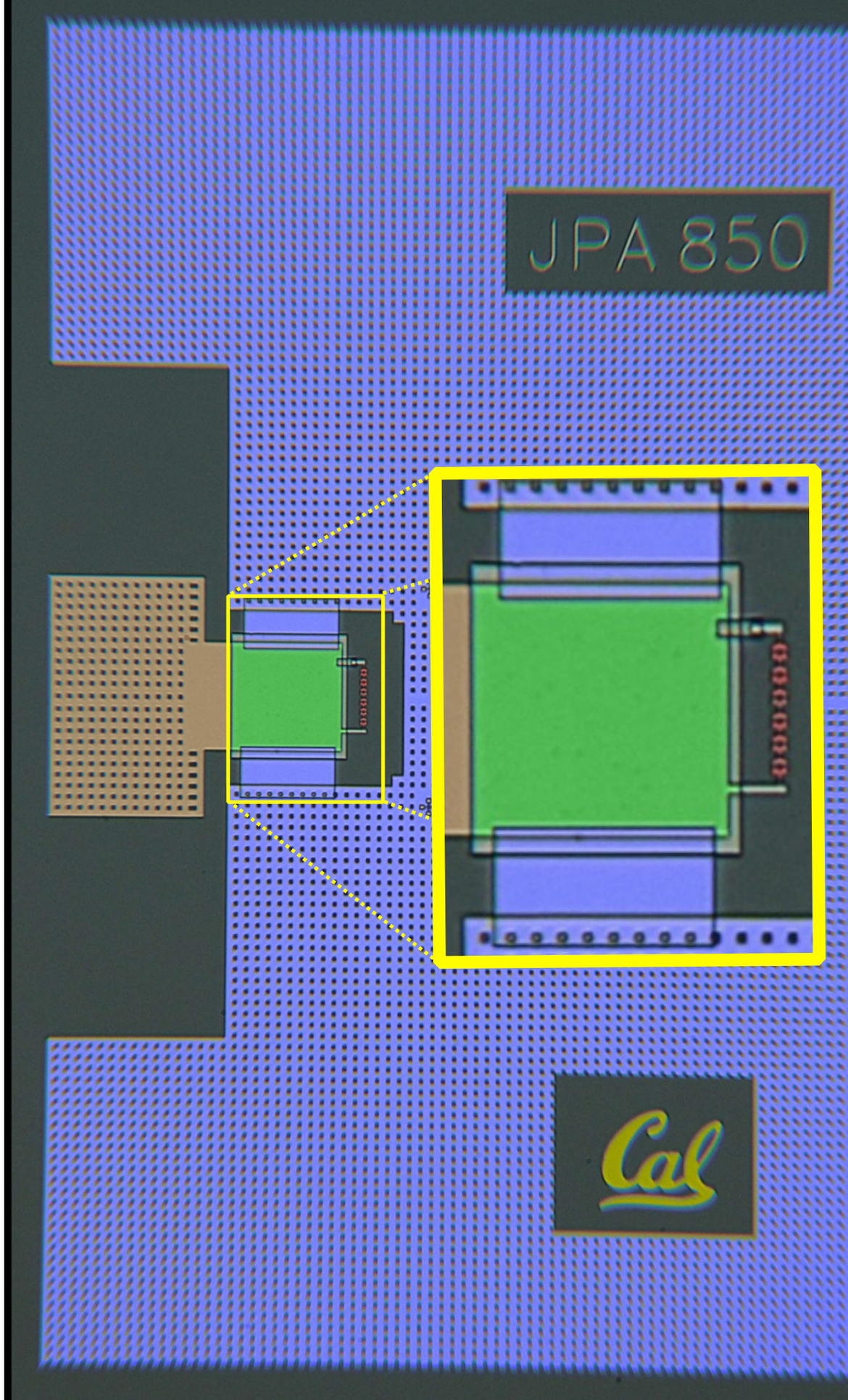
- 5-SQUID design
- SSBW ~ 4-6 MHz
- 10-13dB SNR improvement observed
- Delivered to ADMX at Washington U.



~500-700 MHz JPA

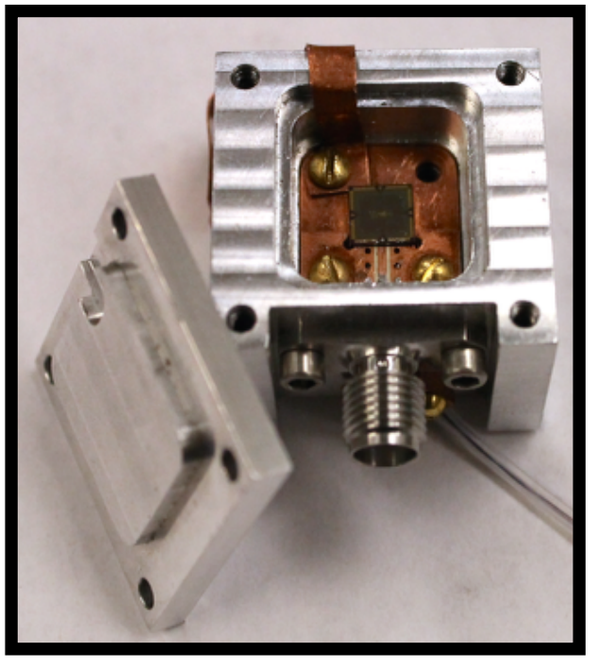


- 6-SQUID design
- SSBW ~ 1.5-2.5 MHz
- P_{1dB} ~ -140 dBm
  — improve with more SQUIDs?
- >13dB SNR improvement observed
- Tunability limited by circulator

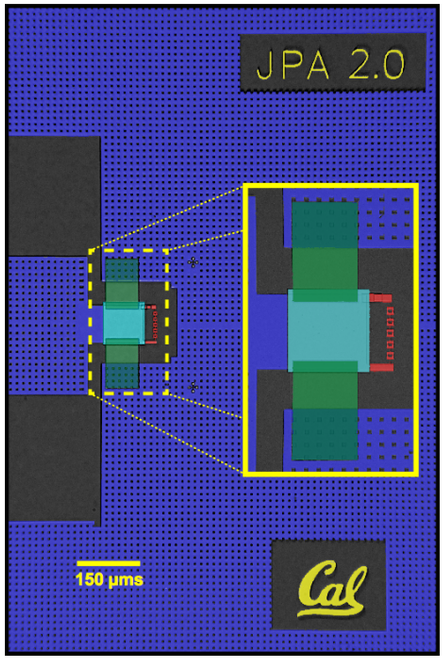


Summary and Outlook

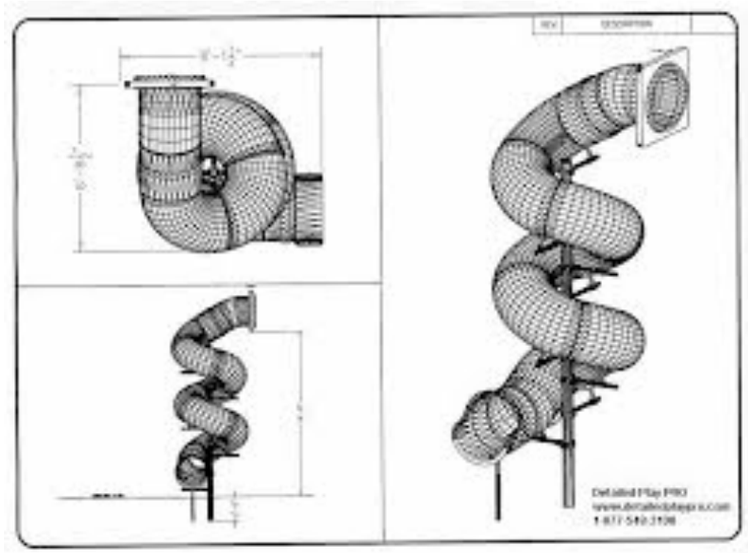
- JPAs dramatically improve measurement efficiency of very small microwave signals
- L-band JPA has been developed, tested, and delivered to ADMX
- 500-700 MHz JPA has been developed and tested.
- Single-ended C-band (4-6 GHz) JPA in development



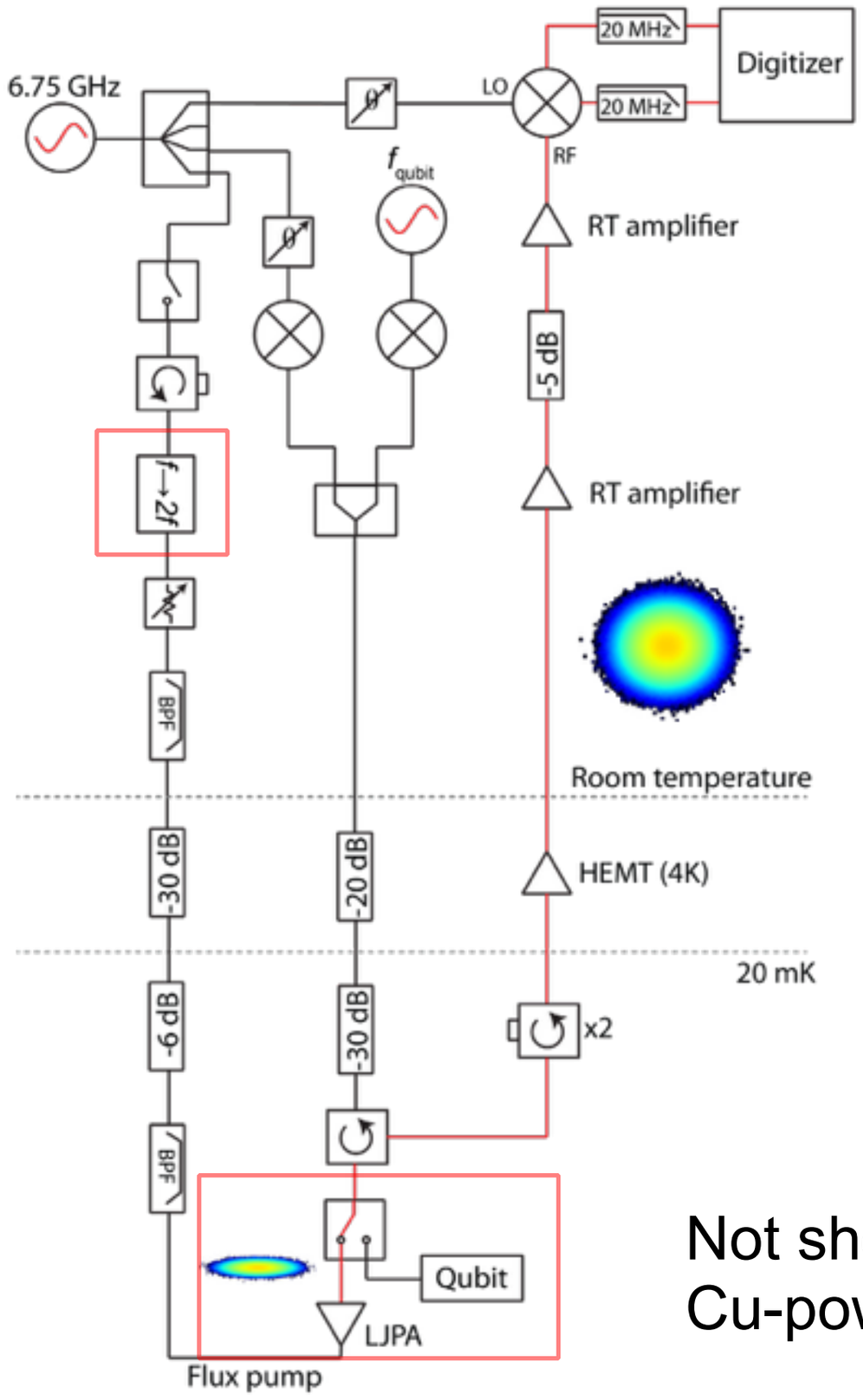
Thank you!



EXTRA SLIDES



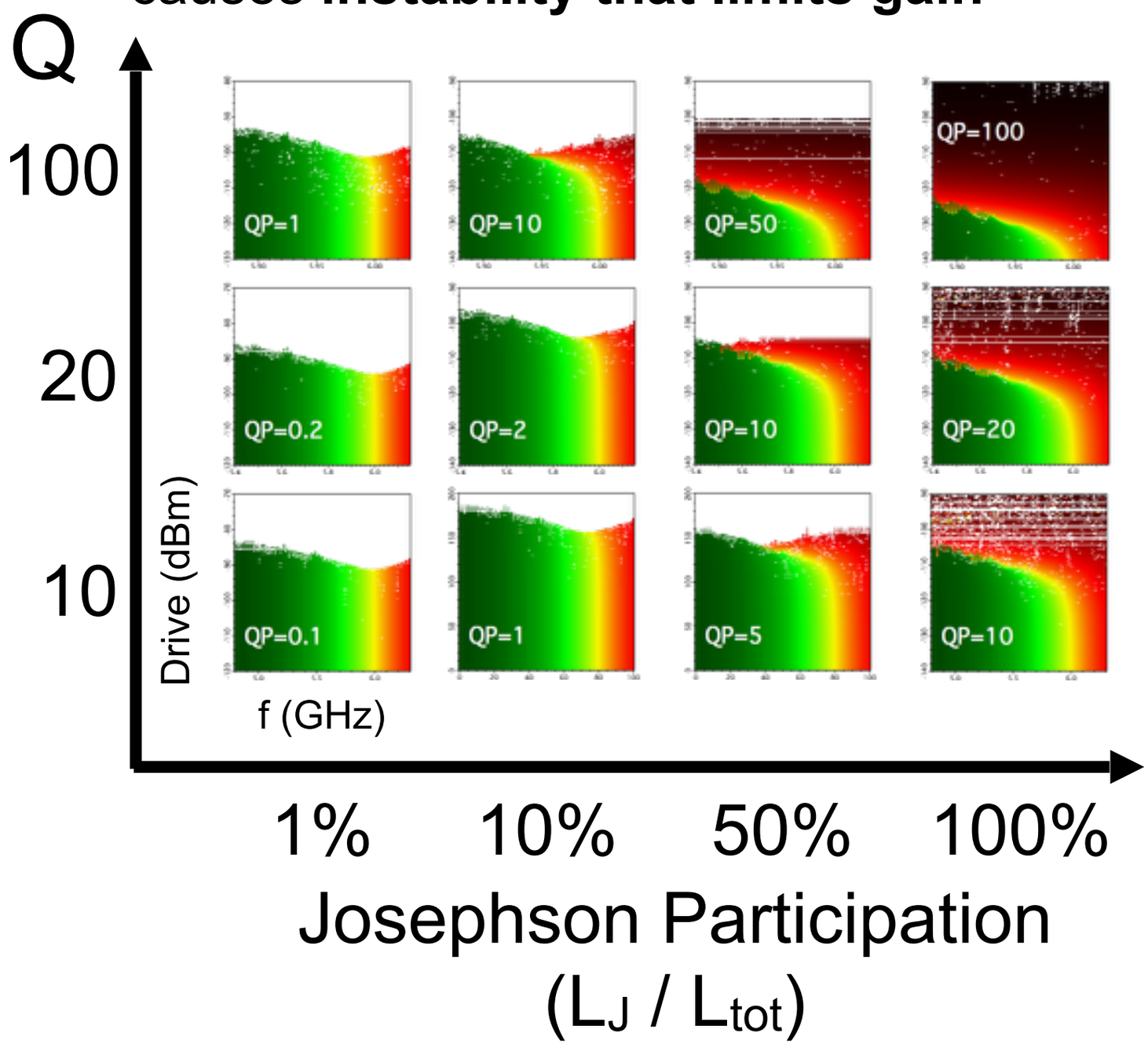
Output field imaging setup

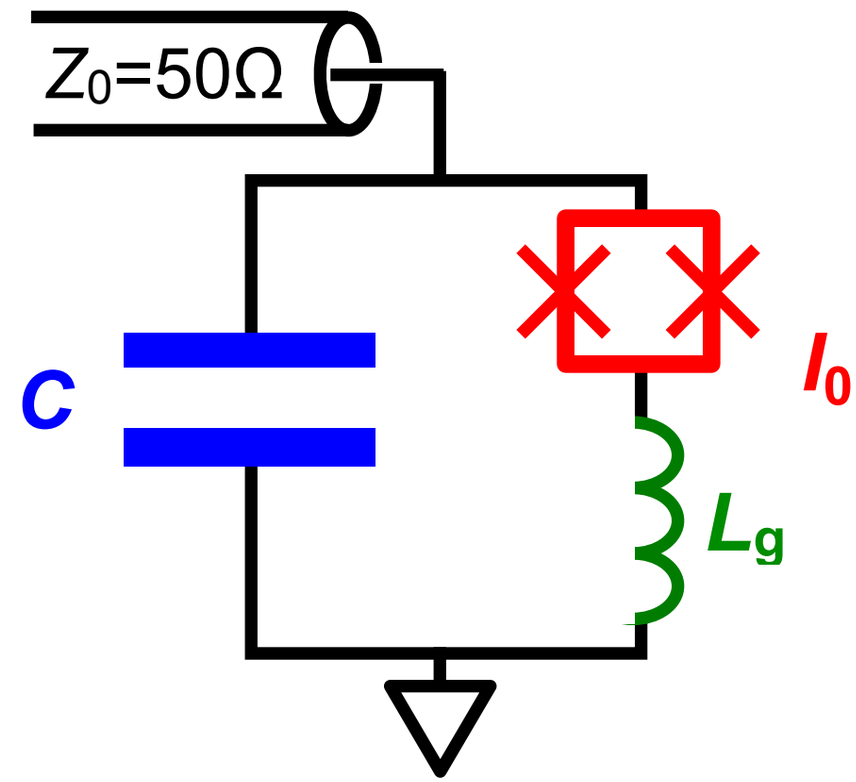


Not shown: DC line with Cu-powder filters for JPA coil.

Device Design III: Bandwidth and Stability

- Any real circuit has some linear inductance, by design or geometric necessity:
  - Total ΔV spread over SQUID, L_g.
    Nonlinearity reduced ➡ greater DR
  - Large L_g ➡ higher-order terms significant, causes **instability that limits gain**



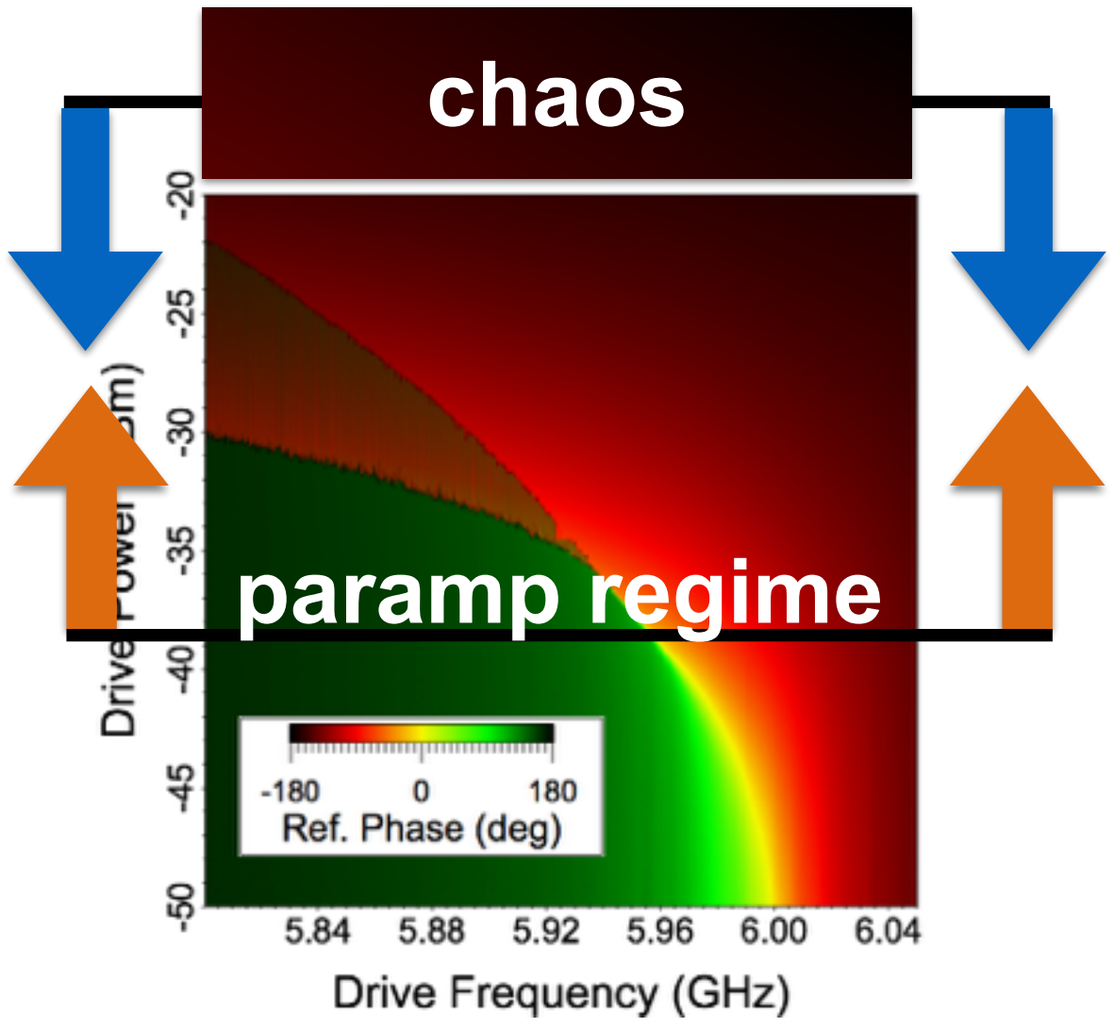


➡ **Rule of thumb: $Q\ L_J/L_{tot}$ > ~5**

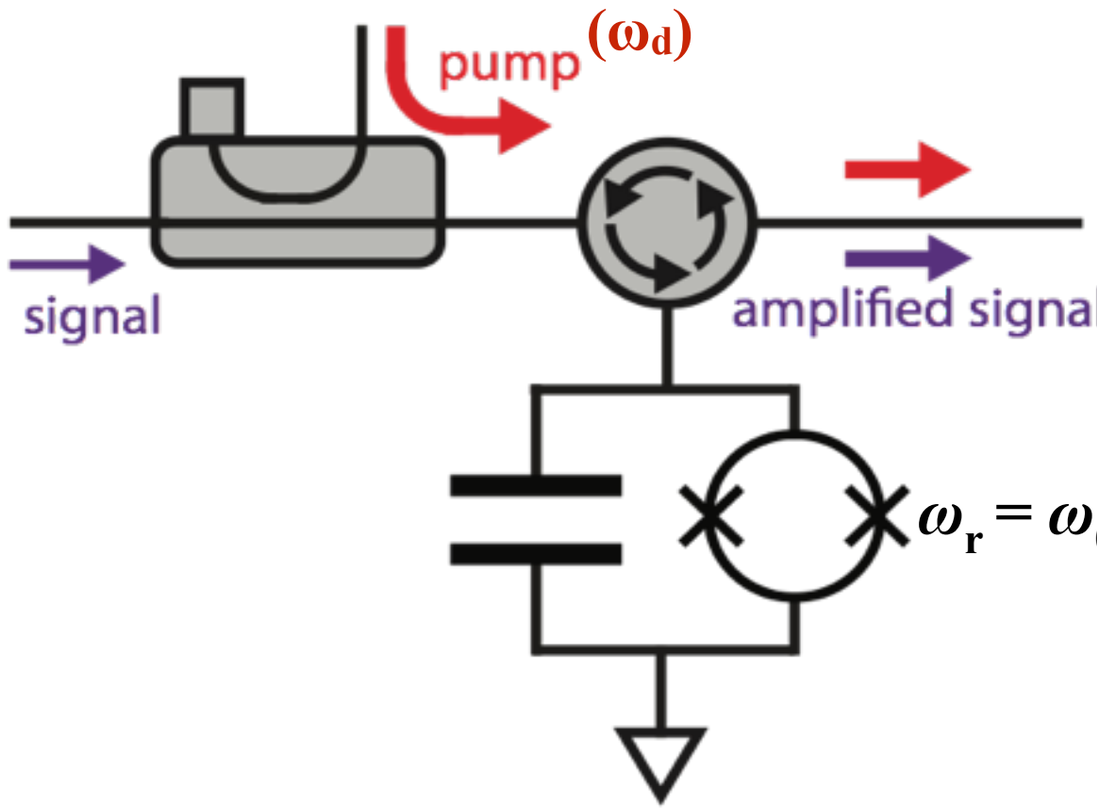
➡ **Minimum possible Q: ~5. Limits maximum bandwidth!**

➡ **Geometric inductance must be minimized in layout to achieve high BW**

Linear Inductance

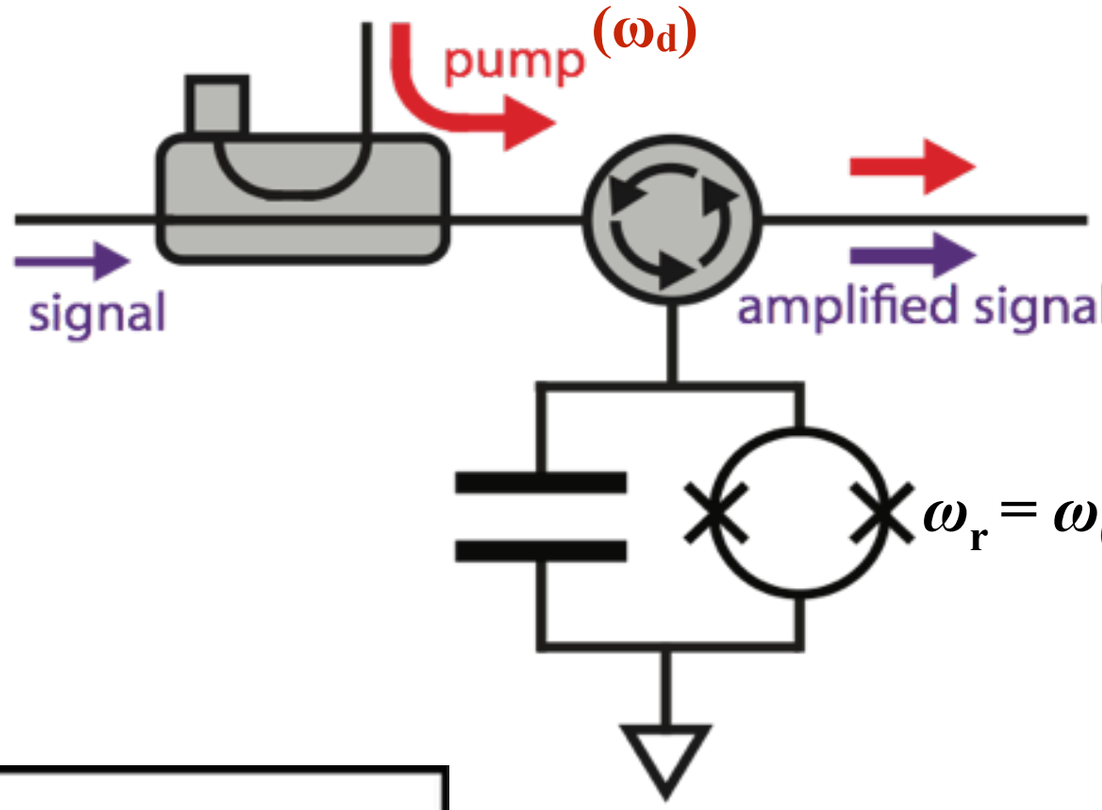


LJPA Operation



$$\omega_r = \omega_0 + \Delta\omega(I_{RF})\cos(2\omega_d t)$$

LJPA Operation



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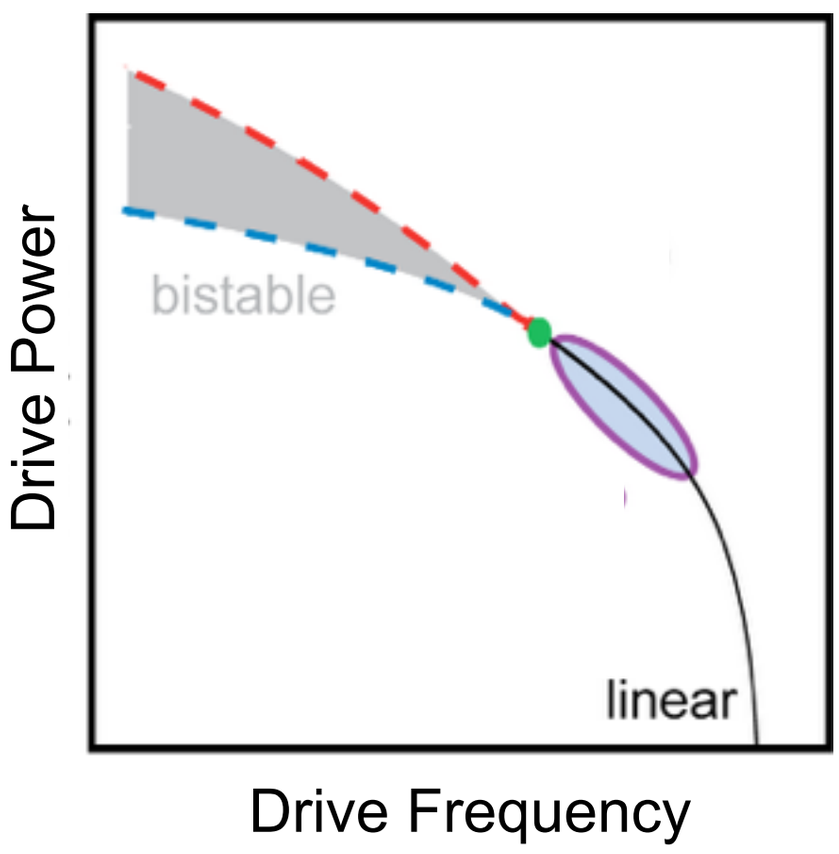
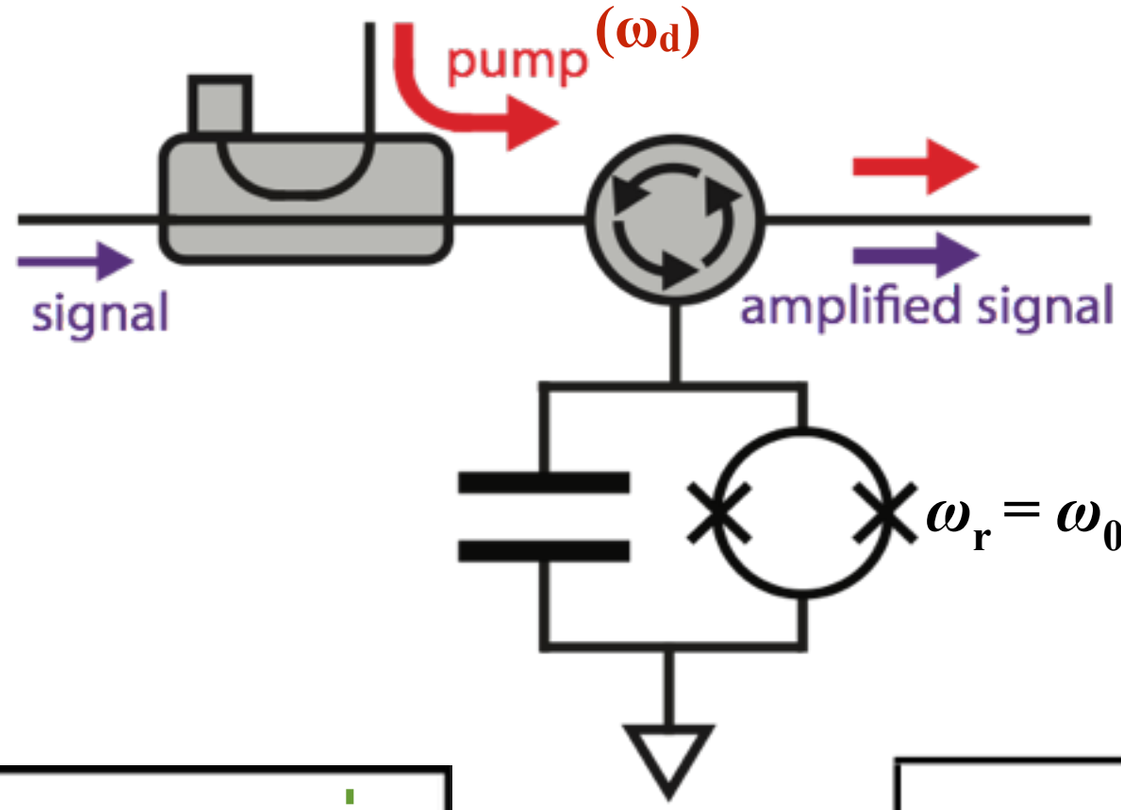


LJPA Operation



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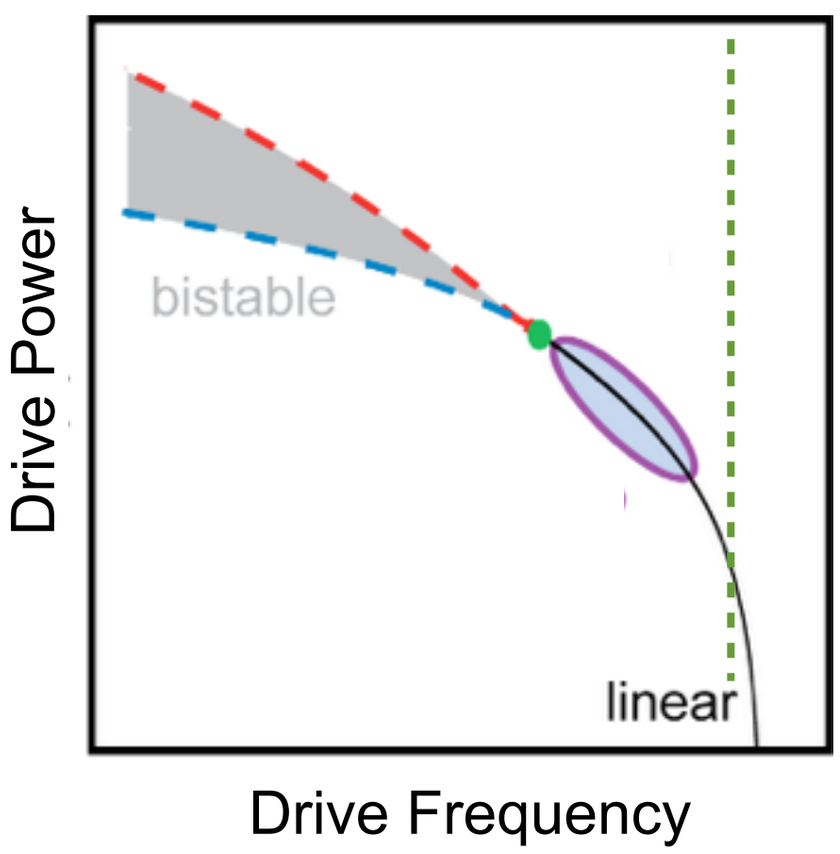
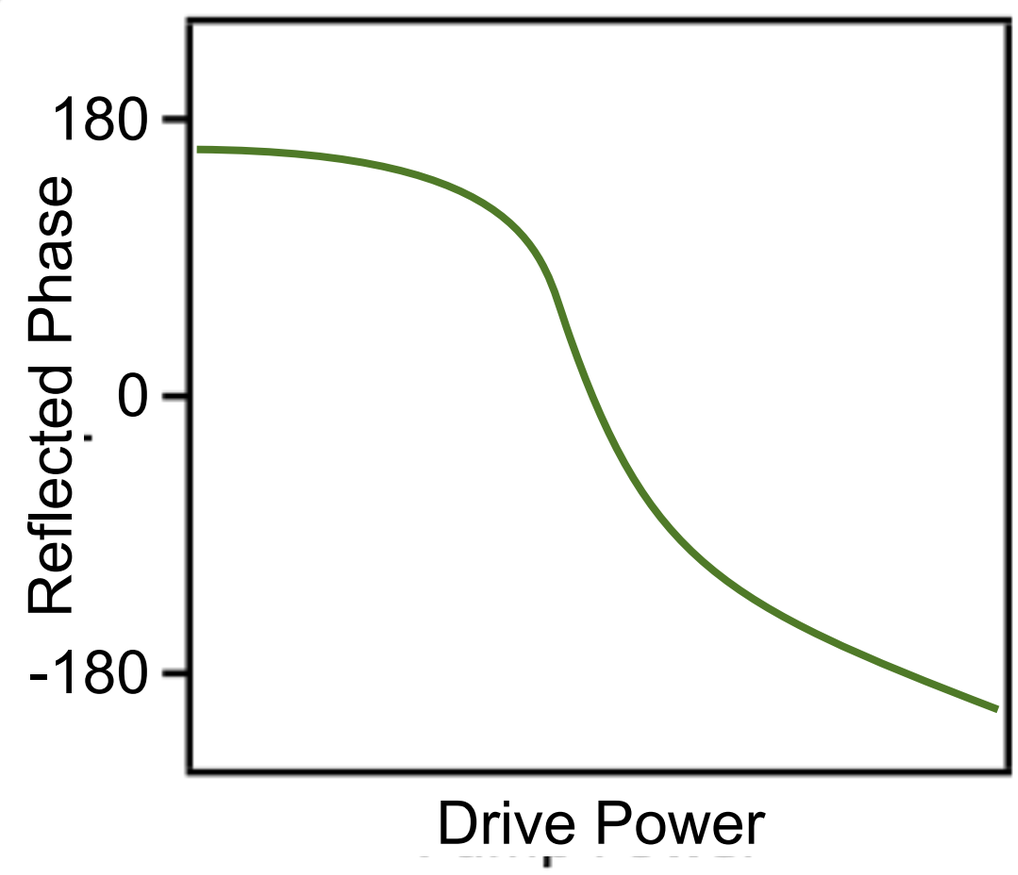
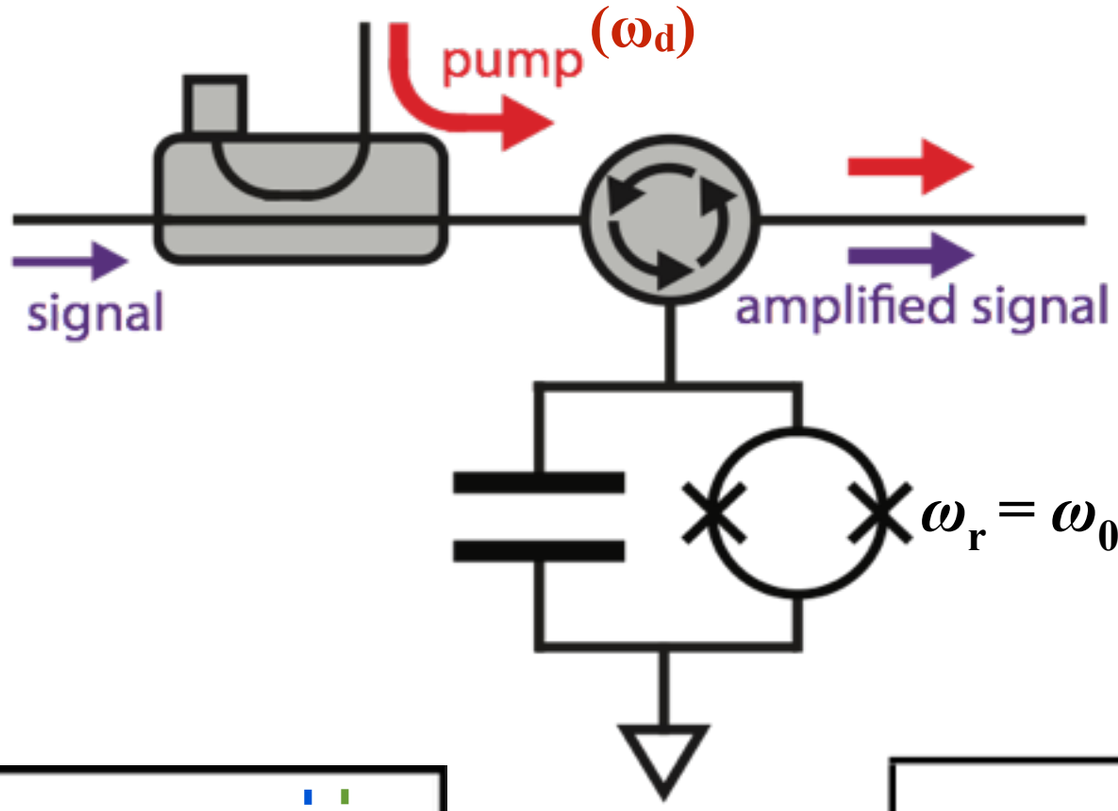




LJPA Operation



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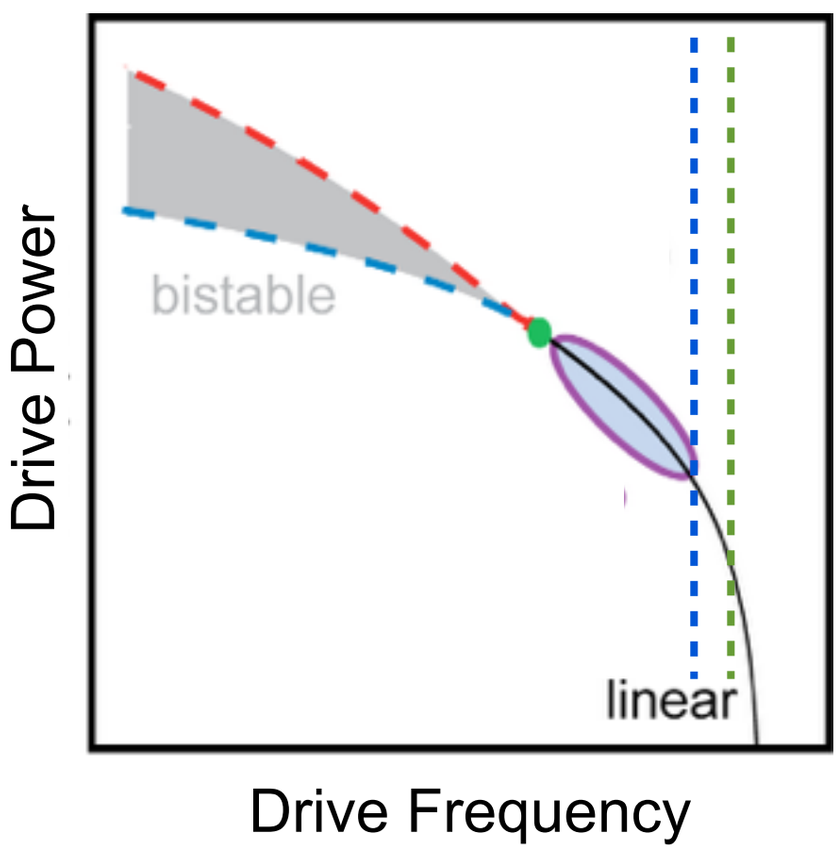
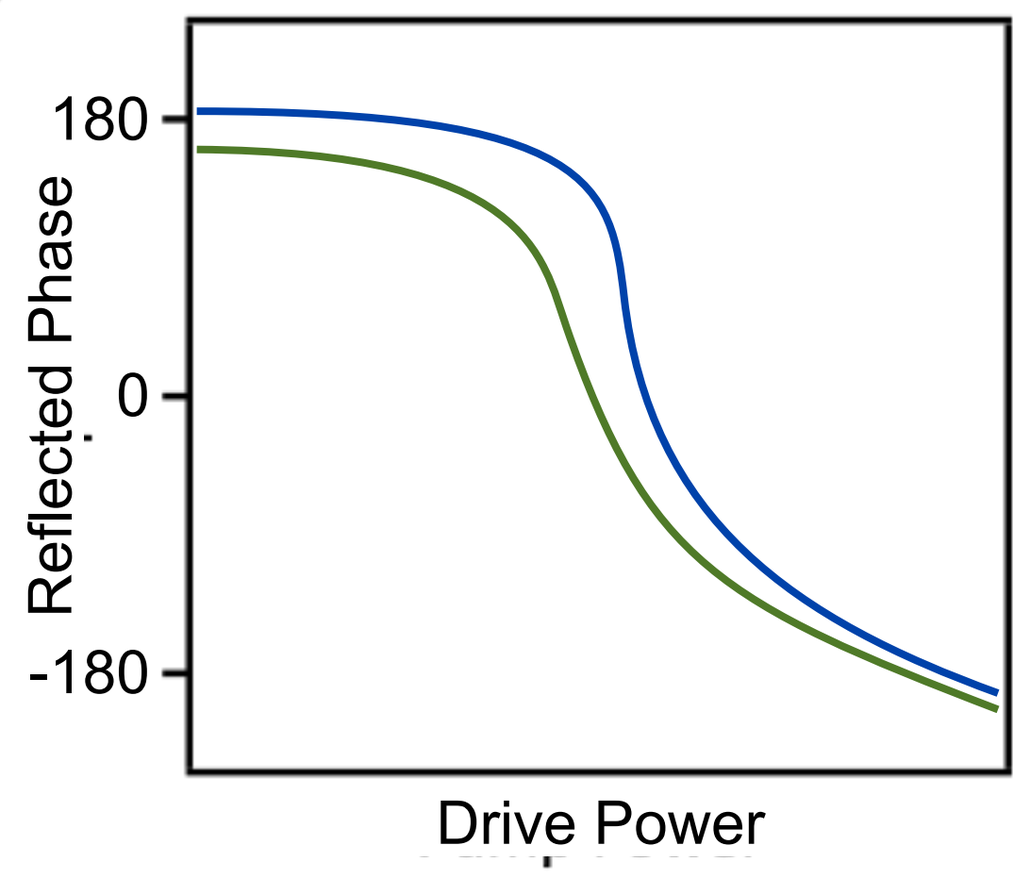
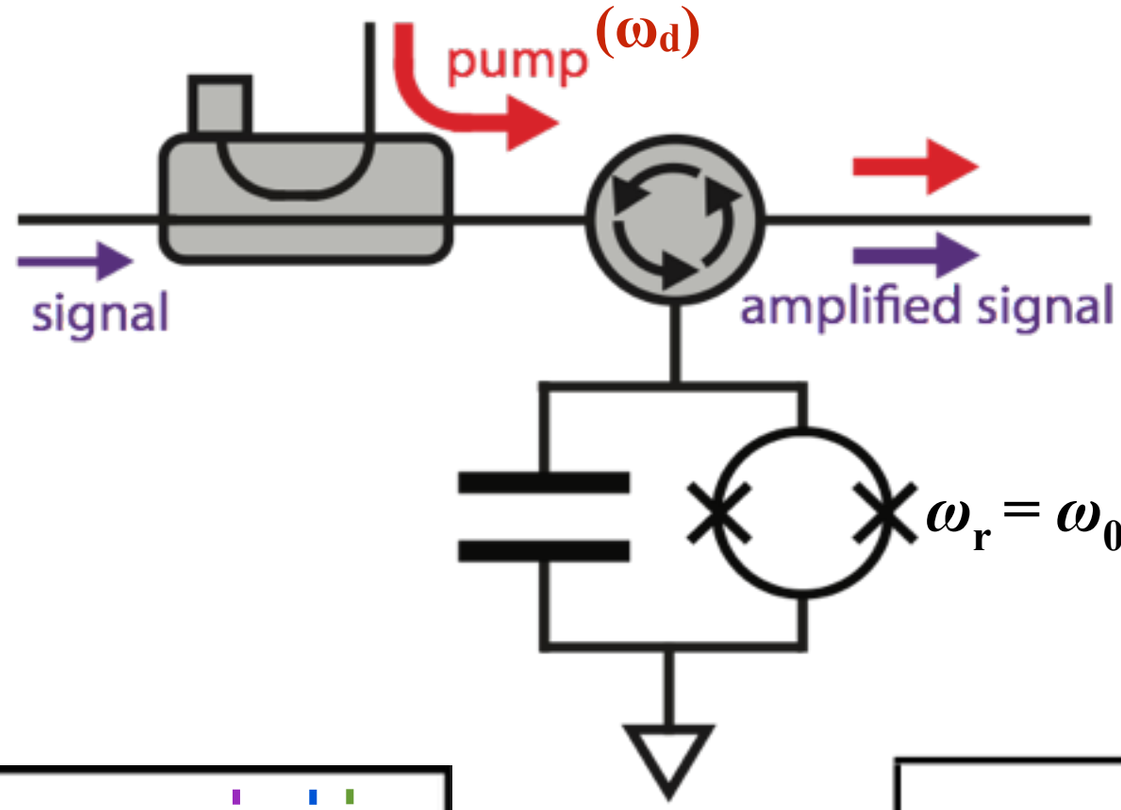




LJPA Operation



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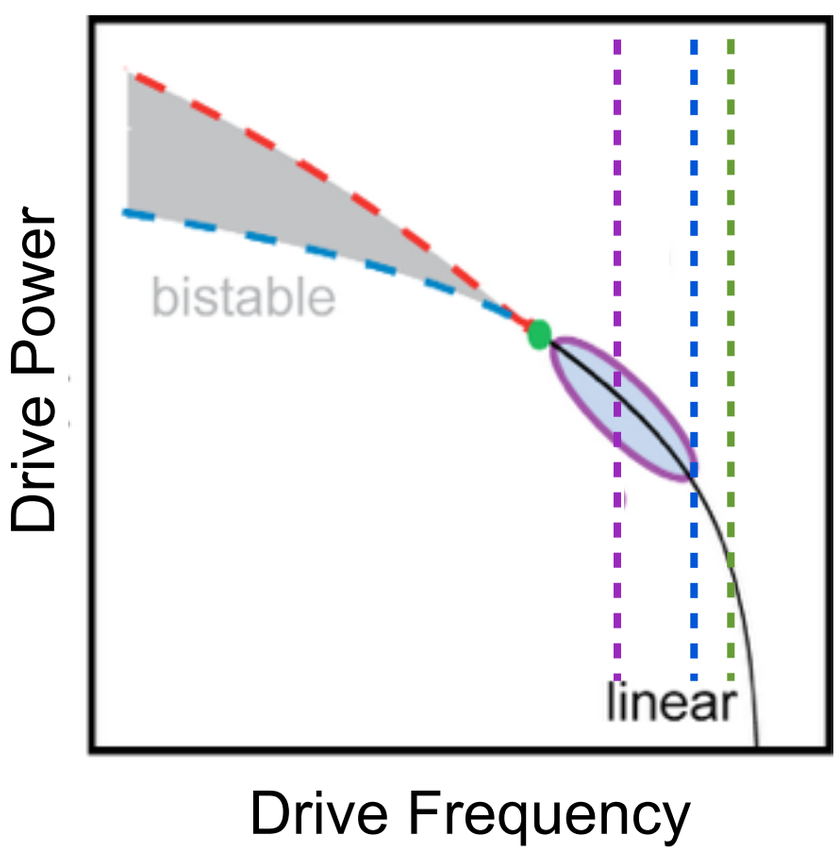
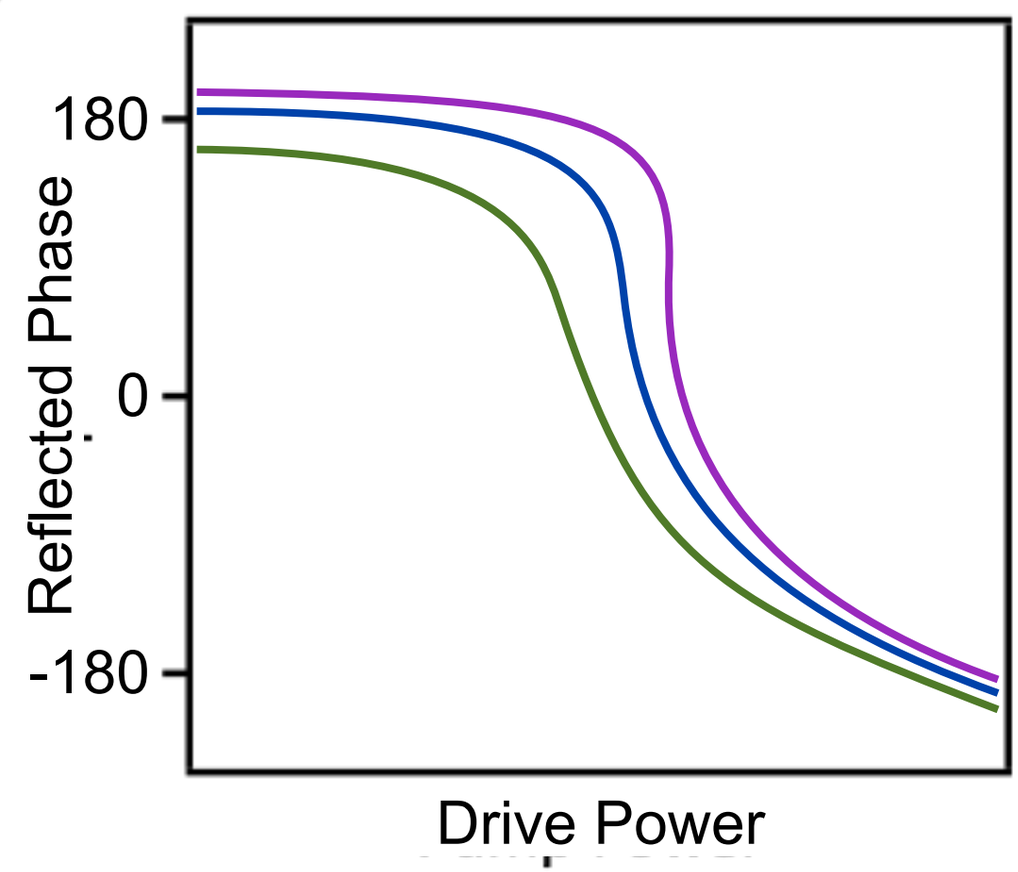
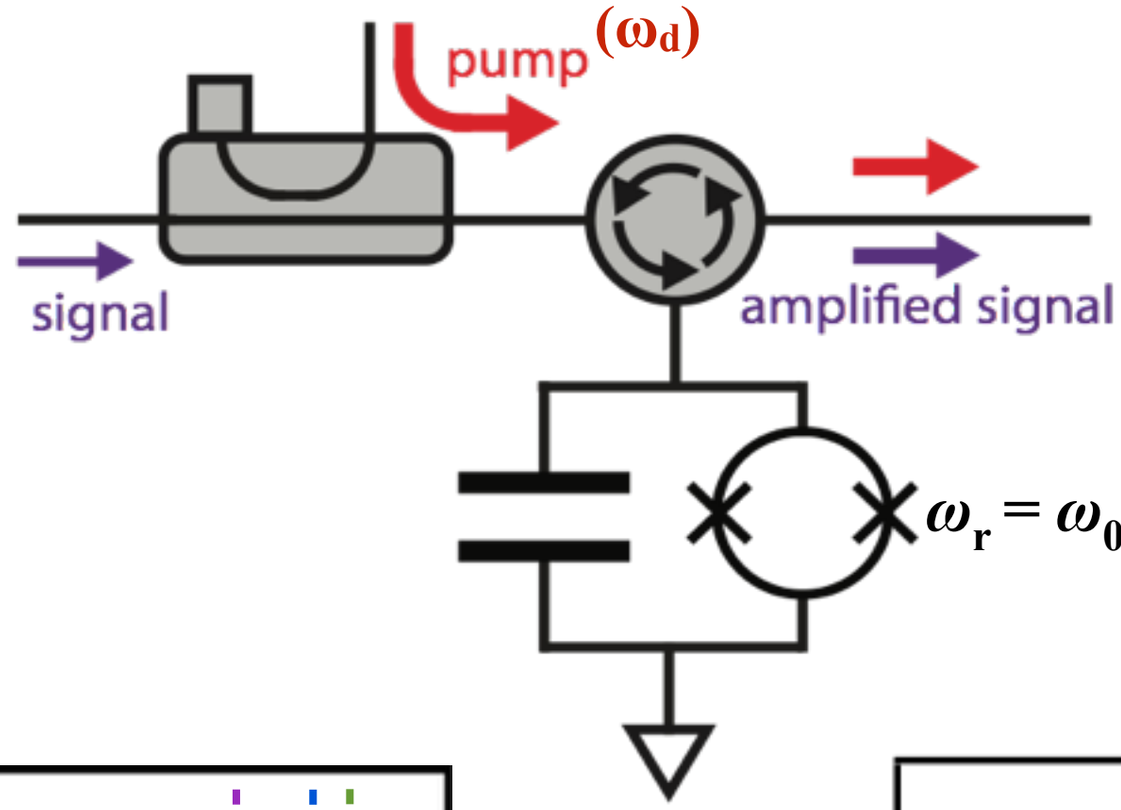




LJPA Operation



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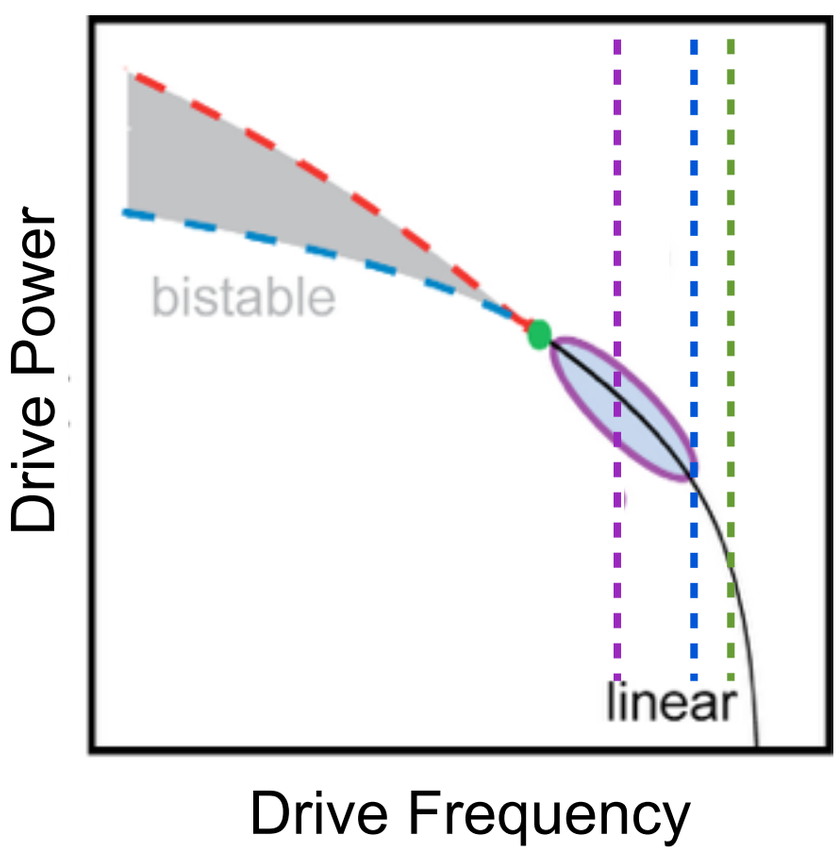
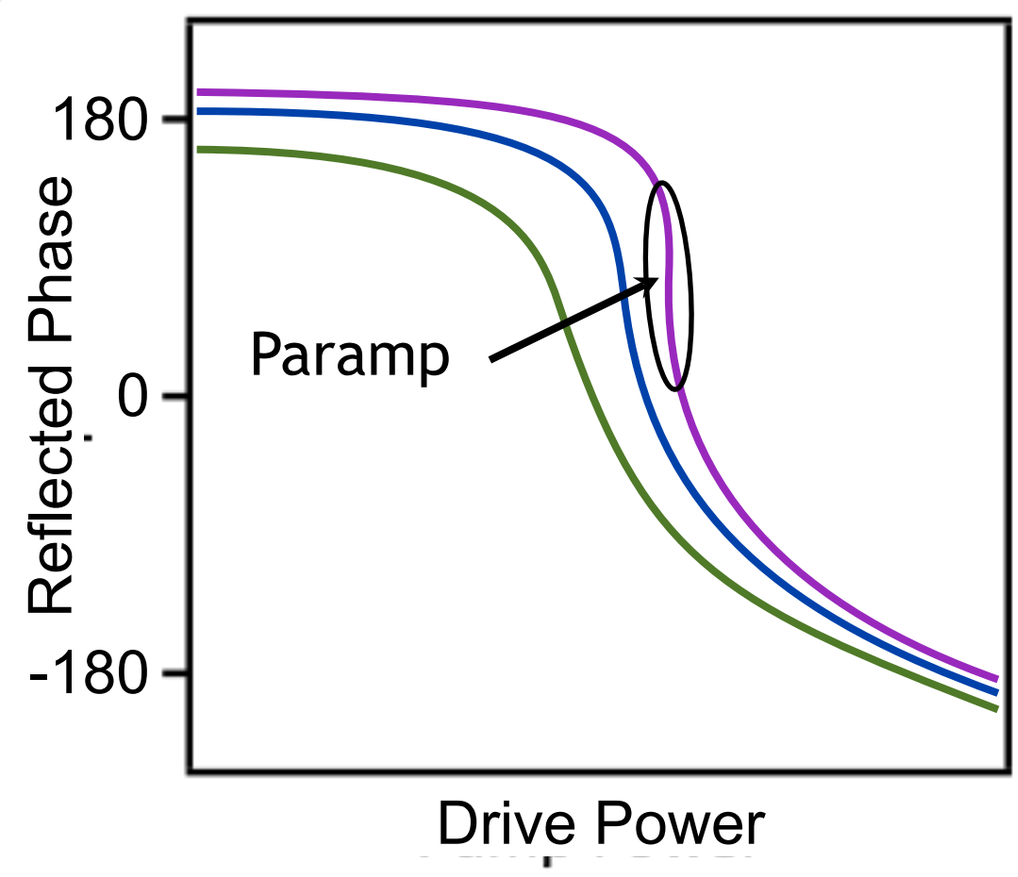
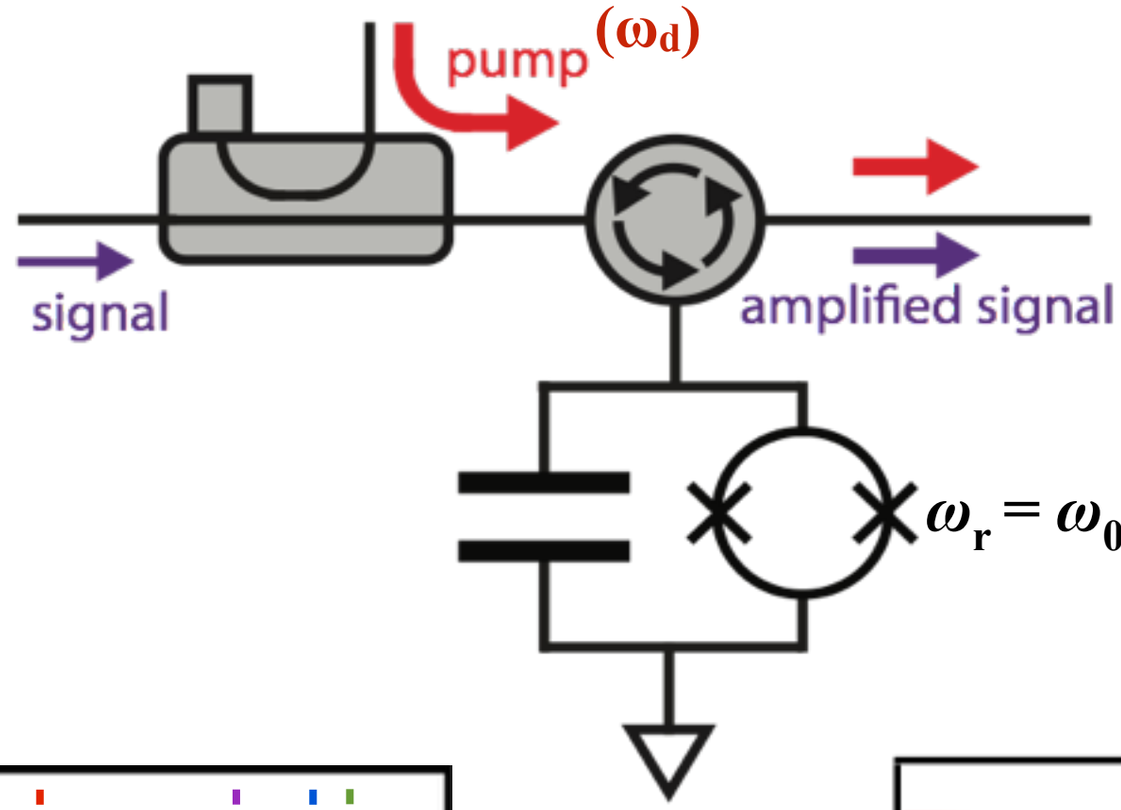




LJPA Operation



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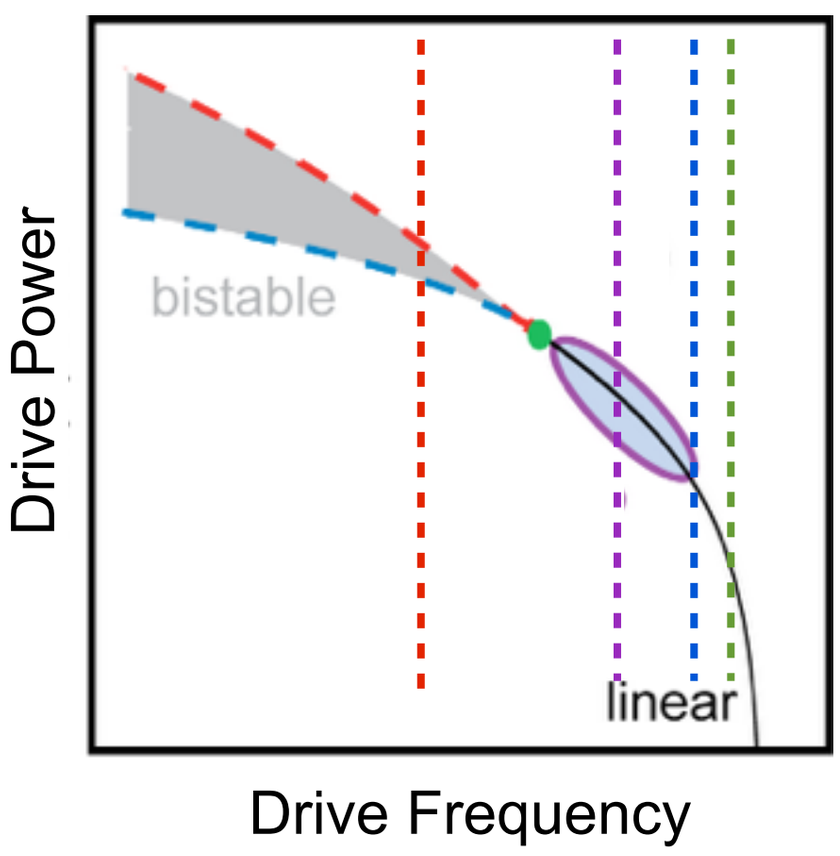
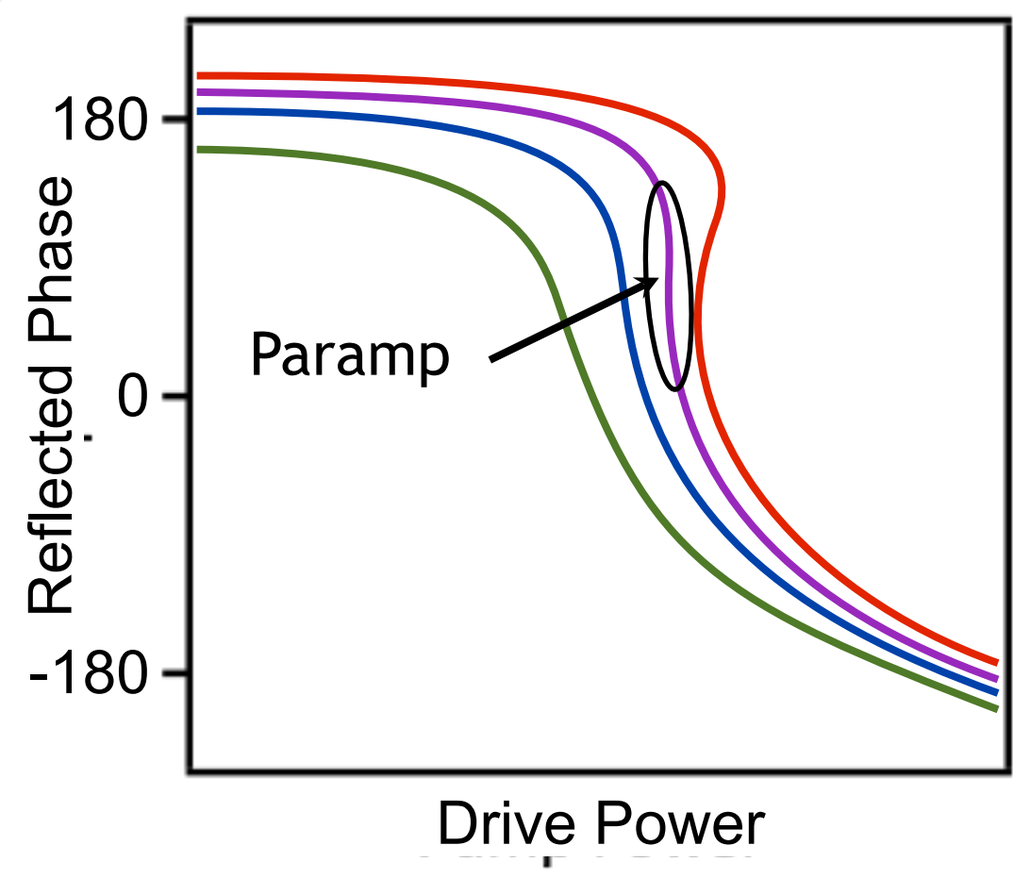
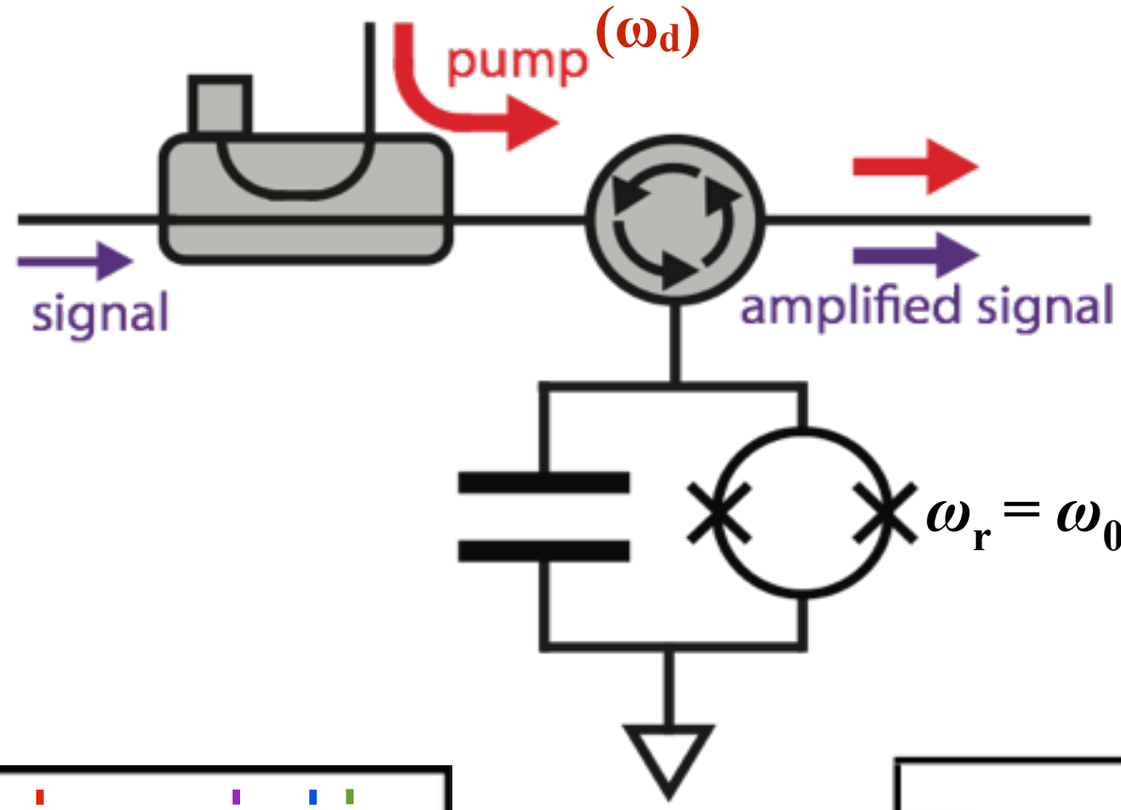
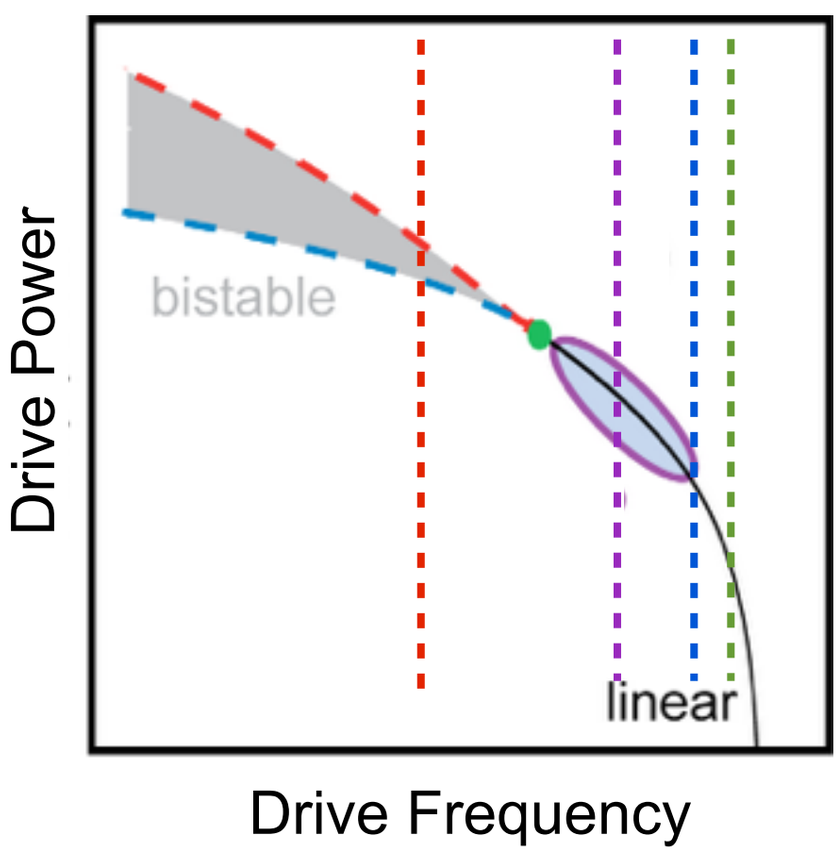


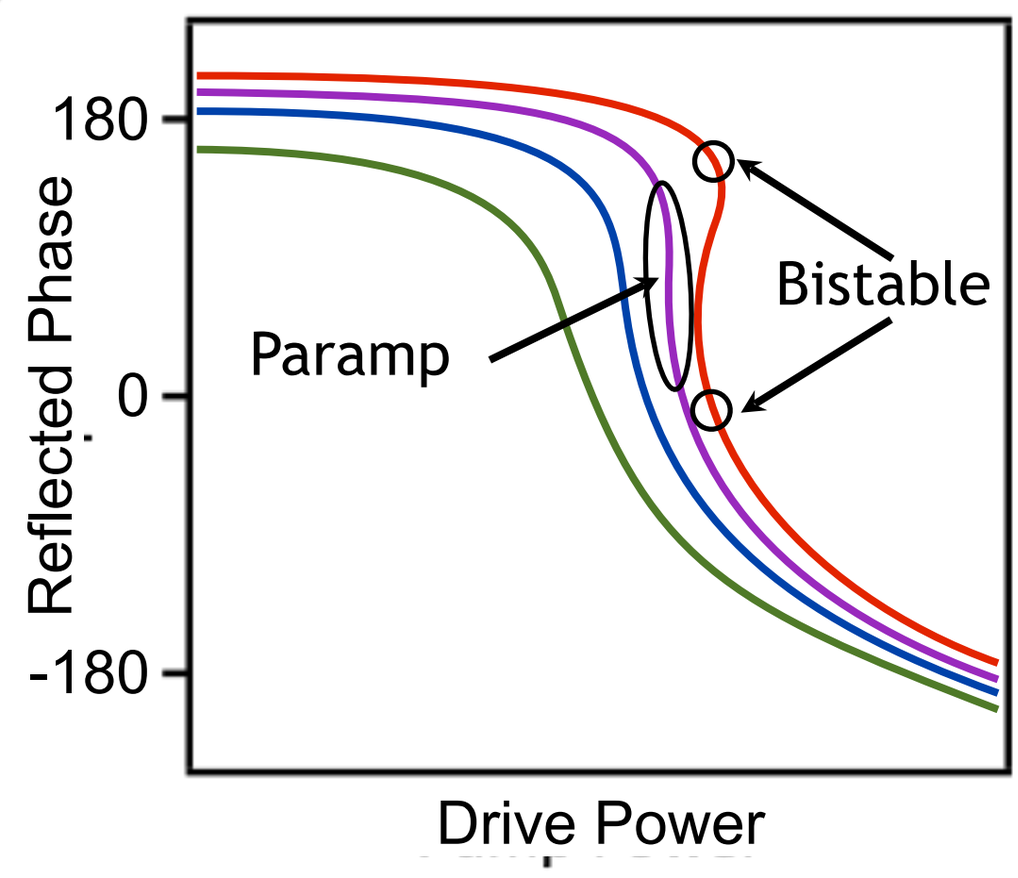


LJPA Operation

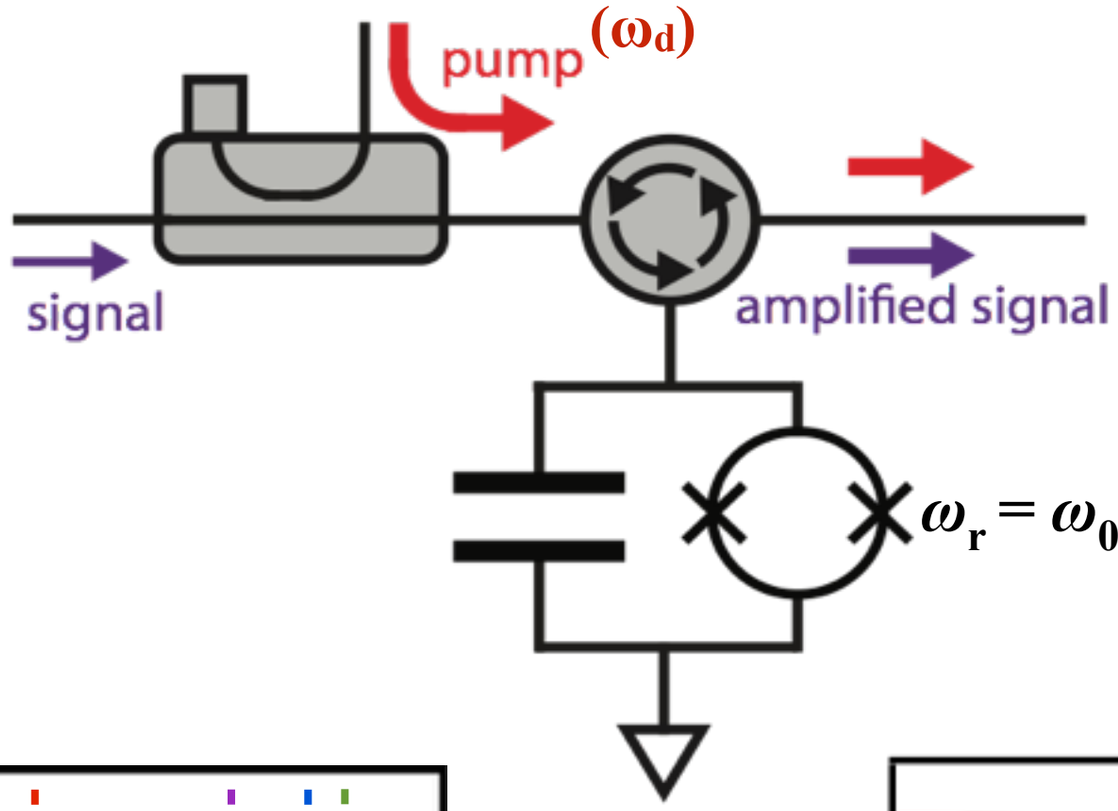


$$\omega_r = \omega_0 + \Delta\omega(I_{RF})\cos(2\omega_d t)$$

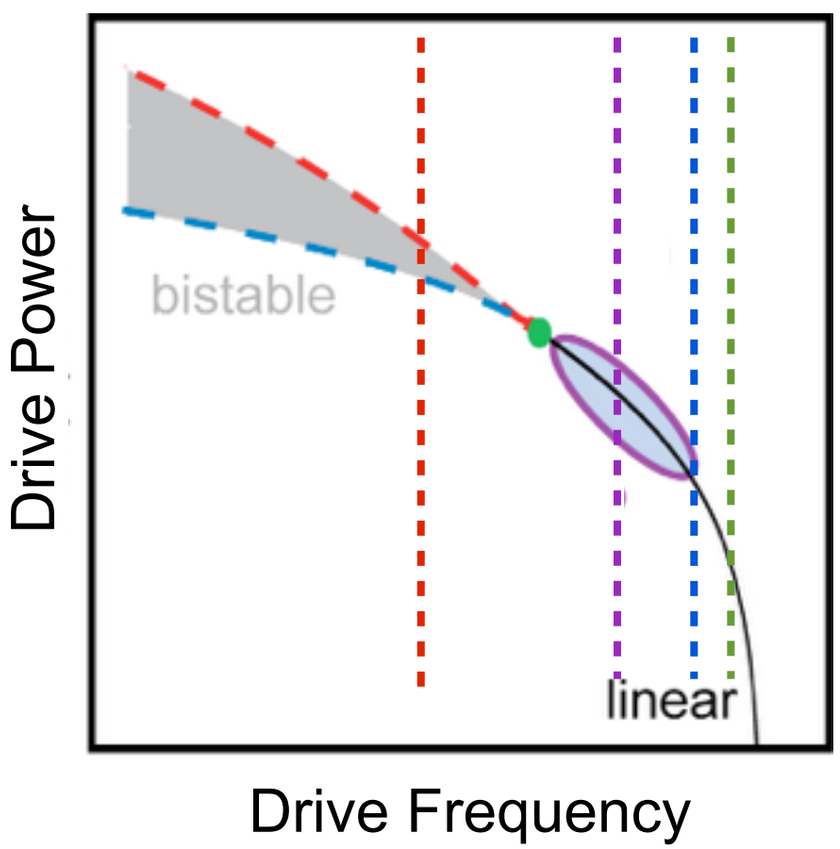


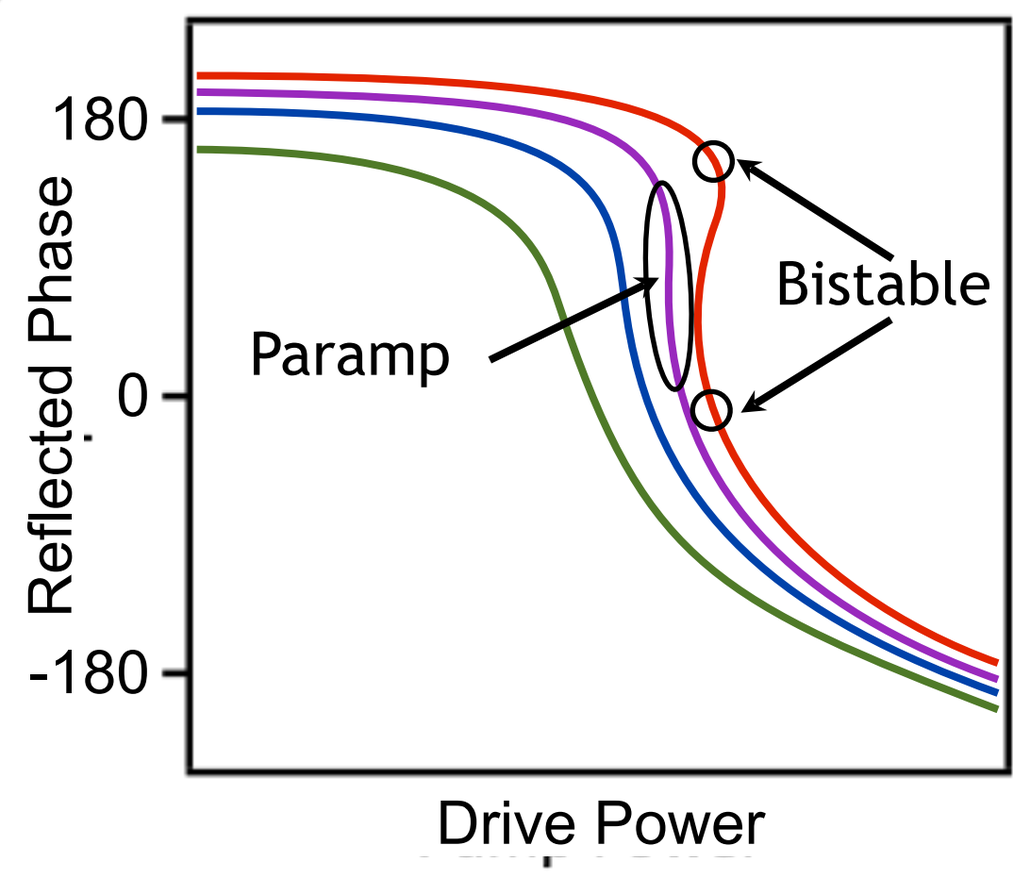


LJPA Operation



$$\omega_r = \omega_0 + \Delta\omega(I_{RF})\cos(2\omega_d t)$$

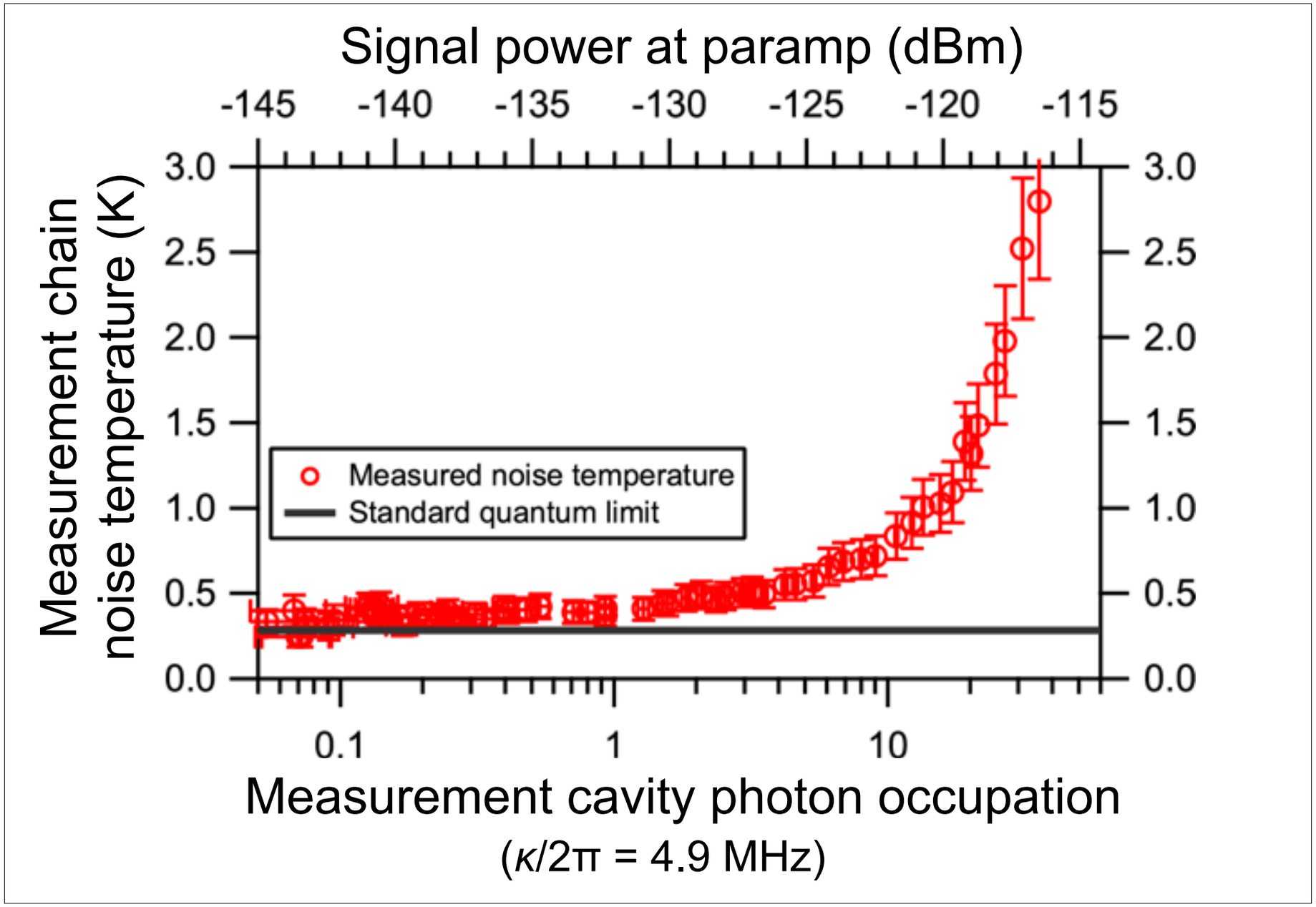




Oscillator nonlinearity fixes pump amplitude

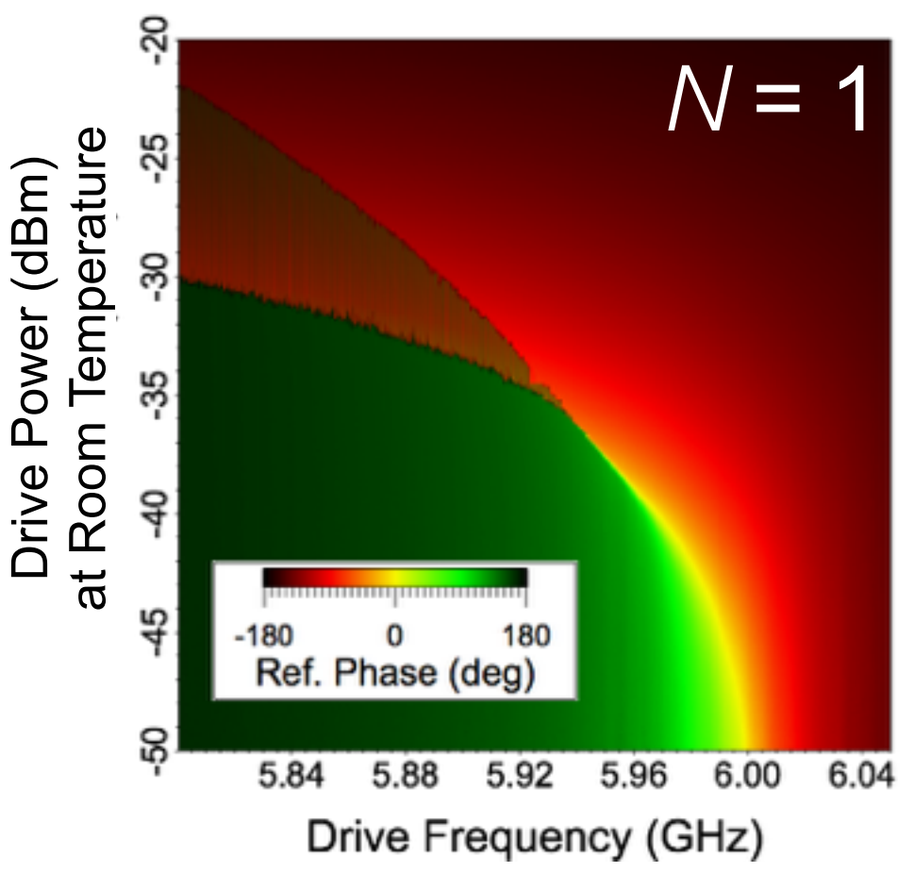
LJPA Dynamic Range

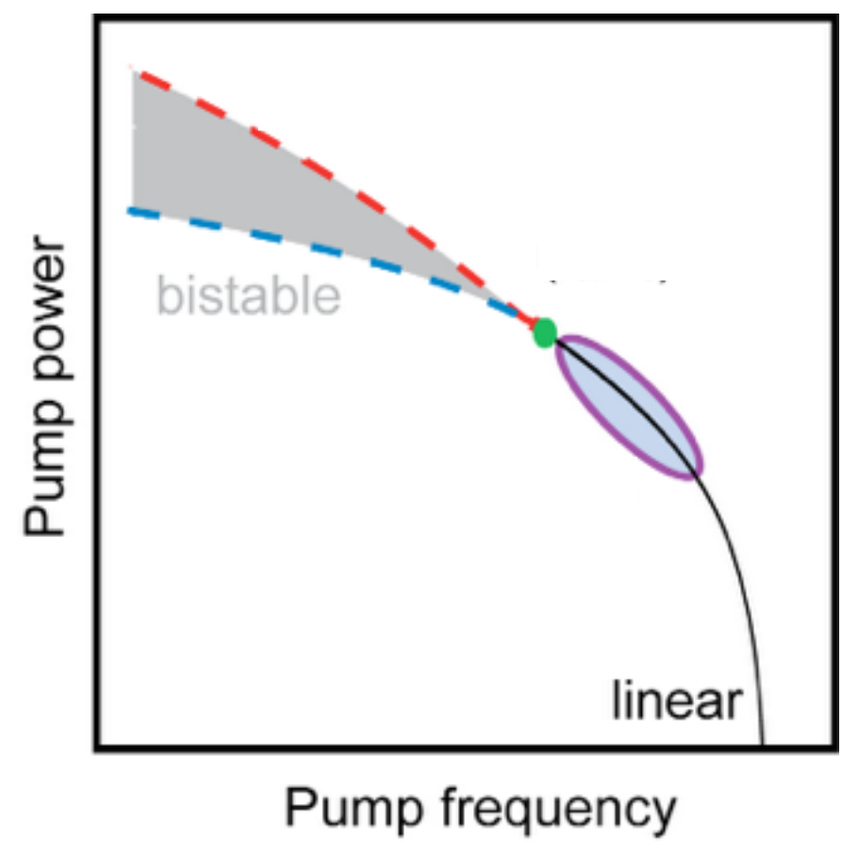
Fixed pump amplitude → **Limits available power for amplification**



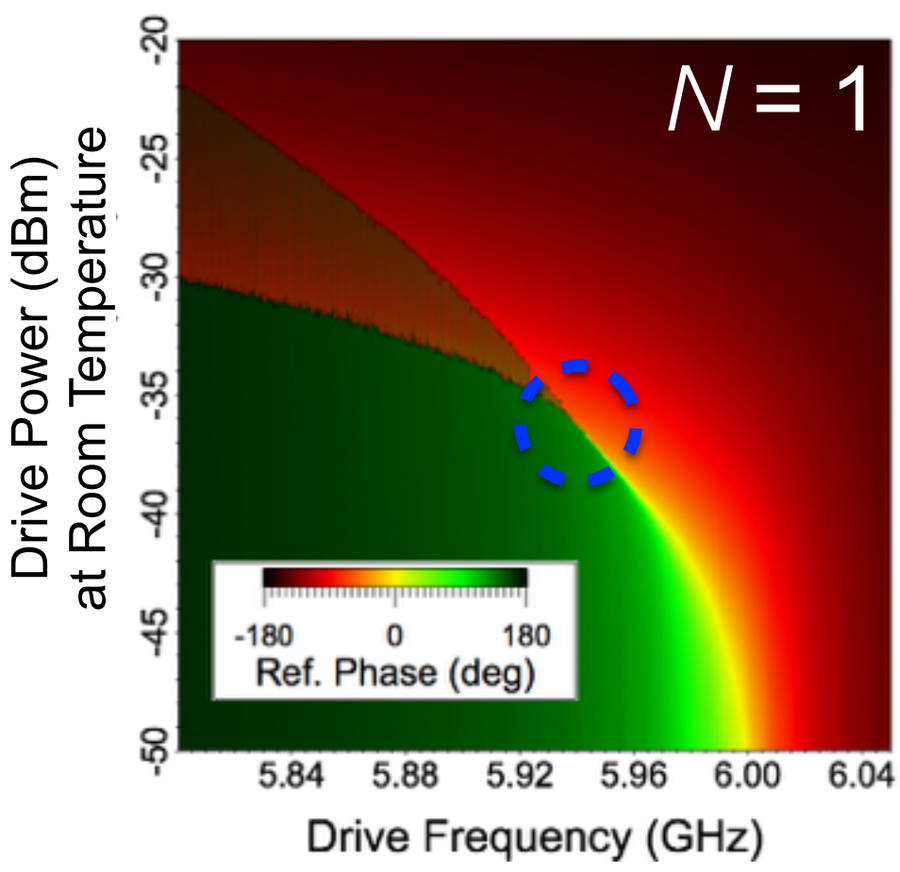
Gain reduced by 1 dB when signal **~ -130 dBm** (1 dB compression point)

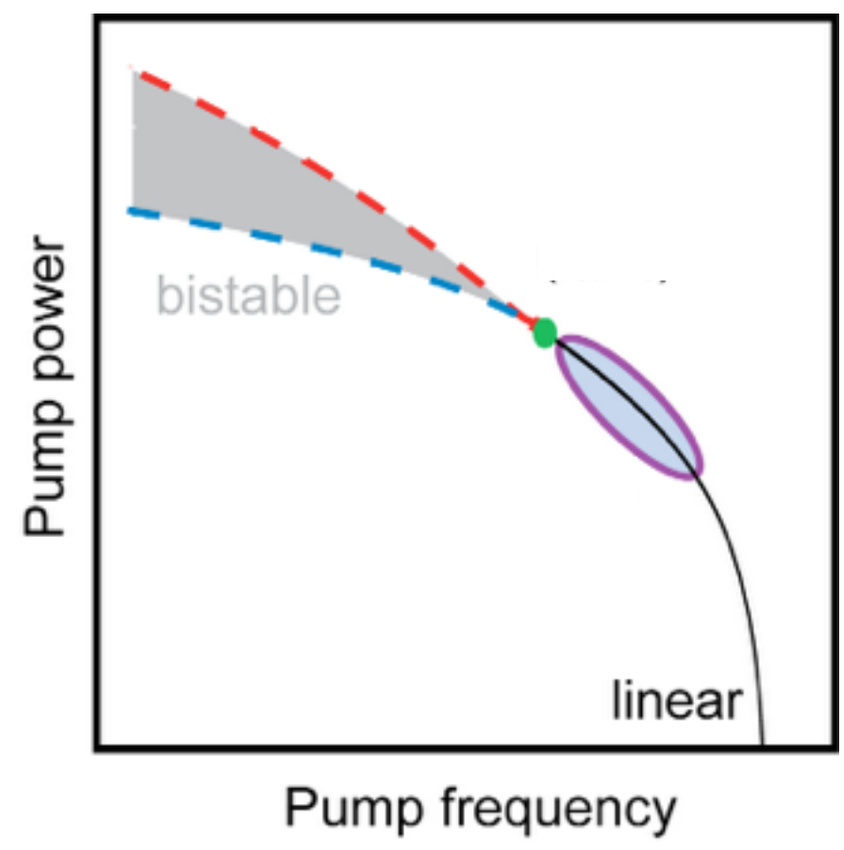
Measured Scaling of Critical Power with *N*



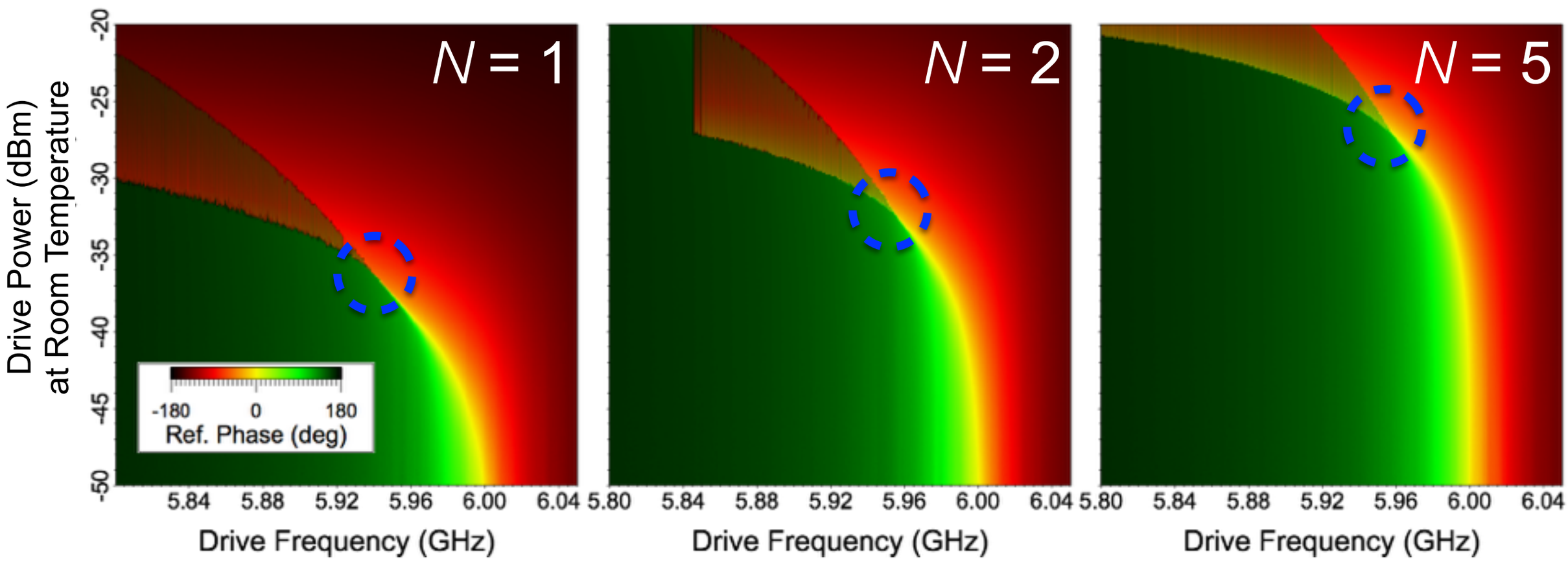


Measured Scaling of Critical Power with *N*

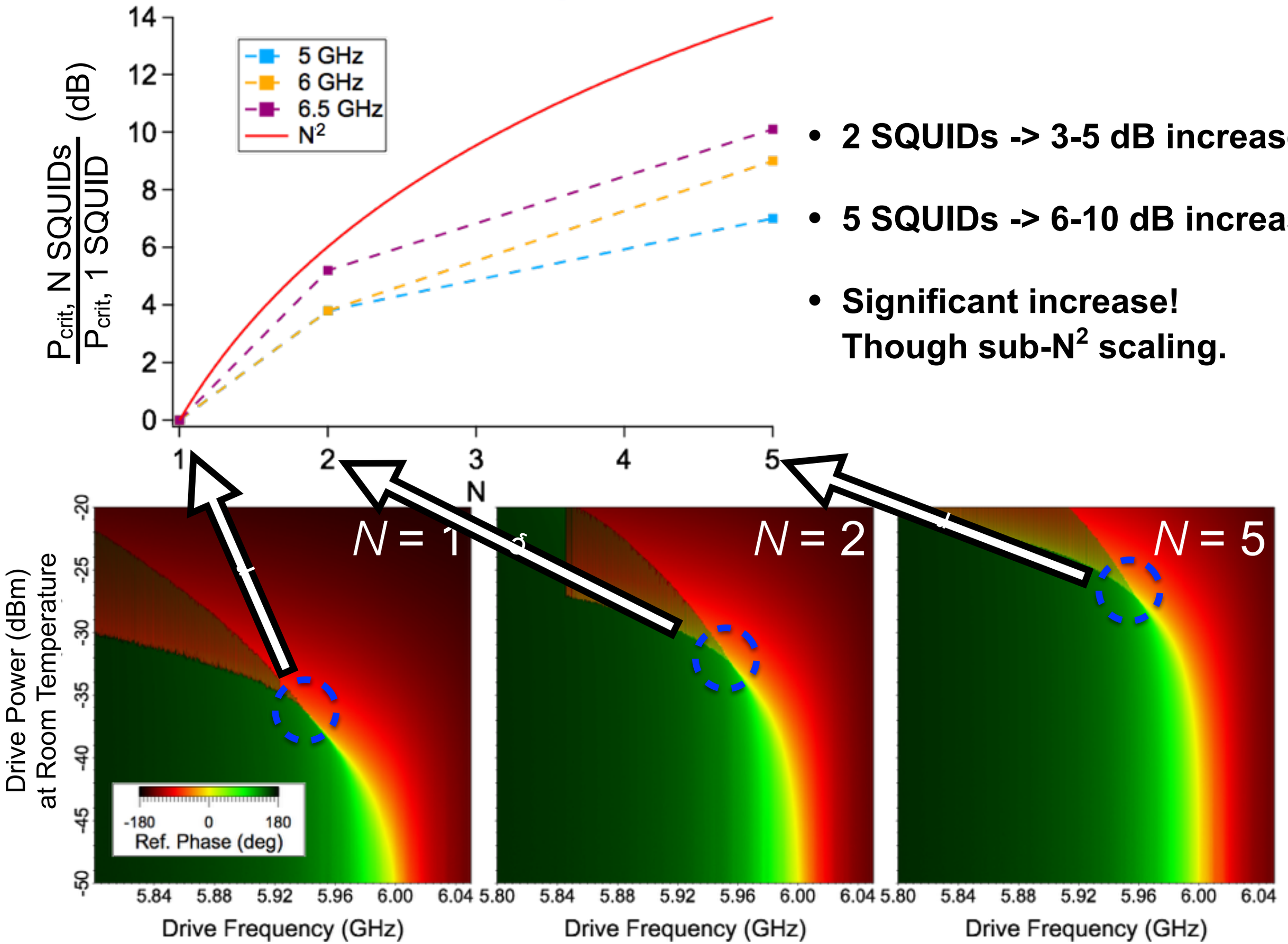




Measured Scaling of Critical Power with *N*



Measured Scaling of Critical Power with *N*



- **2 SQUIDs -> 3-5 dB increase**
- **5 SQUIDs -> 6-10 dB increase**
- **Significant increase! Though sub-N^2 scaling.**