Quantum Limited SQUID Amplifiers for Cavity Experiments

- Axion Dark Matter eXperiment (ADMX)
- Theory of SQUID Amplifiers
- The Microstrip SQUID Amplifier
- ADMX Revisited
- Higher Frequency SQUID Amplifiers
- Parametric Amplifiers

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DOE BES
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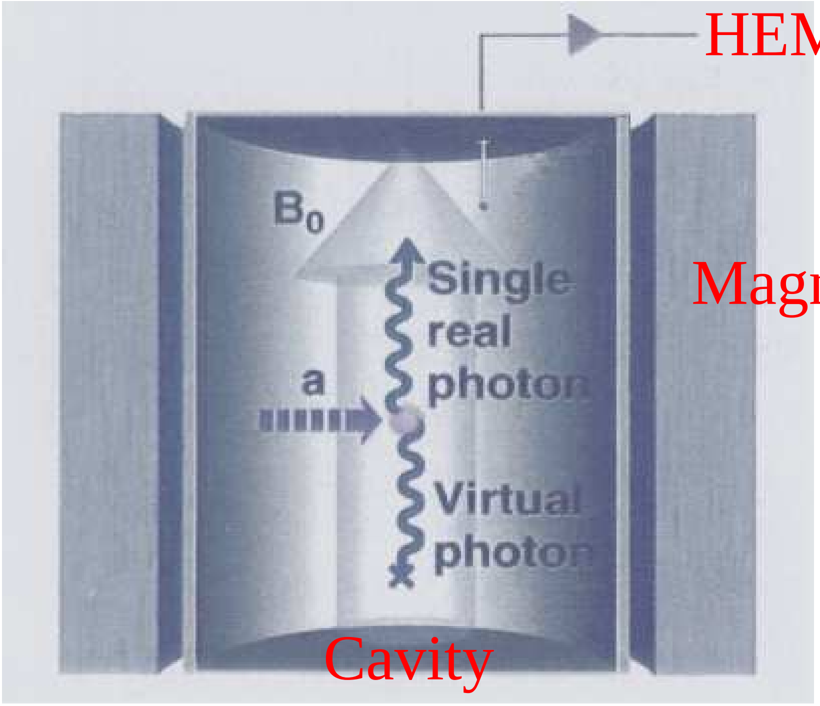
Vistas in Axion Physics
University of Washington
Seattle
24 April 2012

Axion Dark Matter eXperiment

Resonant Conversion of Axions into Photons

Pierre Sikivie (1983)

Primakoff Conversion

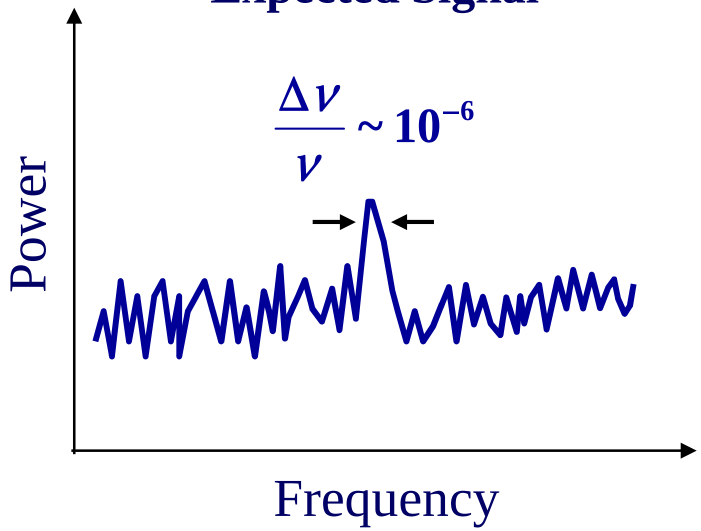


HEMT* Amplifier

Magnet

Cavity

Expected Signal

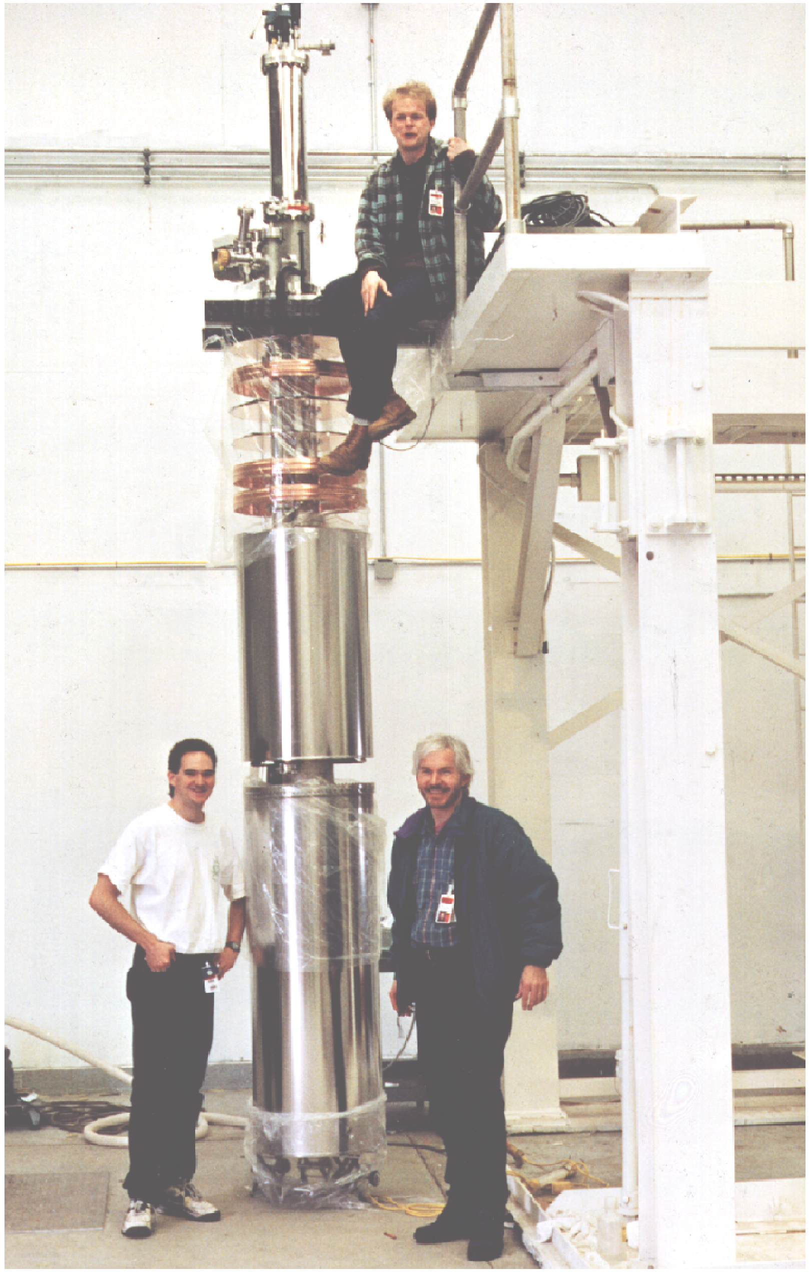


*High Electron Mobility Transistor

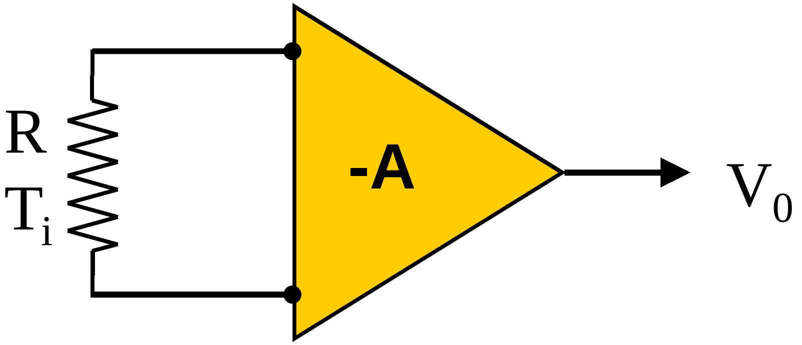
Need to scan frequency

ADMX at Lawrence Livermore National Laboratory

- Cooled to 1.5K
- 7 tesla magnet
- A given cavity can be tuned over a frequency range of about 2



Amplifier Noise Temperature



$$S_V^0(f) = A^2 \cdot 4k_B\left[T_i + T_N(R)\right]R$$

ADMX at LLNL

Cavity temperature:	$T \approx 1.5$ K
HEMT noise temperature:	$T_N \approx 1.7$ K
System noise temperature:	$T_S = T + T_N \approx 3.2$ K

Time* to scan the frequency range from $f_1 = 0.24$ to $f_2 = 0.48$ GHz:

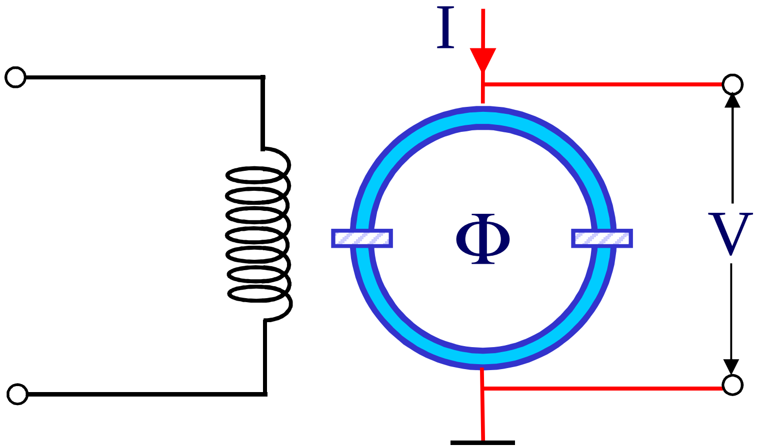
$$\tau(f_1, f_2) \approx 4 \text{ x } 10^{17} \, \mathbf{(T_S/1\ K)^2} \, (1/f_1 - 1/f_2) \text{ sec}$$

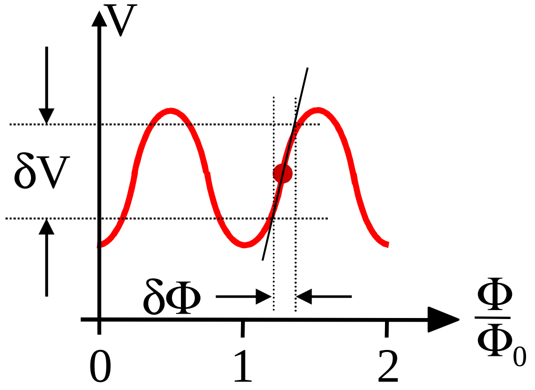
≈ 270 years

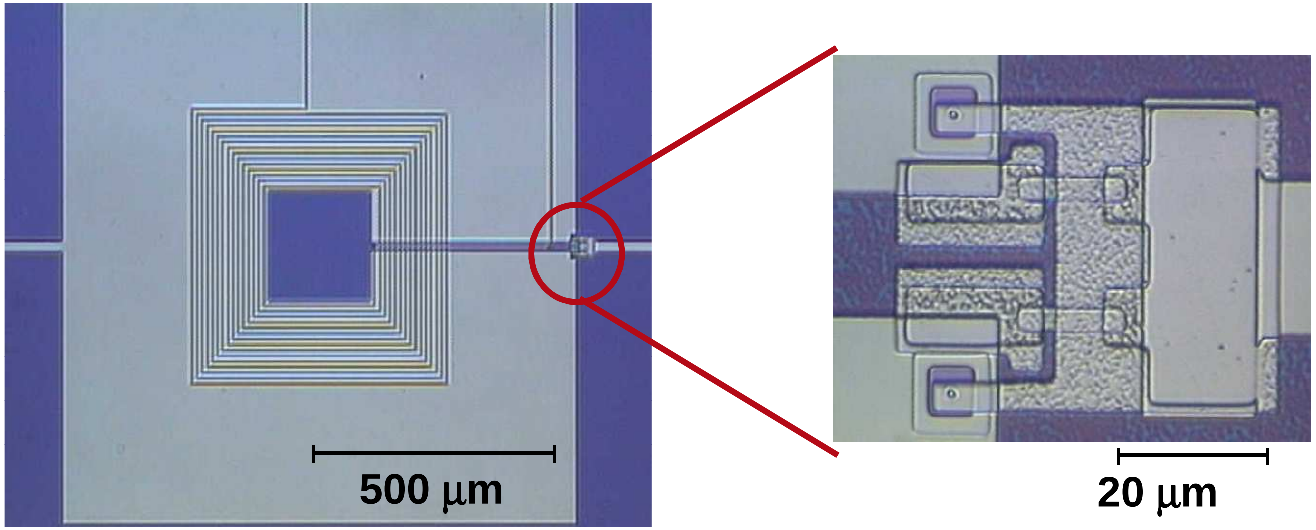
*DFSZ: Dine-Fischler-Srednicki-Zhitnitskii model

Theory of SQUID Amplifiers

The dc SQUID



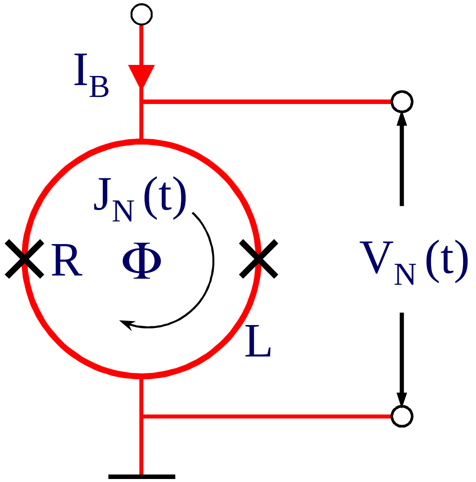




DC SQUID Noise: Classical Langevin Equation

Current noise spectral density

$S_I(f) = 4k_BT/R$



Results for optimized SQUID with

$\Phi = (2n + 1)\Phi_0/4$

$V_\Phi \equiv (\partial V/\partial \Phi)_I \approx R/L$

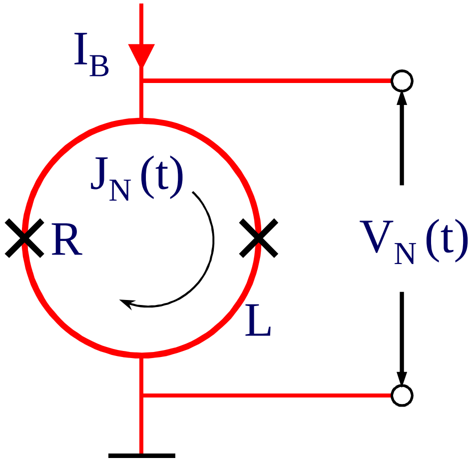
$S_V(f) \approx 16\ k_BTR$

$S_J(f) \approx 11\ k_BT/R$

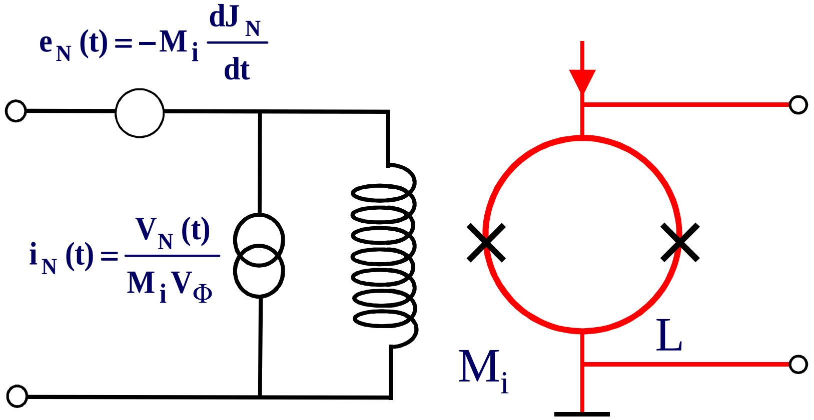
$S_{VJ}(f) \approx 12\ k_BT$

Claudia Tesche & JC

Noise Sources in the SQUID Amplifier



Equivalent Noise Sources Referred to Input Coil



$$e_N(t) = -M_i \frac{dJ_N}{dt}$$

$$i_N(t) = \frac{V_N(t)}{M_i V_\Phi}$$

i_N is a “virtual” current source

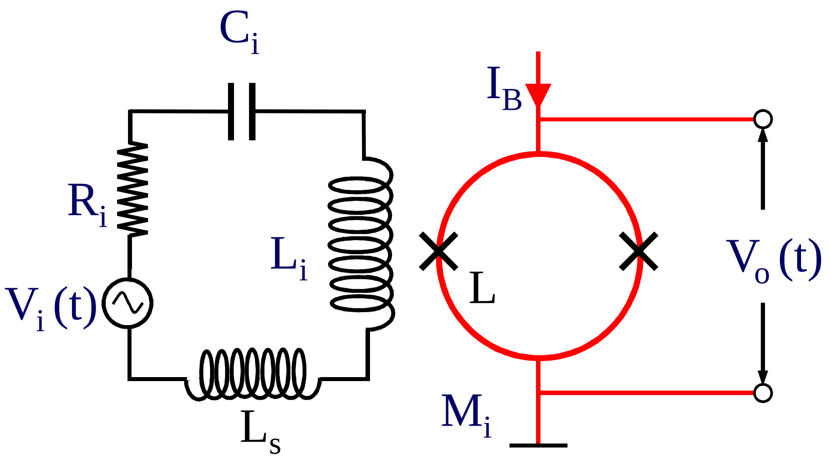
e_N is a “real” voltage source

$e_N(f) = -j(2\pi f)M_iJ_N(f)$ is *in quadrature* with $J_N(f)$

Calculate T_N from $e_n(t)$ and $i_n(t)$ using standard method

Tesche, Giffard, Martinis, JC

DC SQUID as a Tuned Amplifier



Assume coupling between SQUID and input circuit is weak (neglect influence of input circuit on SQUID and vice versa)

Resonance frequency $\omega \approx [(L_i + L_s)C_i]^{-1/2}$

Quality factor $Q \approx \omega(L_i + L_s)/R_i$

Noise Temperature and Gain

On resonance

$$T_N^{res} = \pi f[S_J(f)S_v(f)]^{1/2}/k_B V_\Phi \approx 42f\bullet T/V_\Phi$$

$$G \approx V_\Phi/\omega$$

Introducing the plasma frequency $f_p = (I_0/2\pi\Phi_0 C)^{1/2}$:

$G \approx f_p/\pi f$ (cf parametric amplifier)

Optimized

$$T_N^{opt} = \pi f[S_J(f)S_v(f) - S_{VJ}^2(f)]^{1/2}/k_B V_\Phi \approx 18f\bullet T/V_\Phi \approx T_n^{res}/2.4$$

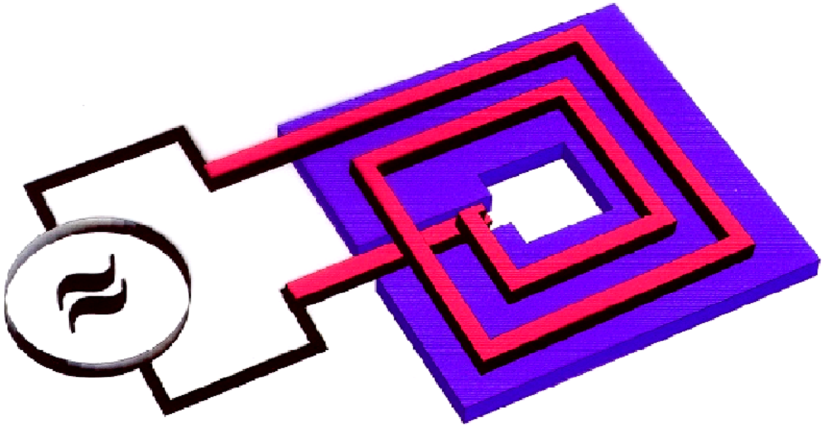
at frequency $f = 1/2\pi[L_iC_i(1 + \alpha^2 S_{VJ}LV_\Phi/S_V)]^{1/2} < f_{res}$

$$T_Q^{opt} \approx hf/k_B$$

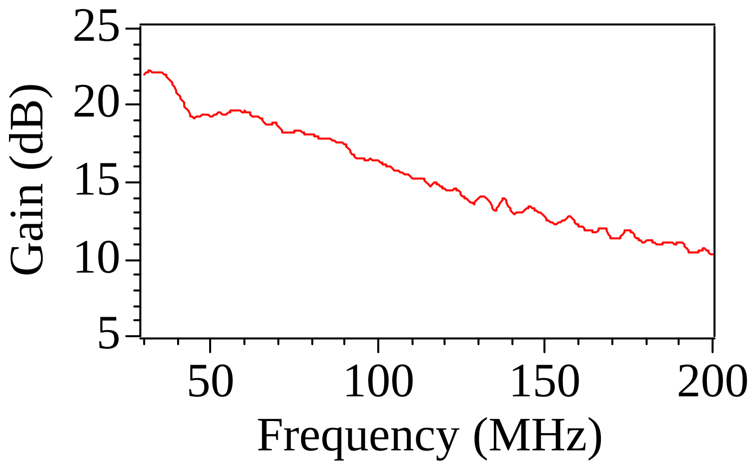
The Microstrip SQUID Amplifier (MSA)

MSA: Principle

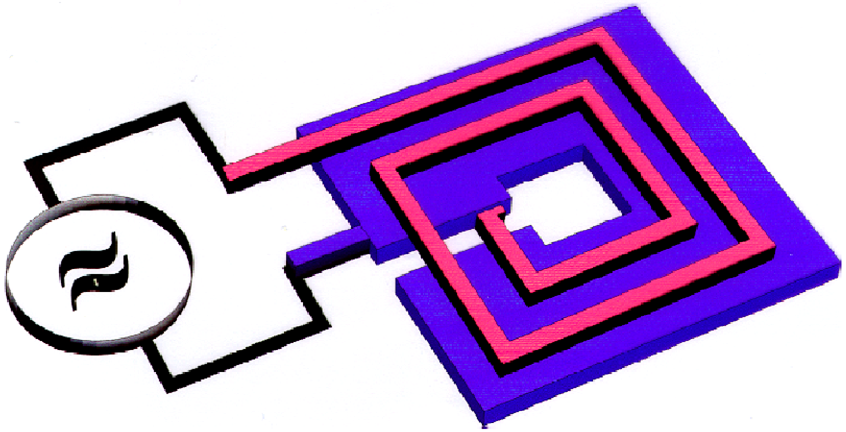
Conventional SQUID Amplifier



- Source connected to both ends of coil

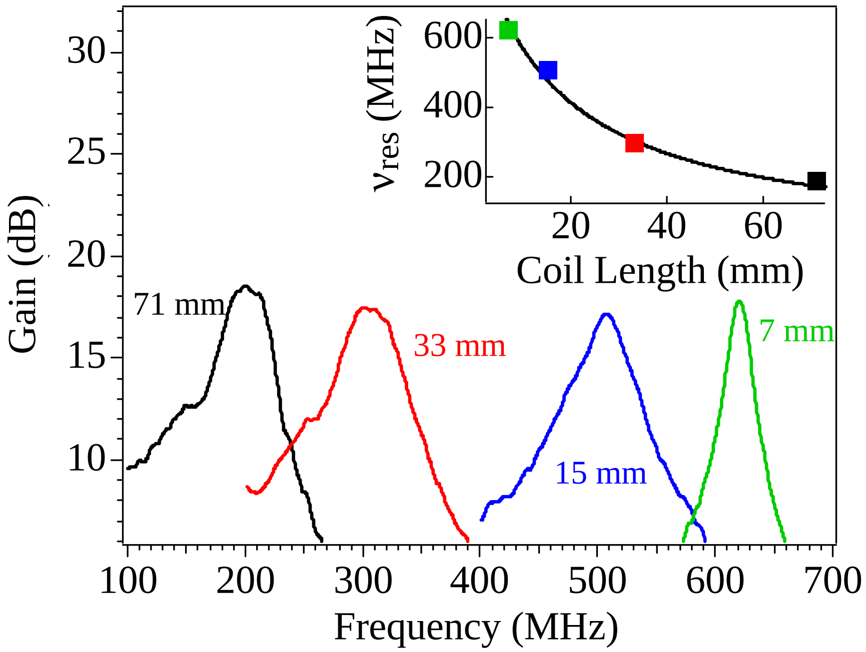


Microstrip SQUID Amplifier



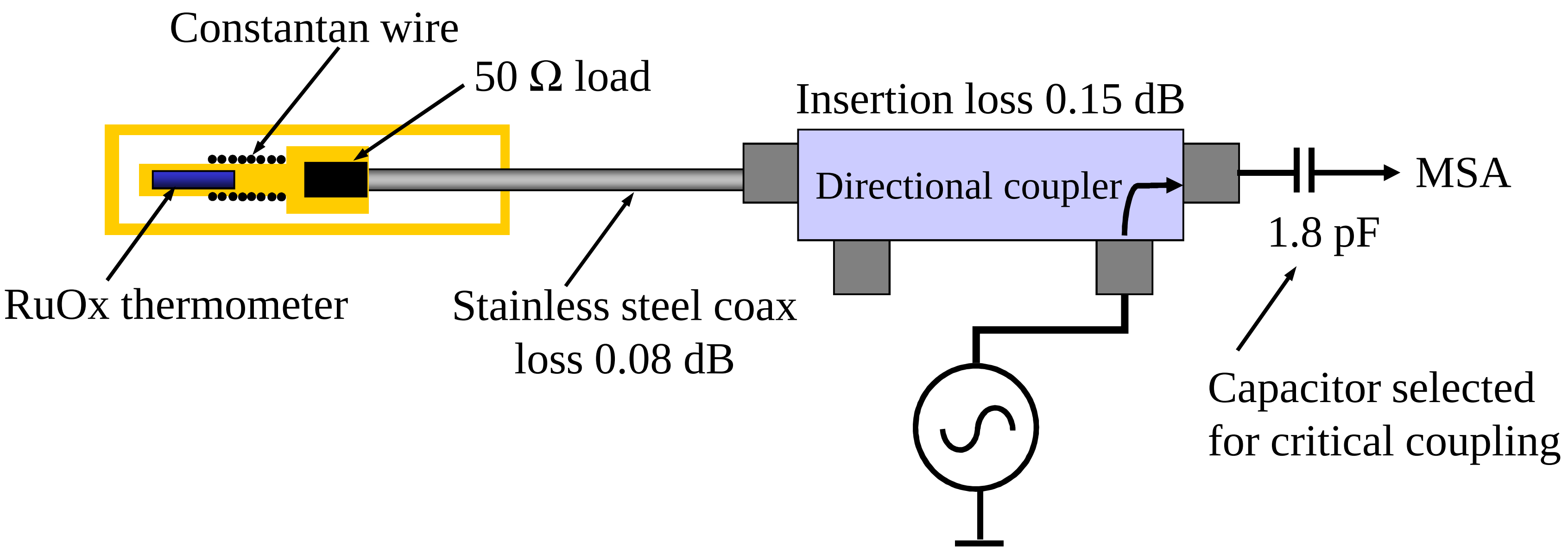
- Source connected to one end of the coil and SQUID washer; the other end of the coil is left open

MSA: Practice



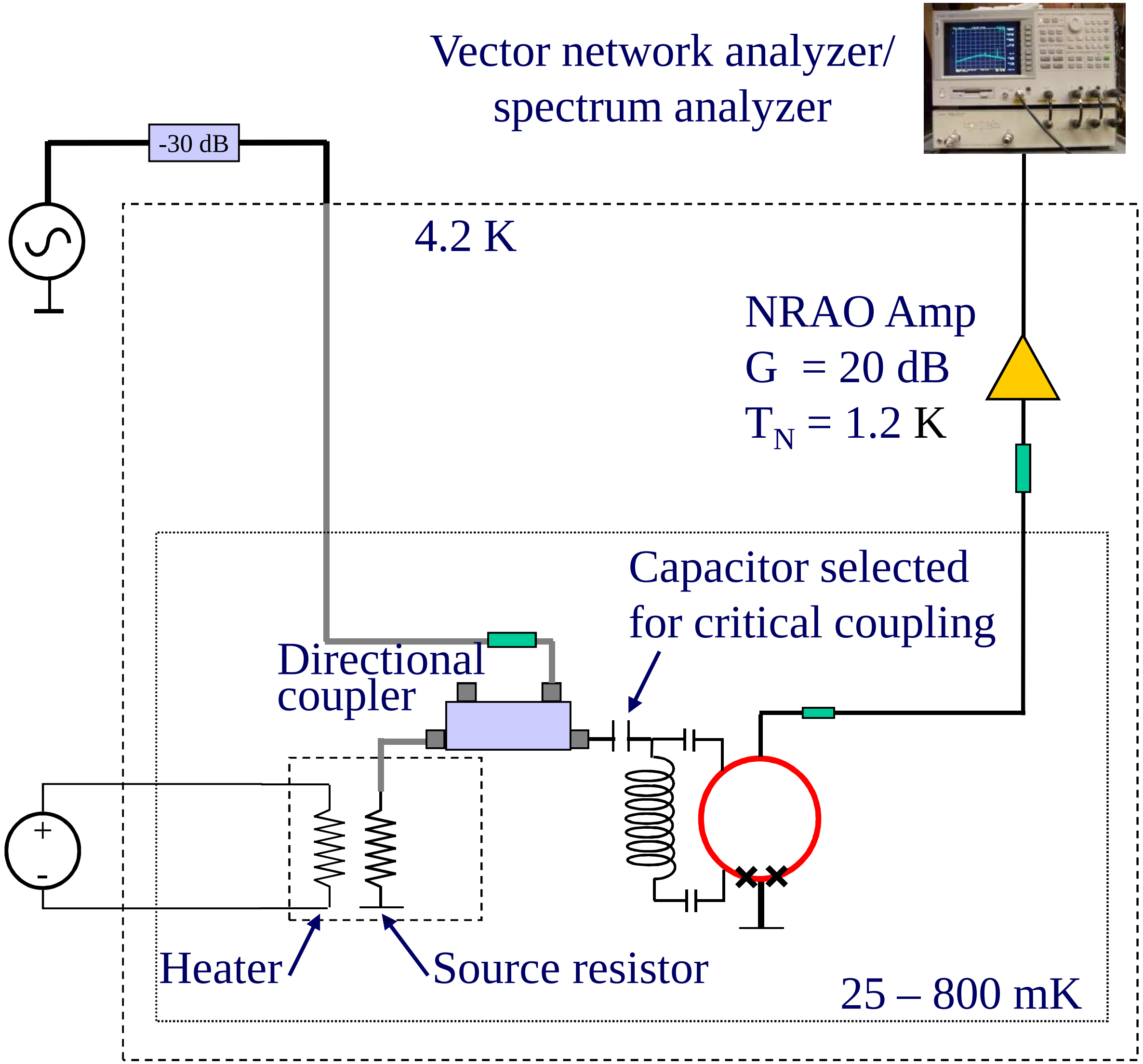
Optimized Version: Measurement of T_N

- Hot/cold load method
  - Input connected to variable temperature 50 Ω load
  - Ratio measurement—no absolute calibration required



Darin Kinion, JC

Measurement of T_N and Gain



Vector network analyzer/ spectrum analyzer

4.2 K

NRAO Amp
G = 20 dB
T_N = 1.2 K

Capacitor selected for critical coupling

Directional coupler

Heater

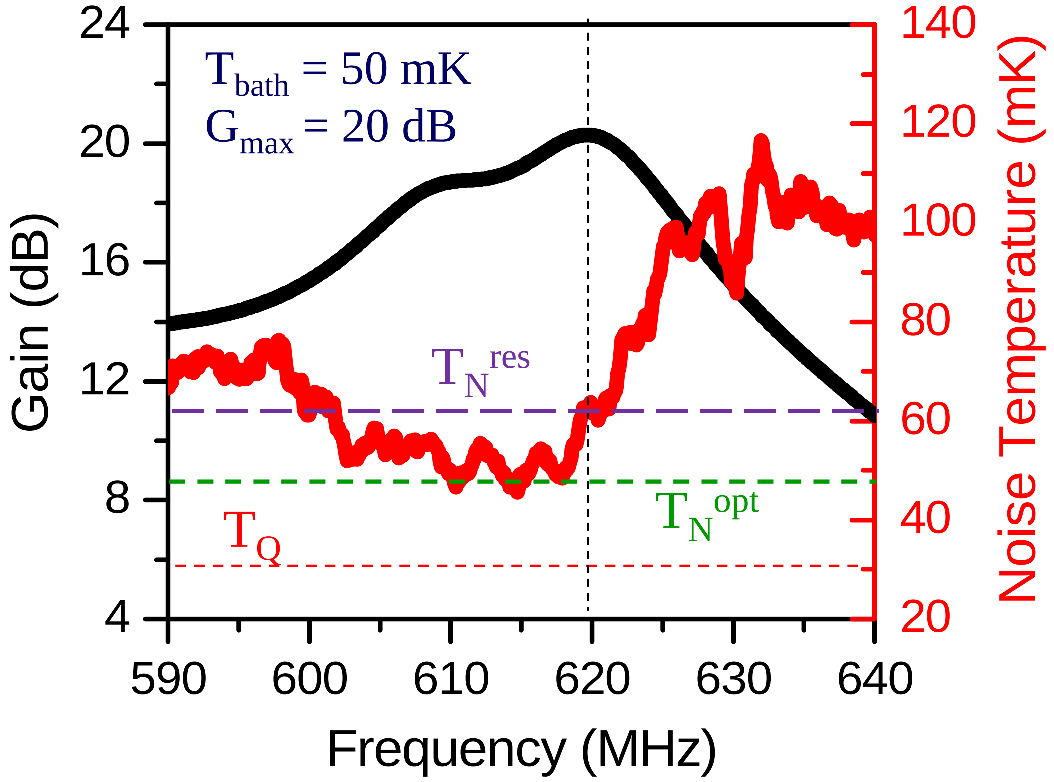
Source resistor

25 – 800 mK

- Very careful optimization of input and output matching

Darin Kinion, JC

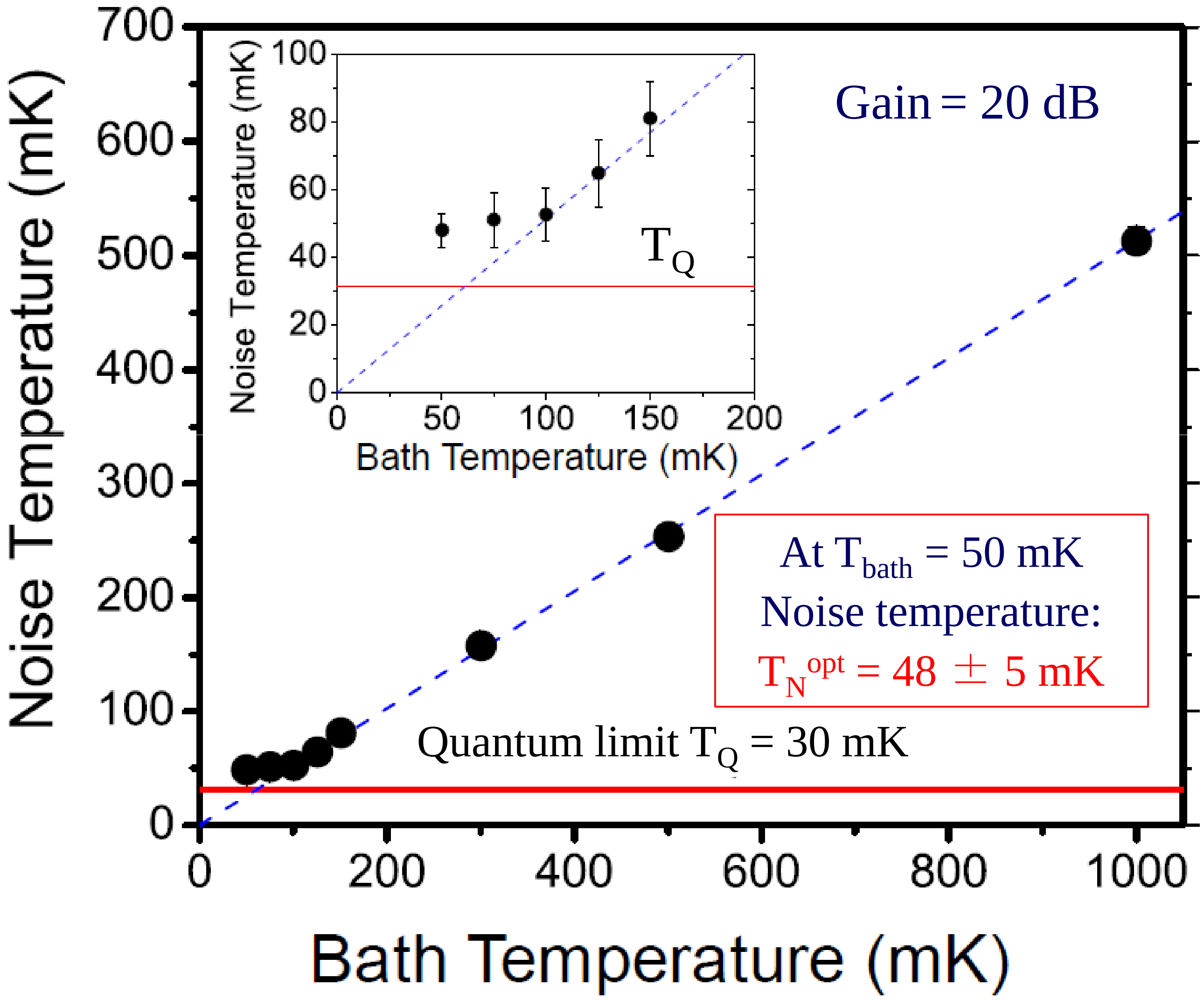
Gain and Noise Temperature



- Quantum limit T_Q = 30 mK
- Optimum noise temperature $T_N^{opt} = 48 \pm 5$ mK
- Occurs slightly below resonance, as predicted
- Typical $T_{HEMT} \approx 2$ K (≈ 40 times higher)

Darin Kinion, JC

MSA Noise Temperature vs. Bath Temperature



- Darin has recently extended the operating frequency to 6 GHz (unpublished)

ADMX Revisited

The Axion Detector: Reduction in Scan Time

- Microstrip SQUID amplifier: $T_N \approx 50$ mK
- Original LLNL axion detector: $T_S \approx 3.2$ K
- Next generation: Cool system in a dilution refrigerator to (say) 100 mK
- Thus $T_S \approx T + T_N \approx 150$ mK

- Scan time $\propto (T_s/1\text{ K})^2$:

$$\tau(0.24\text{ GHz}, 0.48\text{ GHz}) \approx 270\text{ years x } (0.15/3.2)^2$$

$$\approx \mathbf{200\ days}$$

- A “cold” HEMT operates at typically 20 K (thermal heating)
- A SQUID operates at the bath temperature down to typically 100 mK

Outlook for the Axion Detector

- During 2009-10, a microstrip SQUID amplifier was operated on the axion detector at 1.5 K to demonstrate proof-of-principle. (LLNL)

- 88,370, 80-sec data sets were acquired, corresponding to 82 days of data.

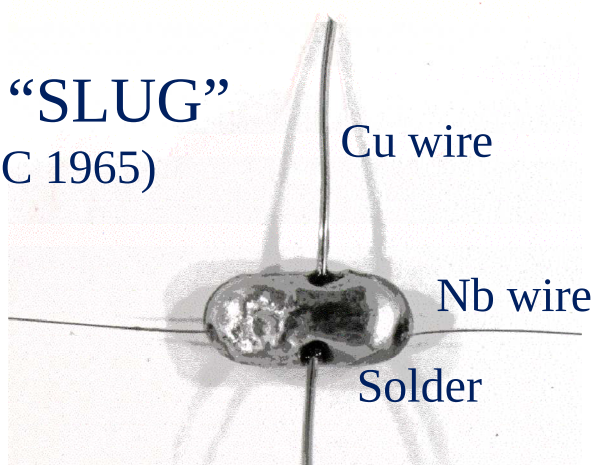
- Given the success of this test, the Department of Energy has funded a second upgrade.

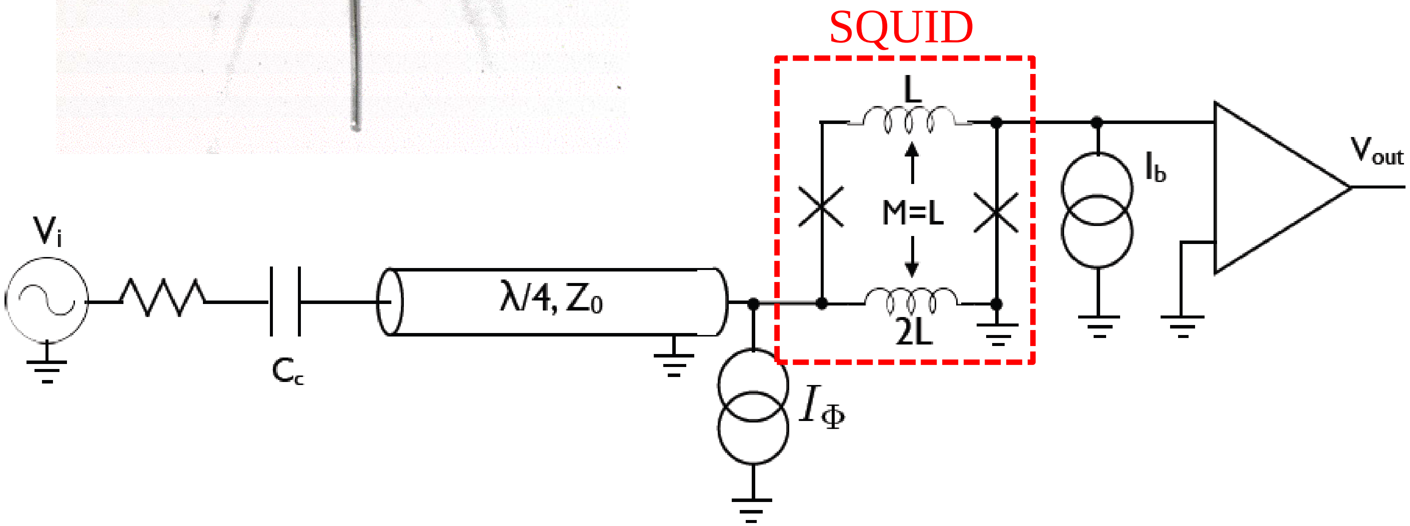
Higher Frequency SQUID Amplifier

The Microwave SLUG Amplifier

Robert McDermott’s Group at Wisconsin

The “SLUG”
(JC 1965)



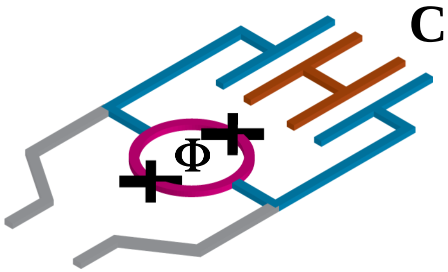


Josephson Parametric Amplifier

Josephson Nonlinear Oscillator

- The Josephson junction is a lossless, nonlinear inductance:

$$L_J = \Phi_0/[2\pi(I_0^2 - I^2)^{1/2}] \quad (I_0 > I)$$

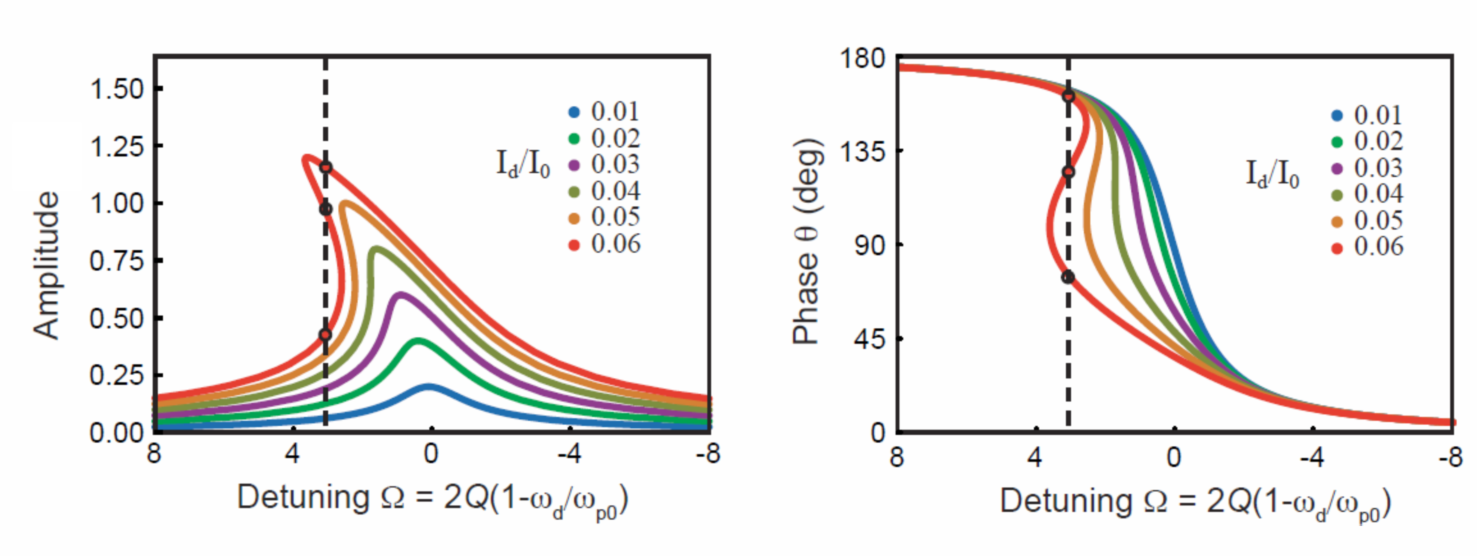


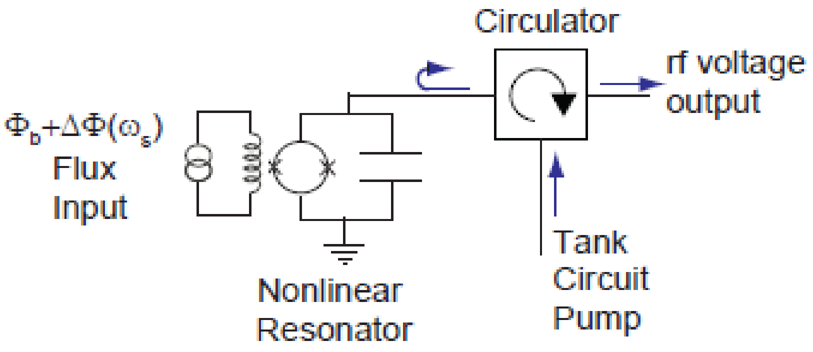
- A shunt capacitor C produces a nonlinear oscillator:

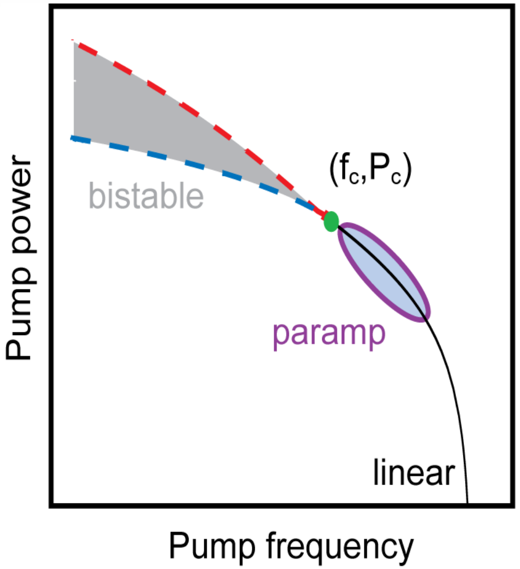
$$f_{osc} = 1/2\pi(L_J C)^{1/2} = (I_0^2 - I^2)^{1/4}/(2\pi C\Phi_0)^{1/2}$$

- Applying a flux to the SQUID changes I_0, providing tuning

Josephson Parametric Amplifier



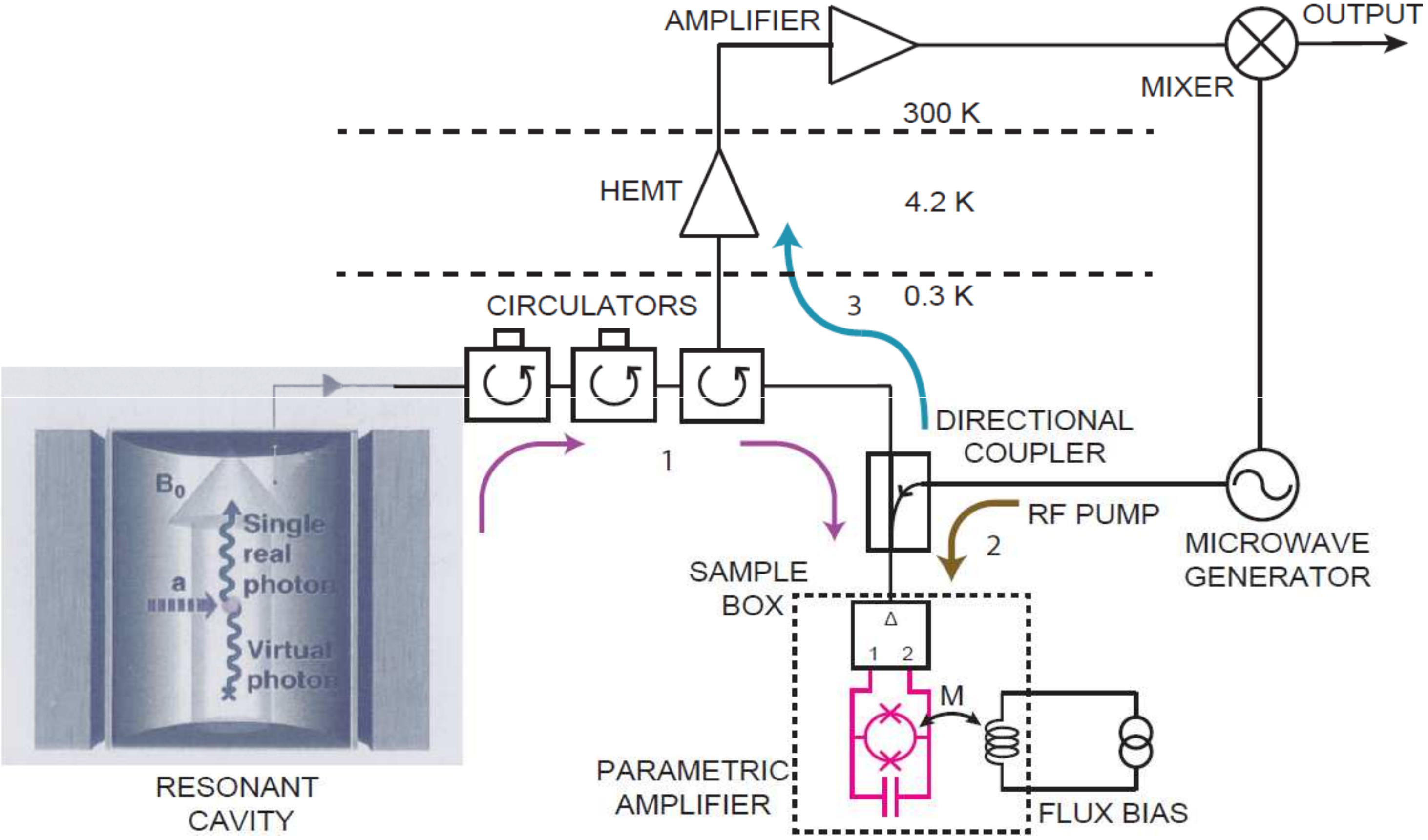




M. Hatridge, R. Vijay, D. H. Slichter, JC, I. Siddiqi (2011)

- G ≈ 30 dB, f = 5 – 6 GHz, within factor of 1.5 of quantum limit

ADMX Readout with Parametric Amplifier



Concluding Remarks

- DC SQUID amplifiers and Josephson parametric amplifiers can be operated at frequencies up to 10 GHz—and potentially higher.

- Both kinds of amplifier can achieve near-quantum limited performance. (In the case of the dc SQUID amplifier this occurs below the peak gain.)

- The dc SQUID amplifier is simple to operate in that it requires only static current and flux biases. It operates at a static voltage, and is therefore a dissipative device.

- The Josephson parametric amplifier requires a very stable microwave generator and a collection of cooled microwave components (circulators, directional couplers,…). It operates in the zero voltage regime. It is currently more readily tunable.

Thank You

SQUID amplifiers

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Jost Gail
Robin Giffard†
Cristoph Heiden†
Darin Kinion

Roger Koch†
John Martinis
Michael Mück
Claudia Tesche
Dale Van Harlingen

SQUID parametric amplifiers

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