Quantum limited amplification using superconducting parametric amplifiers

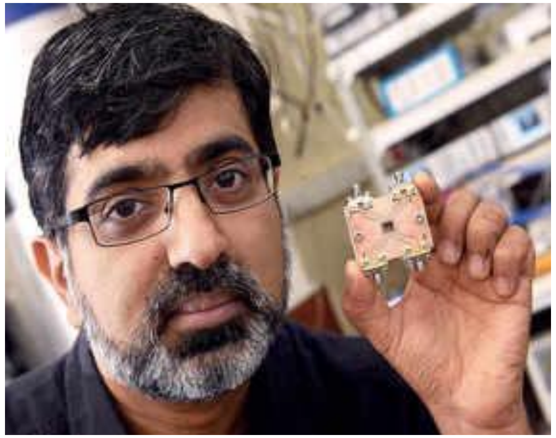
R VIJAYARAGHAVAN

ICTS: HORIZONS IN ACCELERATORS, PARTICLE/NUCLEAR PHYSICS AND LABORATORY -BASED QUANTUM SENSORS FOR HEP/NP

November 16, 2022

TATA INSTITUTE OF FUNDAMENTAL RESEARCH, MUMBAI, INDIA

Quantum Measurement & Control Laboratory @ TIFR, Mumbai



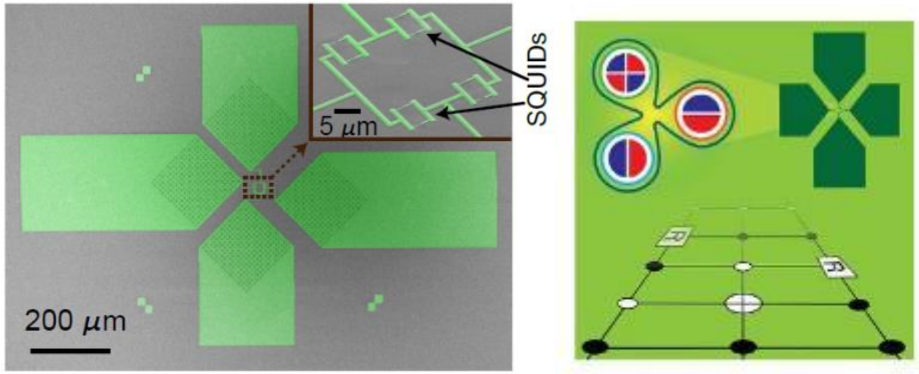
Dr. R. Vijayaraghavan
Associate Professor, Department of Condensed Matter Physics & Materials Science, TIFR, Mumbai
(Since Dec 2012)

- Multi-modal superconducting circuits
- Ultra-low noise parametric amplifiers
- Novel qubit circuits: 3-qubit processor demonstrated - Trimon
- Novel coupling architectures

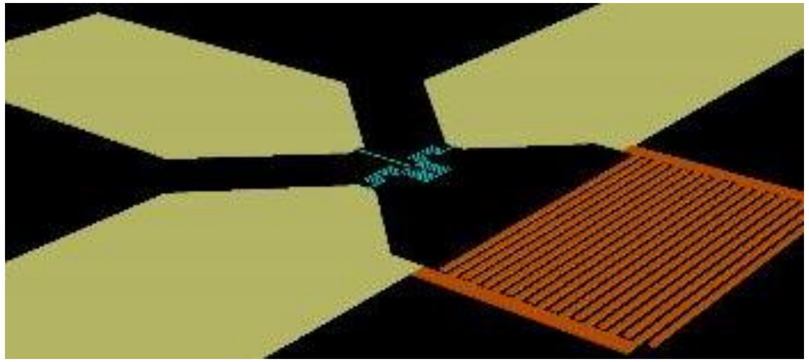
- DST QuEST PI
- Collaboration with DYSL-QT (7-qubit processor)

www.tifr.res.in/~quantro/

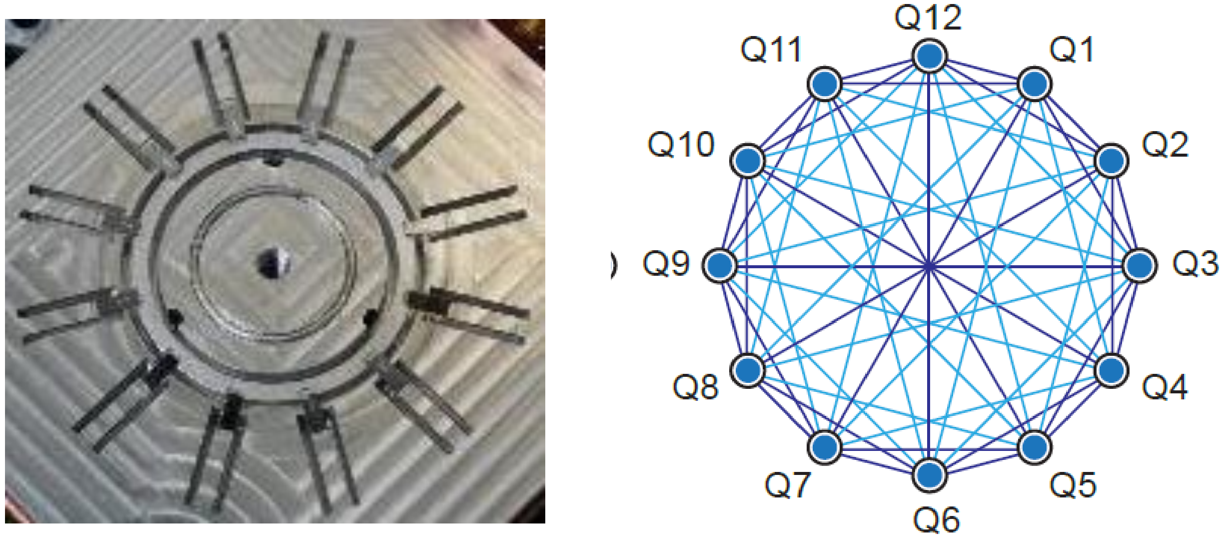
Trimon: A three-qubit circuit



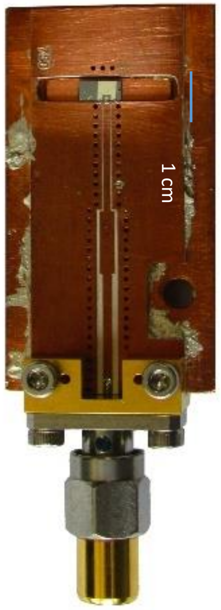
Quantromon



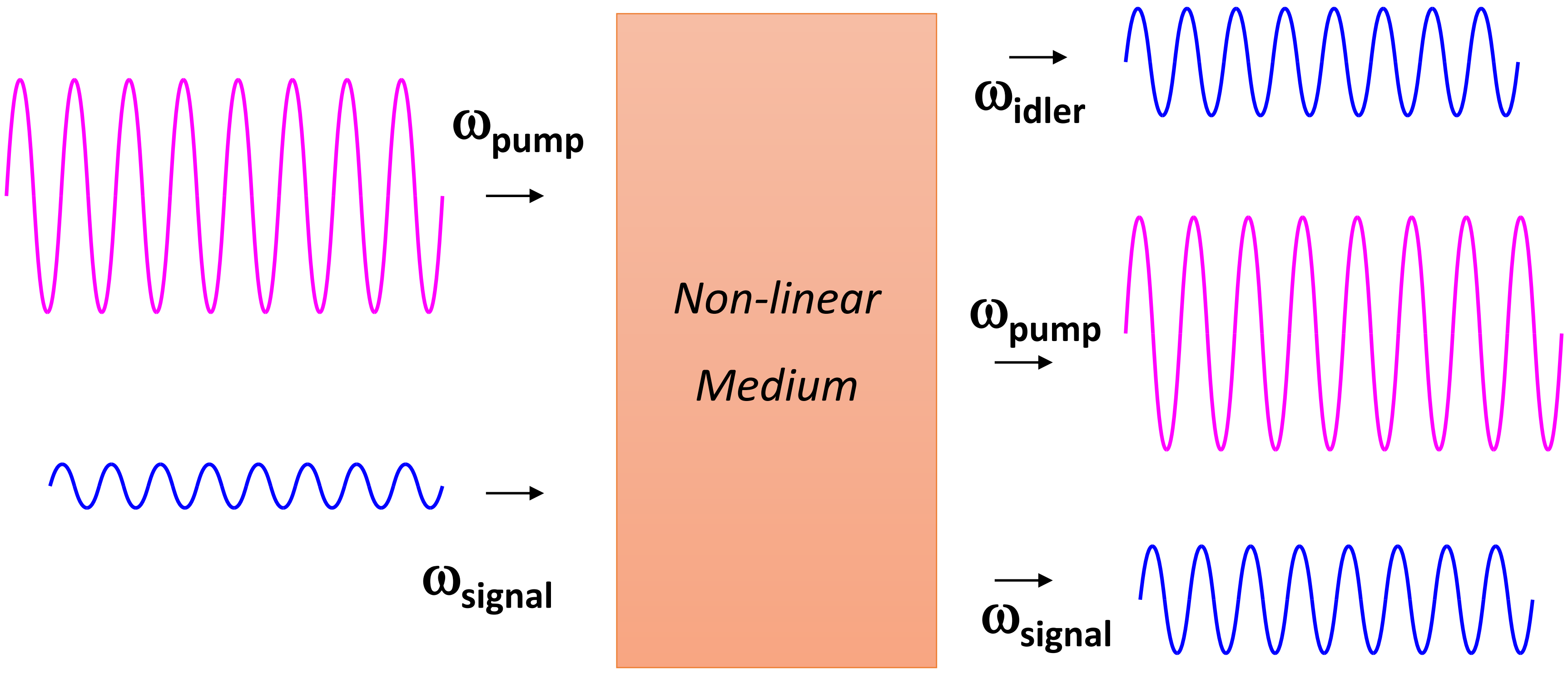
A 12-qubit network with a ring cavity coupler



Impedance engineered parametric amplifier



Parametric Amplification

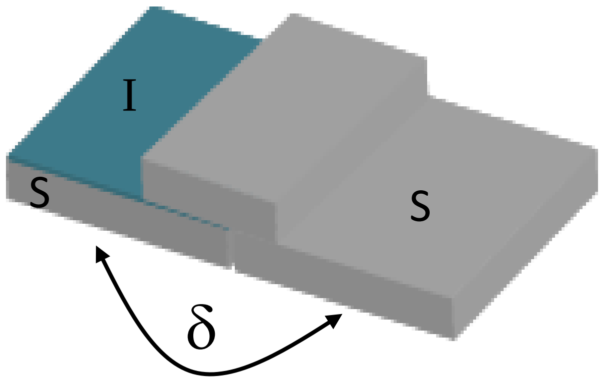


$$\omega_{pump} = \omega_{signal} + \omega_{idler}$$

$$2\omega_{pump} = \omega_{signal} + \omega_{idler}$$

Josephson junction: An “ideal” non-linear element

Superconducting
Tunnel Junction



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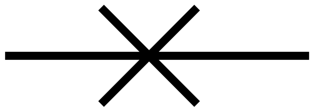
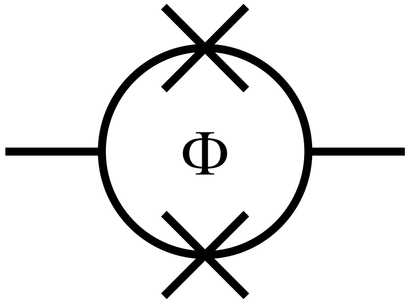


$$I = I_0 \sin \delta \qquad V = \frac{\hbar}{2e}\frac{\partial \delta}{\partial t}$$

$$L_J = \frac{\hbar}{2eI_0 \cos \delta} \equiv \frac{L_{J0}}{\cos \delta}$$

SQUID



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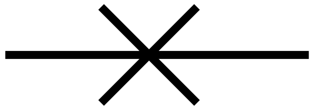
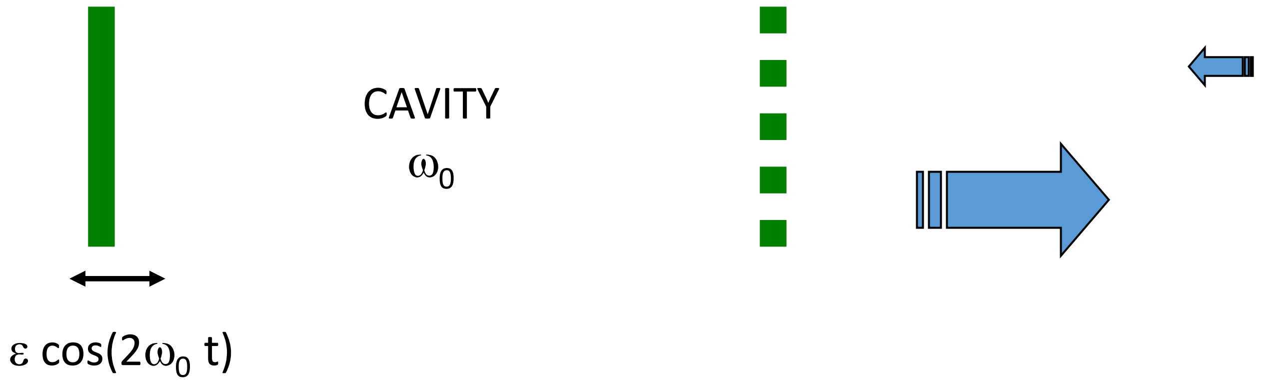


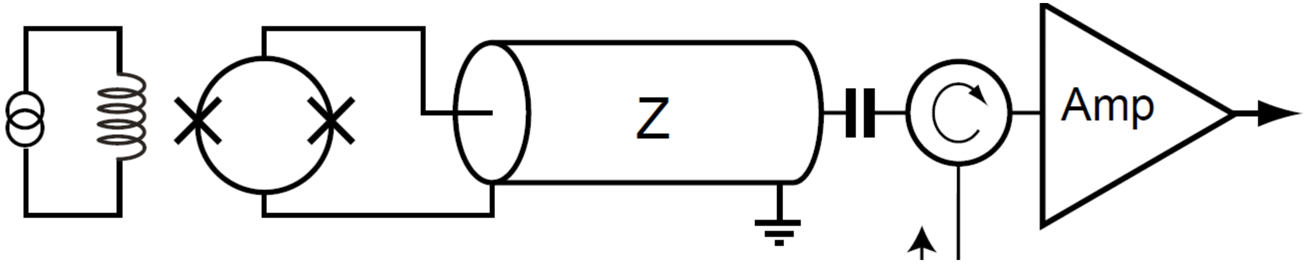
$L_J(\Phi)$

Flux tunable
Nonlinear
Non-dissipative
Inductor

Parametric Amplification in parametrically driven resonators



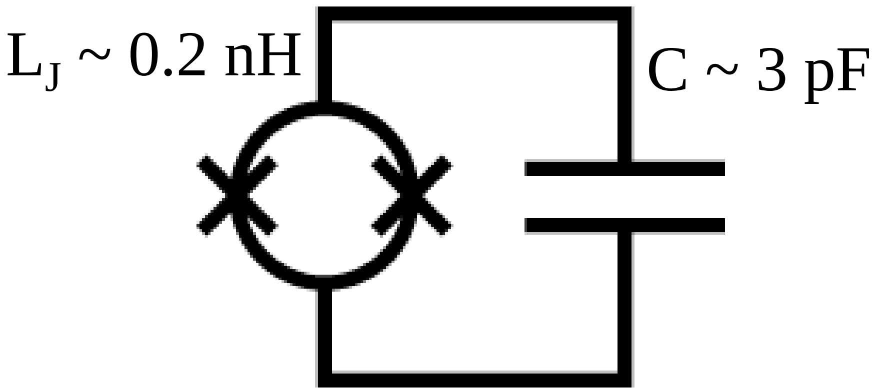
"Fabry-Perot cavity"

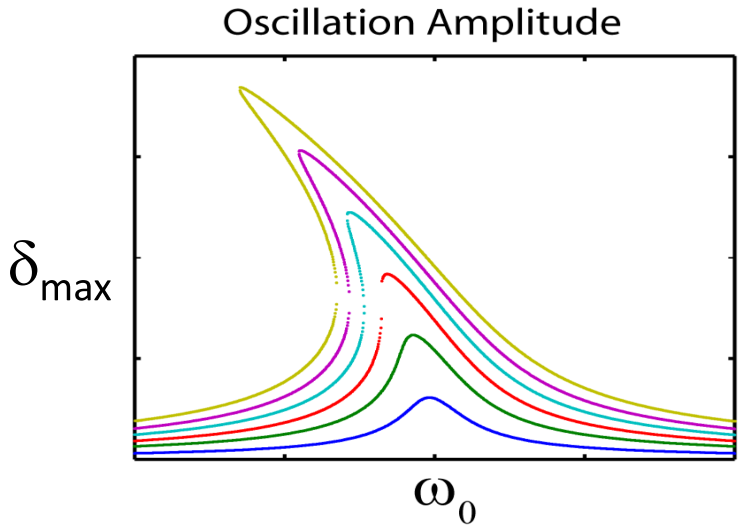


UCSB: APL **103**, 122602 (2013)

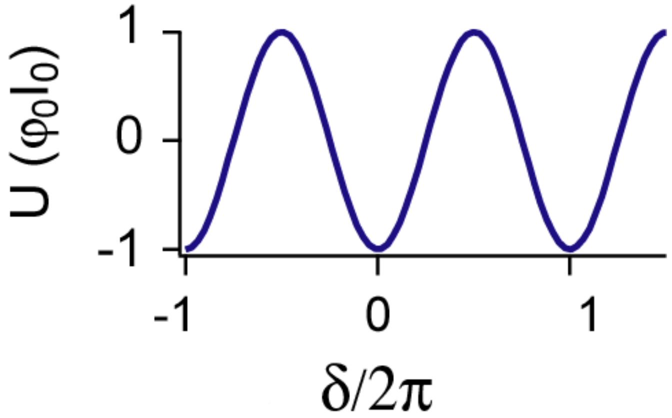
Saclay : Phys. Rev. B 89, 214517 (2014)

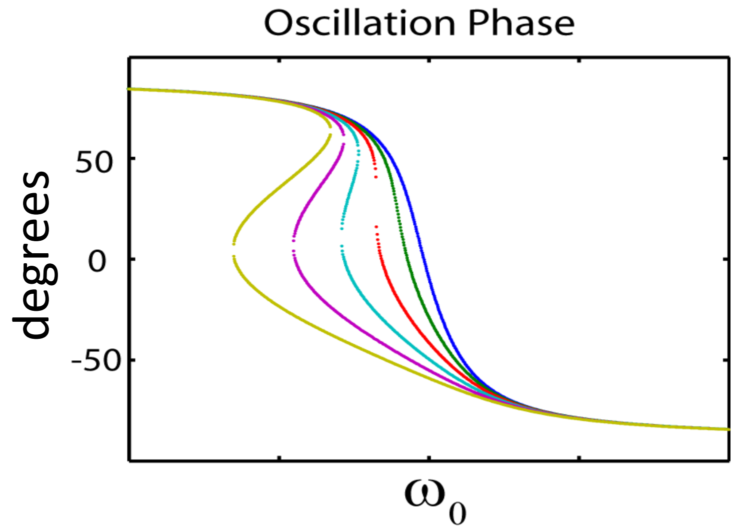
Driven nonlinear oscillator





Classical oscillator





Driven nonlinear oscillator: Equation of motion

$$\ddot{x} + 2\Gamma\dot{x} + {\omega_0}^2[x \; - \alpha x^3] = F_p \cos \omega_p t$$

$$x(t) = x_p \cos(\omega_p t + \theta)$$

$$\ddot{x} + 2\Gamma\dot{x} + {\omega_0}^2[x \; - \alpha x^3] = F_p \cos \omega_p t + F_s \cos \omega_s t$$

$$x(t) = x_p \cos\left(\omega_p t + \phi_p\right) + y(t) \qquad F_s \ll F_p \, , |y(t)| \ll x_p$$

$$\ddot{y} + 2\Gamma\dot{y} + {\omega_{0,eff}}^2\left[1 + k \cos 2\omega_p t\right] y = F_s \cos \omega_s t$$

Driven nonlinear oscillator: Effective equation

$$\ddot{y} + 2\Gamma\dot{y} + {\omega_{0,eff}}^2\left[1 + k\cos(2\omega_p t - 2\theta)\right]y = F_s \cos\omega_s t$$

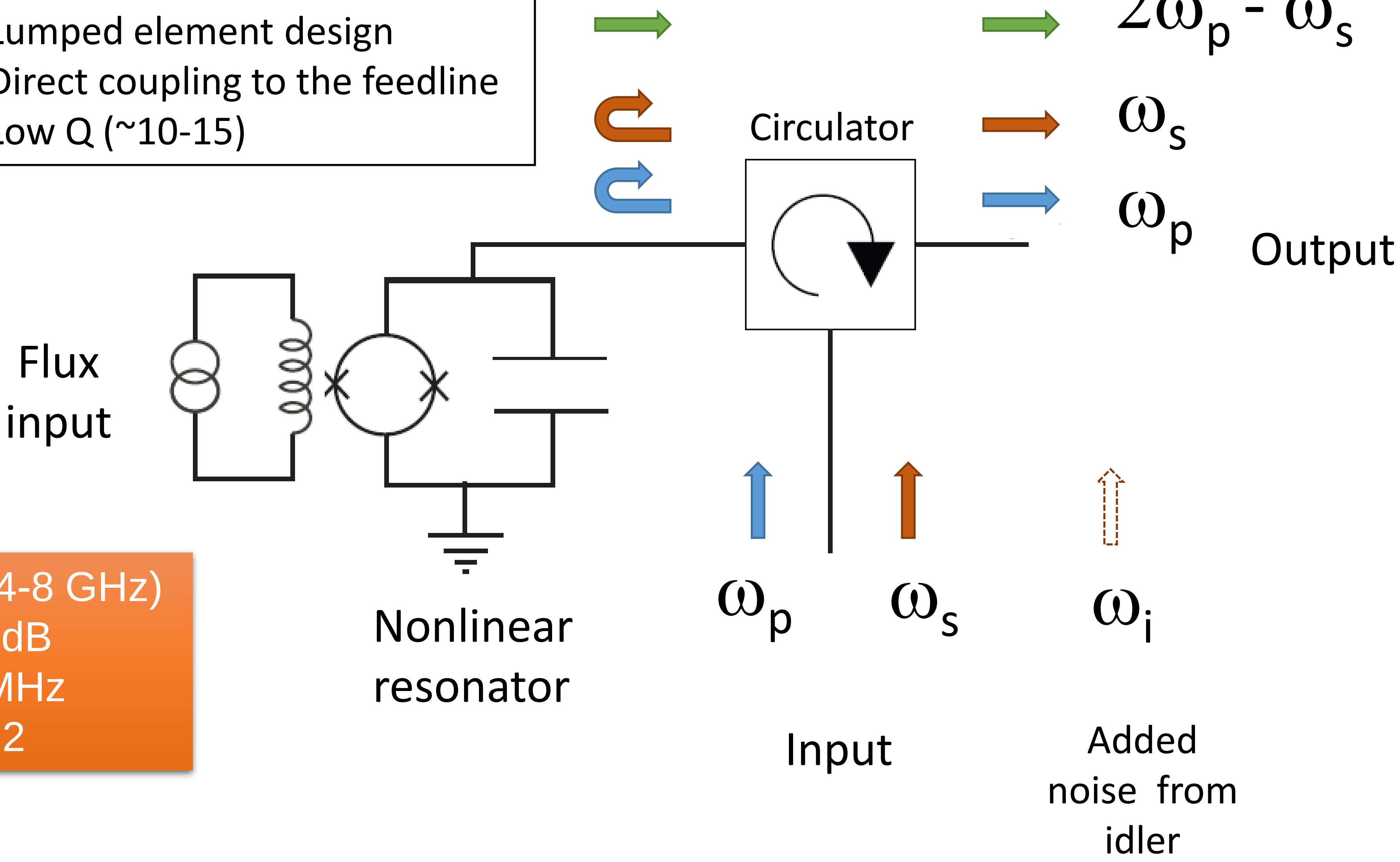
Parametrically driven "harmonic" oscillator

Detuned pump: $\omega_p \neq \omega_{0,eff}$

Pump strength: $\omega_{0,eff}^2\, k \propto \left|x_p\right|^2$

Driven non-linear oscillator as a paramp

- Flux tunable band
- Lumped element design
- Direct coupling to the feedline
- Low Q (~10-15)

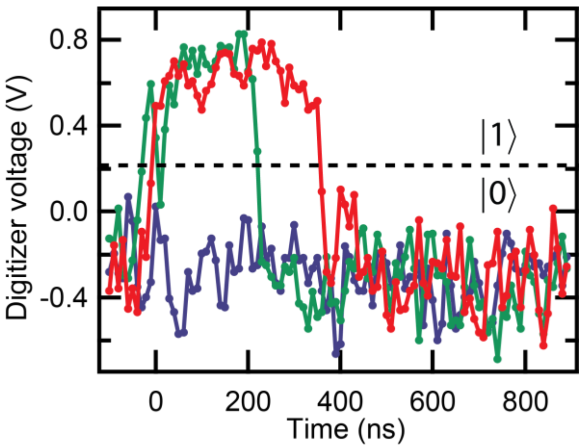


- Tunable (4-8 GHz)
- Gain > 20 dB
- BW > 10 MHz
- $k_B T_N \sim hf / 2$

M. Hatridge, R. Vijay, D. H. Slichter, J. Clarke, and I.Siddiqi, Phys. Rev. B **83**, 134501 (2011)

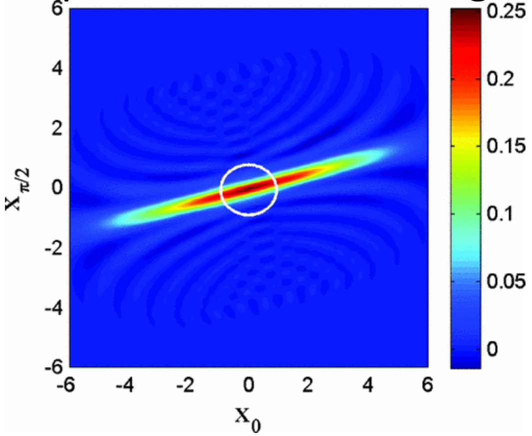
Applications of parametric amplifiers

Quantum jumps



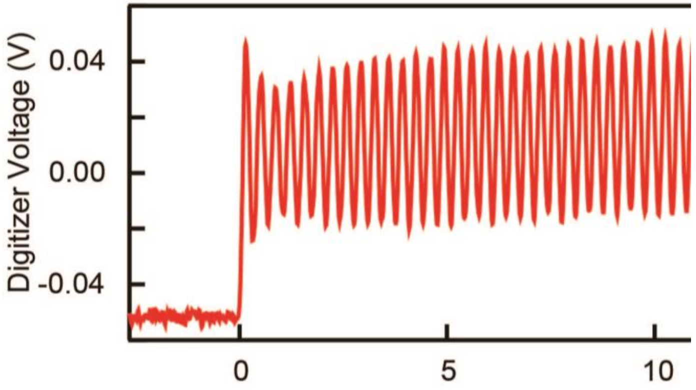
PRL **106**, 110502 (2011))

Squeezed microwave light



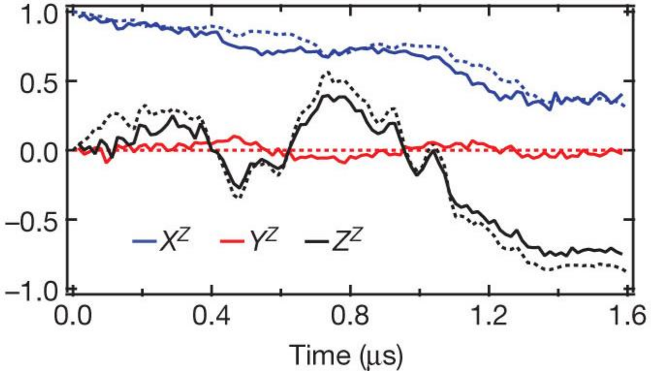
PRL **106**, 220502 (2011)

Quantum feedback



Nature **490**, 77-80 (2012)

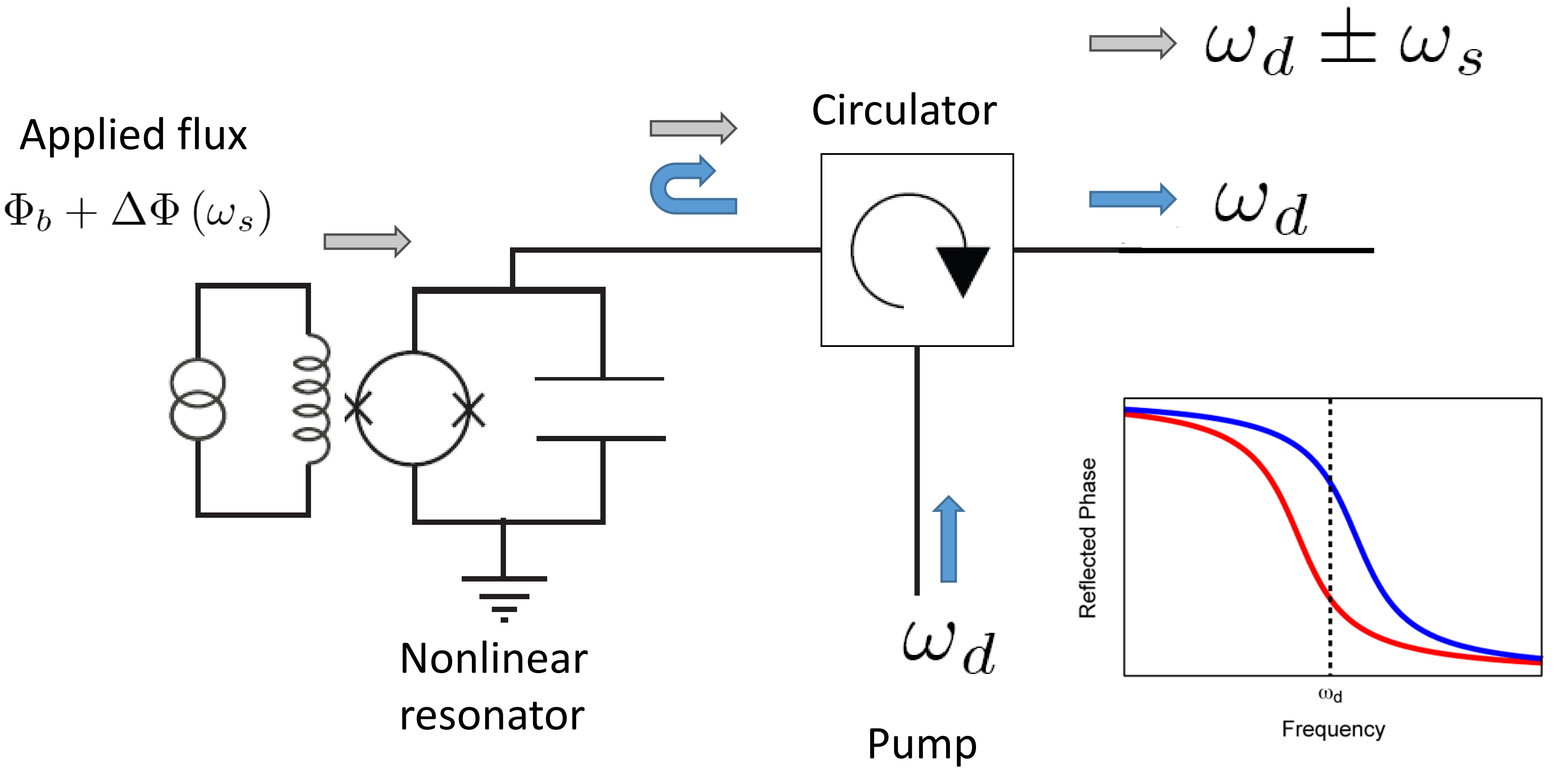
Single quantum trajectories



Nature **502**, 211-214 (2013)

And much much more…..

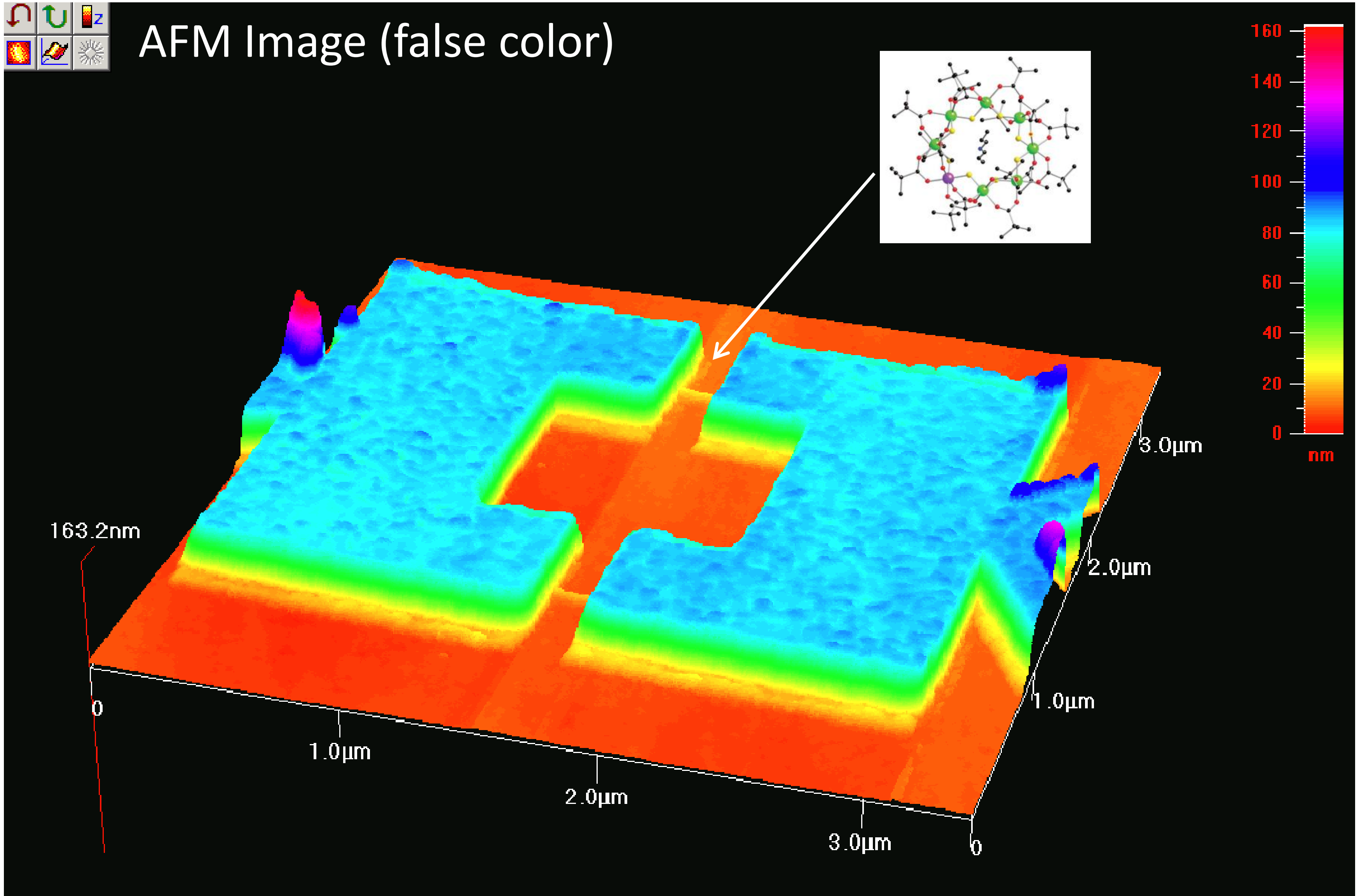
Dispersive Magnetometer



Input flux signal is up-converted and amplified

M. J. Hatridge, R. Vijay, D.H. Slichter, John Clarke and I. Siddiqi, Phys. Rev. B **83**, 134501 (2011)

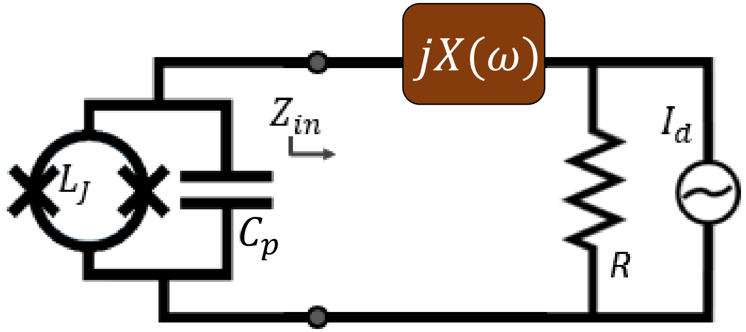
NanoSQUID Magnetometer

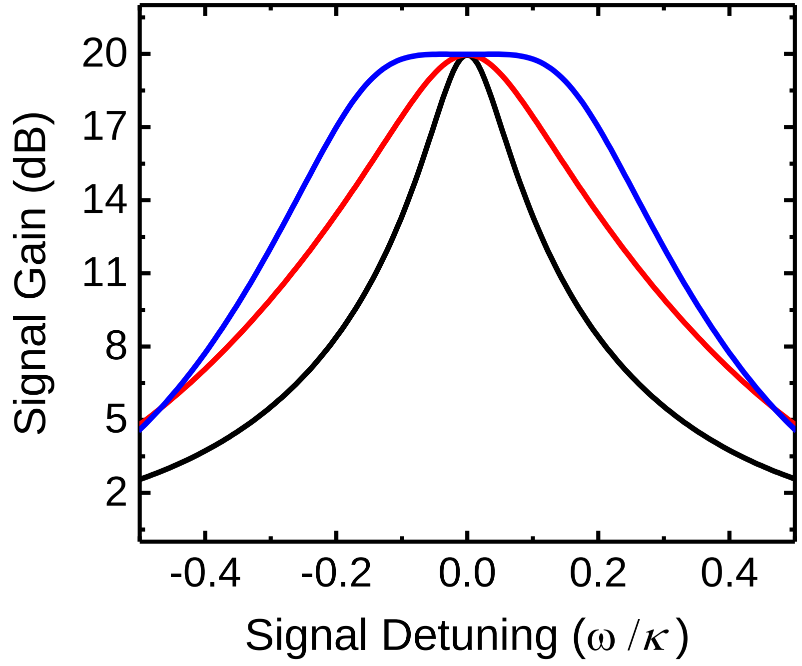


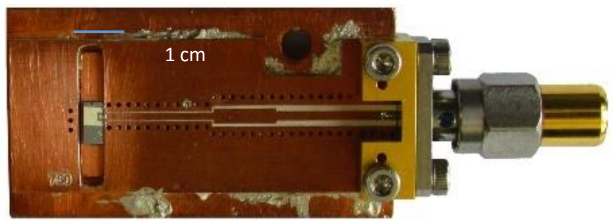
E. Levenson-Falk, R. Vijay et al., Supercond. Sci. Technol. 26 055015 (2013)

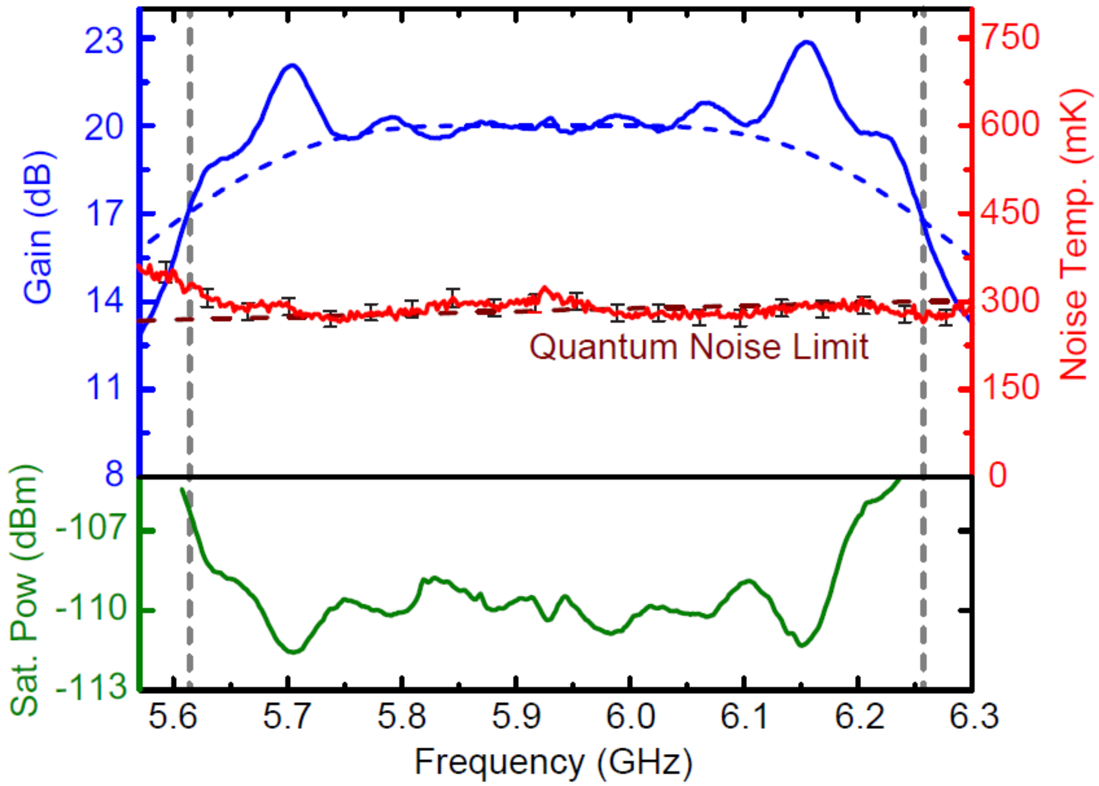
Recent work at TIFR: Broadband Parametric Amplifiers

<u>Impedance engineered parametric amplifier</u>





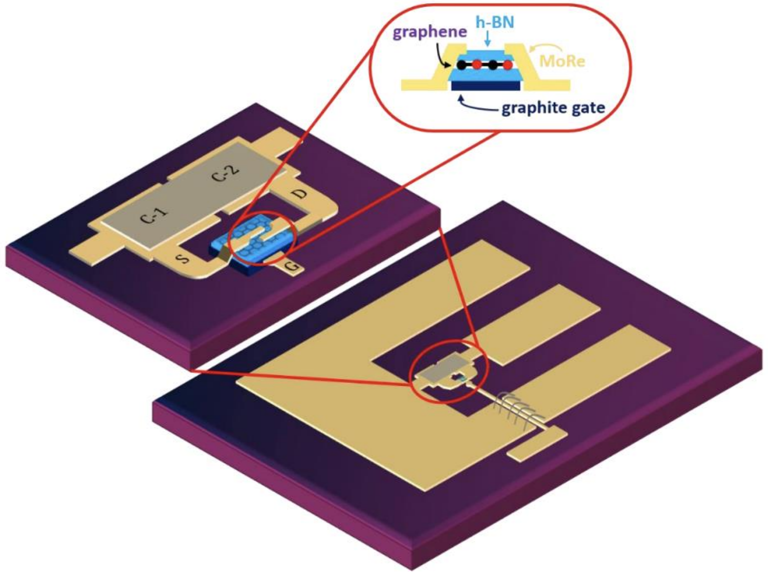




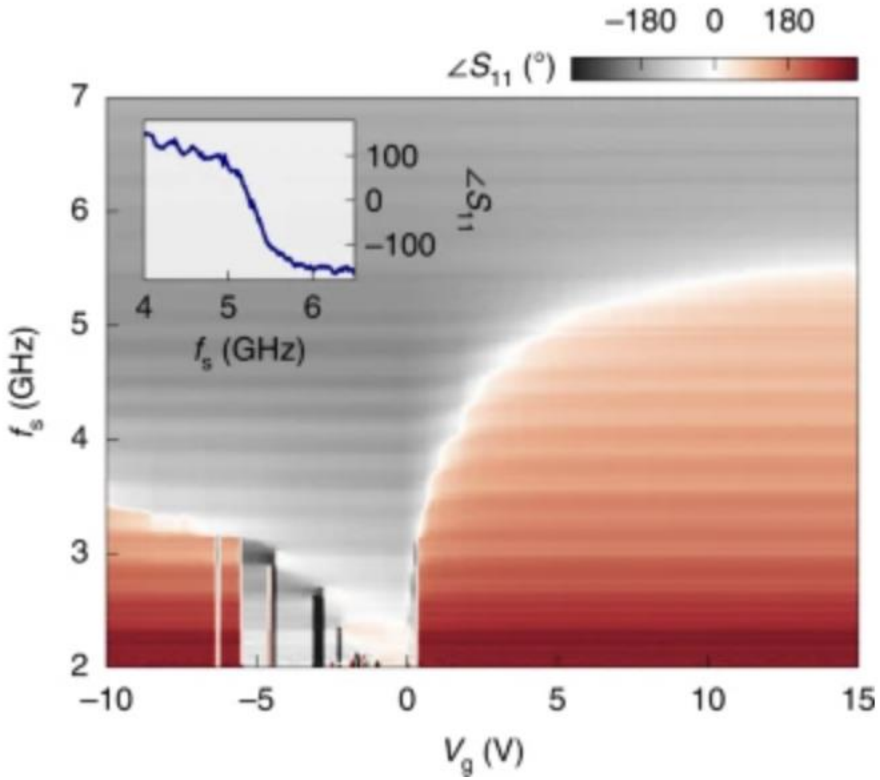
Roy *et. al.* Appl. Phys. Lett. **107**, 262601 (2015)

Recent work at TIFR: Graphene JJ parametric amplifier

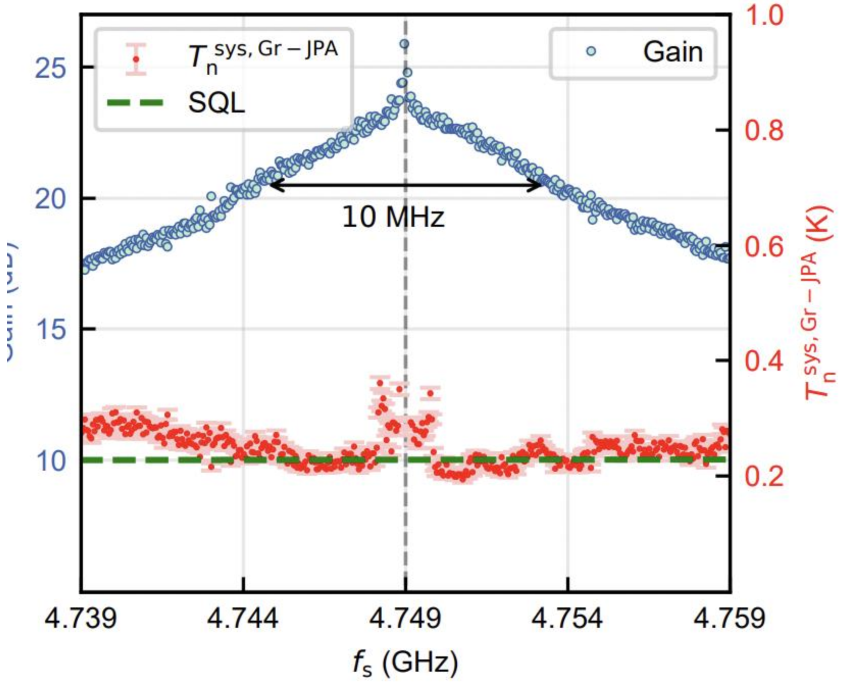
Graphene Josephson Junction



Gate voltage tunability



Quantum limited noise performance



- Gate voltage tunablity
- High field operation
- New types of quantum sensors and bolometers

(in collaboration Prof. Mandar Deshmukh at TIFR)

Joydip Sarkar, Kishor V Salunkhe et al., *Nature Nanotechnology* **volume 17**, pages1147–1152 (2022)

Dark Matter Search using parametric amplifier devices

Dark Matter Axion Search Using a Josephson Traveling Wave Parametric Amplifier

arXiv:2110.10262

C. Bartram, T. Braine, R. Cervantes, N. Crisosto, N. Du, G. Leum, P. Mohapatra, T. Nitta, L. J Rosenberg, G. Rybka, J. Yang, John Clarke, I. Siddiqi, A. Agrawal, A. V. Dixit, M. H. Awida, A. S. Chou, M. Hollister, S. Knirck, A. Sonnenschein, W. Wester, J. R. Gleason, A. T. Hipp, S. Jois, P. Sikivie, N. S. Sullivan D. B. Tanner, S. Hoof, E. Lentz, R. Khatiwada, G. Carosi, C. Cisneros, N. Robertson, N. Woollett, L. D. Duffy, C. Boutan, M. Jones, B. H. LaRoque, N. S. Oblath, M. S. Taubman, E. J. Daw, M. G. Perry, J. H. Buckley, C. Gaikwad, J. Hoffman, K. Murch, M. Goryachev, B. T. McAllister, A. Quiskamp, C. Thomson, M. E. Tobar

We present a new exclusion bound of axion-like particle dark matter with axion-photon couplings above $10^{-13}\ \mathrm{GeV}^{-1}$ over the frequency range 4796.7--4799.5 MHz, corresponding to a narrow range of axion masses centered around 19.84 μeV. This measurement represents the first implementation of a Josephson Traveling Wave Parametric Amplifier (JTWPA) in a dark matter search. The JTWPA was operated in the insert of the Axion Dark Matter eXperiment (ADMX) as part of an independent receiver chain that was attached to a 0.588-liter cavity. The ability of the JTWPA to deliver high gain over a wide (3 GHz) bandwidth has engendered interest from those aiming to perform broadband axion searches, a longstanding goal in this field.

Near-Quantum-Noise Axion Dark Matter Search at CAPP around 9.5 μeV

arXiv:2207.13597

Jinsu Kim, Ohjoon Kwon, Çağlar Kutlu, Woohyun Chung, Andrei Matlashov, Sergey Uchaikin, Arjan Ferdinand van Loo, Yasunobu Nakamura, Seonjeong Oh, HeeSu Byun, Danho Ahn, Yannis K. Semertzidis

We report the results of an axion dark matter search over an axion mass range of 9.39-9.51 μeV. A flux-driven Josephson parametric amplifier (JPA) was added to the cryogenic receiver chain. A system noise temperature of as low as 200 mK was achieved, which is the lowest recorded noise among published axion cavity experiments with phase-insensitive JPA operation. In addition, we developed a two-stage scanning method which boosted the scan speed by 26%. As a result, a range of two-photon coupling in a plausible model for the QCD axion was excluded with an order of magnitude higher in sensitivity than existing limits.

Interests

- Developing new quantum limited detectors using superconducting circuits
- Participating in experiments involving Dark Matter Search, Gravitational Wave Detection
- We will need (in the Indian context):
  - Other scientists who can design the experiments
  - Creating links with international experiments

THANK YOU