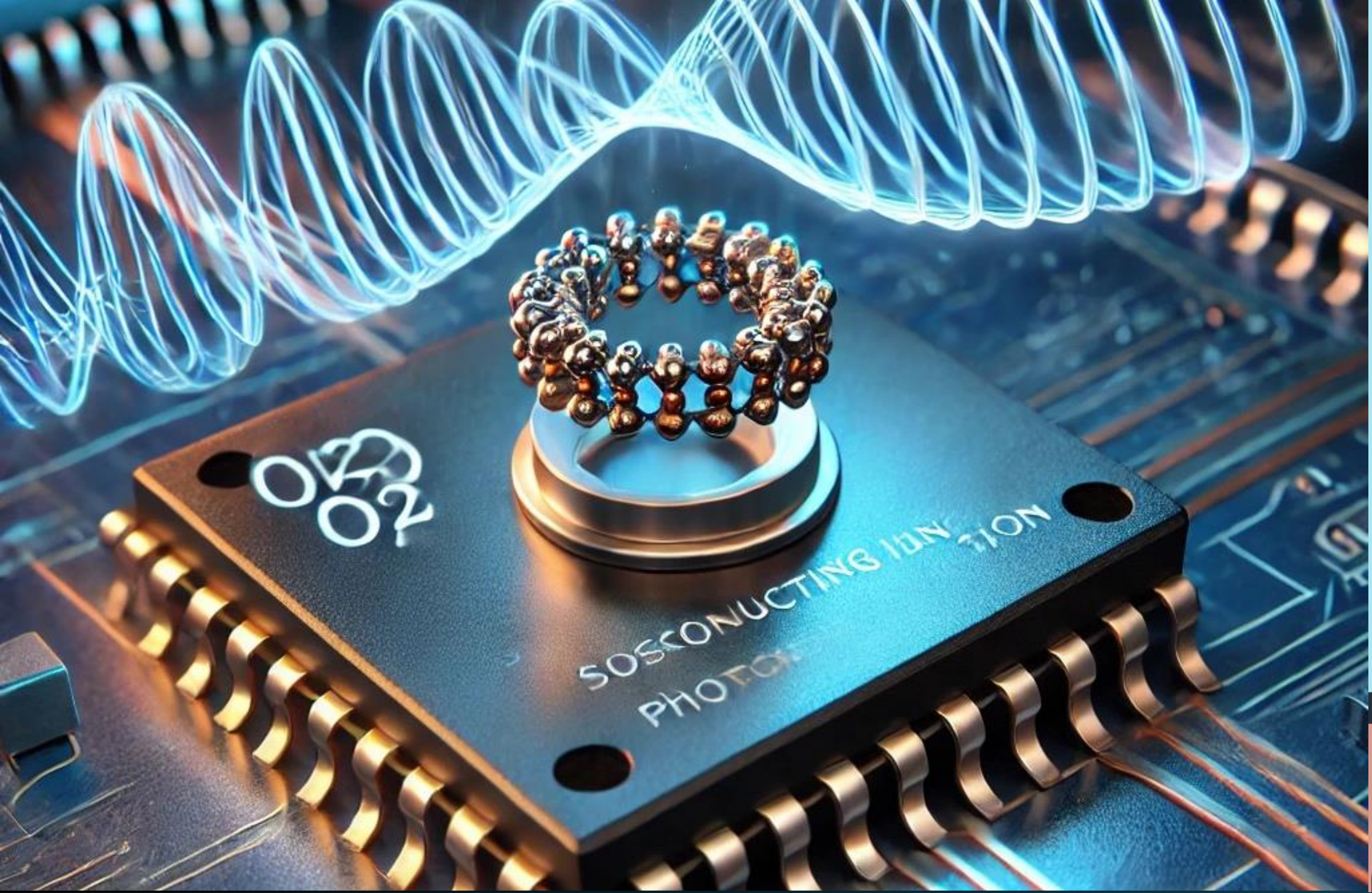


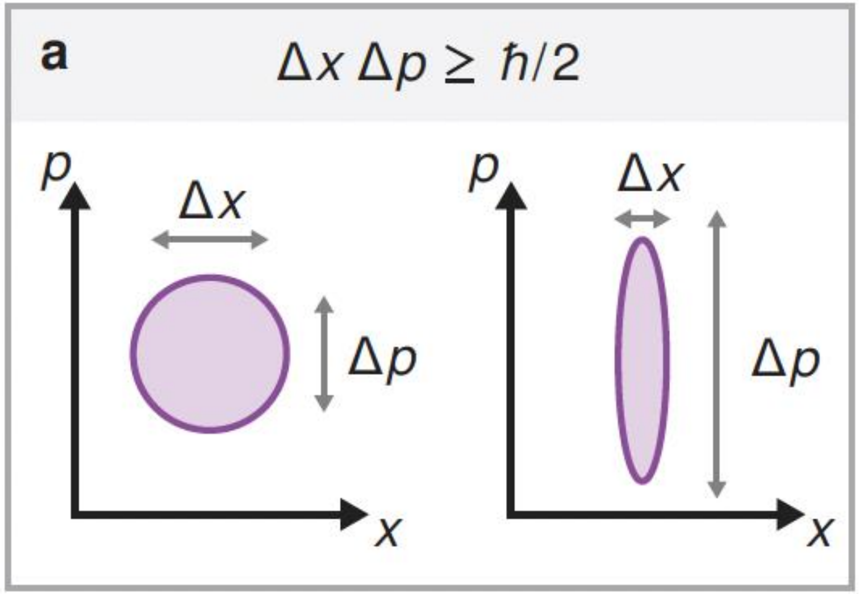
High-sensitivity detectors and readout technologies for axions searches

Claudio Gatti
LNF INFN

Outline

- Parametric Amplifiers
- TWPA
- Beyond Quantum Limit #1: Squeezing; Quantum Sensing
- Single Qubit Sensors
- Multi Qubit Sensors
- Sensing with Non Classical States
- Combining Squeezing and Counting
- Coherent Sum of Signals
- Operating in a Strong Magnetic Field

Quantum limit #1



Quantum limit #2

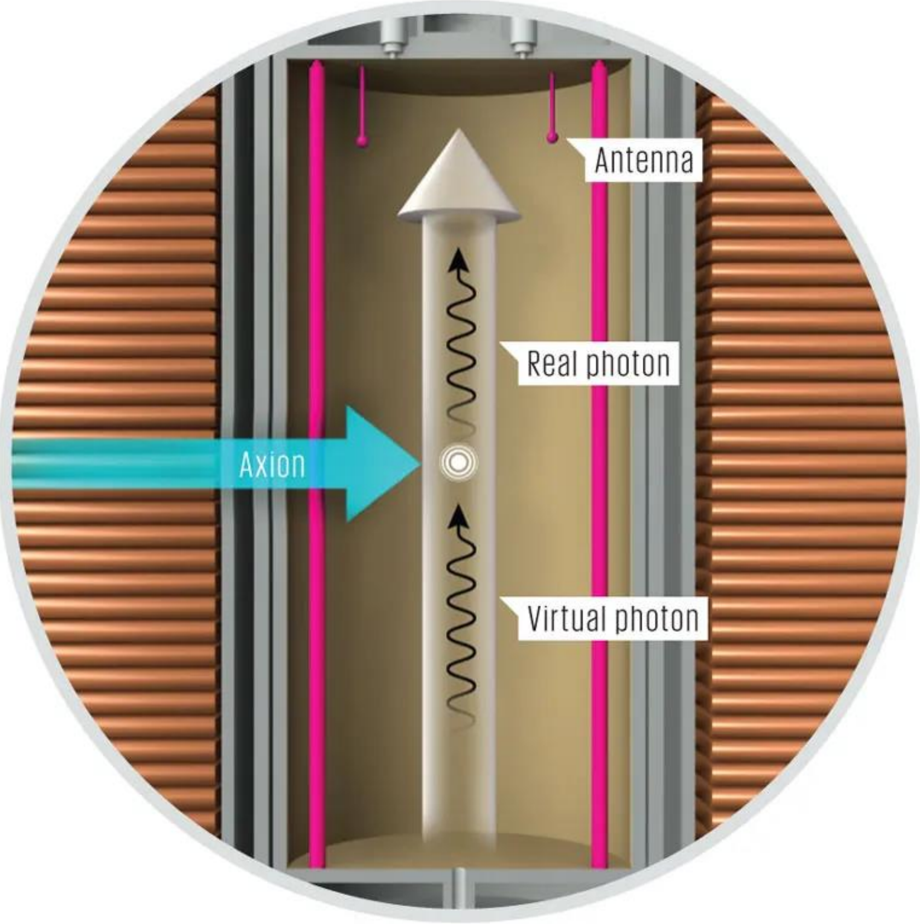
$$\Delta\theta \geq \frac{1}{\sqrt{N}}$$ Standard Quantum Limit

$$\Delta\theta \geq \frac{1}{N}$$ Heisenberg Limit

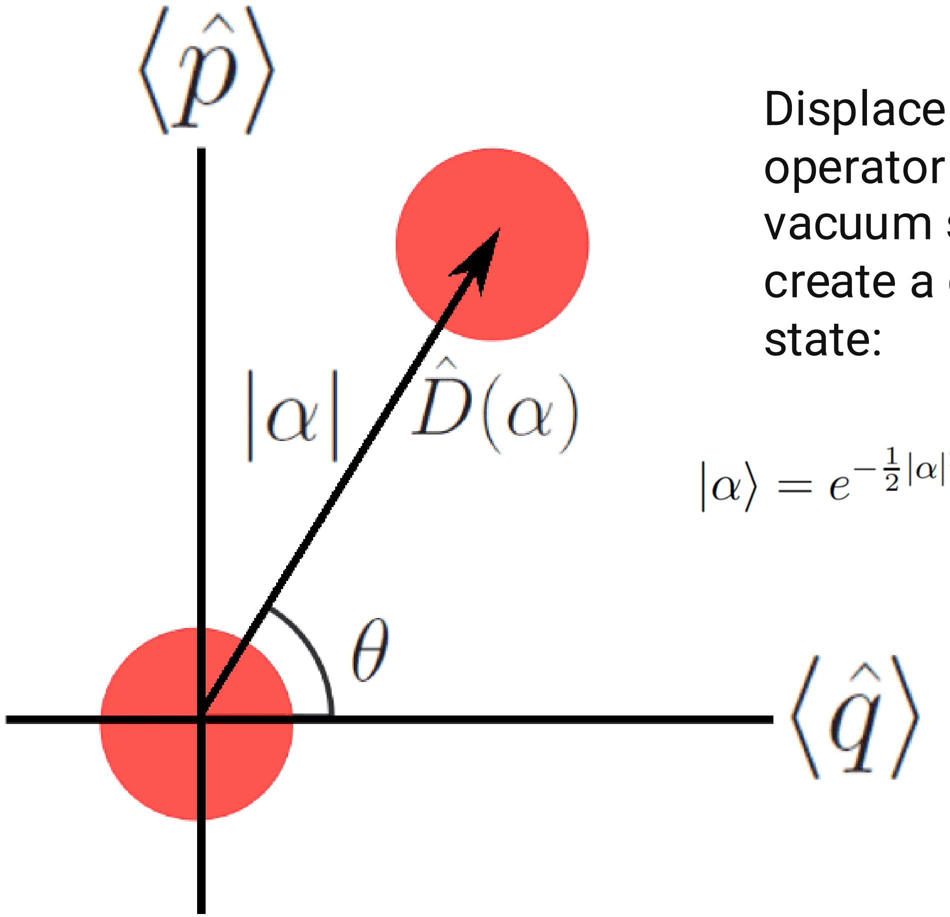
Number of measurements N

Root mean squared error $\Delta\theta$

Axion Interaction in a Microwave Cavity



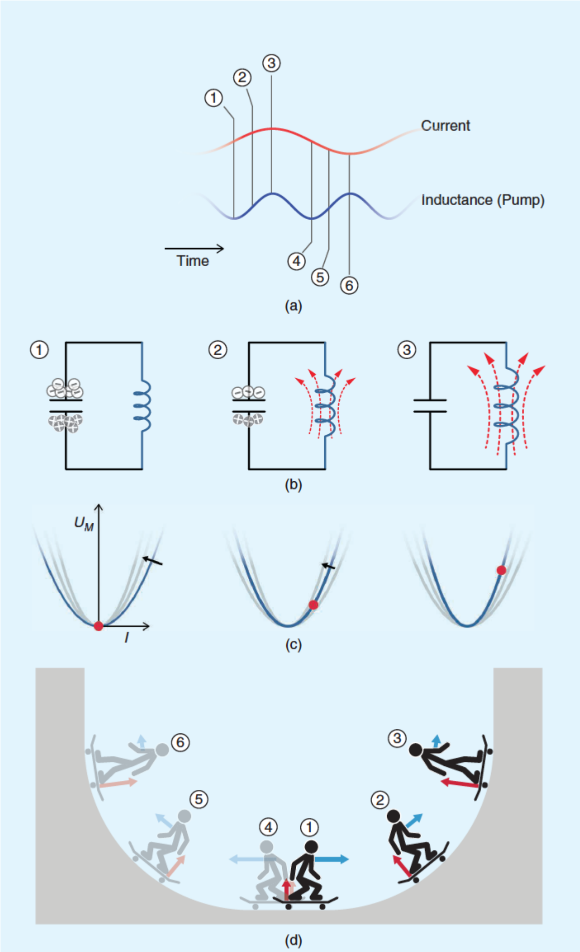
https://spectrum.ieee.org/the-hunt-for-the-invisible-axion



Displacement operator acting on a vacuum state to create a coherent state:

$$|\alpha\rangle = e^{-\frac{1}{2}|\alpha|^2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

Parametric Amplification

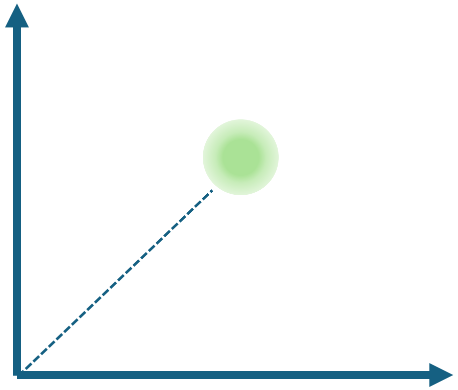


J. Aumentado IEEE Microwave Magazine

- Parametric amplification is obtained by modifying the parameters of an oscillating system.
- In electrical circuits is obtained by modulating capacitances or inductors with “pump” currents.
- In lossless superconducting circuits parametric amplification allows to reach the noise at the quantum limit.

$$V(t) = i\sqrt{\hbar\omega/C}\,[(a^+ - a)cos\omega t + i(a^+ + a)sin\omega t]$$

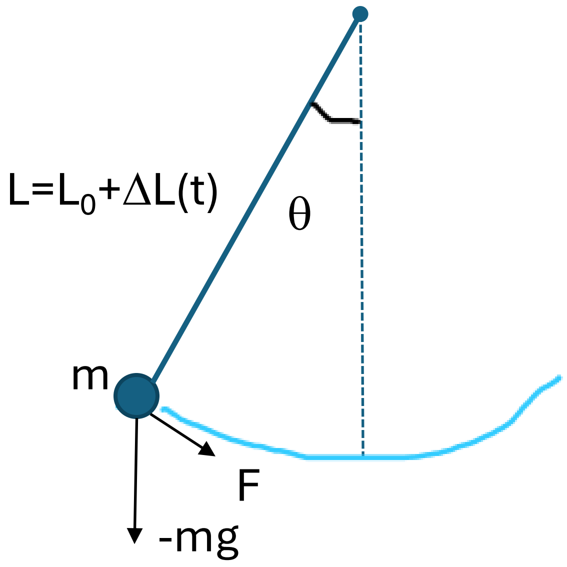
$$Y = \frac{(a^+ + a)}{\sqrt{2}}$$



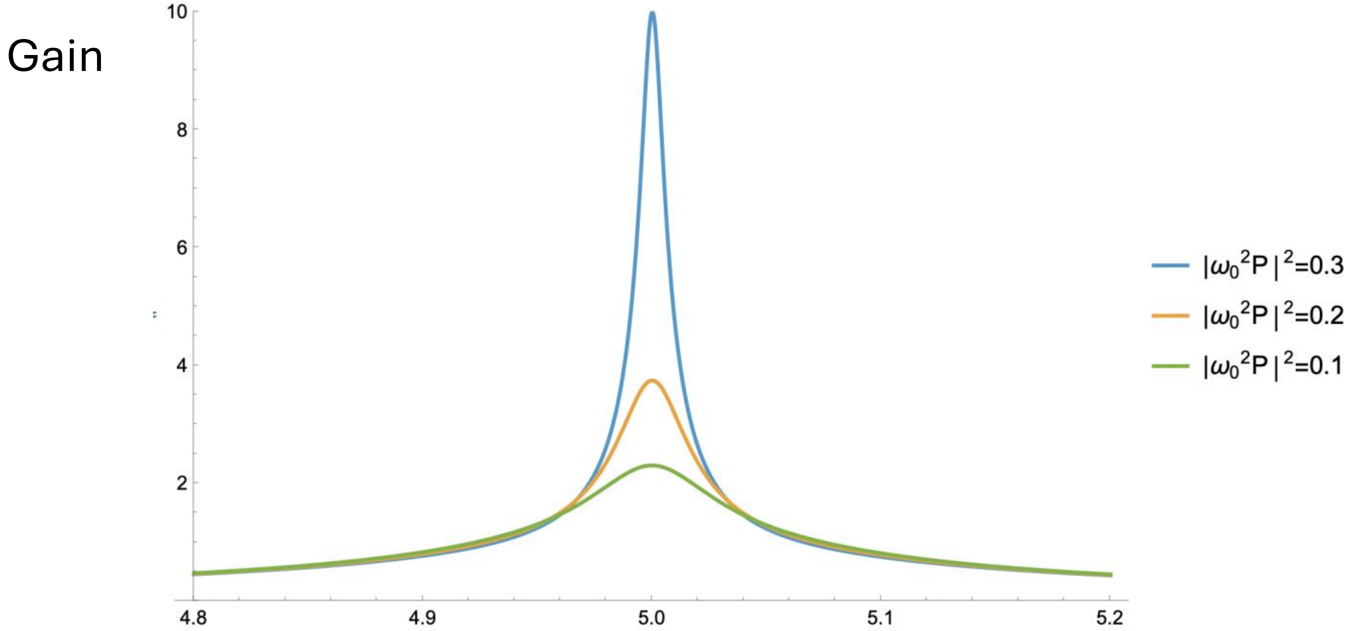
$$k_B T_{noise}^{min} = \hbar\omega/2$$

$$X = \frac{(a^+ - a)}{\sqrt{2}}$$

Parametric Amplification



$$|S|_{\omega_p\to 2\omega} = \frac{F}{m\,L_0}\frac{\sqrt{(\omega^2-\omega_0^2)^2+(\omega\gamma)^2}}{(\omega^2-\omega_0^2)^2+(\omega\gamma)^2-\omega_0^4|p|^2}$$



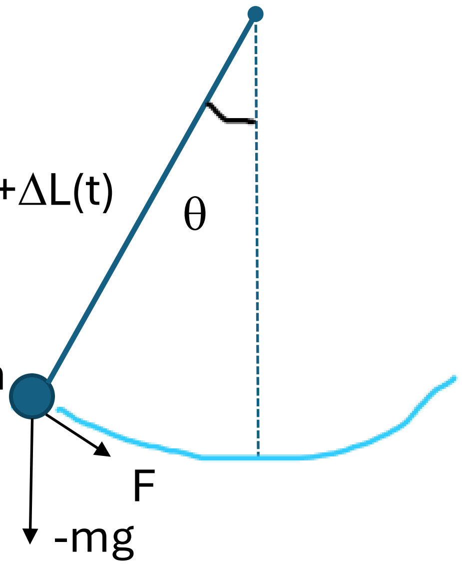
Loss

Pump

$$\ddot{\theta} + \gamma\dot{\theta} + \omega_0^2(1-p(t))\theta = \frac{Fe^{-i\omega t}}{m\,L_0}$$

$$p(t) = \frac{\Delta L(t)}{L_0} = p\,e^{-i\omega_p t} + \text{c.c.}$$

Parametric Amplification



Loss

Pump

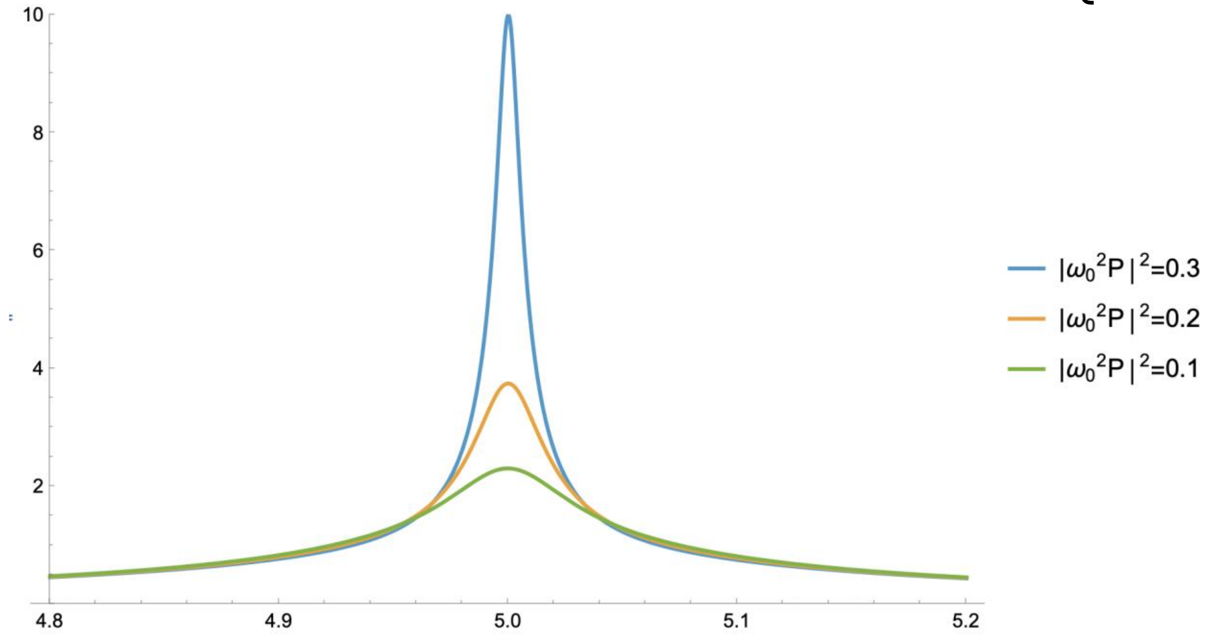
$$\ddot{\theta} + \gamma\dot{\theta} + \omega_0^2(1 - p(t))\theta = \frac{Fe^{-i\omega t}}{m\,L_0}$$

$$p(t) = \frac{\Delta L(t)}{L_0} = p\,e^{-i\omega_p t} + \text{c.c.}$$

$$|S|_{\omega_p \to 2\omega} = \frac{F}{m\,L_0}\frac{\sqrt{(\omega^2 - \omega_0^2)^2 + (\omega\gamma)^2}}{(\omega^2 - \omega_0^2)^2 + (\omega\gamma)^2 - \omega_0^4|p|^2}$$

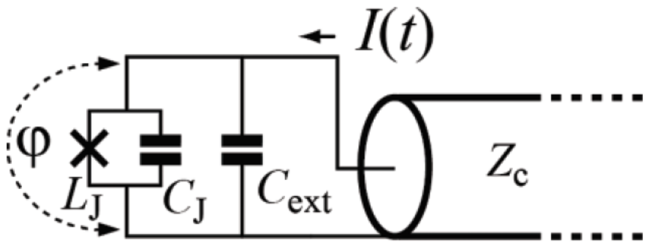
Effective increase in Q

Gain



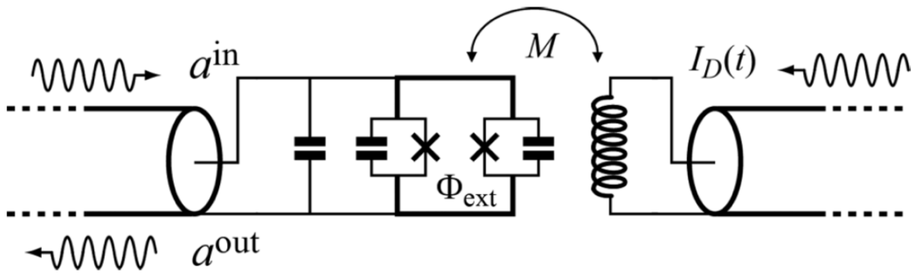
Josephson Parametric Amplifier

Quantum limited parametric amplification is obtained by driving non-linear non-dissipative elements such as Josephson junctions



Current Driven

Parametric amplification achieved by modulating the bias current in the JJ: $\omega_{pump} \sim \omega_{signal}$ 4 wave mixing

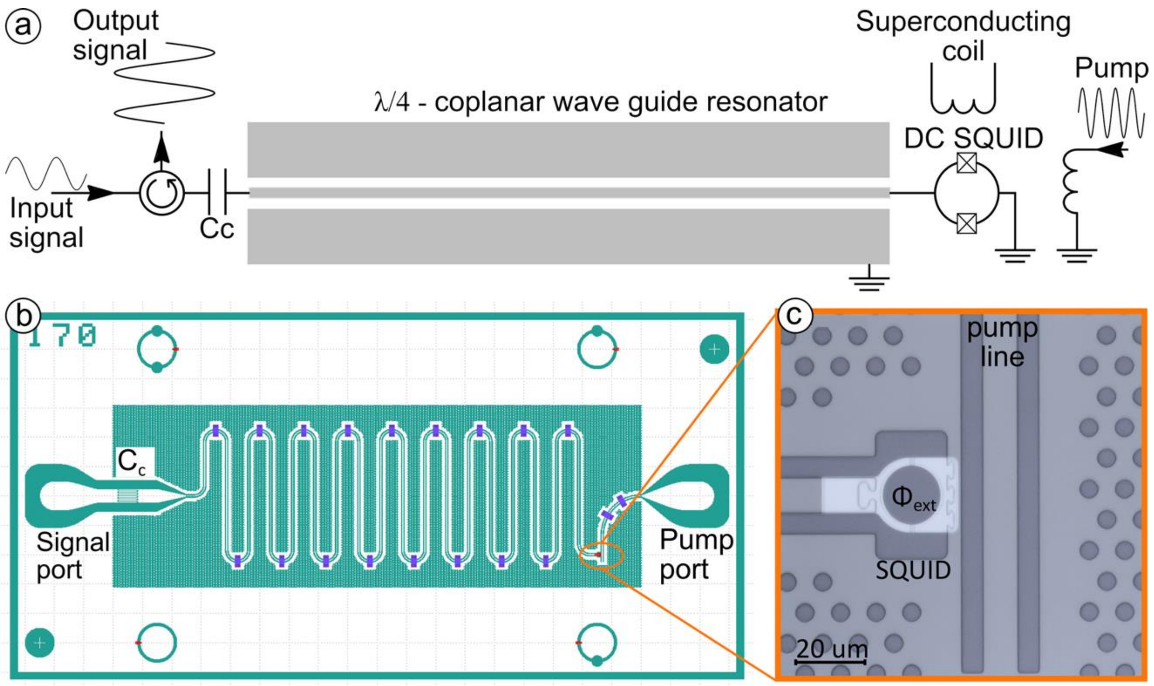


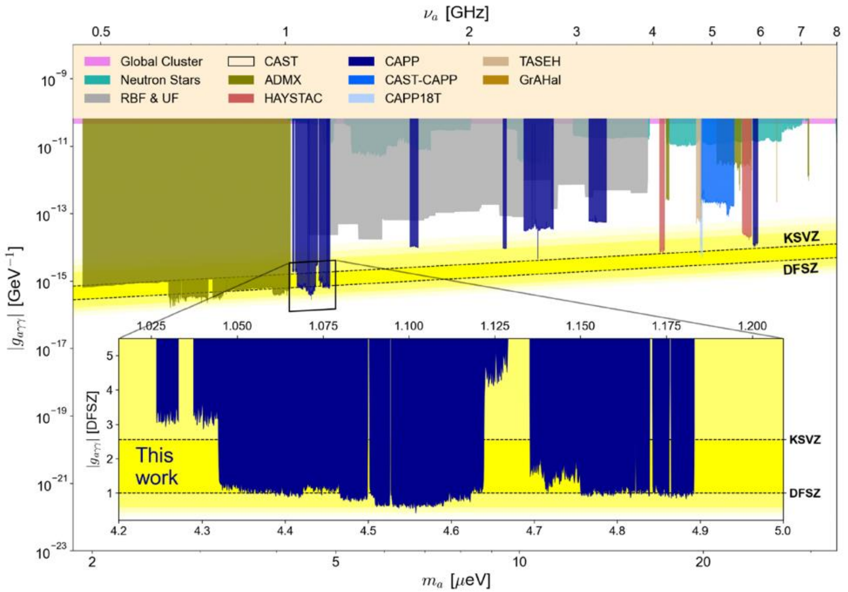
Flux Driven

Parametric amplification achieved by modulating the flux in the DC-Squid: $\omega_{pump} \sim 2\omega_{signal}$ 3 wave mixing

ROY DEVORET PHYSICAL REVIEW B 98, 045405 (2018)

IBS-CAPP – Flux Driven JPA





$T_{add\ noise}$	120 mK
mixing	3 wave
Gain	20 dB
BW	100 kHz
Tunability	100 MHz

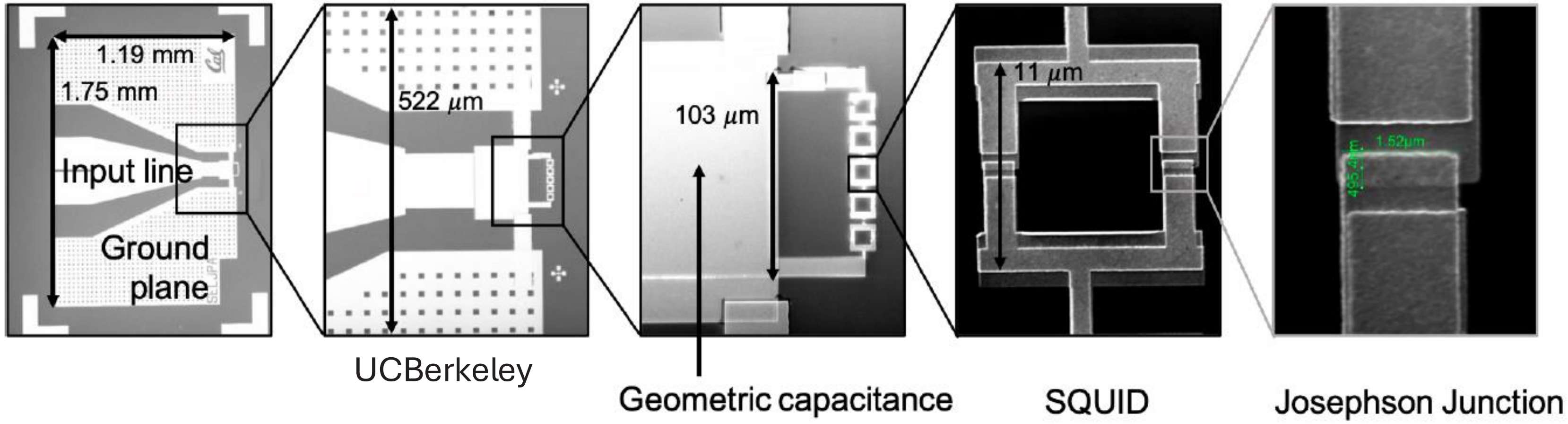
PHYSICAL REVIEW X 14, 031023 (2024)

Superconductor Science and Technology, Volume 34, Number 8

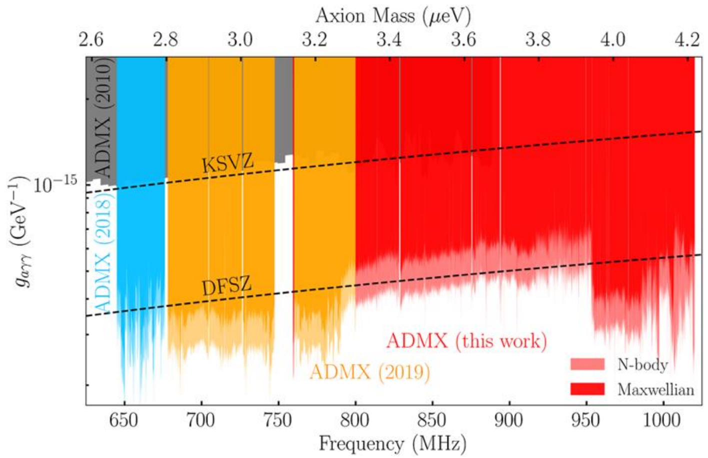
ADMX – JPA

ADMX operates a 4 wave mixing JPA in a phase insensitive mode by pumping with a microwave tone 375 kHz detuned from the cavity resonance.

See talk of Yanjie Qiu et al at Workshop on Microwave Cavities and Detectors for Axion Research



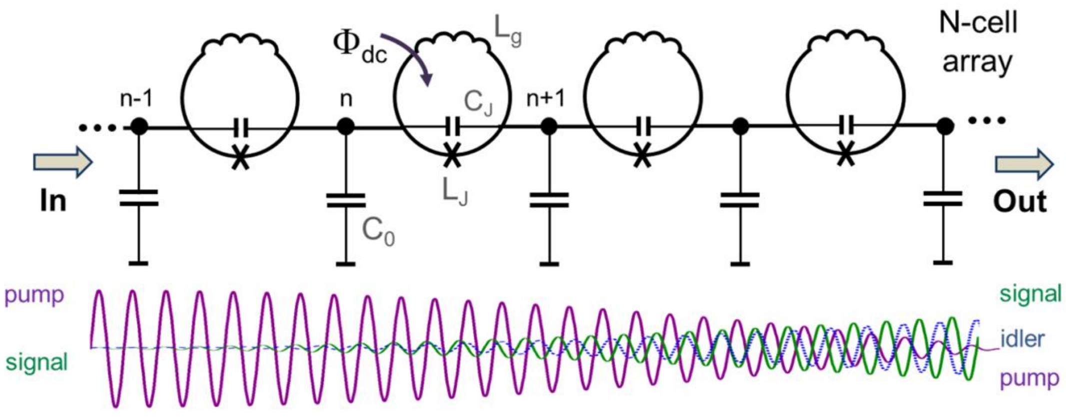
T_{JPA}	250 mK
mixing	4 wave
Gain	20 dB
BW	10 MHz
Tunability	500 MHz

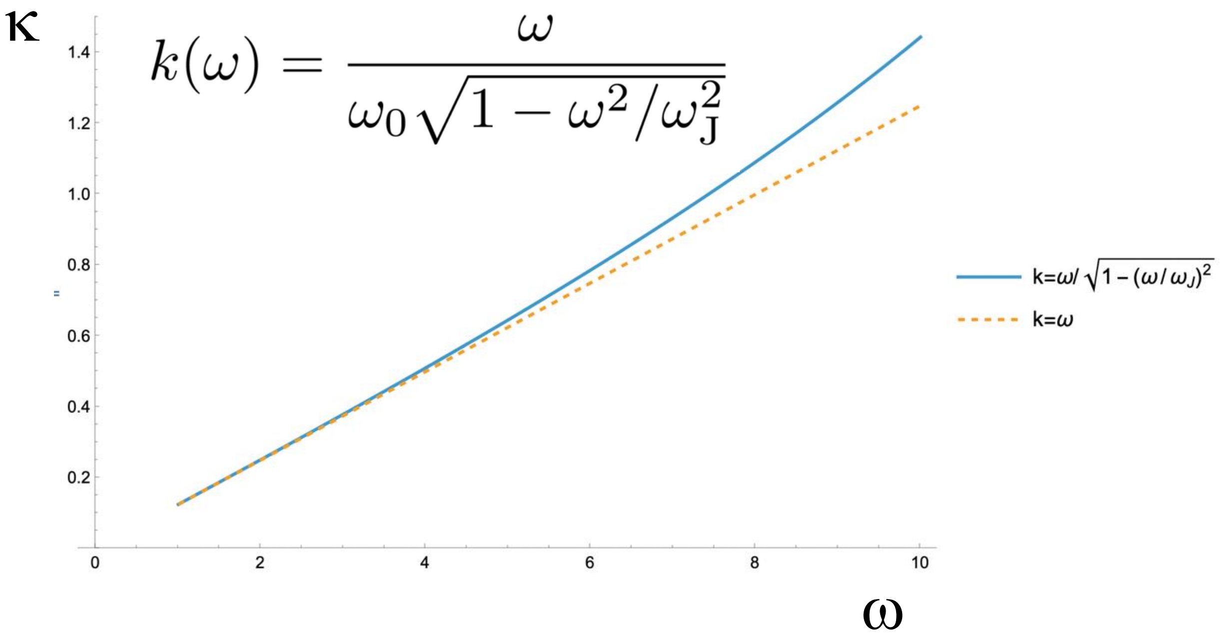


FERMILAB-PUB-20-331-AD-E-QIS Arxiv:2010.00169

PHYSICAL REVIEW LETTERS 127, 261803 (2021)

Traveling Wave Parametric Amplifier





Pump

Signal

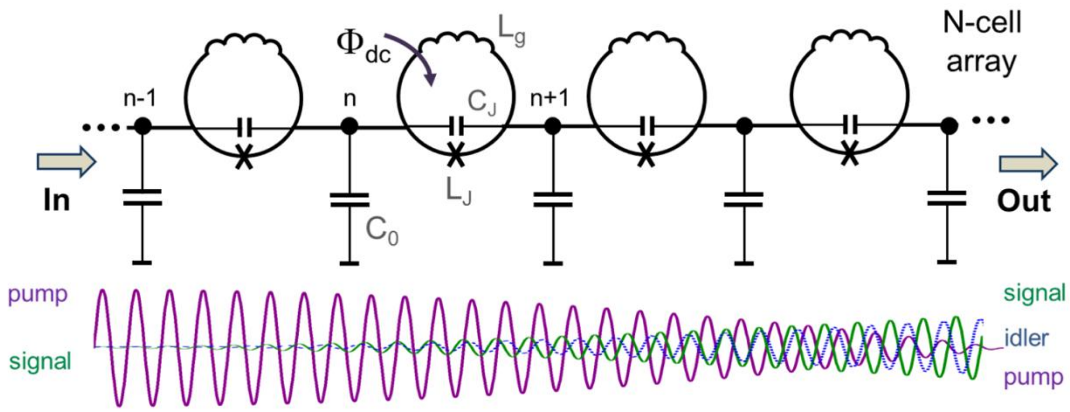
$$\varphi(z,t) = \frac{1}{2}[A_p(z)e^{i(k_p z - \omega_p t)} + A_s(z)e^{i(k_s z - \omega_s t)} + A_i(z)e^{i(k_i z - \omega_i t)} + \text{c.c.}],$$

Idler

$$\omega_s + \omega_i = 2\omega_p$$

$$2k_p \neq k_s + k_i$$

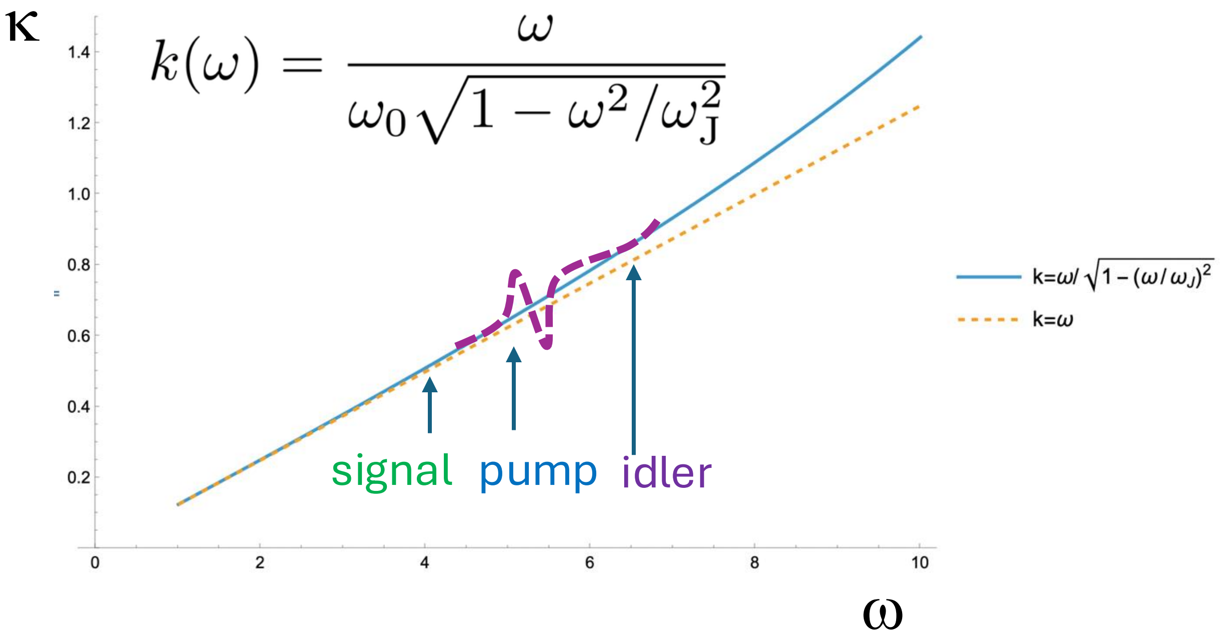
Traveling Wave Parametric Amplifier



Pump Signal

$$\varphi(z,t) = \frac{1}{2}\left[A_p(z)e^{i(k_p z - \omega_p t)} + A_s(z)e^{i(k_s z - \omega_s t)} + A_i(z)e^{i(k_i z - \omega_i t)} + \text{c.c.}\right],$$

Idler



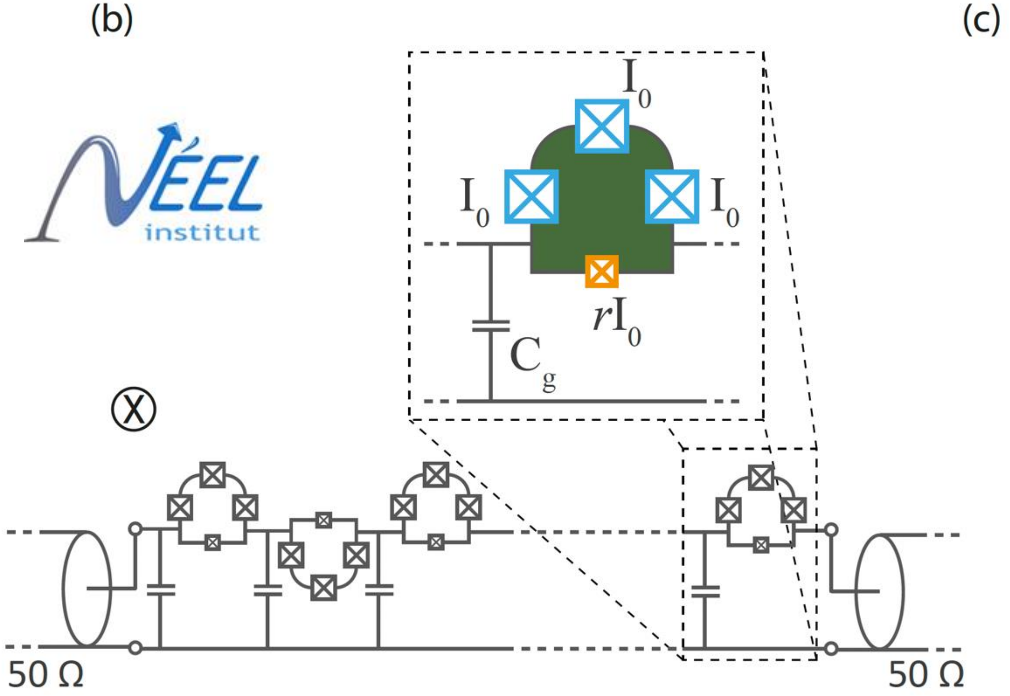
$$\omega_s + \omega_i = 2\omega_p$$

$$2k_p \neq k_s + k_i$$

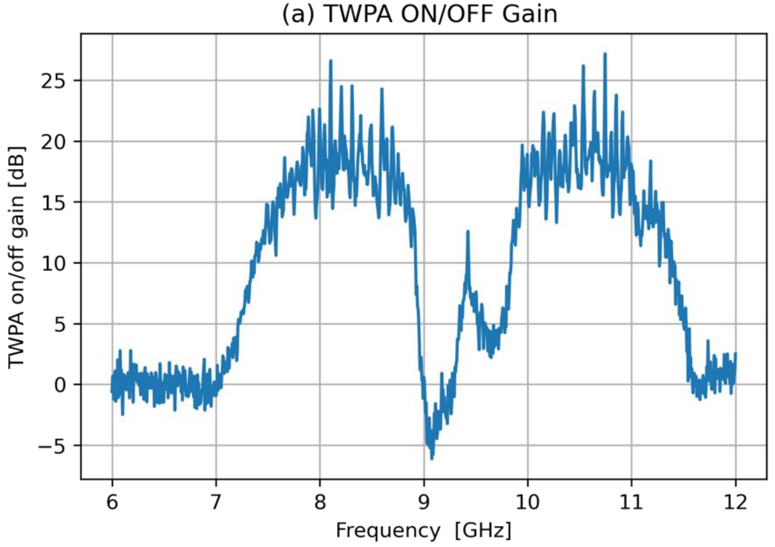
Techniques like gap engineering are used to modify the dispersion relation and recover momentum conservation

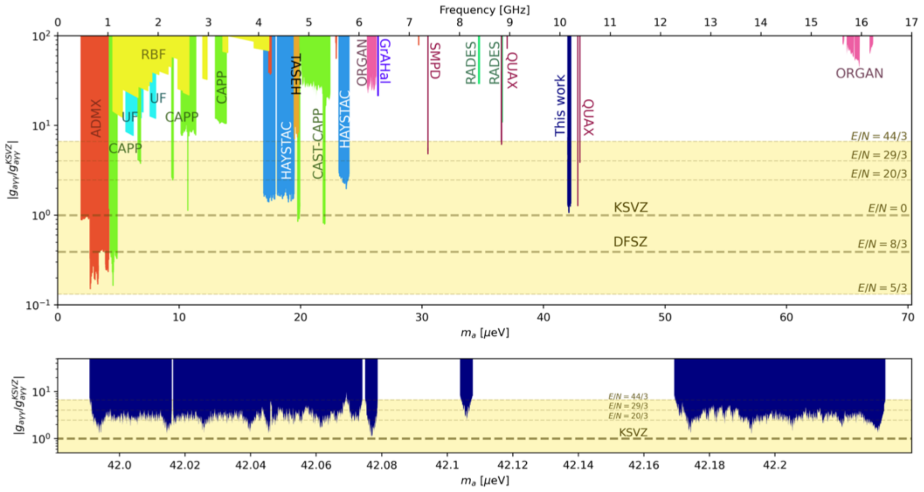
QUAX - TWPA

6 mm transmission line composed by 700 cells made of superconducting nonlinear asymmetric inductive elements (SNAIL)



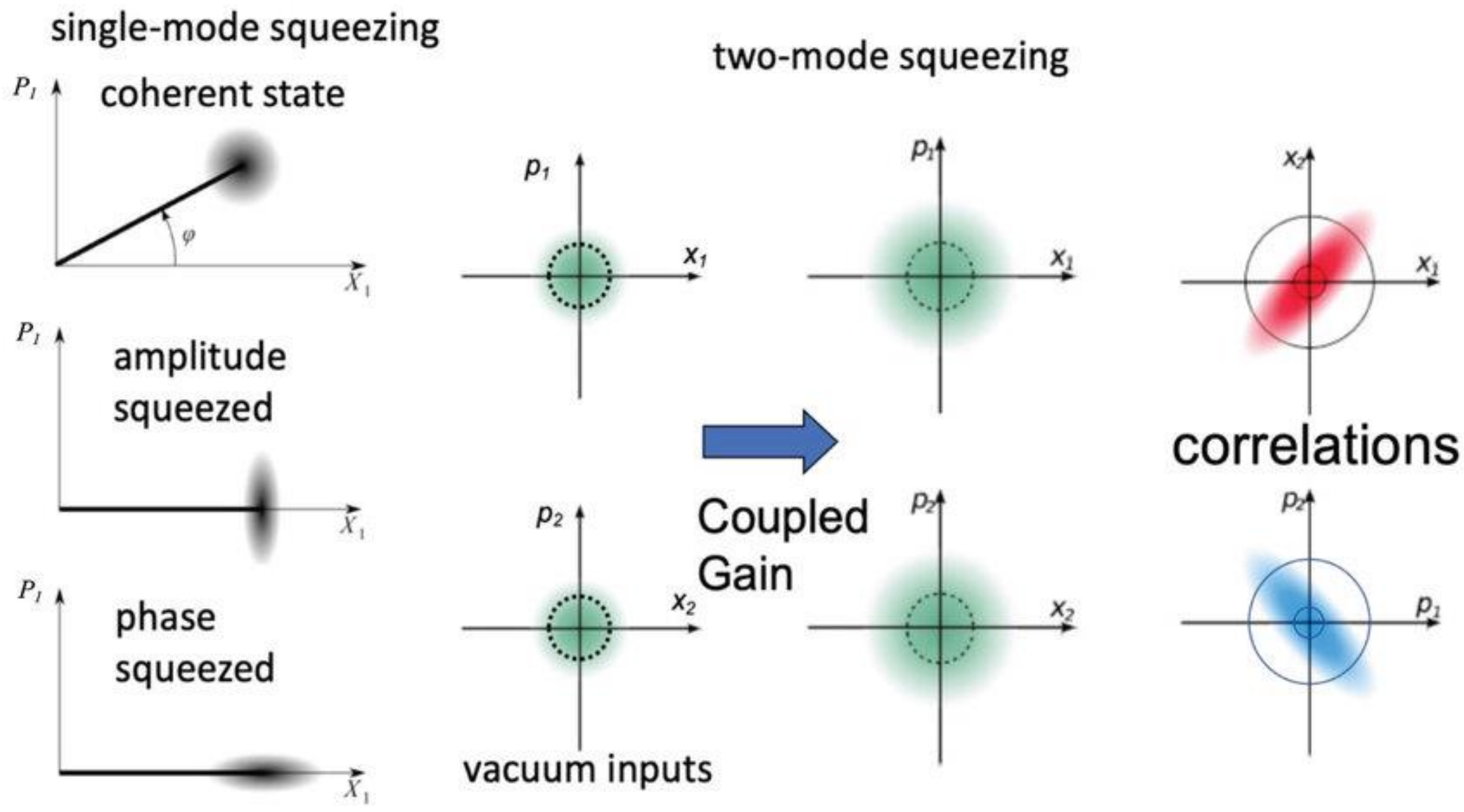
T_{sys}=1.1K





arXiv:2506.11589

Beyond Quantum Limit #1: Squeezing



JPA are phase sensitive amplifiers:

$$G_{\parallel} \times G_{\perp} = 1$$

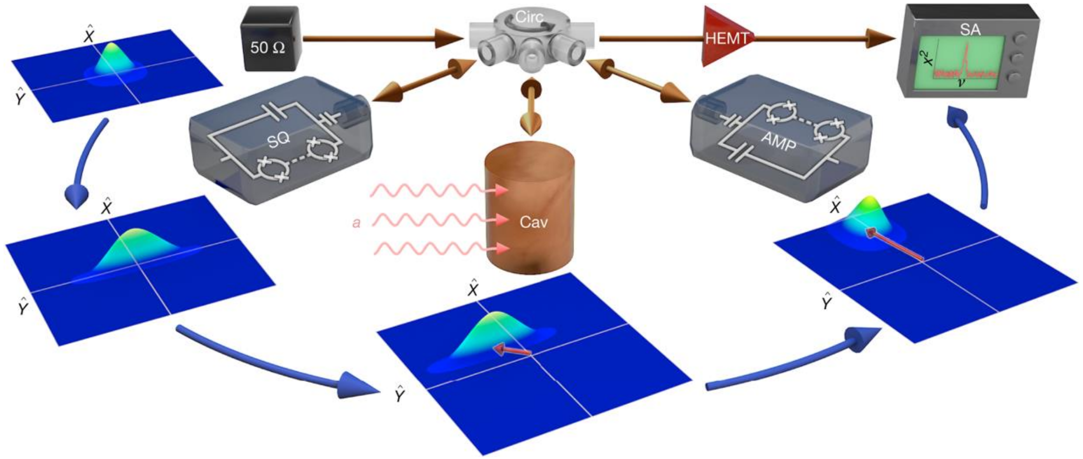
They can be used to amplify in one direction and attenuate in the orthogonal direction.

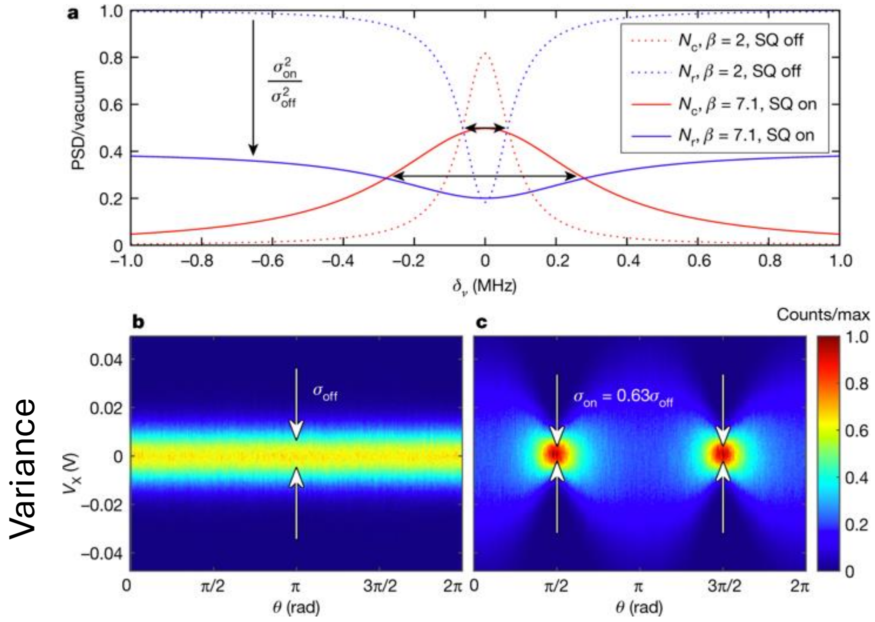
arXiv:1607.02529

Quentin Glorieux et al 2023 New J. Phys. 25 051201

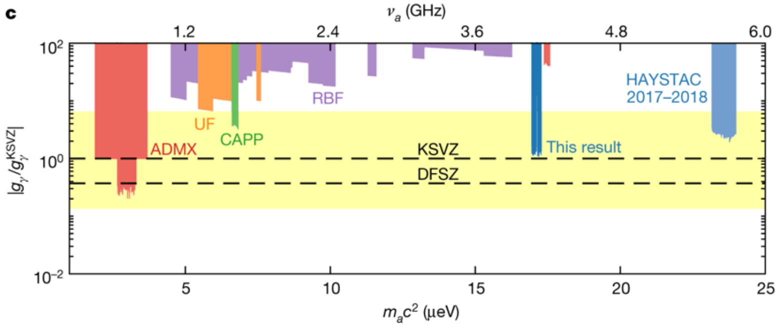
HAYSTAC – A Squeezed State Receiver With JPA

50 ohm noise T 60 mK





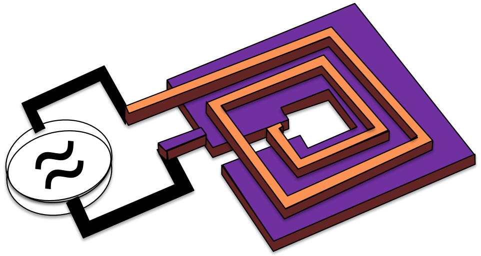
Backes *et al*. A quantum enhanced search for dark matter axions. *Nature* **590,** 238–242 (2021).

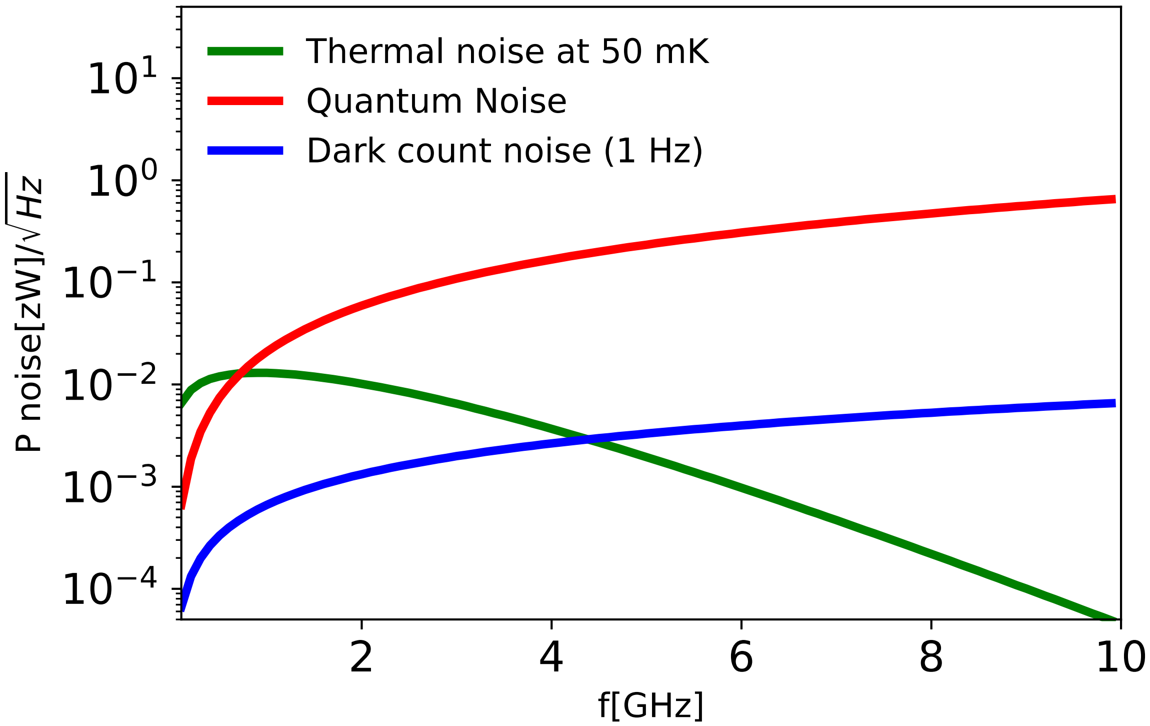


1. JPA operated as phase sensitive amplifier
2. Amplify Y quadrature and squeeze along X
3. $P_X^{out} = (n_T+1/2)/G\,|S_{11}|^2 + (n_T+1/2 + n_{Axion})|X(w)|^2$
4. Squeeze along Y and amplify along X
5. Scan rate increases by a factor 2 thanks to lower noise/larger bandwidth

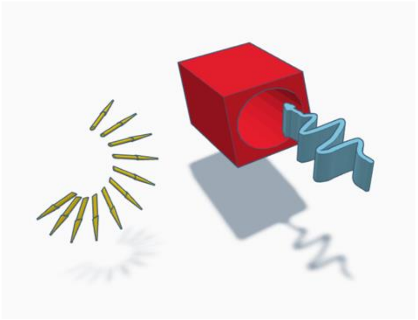
Beyond Quantum Limit #1: Quantum Sensing

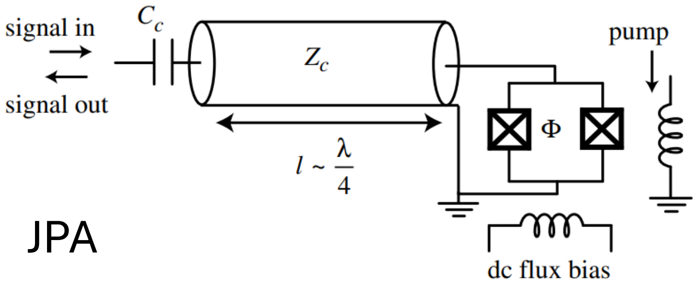
SQUID





Counter based on superconducting qubits



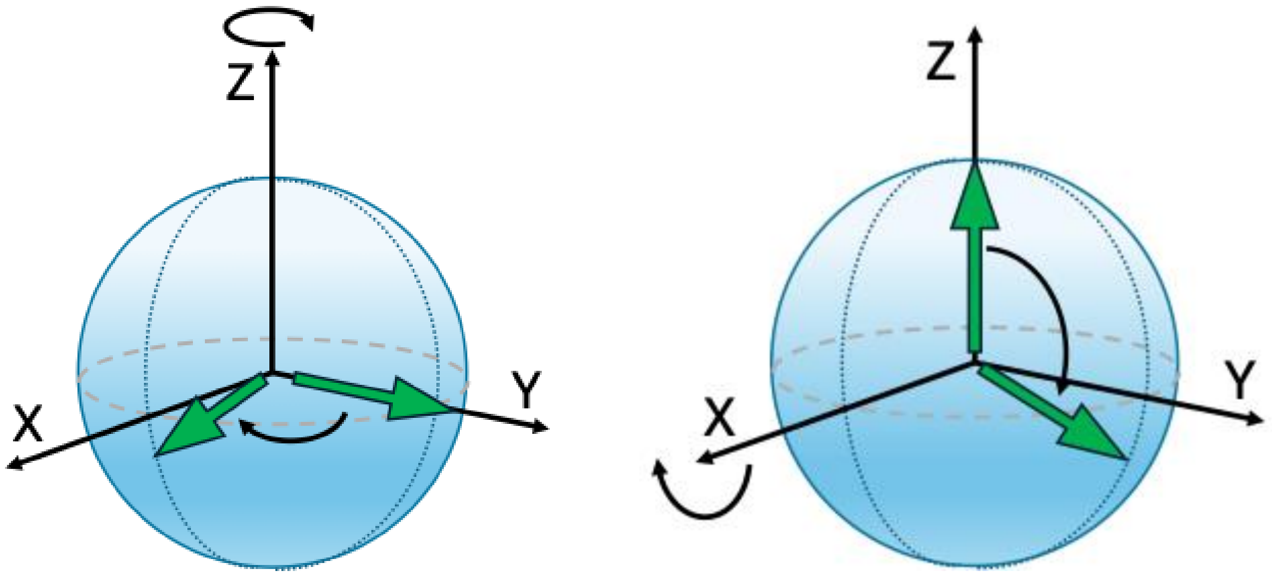


JPA

arXiv:1607.02529

PHYSICAL REVIEW D 88, 035020 (2013)

Single Qubit Sensors

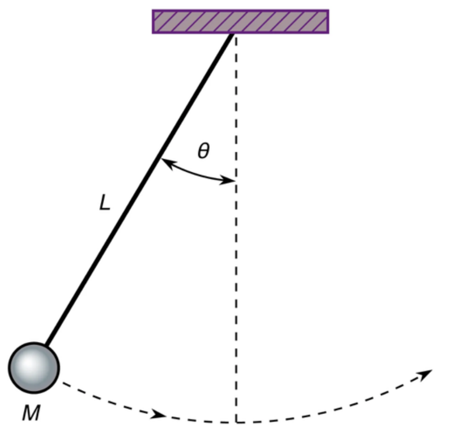


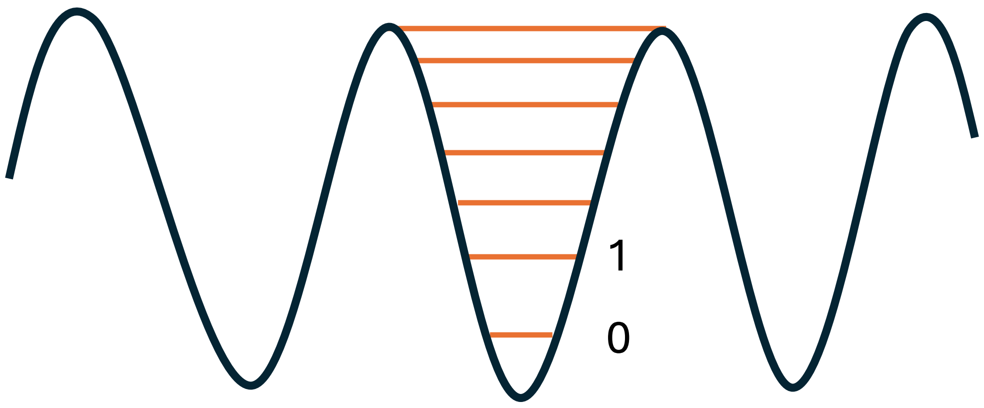
$$\begin{cases} H_{int} = \epsilon\sigma_x \\ H_{int} = \epsilon\sigma_z \end{cases}$$

$H_{int} = \epsilon\sigma_x$ → Excitation

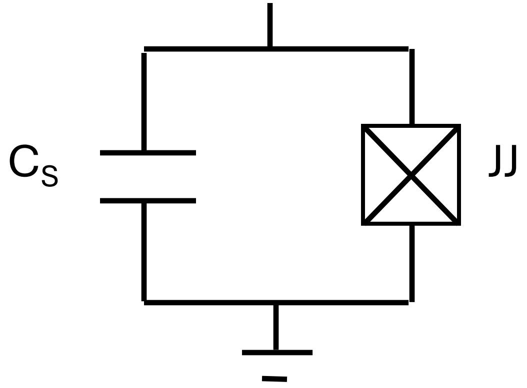
$H_{int} = \epsilon\sigma_z$ → Phase Rotation

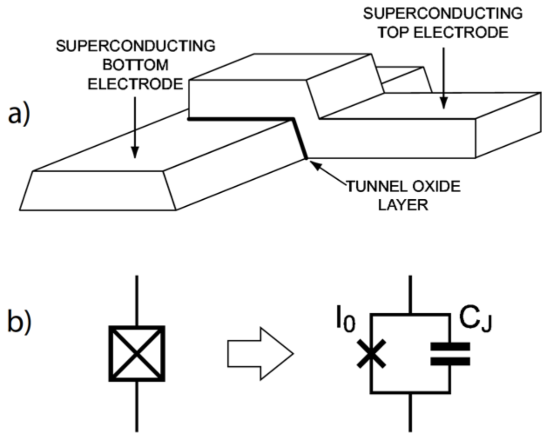
The Superconducting Qubit





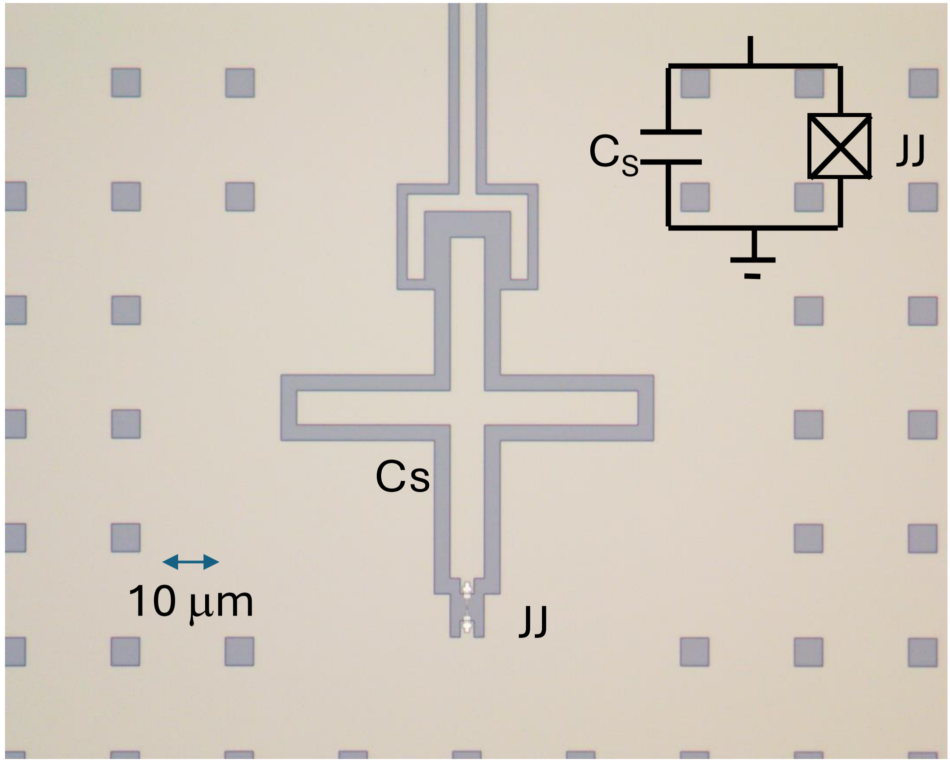
$$E = \frac{Q^2}{2C} - E_J cos 2\pi\phi/\phi_0$$

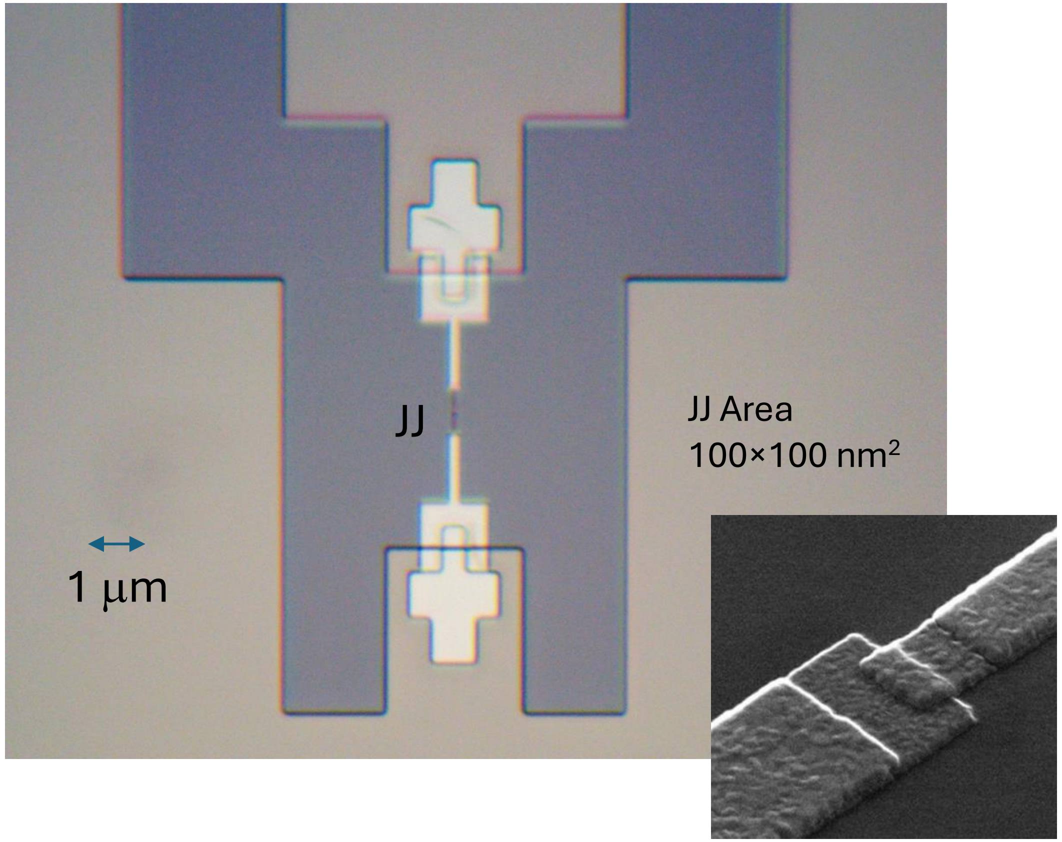




J Koch Phys. Rev. A 76 042319 (2007)

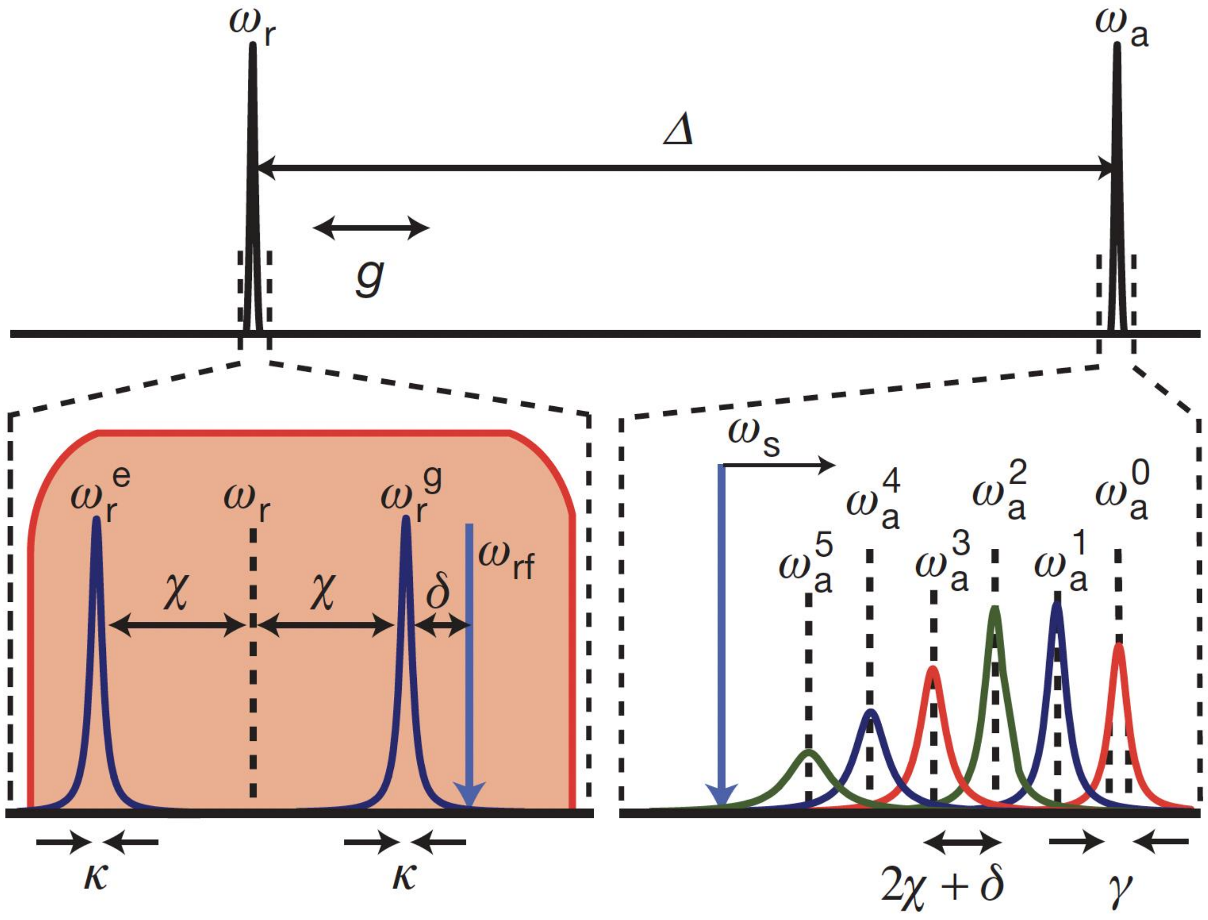
Superconducting Qubits

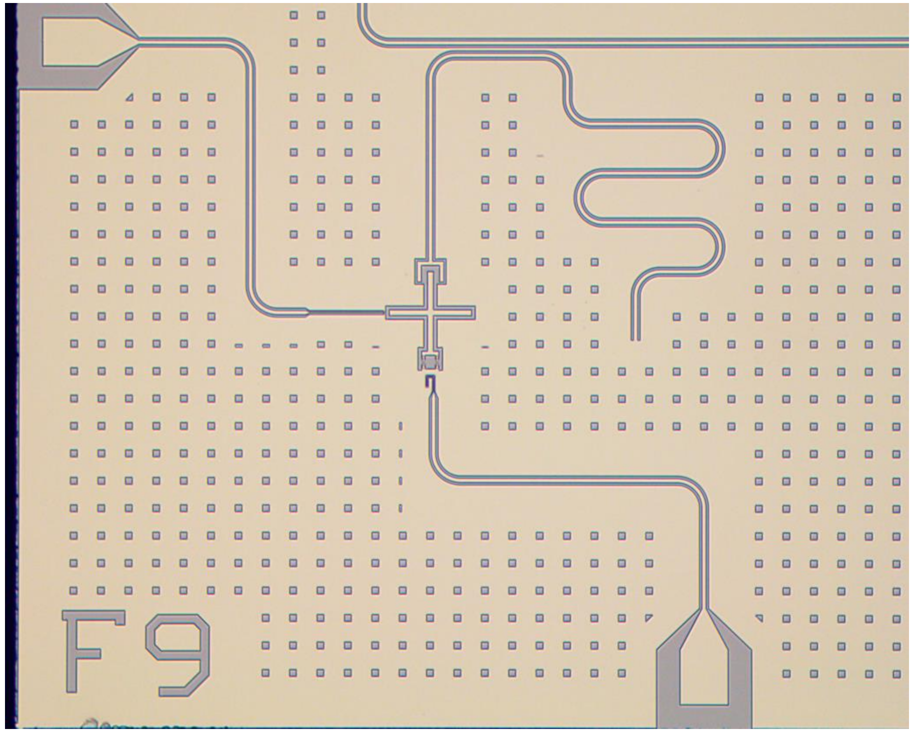




https://arxiv.org/abs/2409.05988

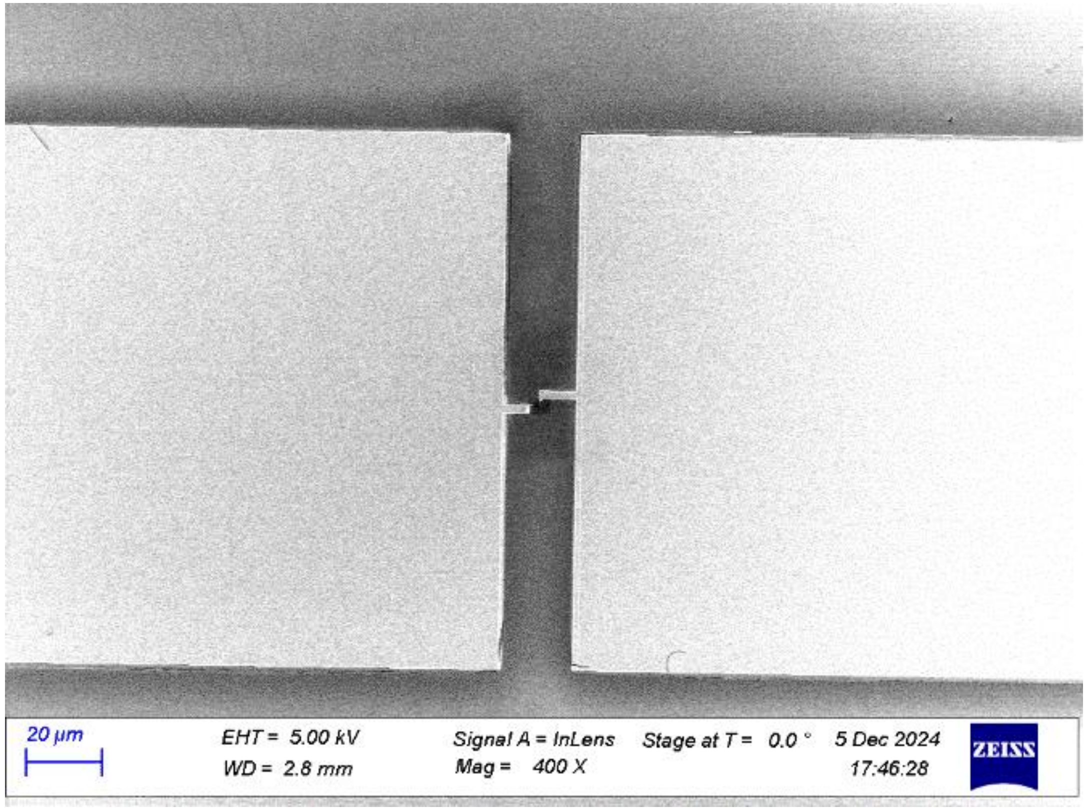
Resolving Photon Number States in a Superconducting Circuit

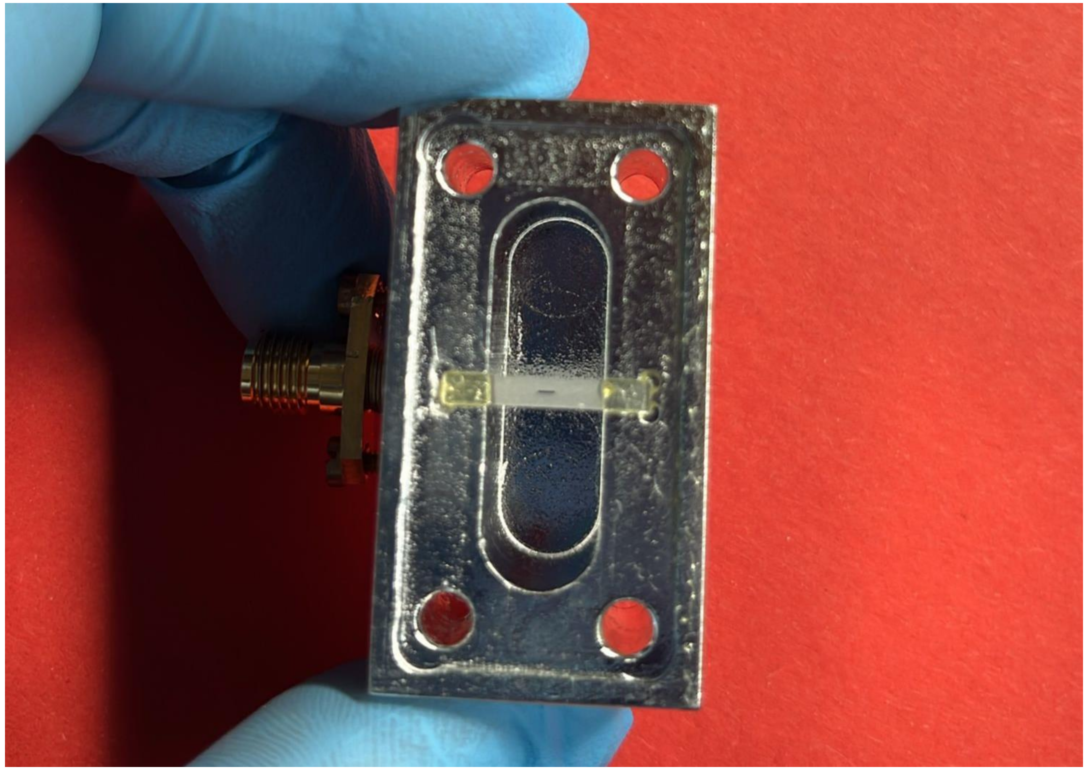




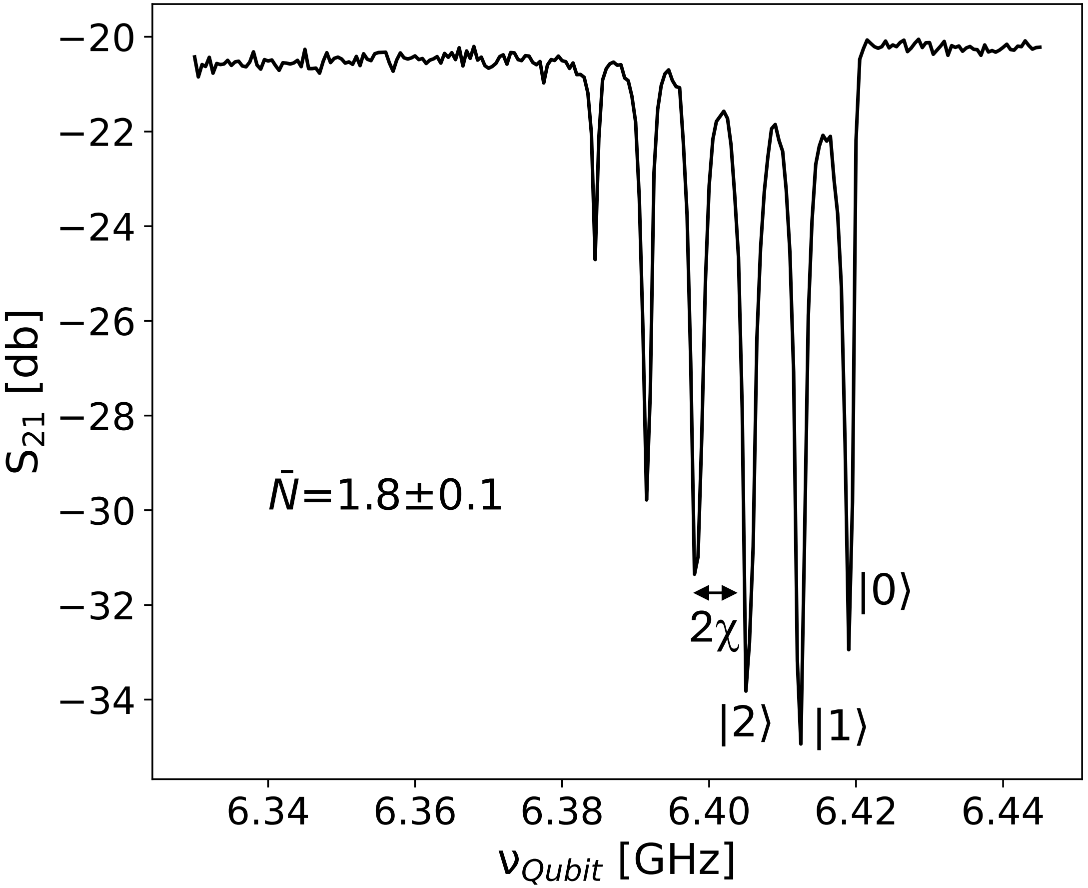
doi:10.1038/nature05461

3D Qubit


20 µm
EHT = 5.00 kV
WD = 2.8 mm
Signal A = InLens
Mag = 400 X
Stage at T = 0.0 °
5 Dec 2024
17:46:28
ZEISS



Resolving Photon Number States in a Superconducting Circuit



$$\omega'_q = \omega_q + 2n_\gamma \chi$$

Photon number in resonator

Appl. Sci. 2024, 14(4), 1478

Quantum Sensing

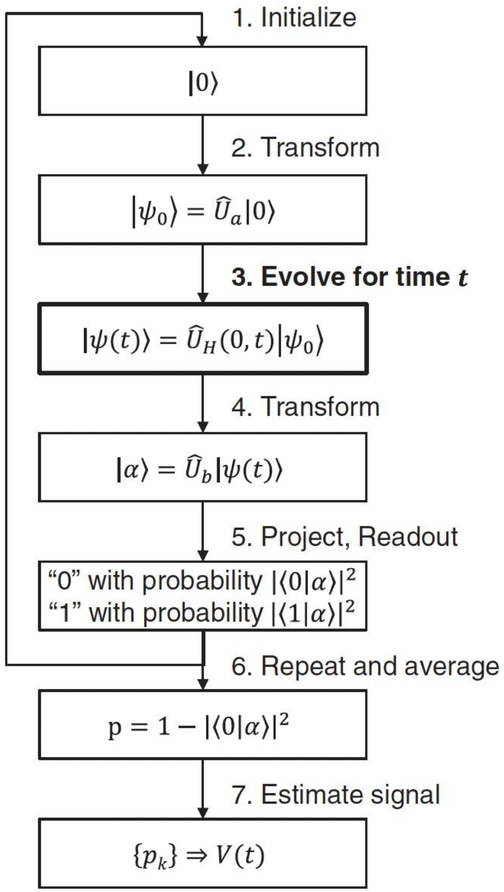
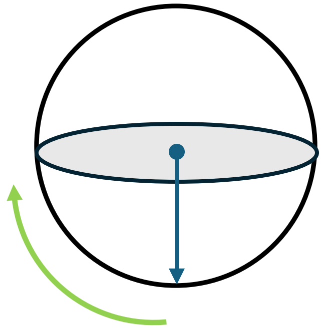


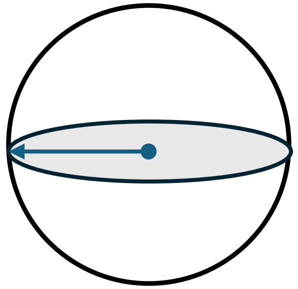
FIG. 2. Basic steps of the quantum sensing process.

REVIEWS OF MODERN PHYSICS, VOLUME 89 (2017)

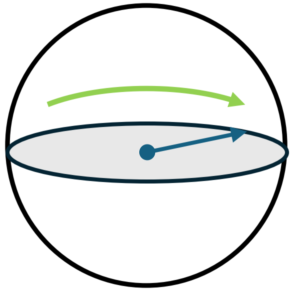
Ramsey Measurement $H_{int} = \epsilon\sigma_z$



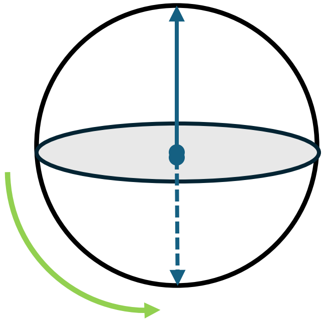
$|\psi\rangle = |0\rangle$



$|\psi\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$



$|\psi\rangle = \left(|0\rangle + e^{-i\omega_0 t}|1\rangle\right)/\sqrt{2}$



$P(1) = 1 - |\langle 0|\psi\rangle|^2 = \sin^2\left(\frac{\omega_0 t}{2}\right)$

Quantum Sensing

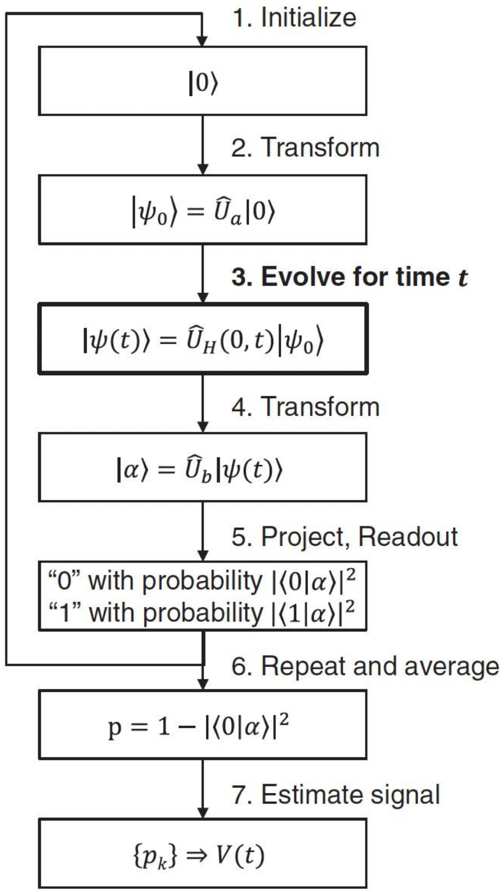
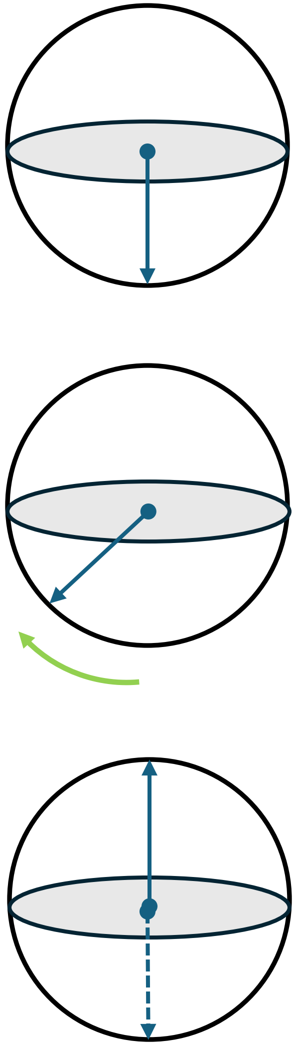


FIG. 2. Basic steps of the quantum sensing process.

REVIEWS OF MODERN PHYSICS, VOLUME 89 (2017)

Rabi Measurement $H_{int} = \epsilon\sigma_x$



$$|\psi\rangle = |0\rangle$$

$$|\psi\rangle = \left[\left(1 + e^{-i\omega_0 t}\right)|0\rangle + \left(1 - e^{-i\omega_0 t}\right)|1\rangle\right]/2$$

$$P(1) = 1 - |\langle 0|\psi\rangle|^2 = \sin^2\left(\frac{\omega_0 t}{2}\right)$$

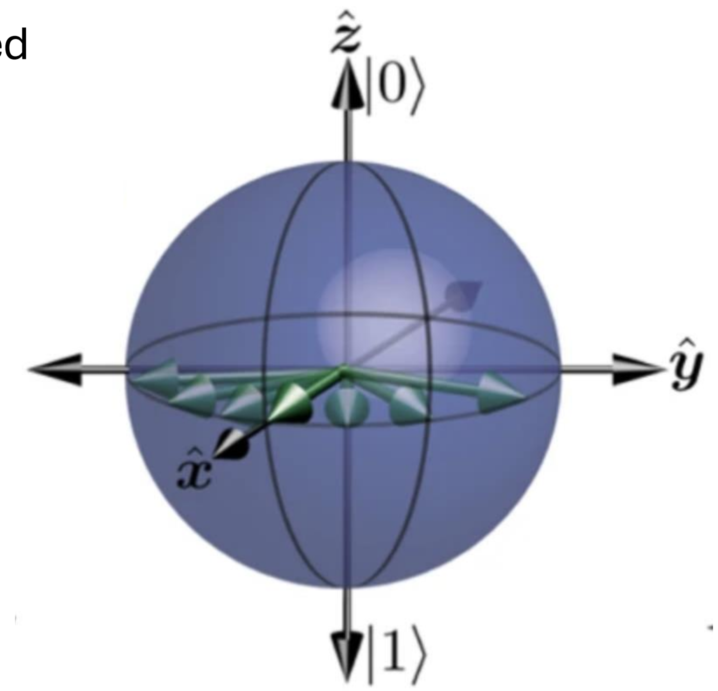
Searching for Dark Matter with a Superconducting Qubit

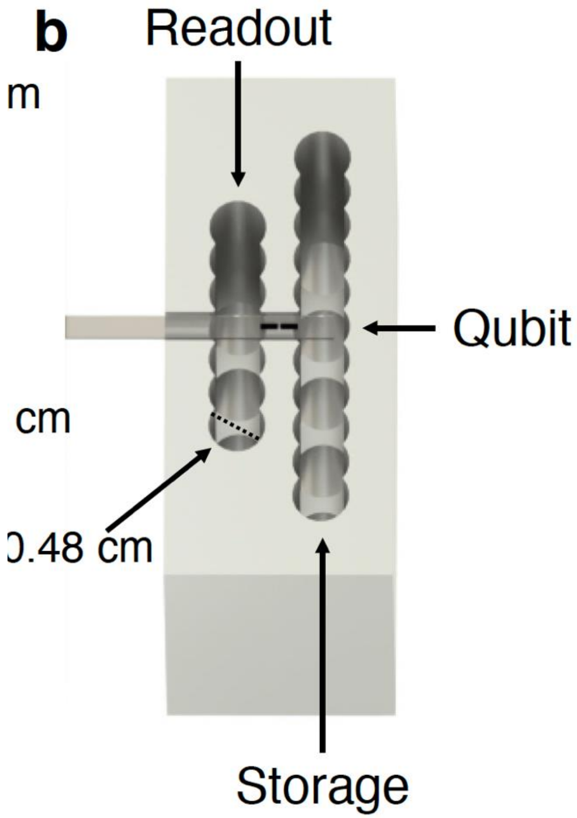
Photon detection by repeated
Ramsey measurements

$$\Delta\omega_q = 2n_\gamma\chi$$

$$\bar{S}_x = cos\Delta\omega_q t$$
$$\bar{S}_y = sin\Delta\omega_q t$$

$$\Gamma_{DarkCounts} \sim \frac{1}{T_2}$$

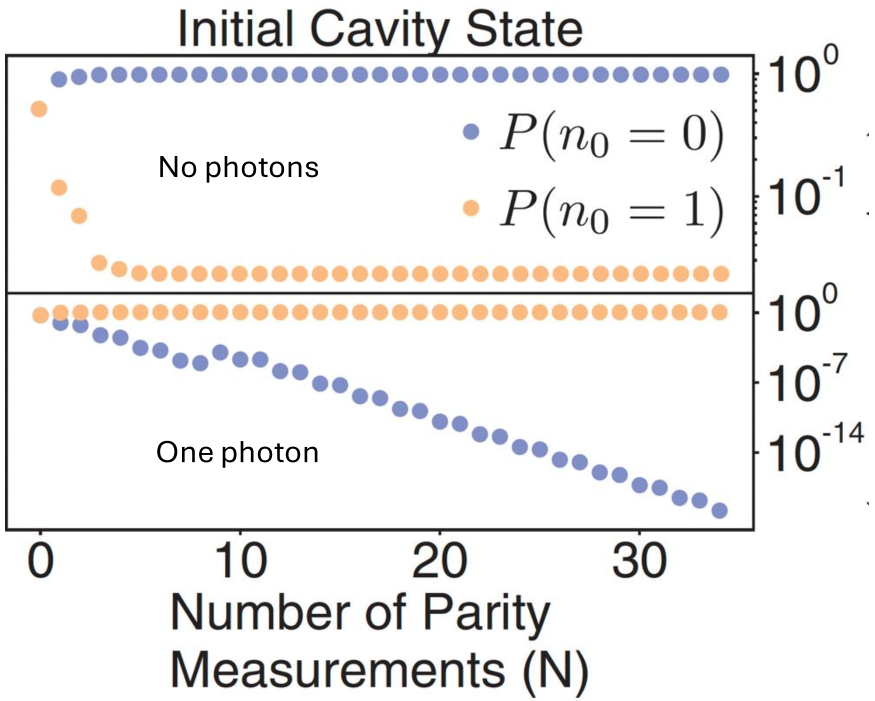


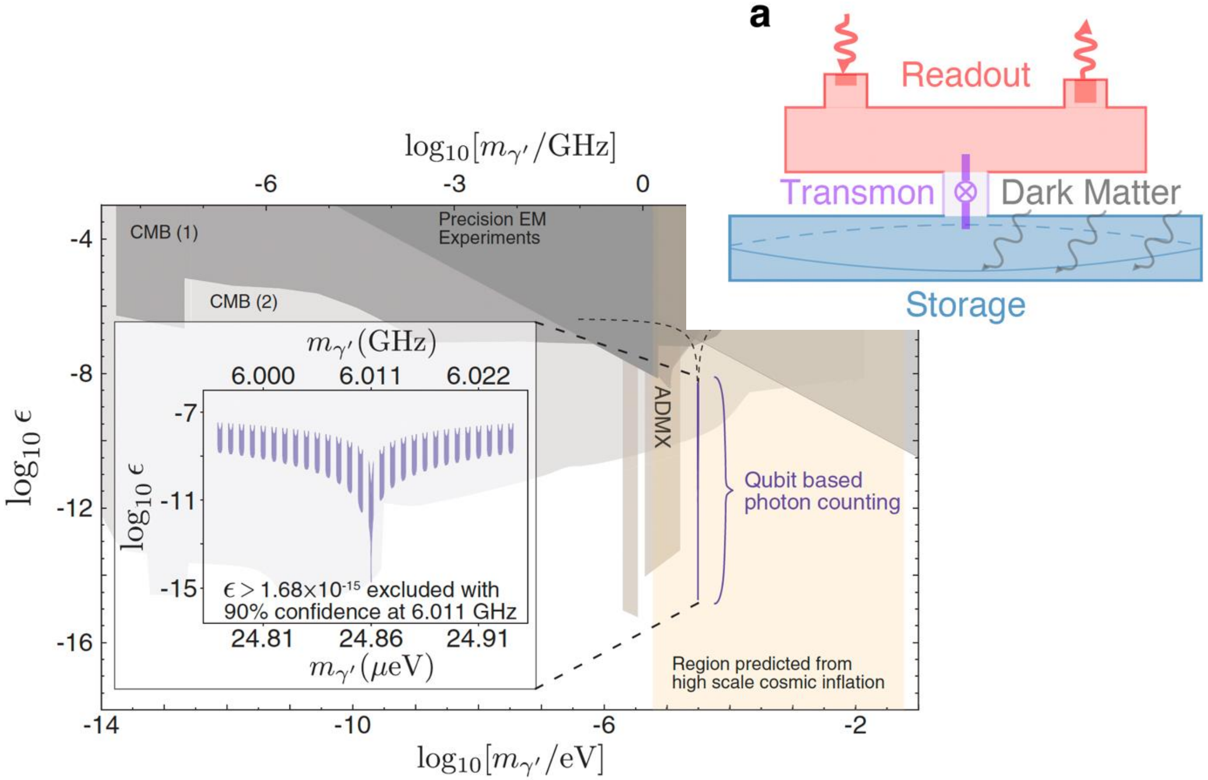


PHYSICAL REVIEW LETTERS 126, 141302 (2021)

Searching for Dark Matter with a Superconducting Qubit

QND allows repeated measurements

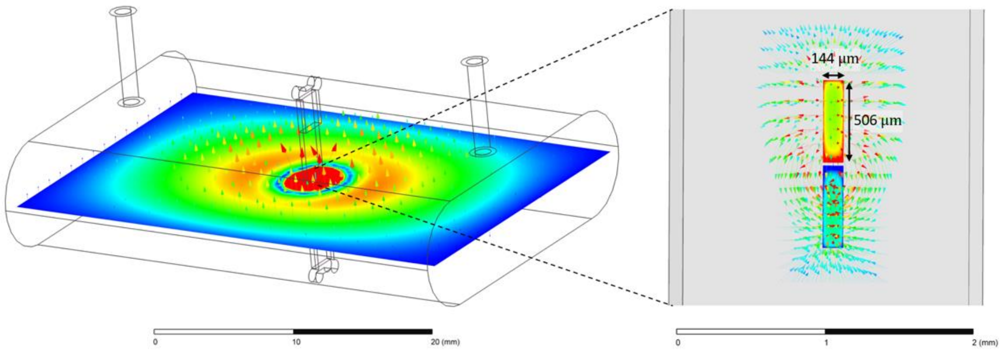




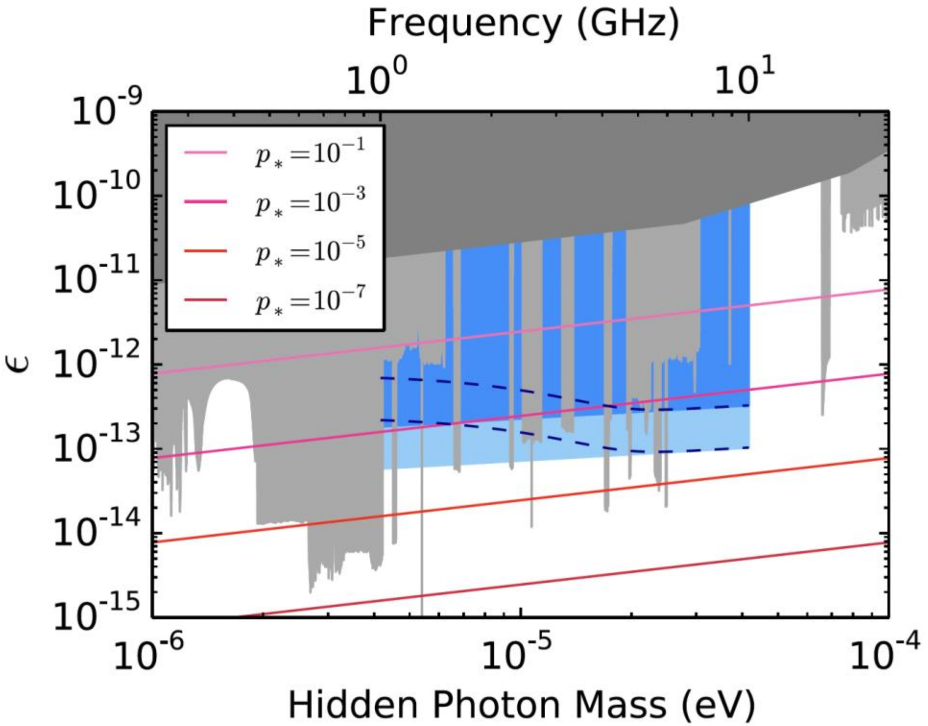
PHYSICAL REVIEW LETTERS 126, 141302 (2021)

Detecting Hidden Photon Dark Matter Using the Direct Excitation of Transmon Qubits

Dark Photon detection by repeated **Rabi measurements**



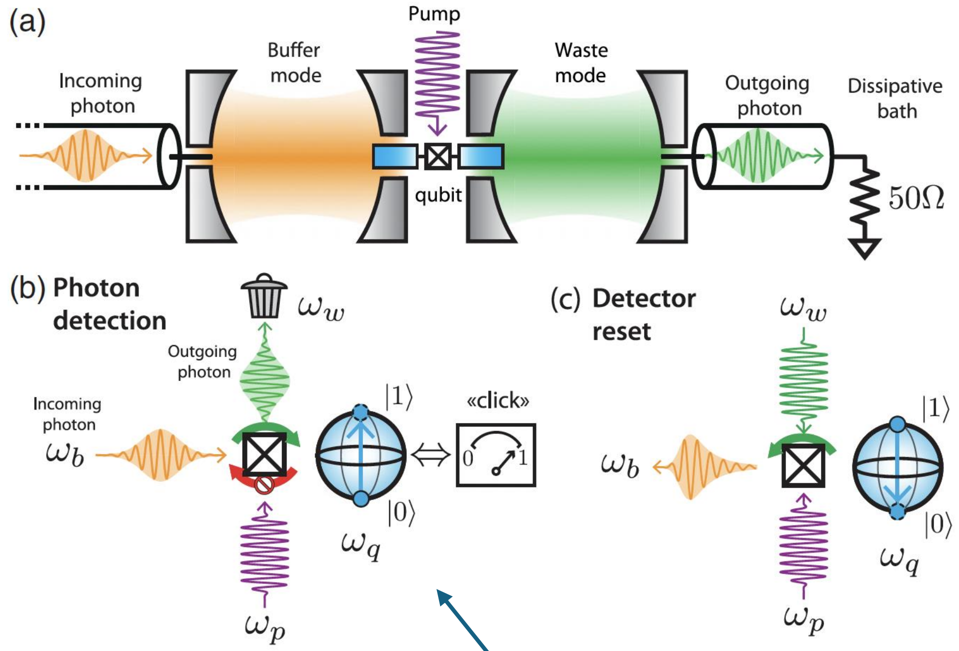
$$\bar{E}^{(X)} \equiv \epsilon m_X \bar{X} = \epsilon\sqrt{2\rho_{\rm DM}}$$



PHYSICAL REVIEW LETTERS 131, 211001 (2023)

Irreversible Qubit-Photon Coupling for the Detection of Itinerant Microwave Photons

Itinerant photon



$$\omega_p = \bar{\omega}_q + \omega_w^e - \omega_b^g$$

$\varepsilon \sim 47\%$

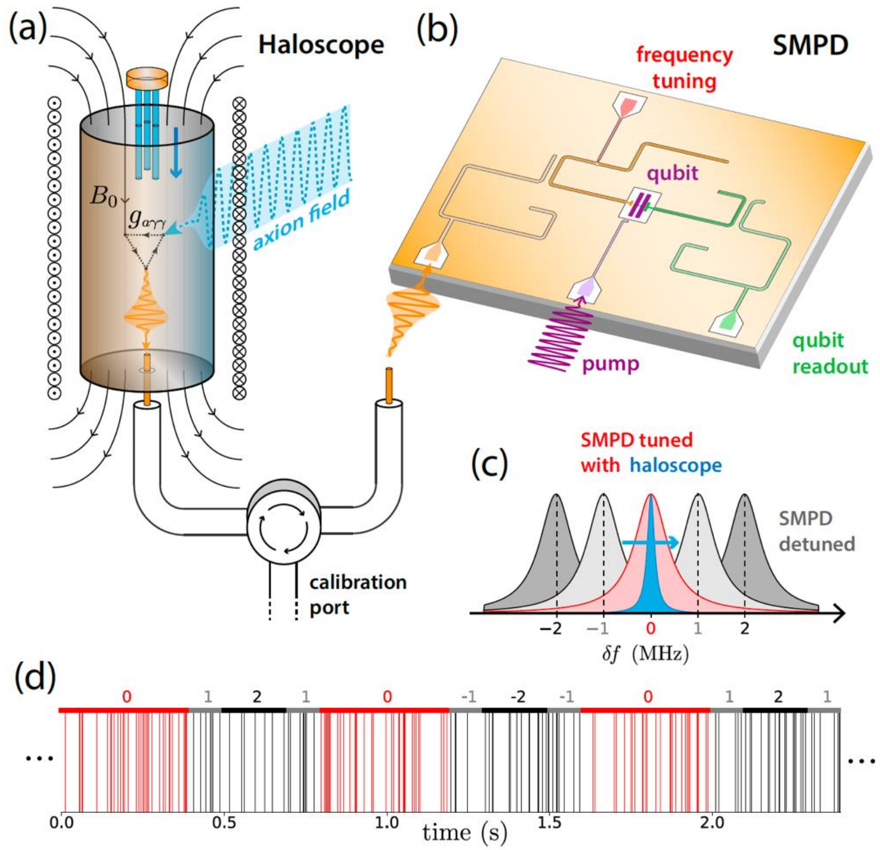
$bw \sim 0.7\ MHz$

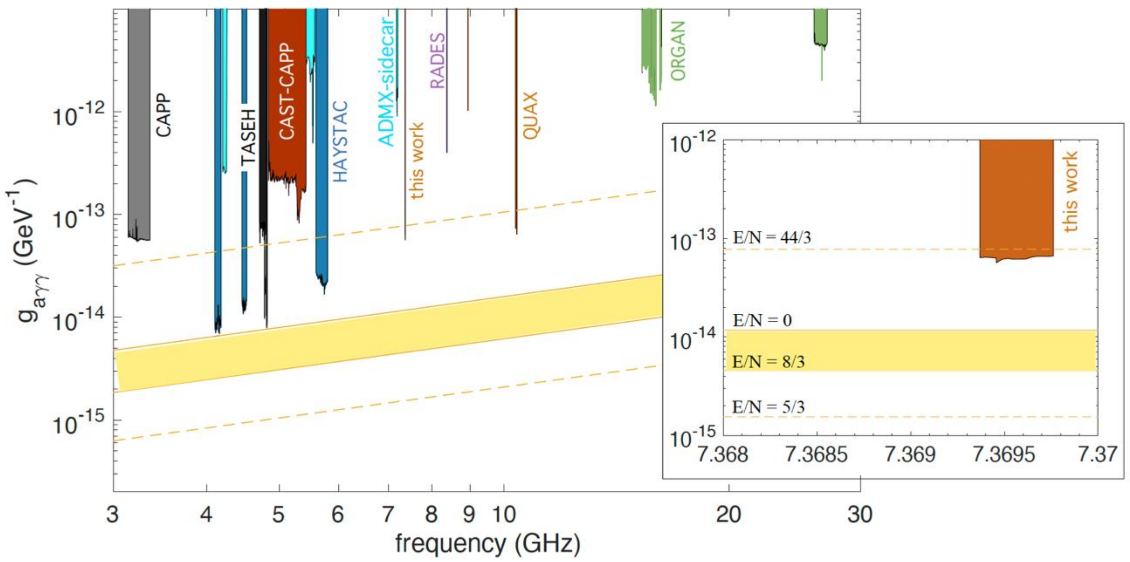
$$\Gamma_{DarkCounts} \sim \frac{n_{q,th}}{T_1} \sim 85Hz$$

Irreversible process, no photon reflection

PHYSICAL REVIEW X 10, 021038 (2020)

Quantum-Enhanced Sensing of Axion Dark Matter with a Transmon-Based Single Microwave Photon Counter

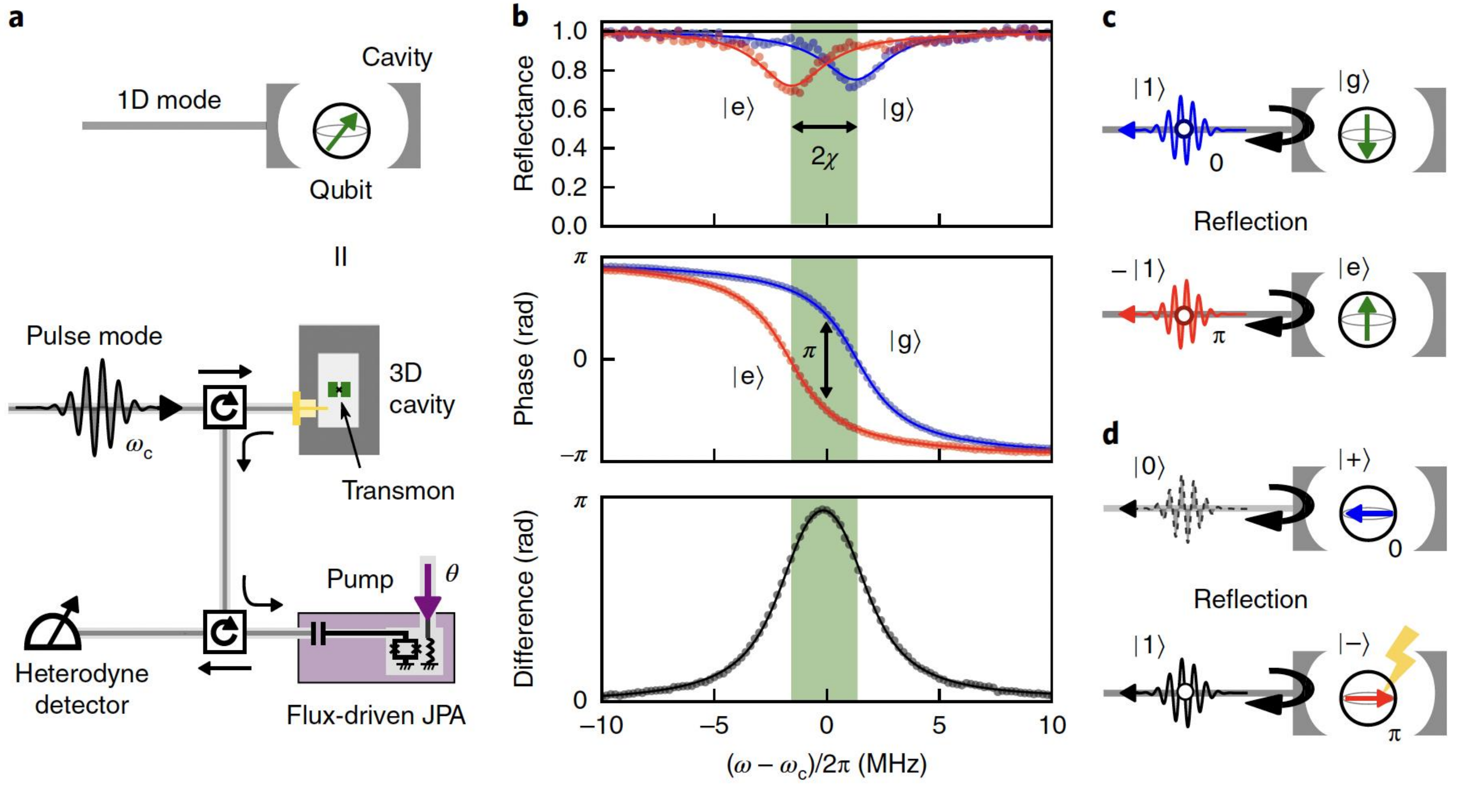


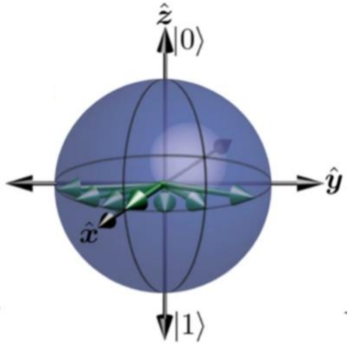


Phys. Rev. X 15, 021031

Quantum Non-Demolition Detection of an Itinerant Microwave Photon

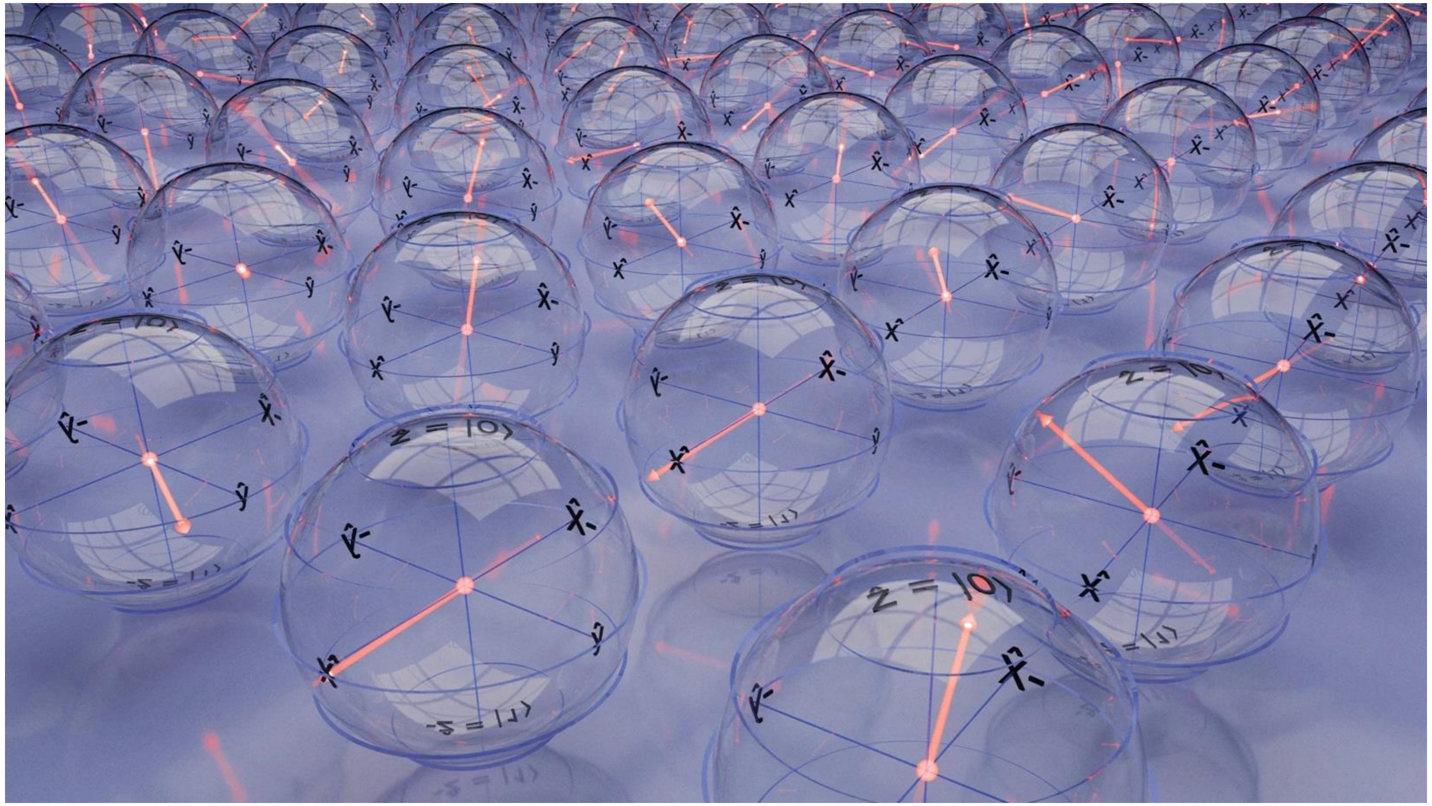
Itinerant photon



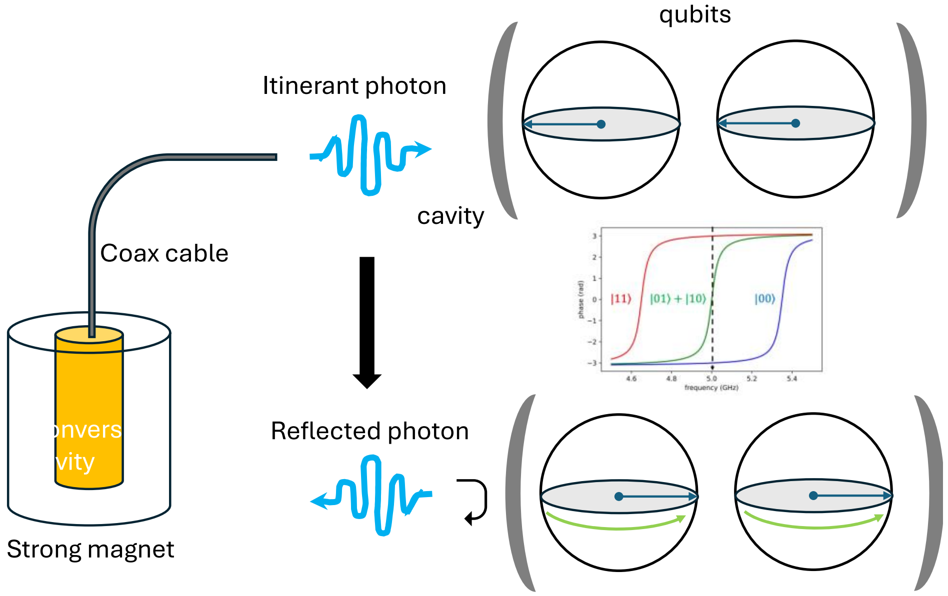


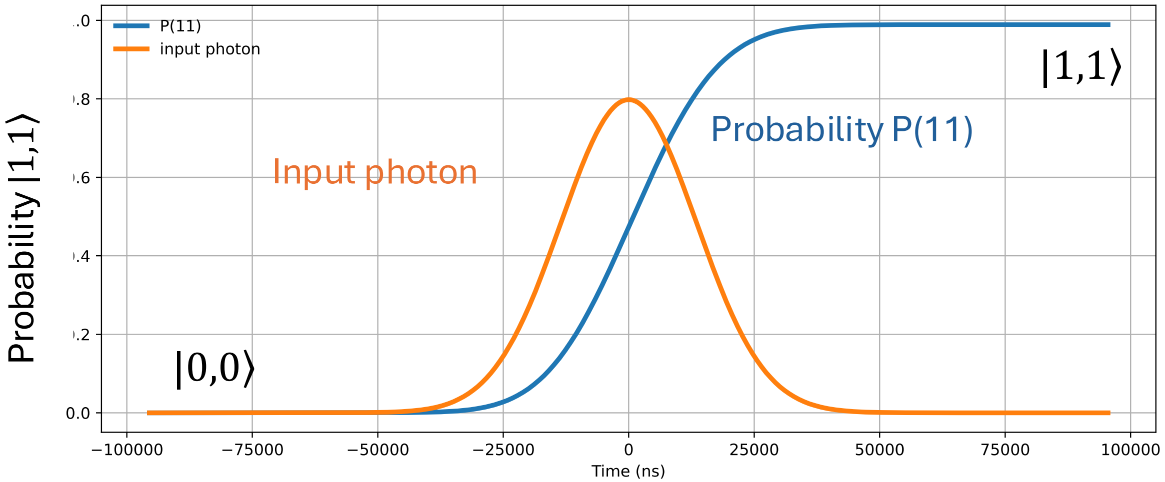
https://doi.org/10.1038/s41567-018-0066-3

Multi Qubit Sensors



Error Correction with Two Qubits





Reduced dark counts:

$$Error\ rate \propto p(1|0)^2$$

Appl. Sci. 2024, 14(4), 1478

https://doi.org/10.1016/j.nima.2024.170010

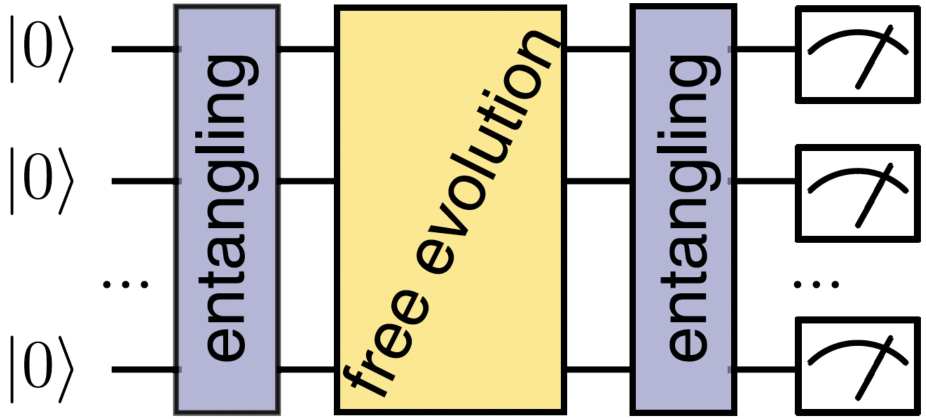
Sensing with Multiqubit Entangled States

Greenberger–Horne–Zeilinger (GHZ) state

$$|\psi\rangle = (|000000\ldots\rangle + |111111\ldots\rangle)/\sqrt{2}$$

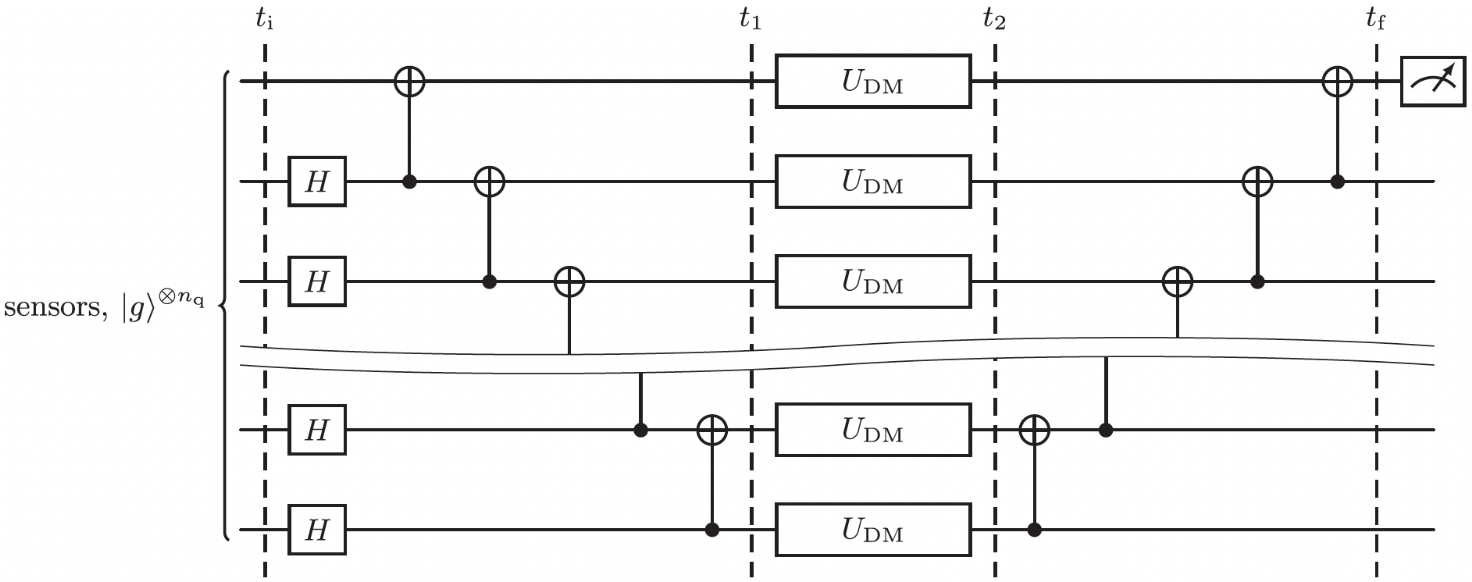
$$|\psi\rangle = \left(|000000\ldots\rangle + e^{-iN\omega_0 t}|1111111\ \ldots\rangle\right)/\sqrt{2}$$

$$P = 1 - |\langle 0|\psi\rangle|^2 = \sin^2\left(N\frac{\omega_0 t}{2}\right)$$



REVIEWS OF MODERN PHYSICS, VOLUME 89 (2017)

Quantum Enhancement in Dark Matter Detection with Quantum Computation

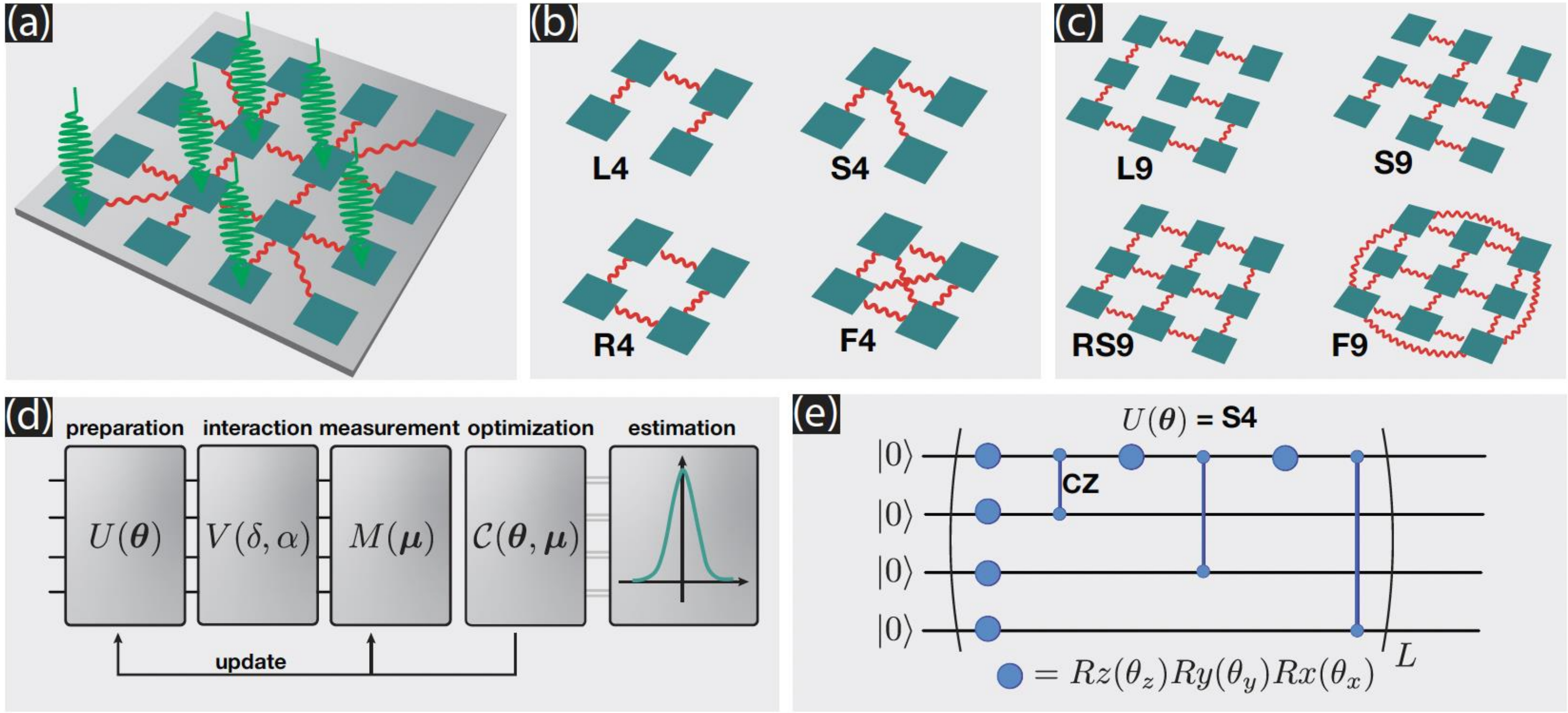


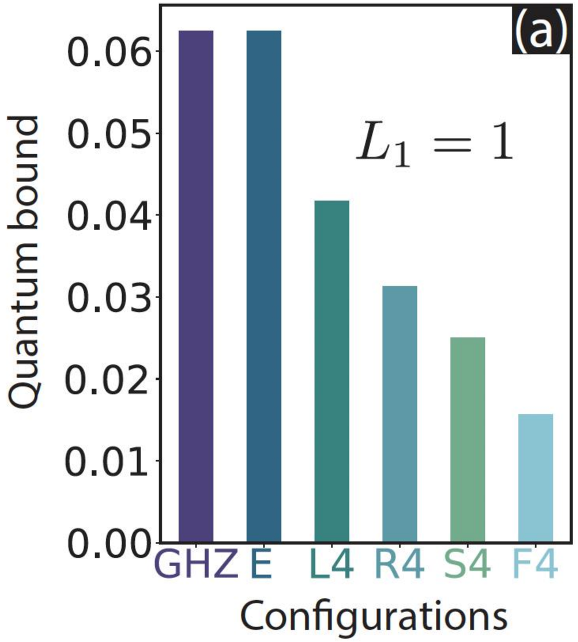
Use n_q entangled qubit state to enhance dark matter sensing by n_q^2

$$P_{g\to e}^{(\alpha=0)} = \sin^2(n_q\delta) \simeq n_q^2\delta^2$$

PHYSICAL REVIEW LETTERS 133, 021801 (2024)

Optimized Quantum Sensor Networks for Ultralight Dark Matter Detection

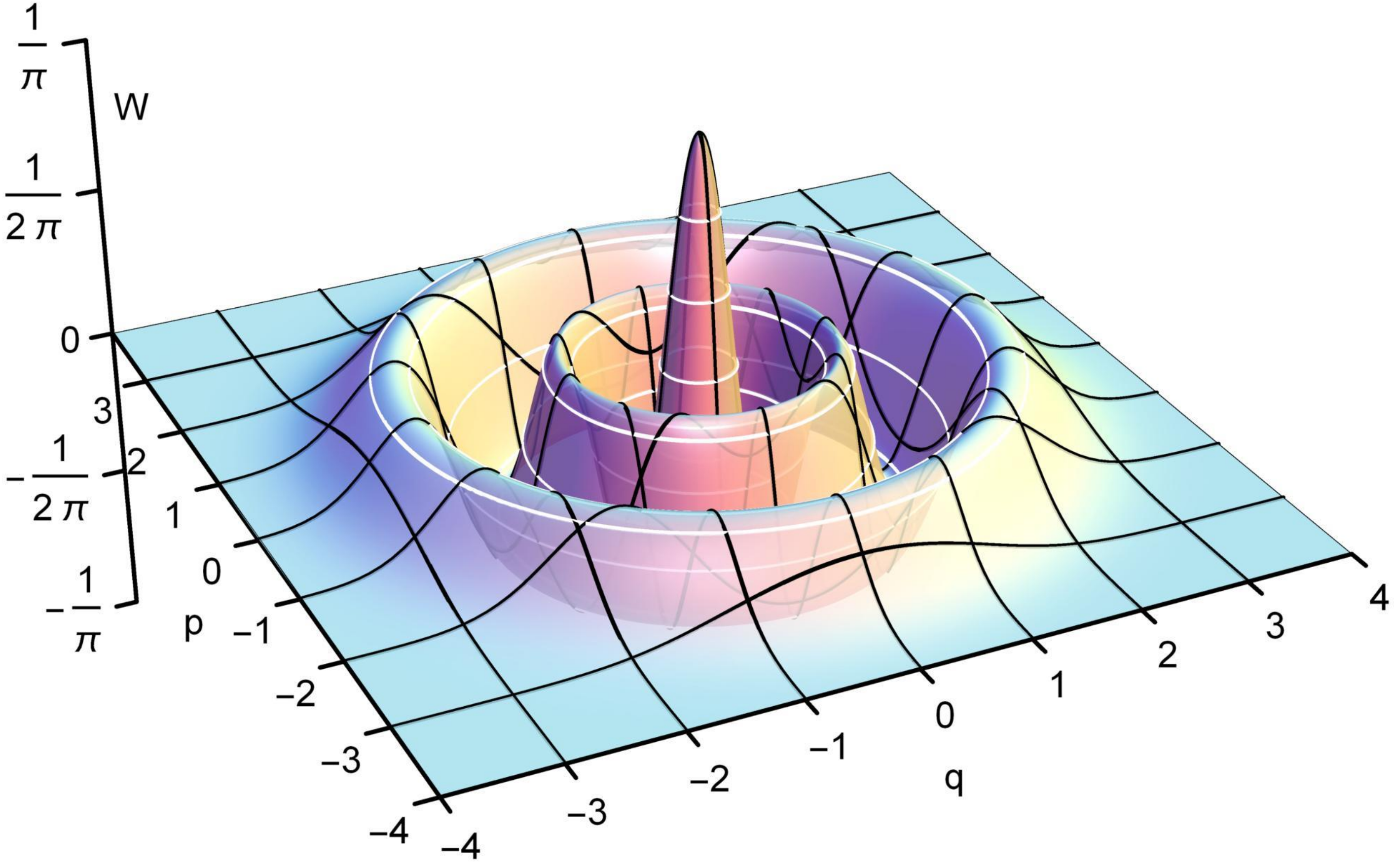




Multi-qubit systems, optimizing both state preparation and measurement using a variational quantum metrology framework

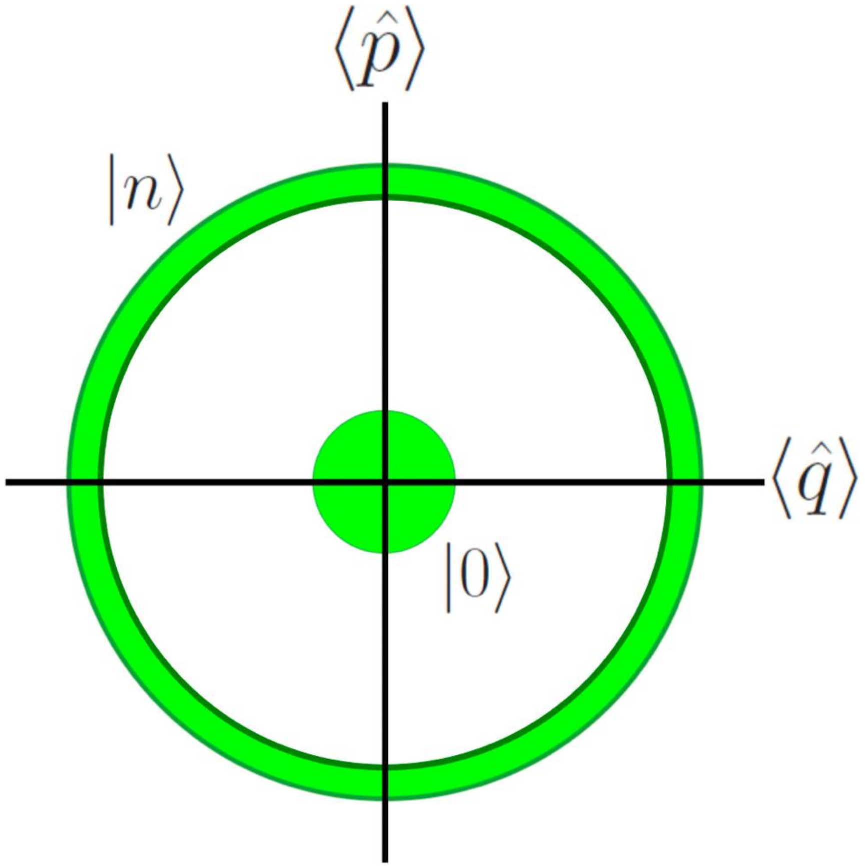
arXiv:2505.2118

Non Classical States



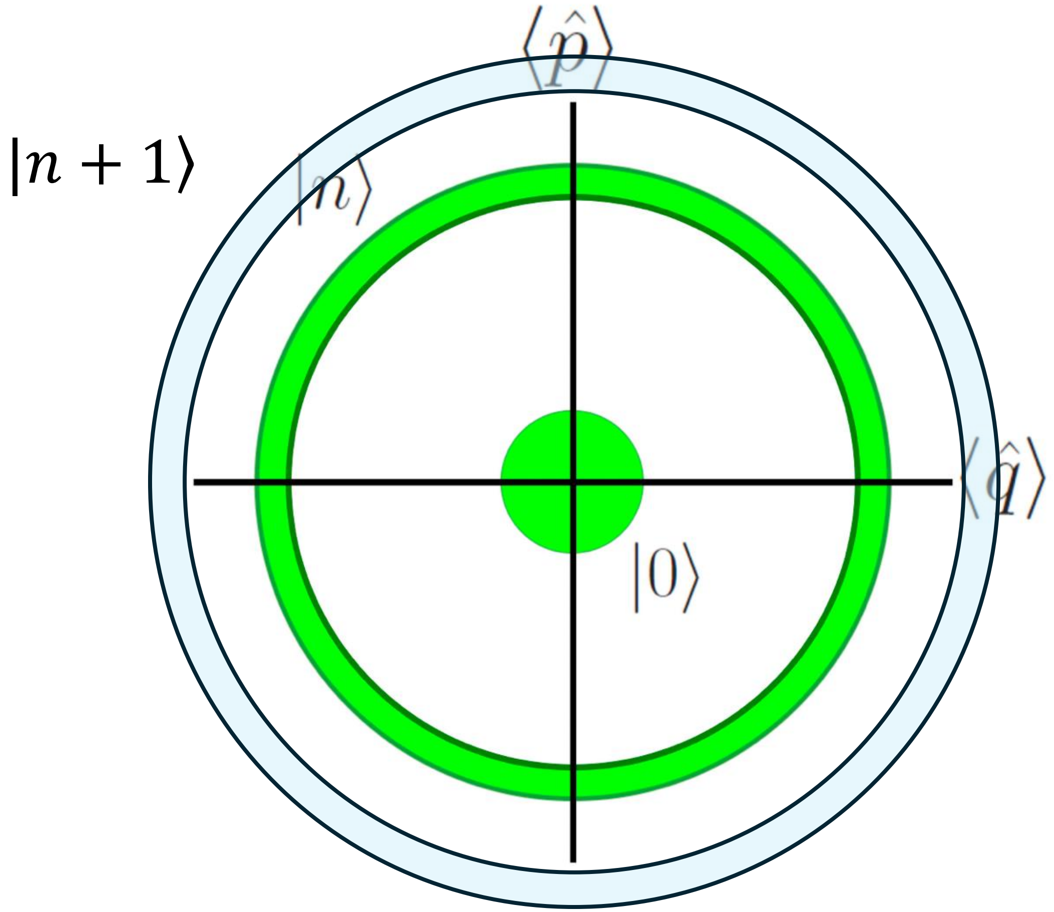
Fock States

X



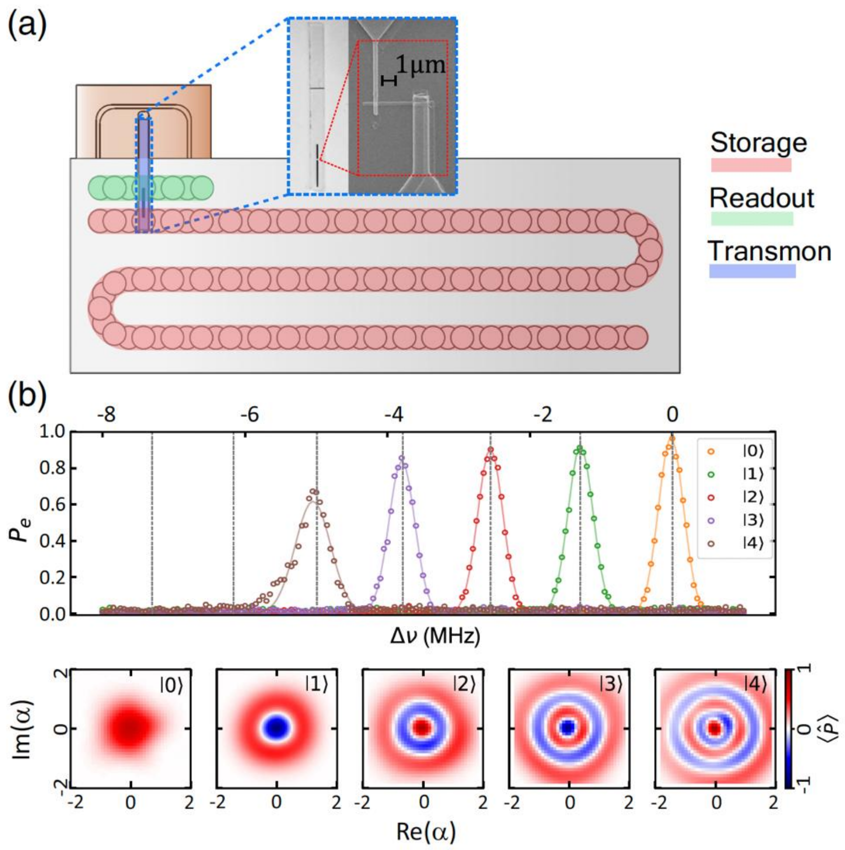
Fock States

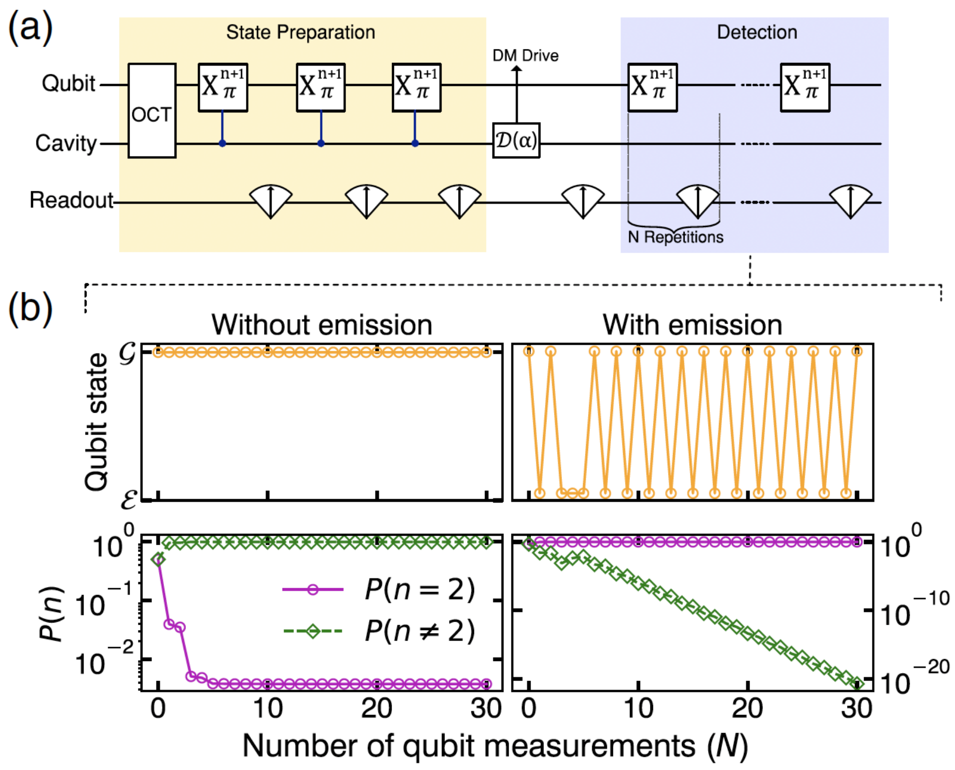
$$|\langle n+1|\hat{\mathcal{D}}(\alpha)|n\rangle|^2 = |\langle n+1|e^{(\alpha a^\dagger - \alpha^* a)}|n\rangle|^2$$
$$\sim |\langle n+1|\alpha a^\dagger|n\rangle|^2 = (n+1)\alpha^2$$



Enhancement of the signal by (n+1)

Stimulated Emission of Signal Photons from Dark Matter Waves

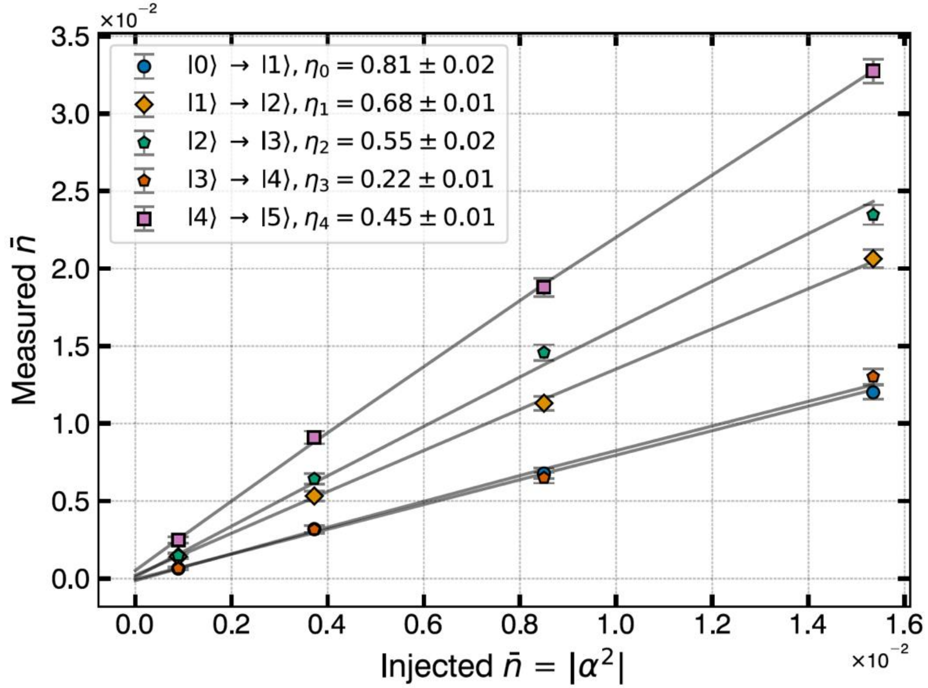




30 repeated qubit measurements

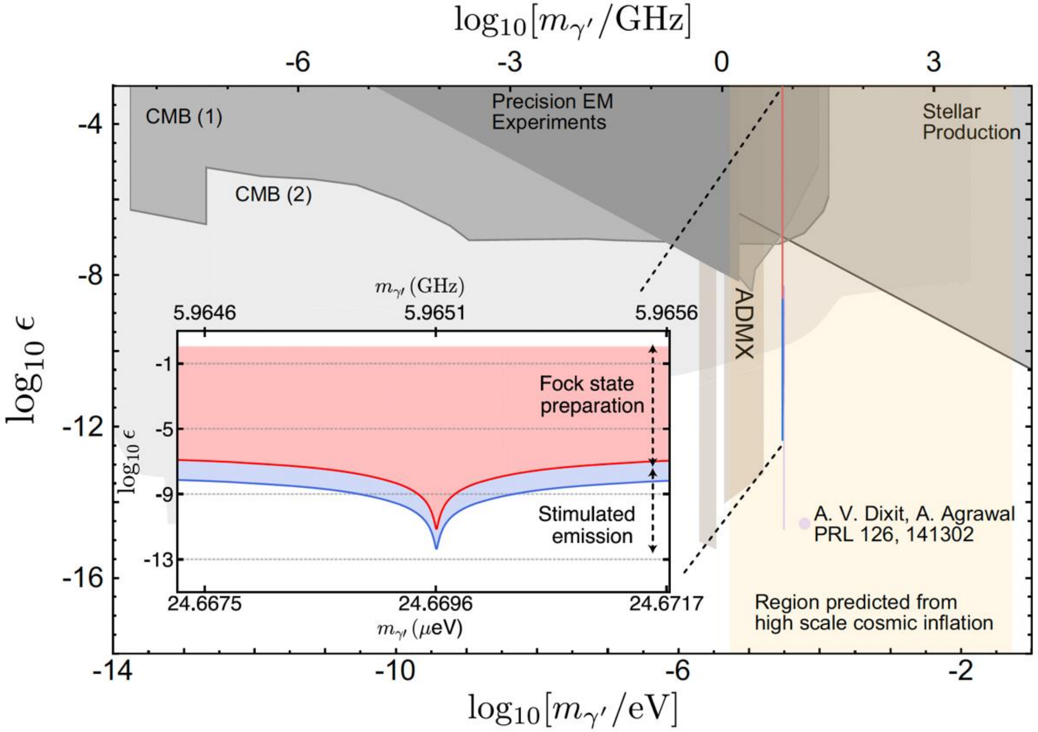
PHYSICAL REVIEW LETTERS 132, 140801 (2024)

Stimulated Emission of Signal Photons from Dark Matter Waves



Stimulated emission enhancement

$$n_{meas} \sim \eta(n+1)\alpha^2$$

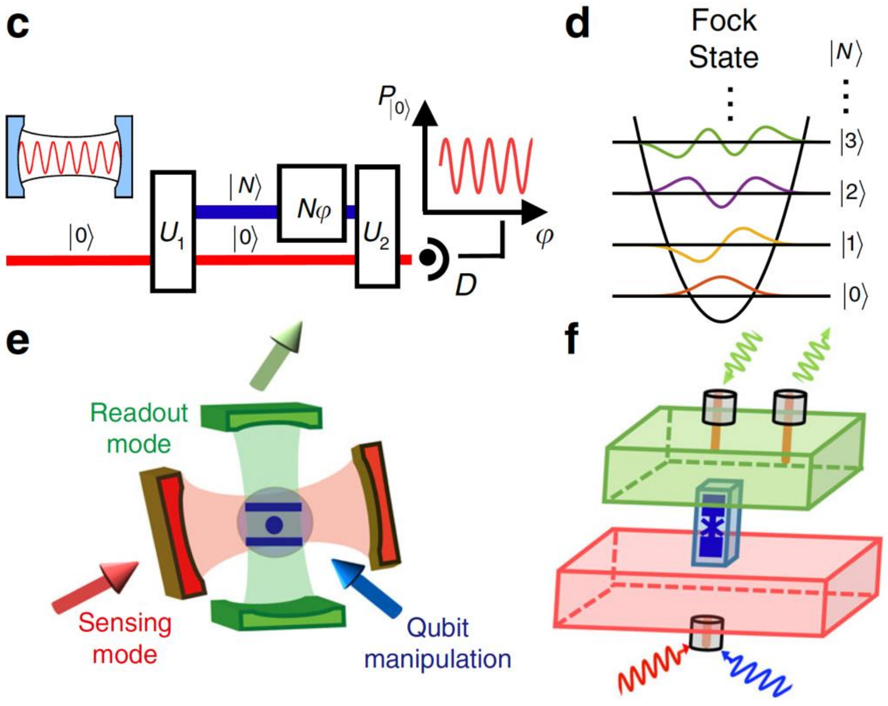


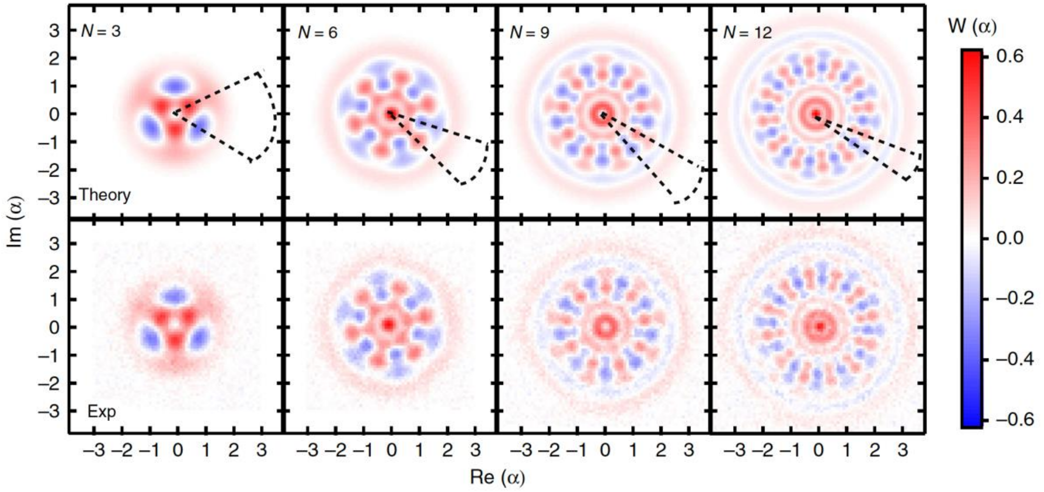
PHYSICAL REVIEW LETTERS 132, 140801 (2024)

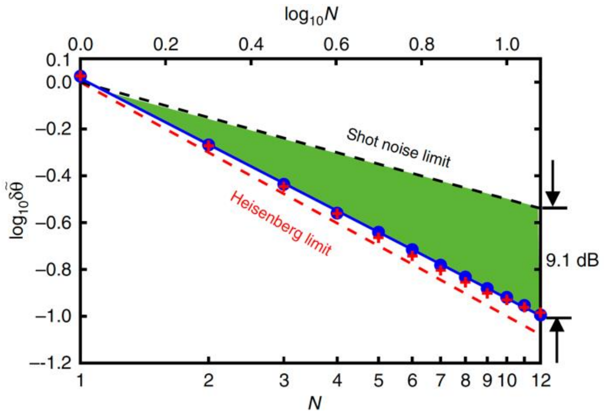
Heisenberg-Limited Single-Mode Quantum Metrology in a Superconducting Circuit

Maximum Variance State

$$|\psi(N)\rangle = (|0\rangle + i\,|N\rangle)/\sqrt{2}$$







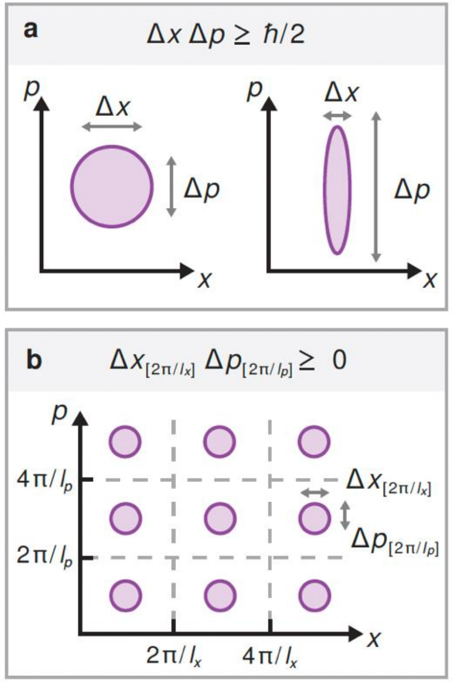
Heisenberg Scaling Limit

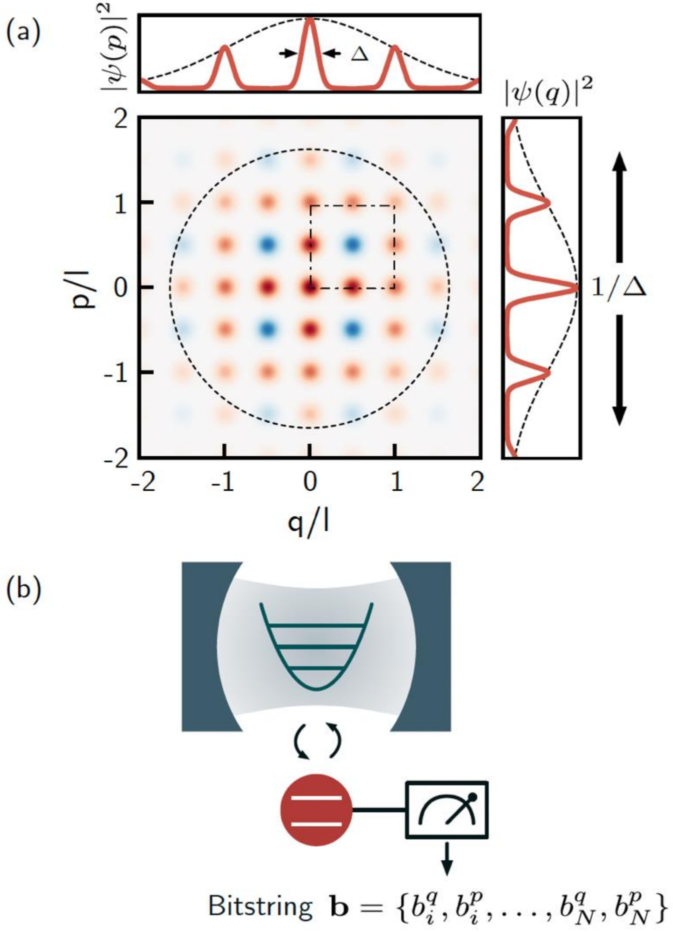
$$\delta\theta \sim 1/N$$

https://doi.org/10.1038/s41467-019-12290-7

Quantum Sensing of Displacements with GKP States

Gottesman-Kitaev-Preskill (GKP) State





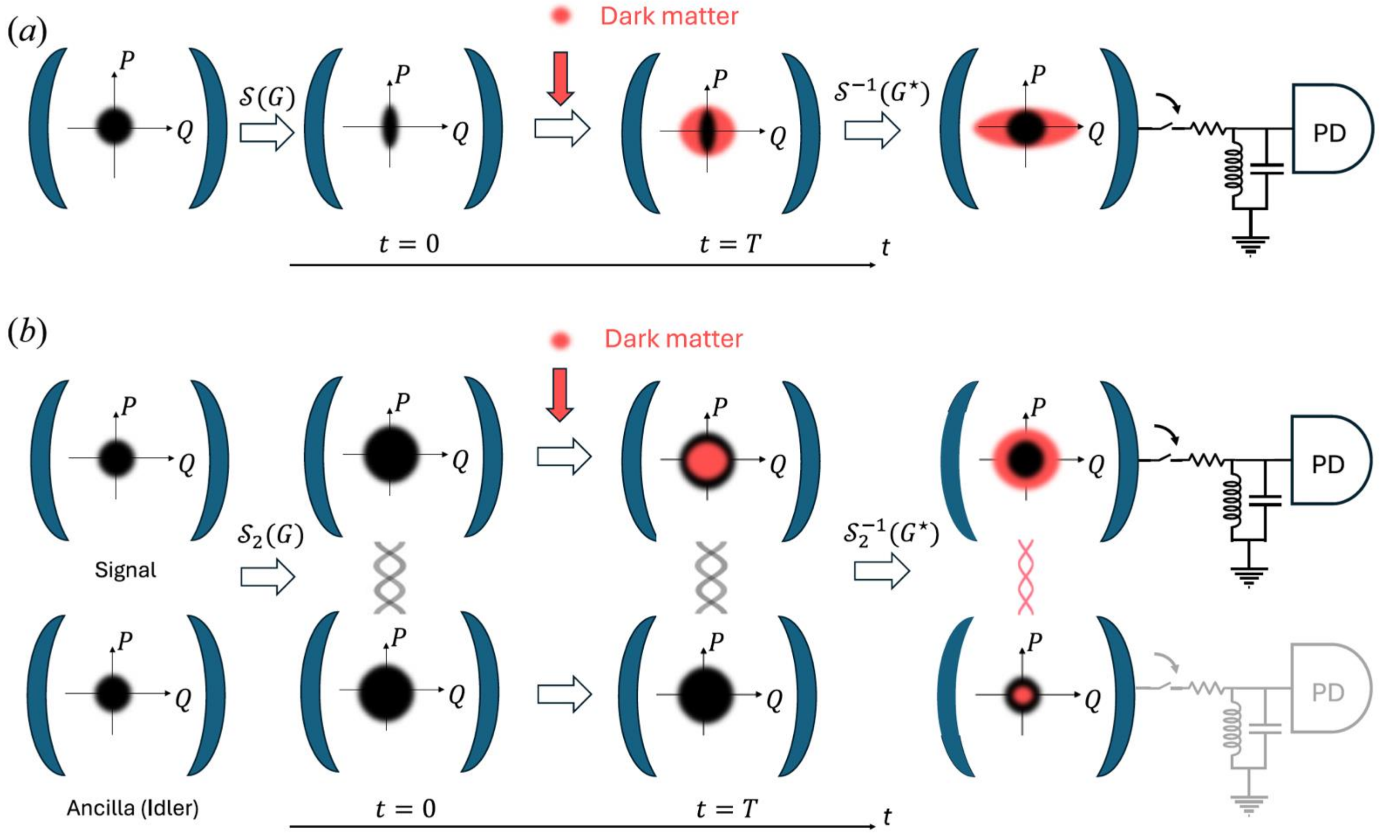
Due to the translation invariant property of the GKP state in phase space, it is possible to simultaneously and precisely measure both quadrature variables, Q and P, modulo $\sqrt{2\pi}$.

arXiv:2412.04865

arXiv:2506.20627

PRX QUANTUM 3, 030333 (2022)

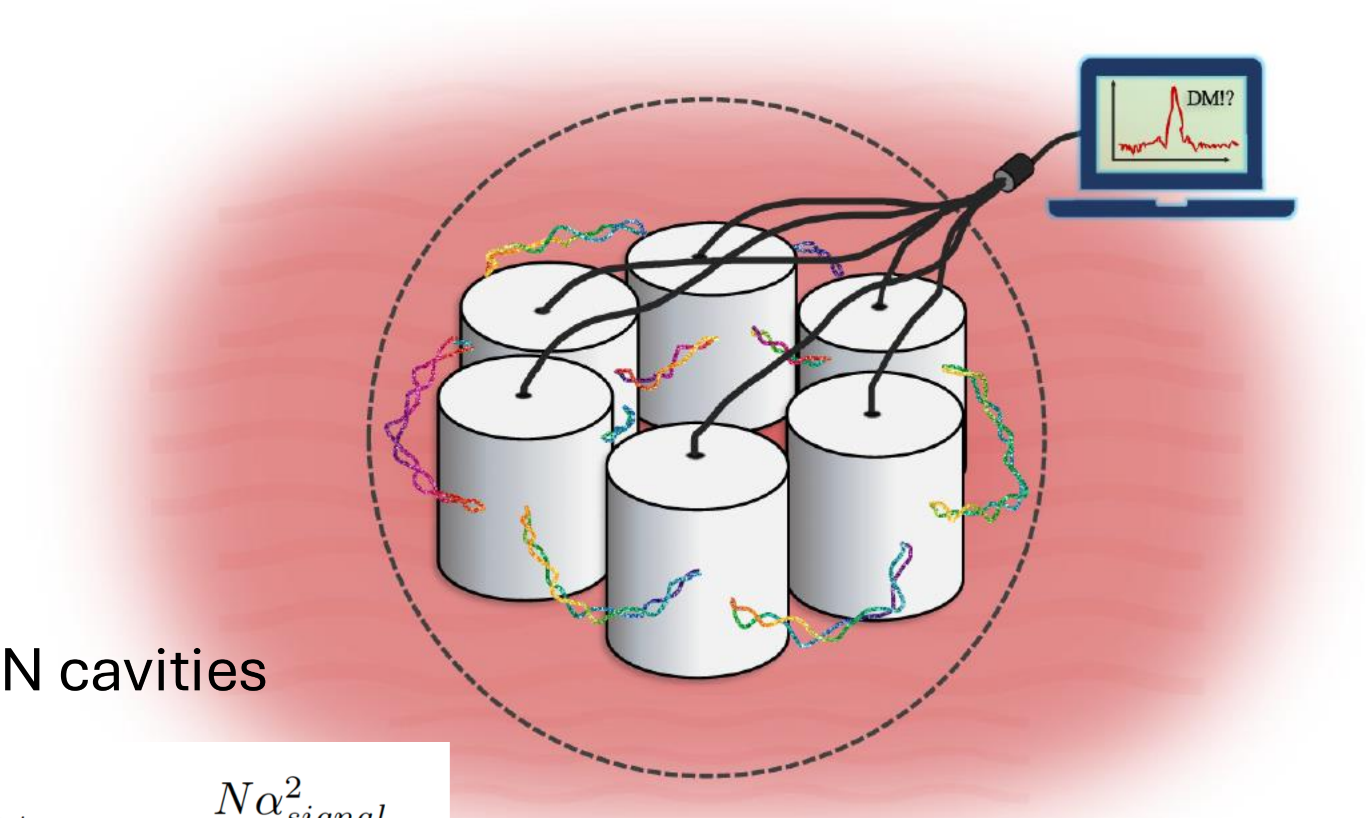
Combining Squeezing and Photon Counting



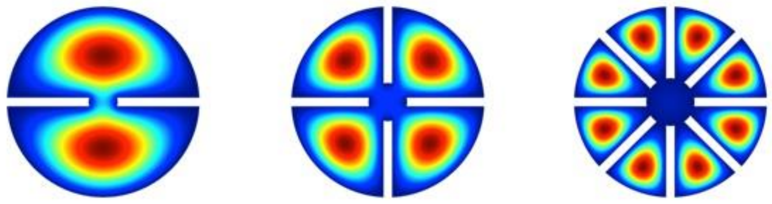
npj Quantum Information (2025) 11:48

npj Quantum Information (2023) 9:27

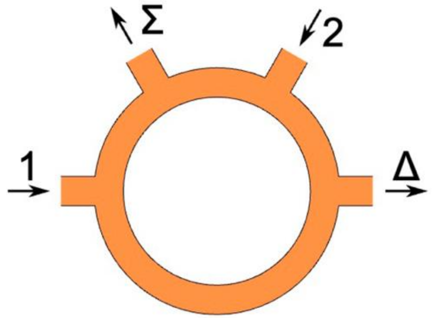
Coherently Sum Signals



Pizza cavity



Hybrid couplers



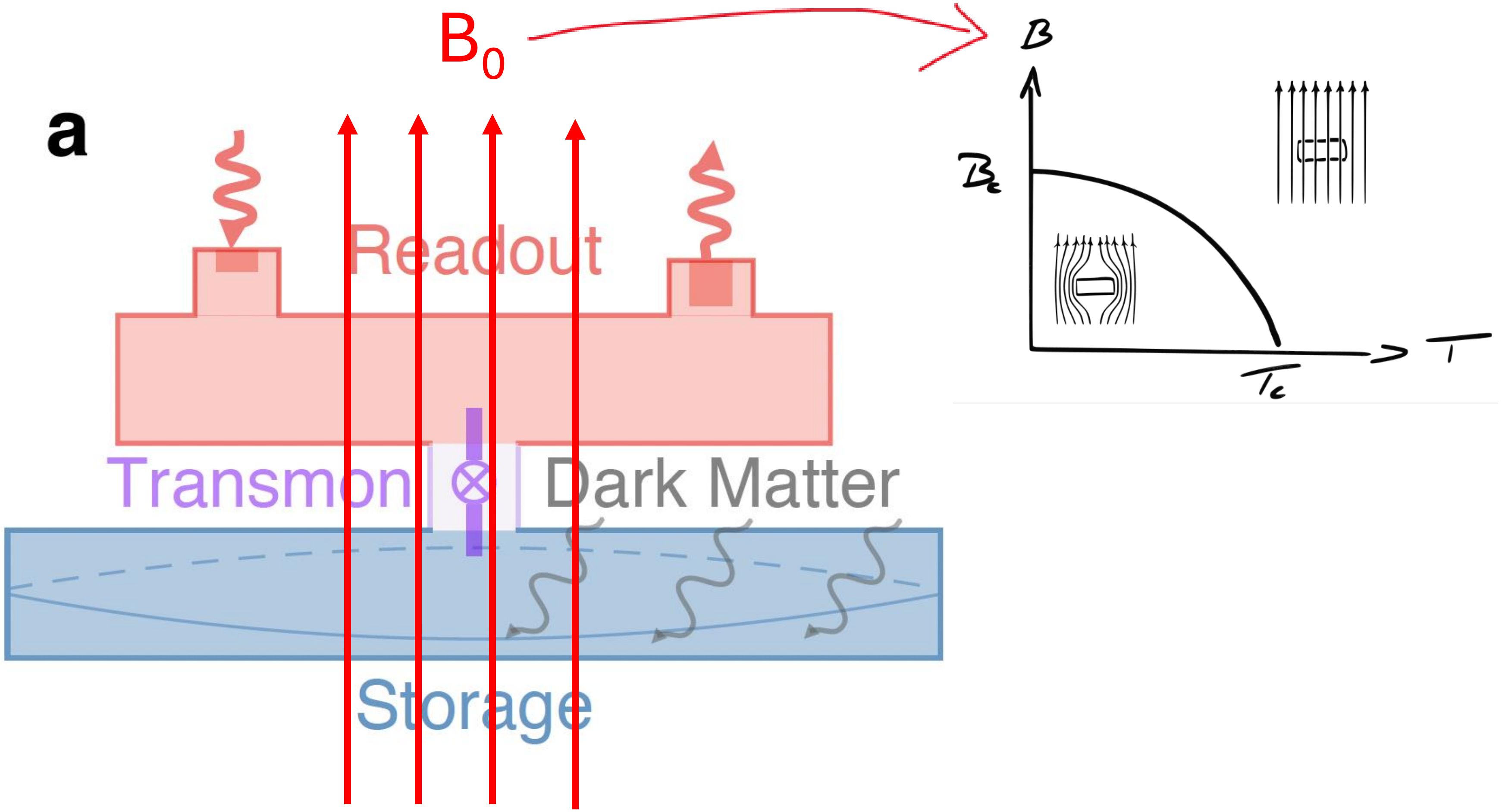
With N cavities

$$Signal/Noise = \frac{N\alpha^2_{signal}}{\alpha^2_{noise}}$$

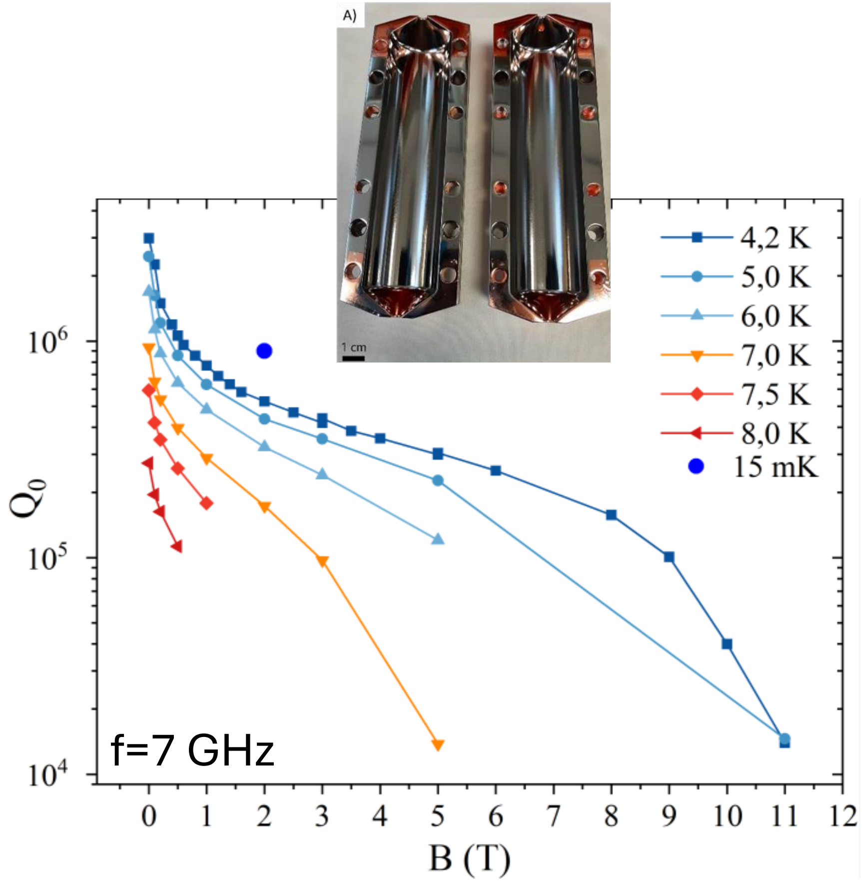
$\lambda \gg \bar{r}$

PRX QUANTUM 3, 030333 (2022)

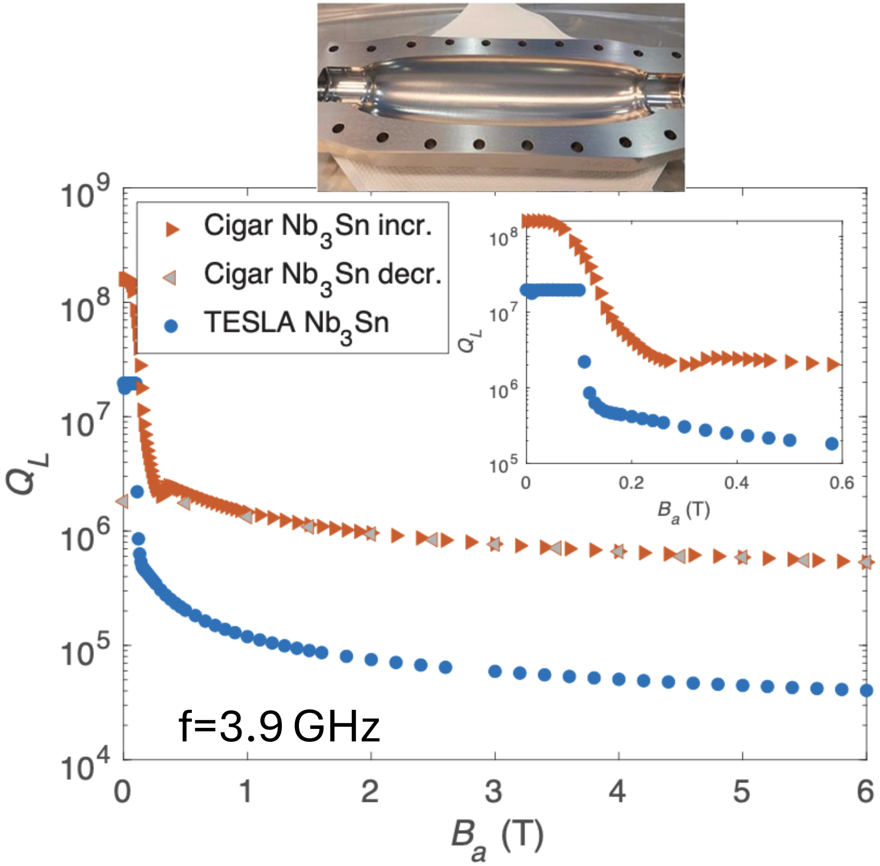
Operating in a Strong Magnetic Field



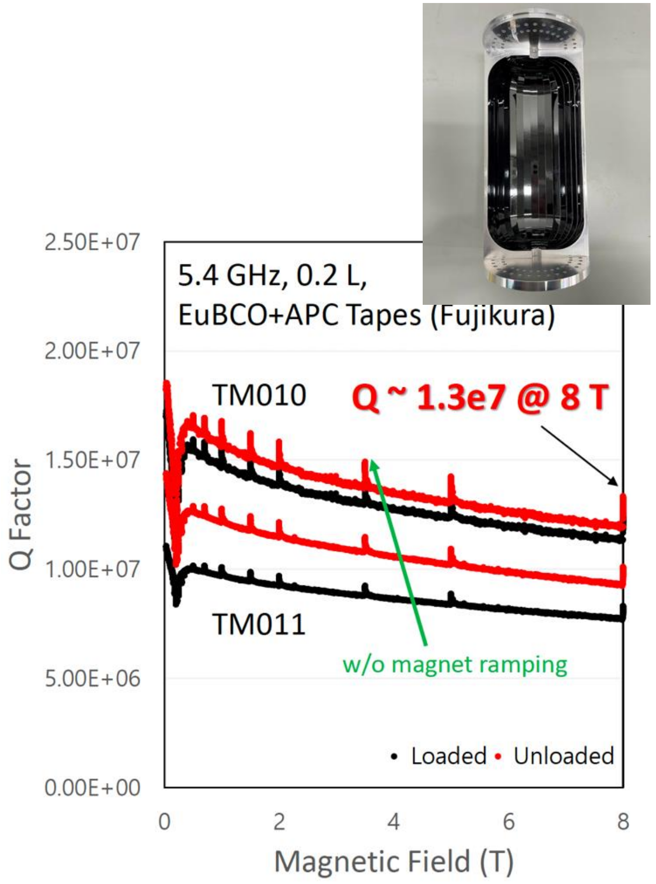
Superconducting Cavities



G. Marconato et al., "NbTi Thin-Film SRF Cavities for Dark Matter Search," in IEEE Transactions on Applied Superconductivity, vol. 34, no. 7, (2024).

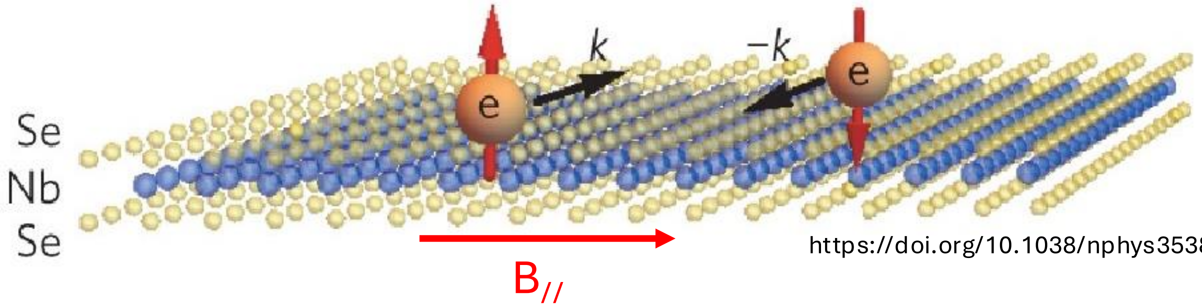


S. Posen et al. PHYS. REV. APPLIED 20, 034004 (2023)



Danho Ahn 18th Patras Workshop

Can we Build a Magnetically Resilient Qubit?



https://doi.org/10.1038/nphys3538

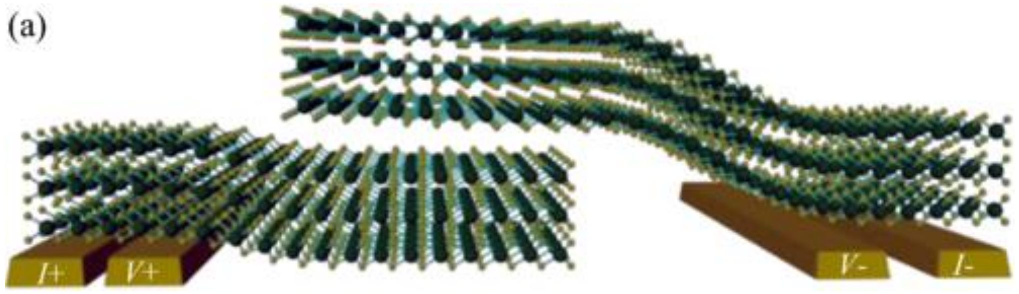
NbSe2 : Transition-metal dichalcogenide (TMD) superconductors

Thin $NbSe_2$ (niobium diselenide) retains superconductivity at a high **inplane** magnetic field up to 30 T! Spins pinned on the orthogonal directioin by strong spin orbit coupling insensitive to inplane magnetic field.

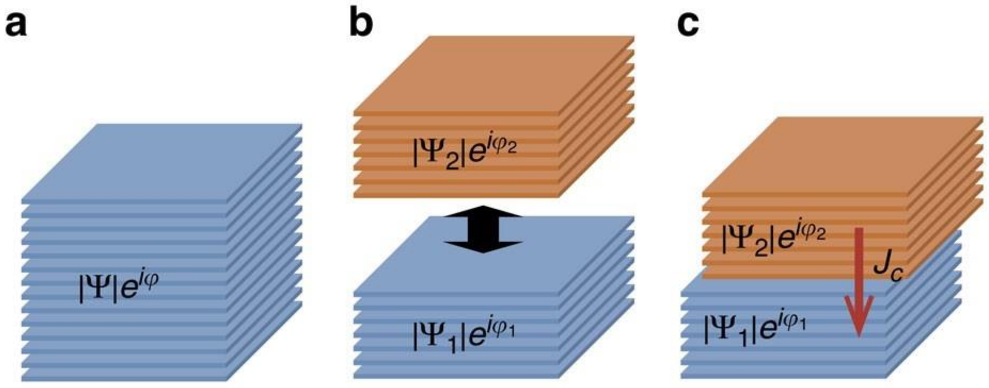
*See https://journals.aps.org/prd/pdf/10.1103/PhysRevD.110.115021 for axion searches with resilient qubits.

$NbSe_2$ van der Waals Josephson Junctions

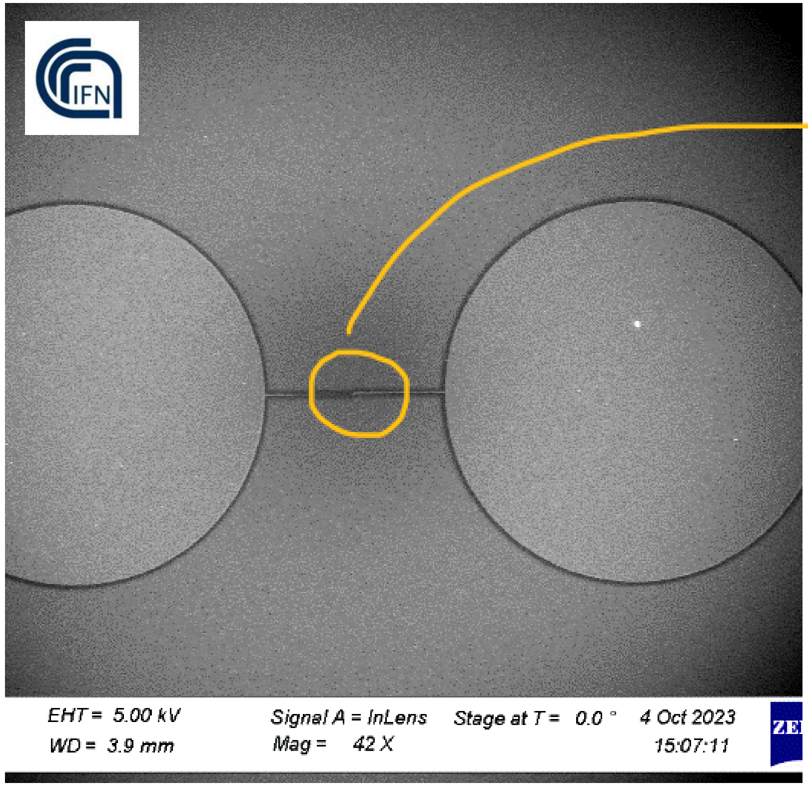
- The layered structure of NbSe2 allows it to be exfoliated into thin flakes. When the vdW interface has a misalignment, decoupling becomes sufficiently large and the superconducting state of the NbSe2 crystal cannot be described by a single-order parameter.

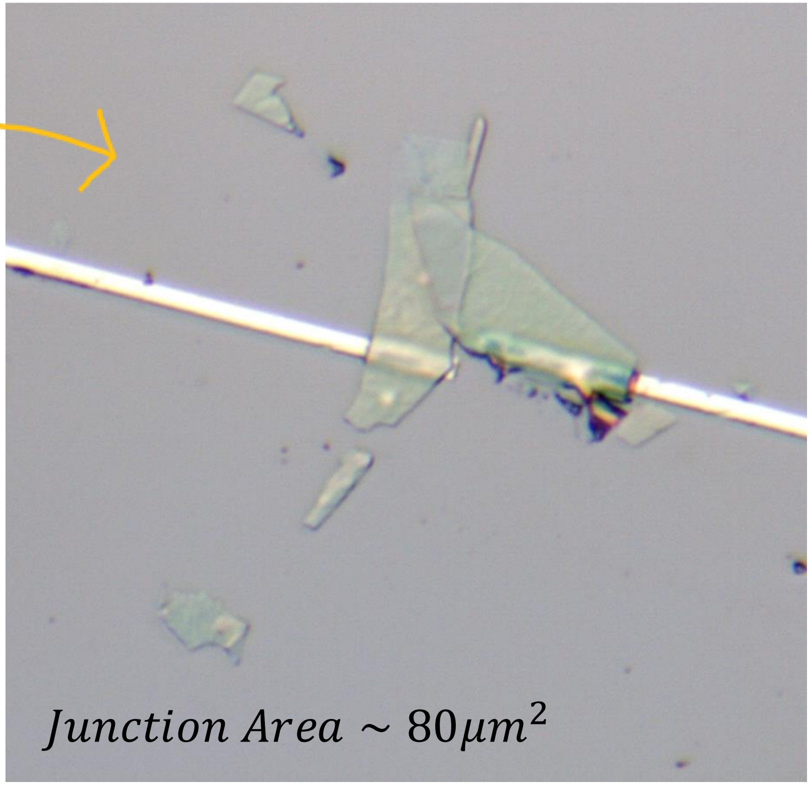


https://doi.org/10.1103/PhysRevB.104.214512



https://doi.org/10.1038/ncomms10616



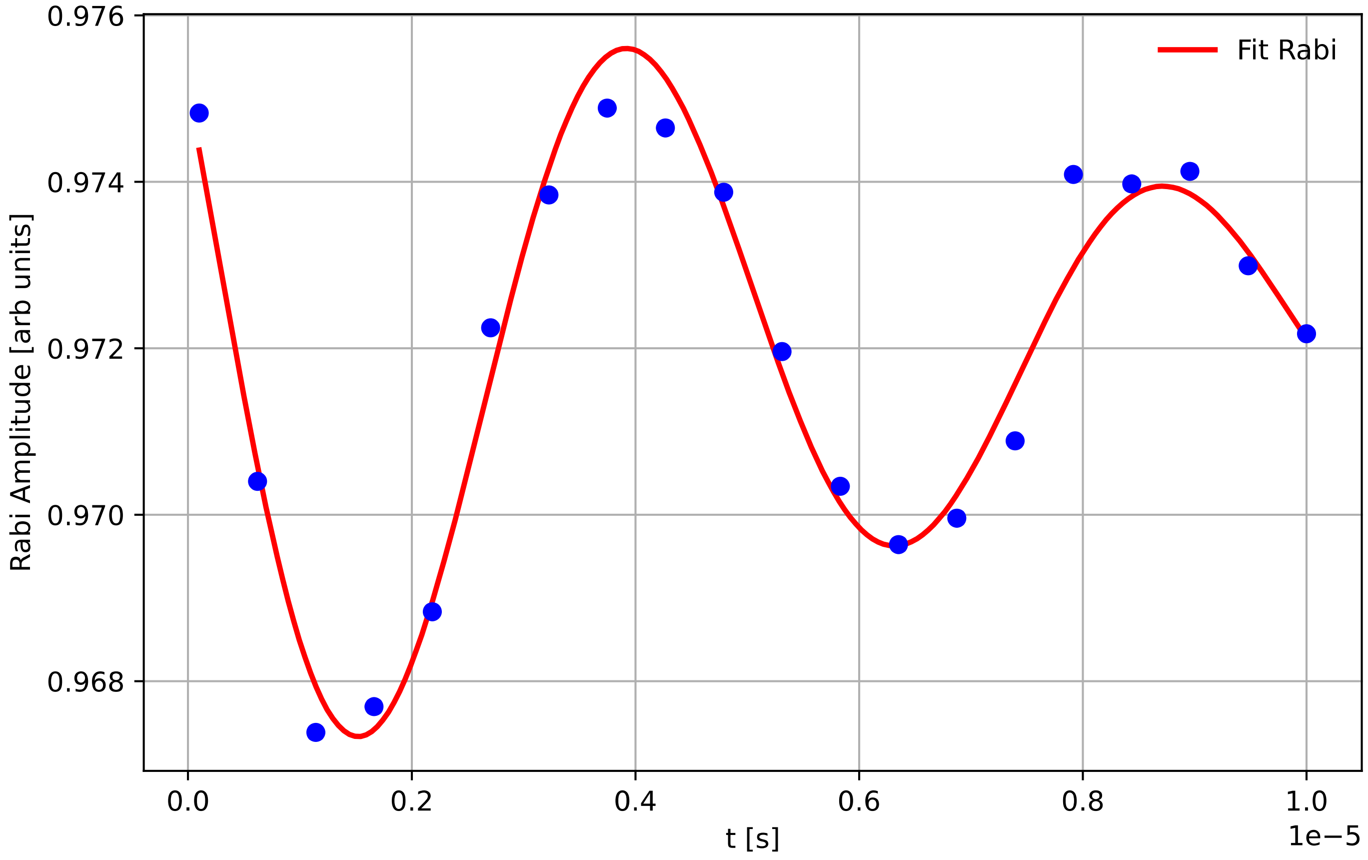


$NbSe_2$ 3D qubit

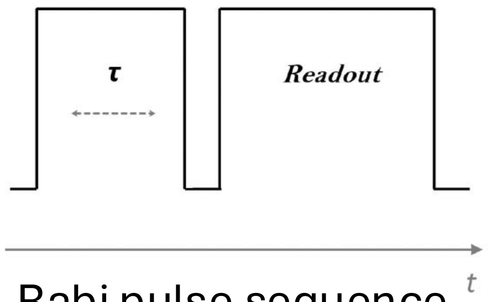
Resilience

Principal Investigator: A. D’Elia (LNF INFN)

Rabi-Like Oscillation in $NbSe_2$ 3D qubit



$\nu_{qubit} = 12.6\ GHz$
$T_1 \sim 6\mu s$



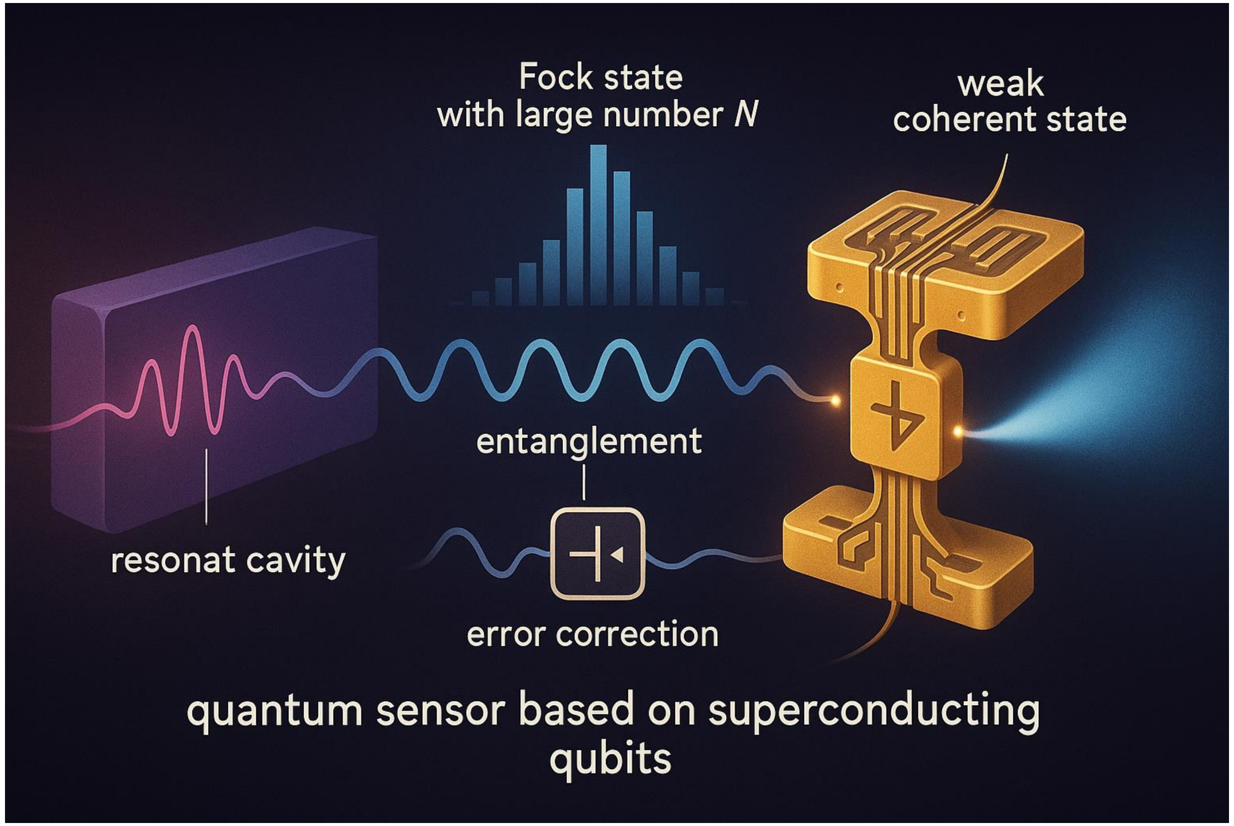
Rabi pulse sequence

Resilience

Principal Investigator: A. D'Elia (LNF INFN)

Towards an optimal detector for Axions and HFGW

- An advanced quantum sensor leveraging superconducting qubits that utilizes entanglement, quantum error correction, and high-photon-number Fock states (large N) to significantly boost the sensitivity for detecting weak coherent states.



Maybe in 10 years:

$$\text{Signal} \propto (n_{Fock} + 1) \times n_{qubits}^2 \times N_{Detectors}^{(2)} \rightarrow (10 + 1) \times 100 \times 100 = 10^5$$