Quantum sensing with superconducting qubits

Logan Bishop-Van Horn

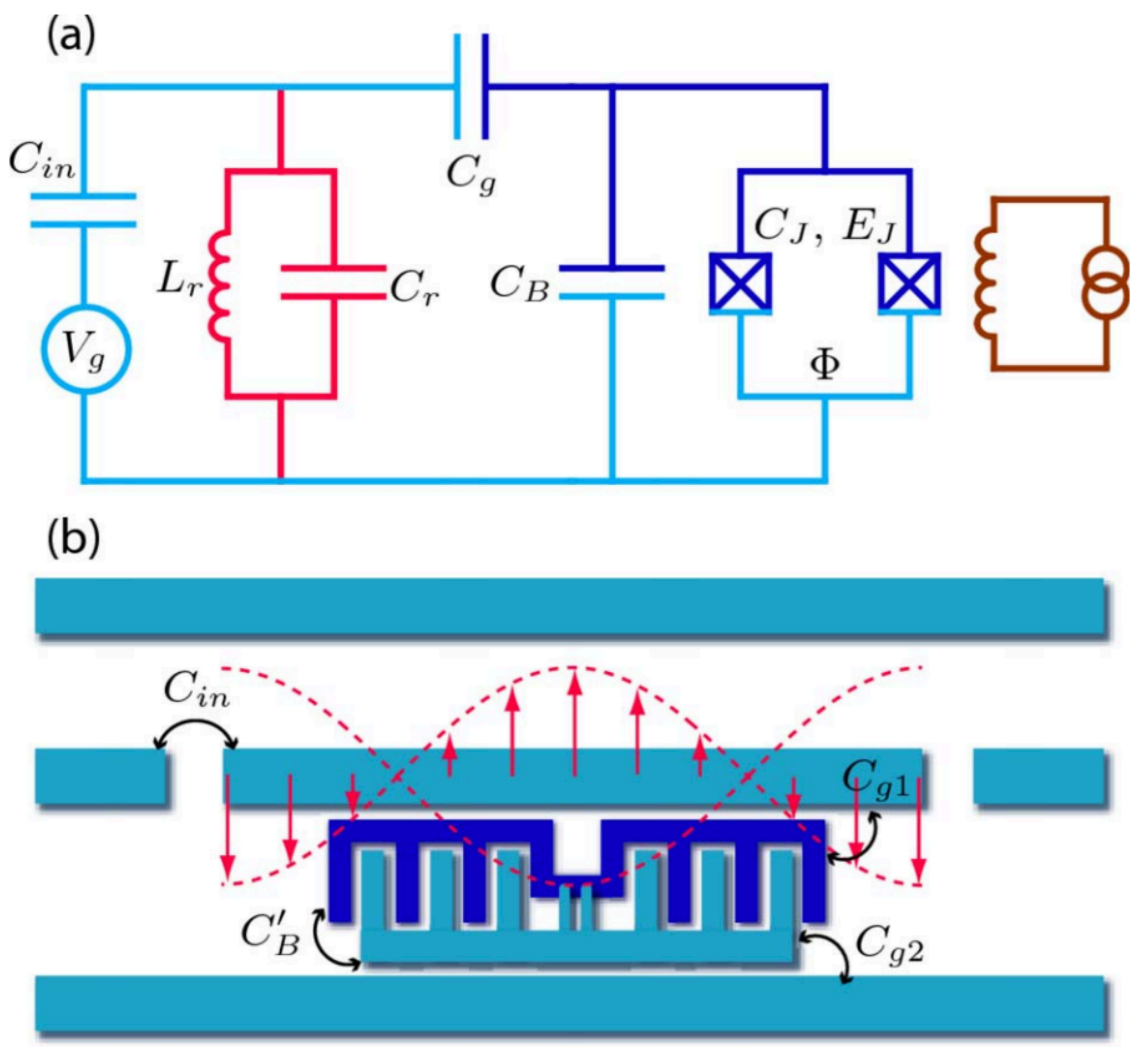
QSQM Symposium

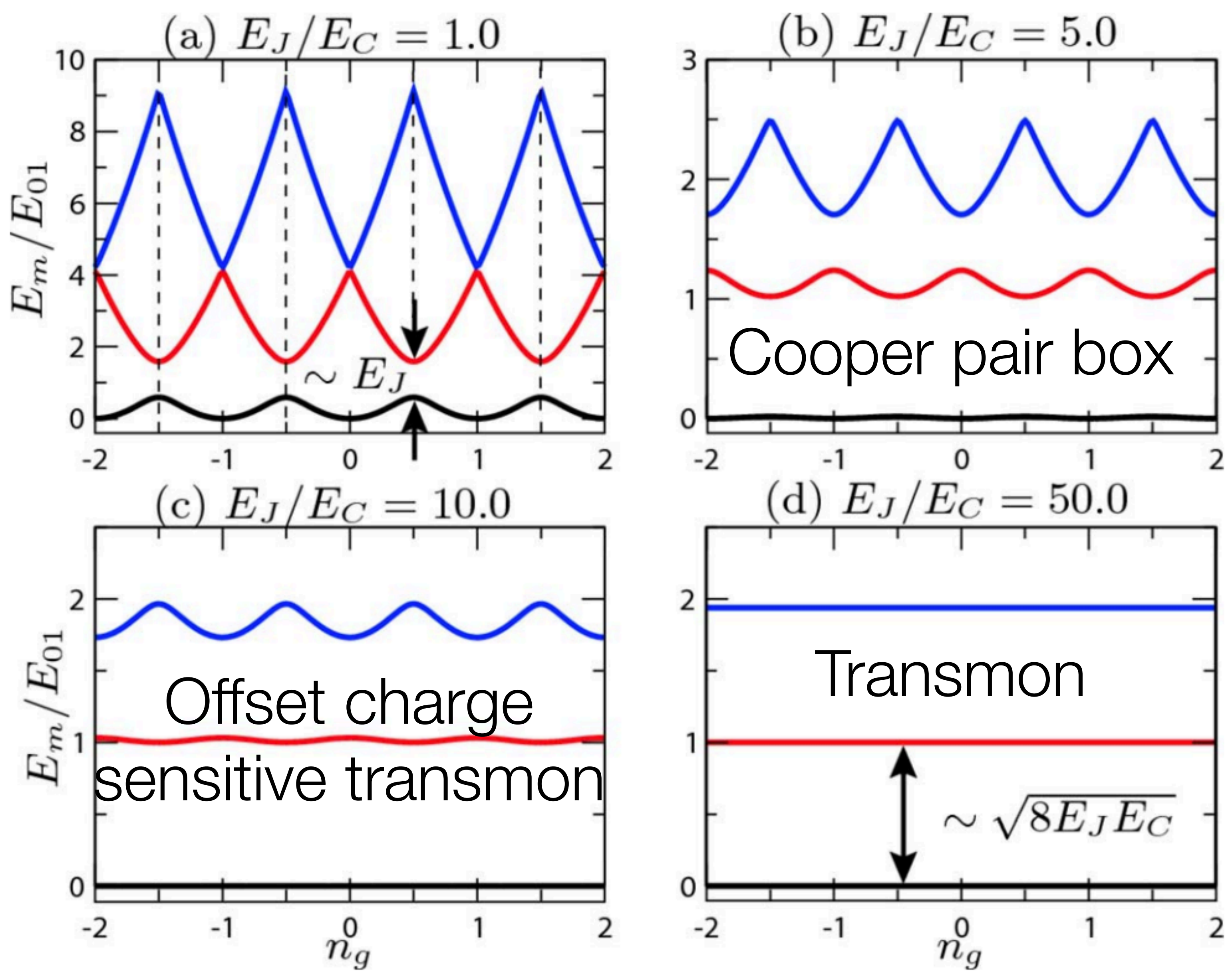
2021-09-10

Transmon Hamiltonian

PHYSICAL REVIEW A **76**, 042319 (2007)

Charge-insensitive qubit design derived from the Cooper pair box

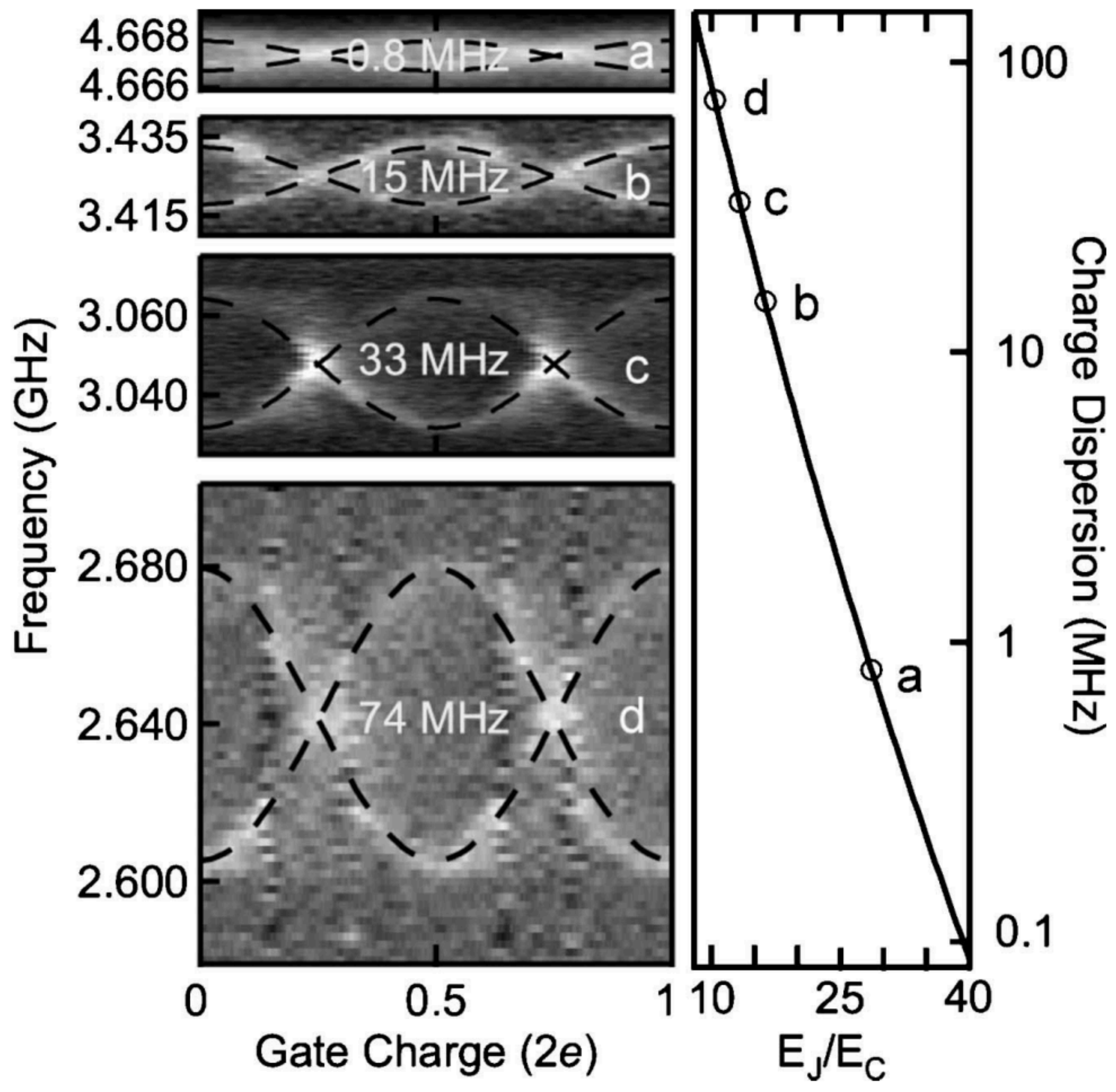




PHYSICAL REVIEW B **77**, 180502(R) (2008)

Suppressing charge noise decoherence in superconducting charge qubits

J. A. Schreier,[1] A. A. Houck,[1] Jens Koch,[1] D. I. Schuster,[1] B. R. Johnson,[1] J. M. Chow,[1] J. M. Gambetta,[2] J. Majer,[1] L. Frunzio,[1] M. H. Devoret,[1] S. M. Girvin,[1] and R. J. Schoelkopf[1]



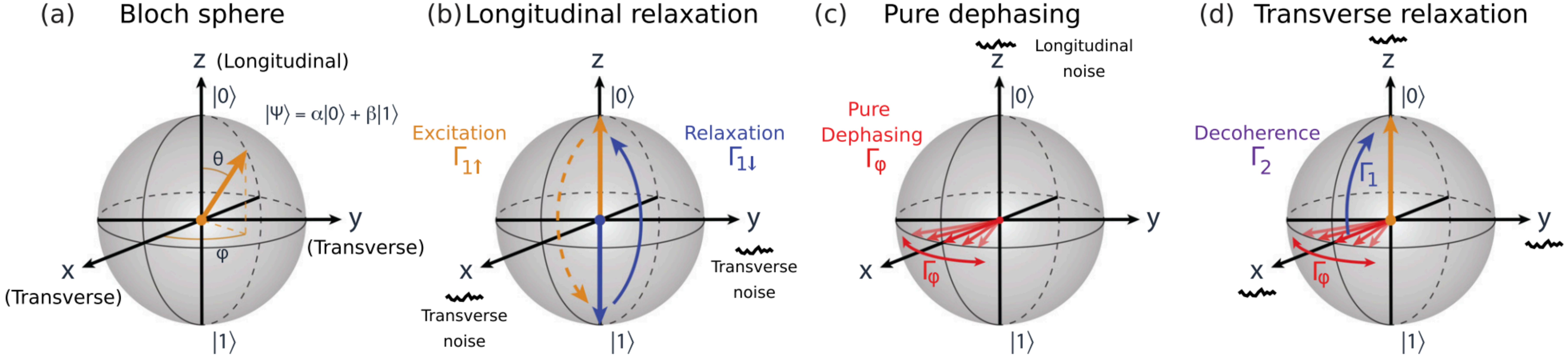
$$\hat{H} = 4E_C(\hat{n} - n_g)^2 - E_J(\Phi)\cos\hat{\varphi}$$

- Superconducting circuit with tunable charge and flux sensitivity
- Transition frequencies $\omega_{ij} = 2\pi f_{ij}$ are periodic in n_g and Φ
- E_J/E_C determines anharmonicity and charge sensitivity

Decoherence limits sensitivity

A quantum engineer's guide to superconducting qubits

Cite as: Appl. Phys. Rev. 6, 021318 (2019); https://doi.org/10.1063/1.5089550



Goal: Measure qubit frequency $f_{01}(n_g, \Phi)$ to quantify electric potential (via n_g), magnetic field (via Φ), or fluctuations in those parameters (noise spectroscopy).

High frequency noise: drives transitions between states (T_1)

Control electronics
Lossy environment
Thermal radiation
Pair-breaking photons

$|\langle 0|\hat{O}_\lambda|1\rangle|^2, S_\lambda(f_{01})$

Low frequency (e.g. 1/f) noise: stochastically shifts qubit frequency (T_φ)

Control electronics
Two-level systems
Readout photons
???

$\frac{\partial f_{01}}{\partial \lambda}, S_\lambda(f)$

$$T_2 = \left(\frac{1}{T_\varphi} + \frac{1}{2T_1}\right)^{-1}$$

$$\delta n_g \sim \frac{1}{T_2 \left|\frac{\partial f_{01}}{\partial n_g}\right|}$$ Uncertainty in offset charge

$$\delta \Phi \sim \frac{1}{T_2 \left|\frac{\partial f_{01}}{\partial \Phi}\right|}$$ Uncertainty in flux bias

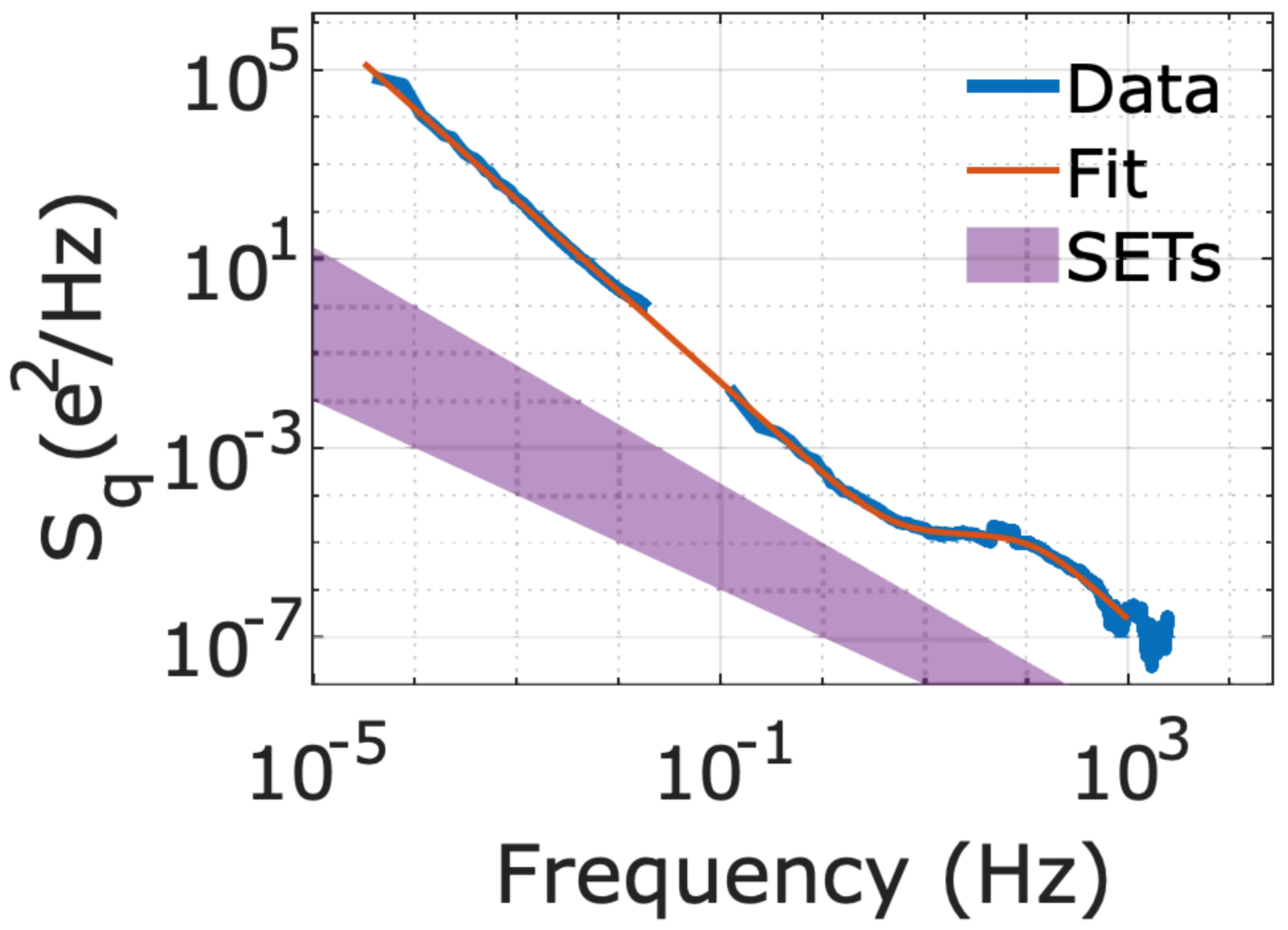
Low frequency charge noise

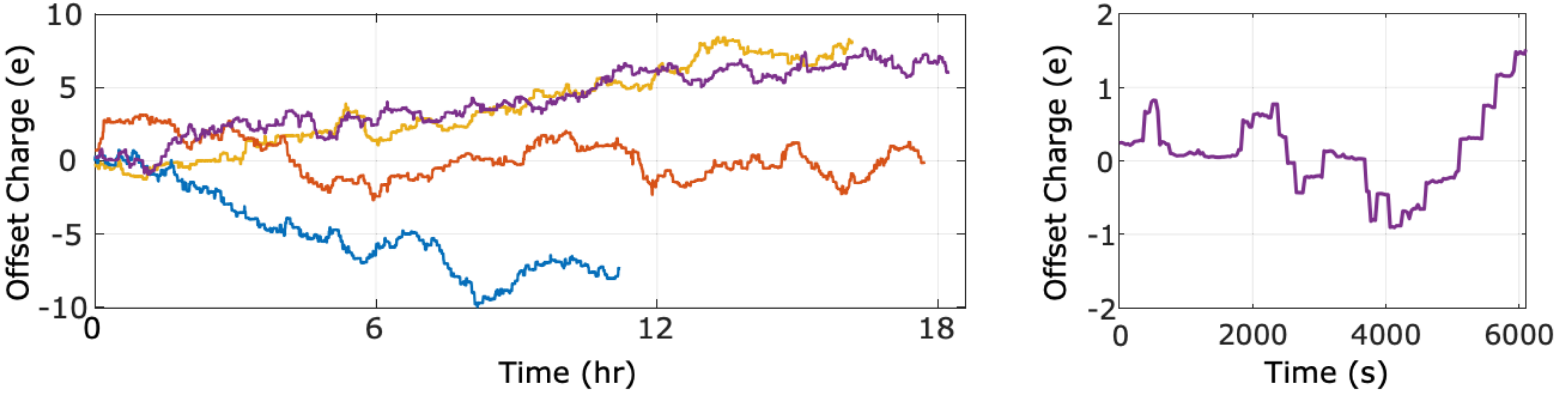
- 1/f-like charge noise in offset charge sensitive qubits is orders of magnitude worse than typically seen in SETs
- $\sim 0.1 - 1{,}000\,\mathrm{Hz}$: limits sensitivity via T_2
- $\lesssim 0.1\,\mathrm{Hz}$: frequency drift complicates data-taking and analysis

PHYSICAL REVIEW B **100**, 140503(R) (2019)

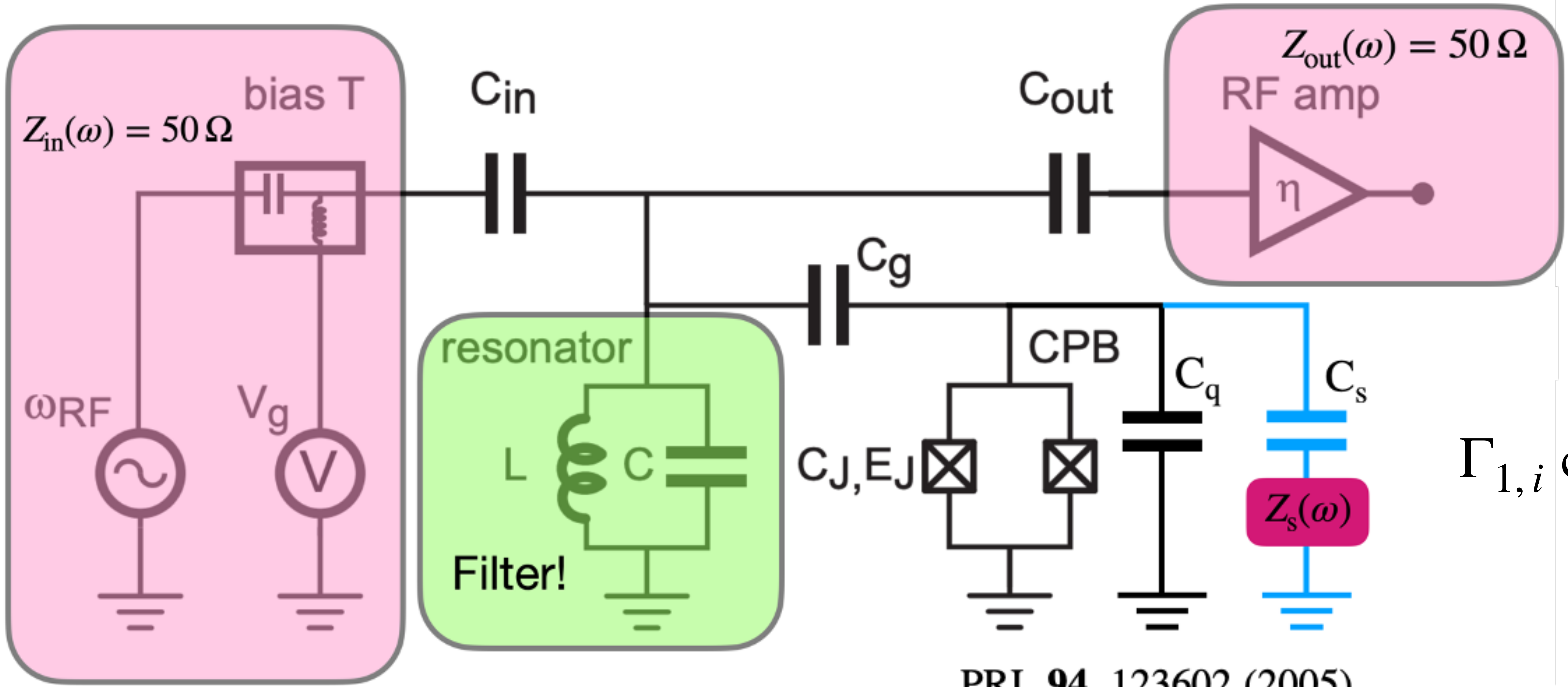
Anomalous charge noise in superconducting qubits

B. G. Christensen,[1] C. D. Wilen,[2] A. Opremcak,[2] J. Nelson,[3] F. Schlenker,[2] C. H. Zimonick,[2] L. Faoro,[2,4] L. B. Ioffe,[2,4] Y. J. Rosen,[5] J. L. DuBois,[5] B. L. T. Plourde,[3] and R. McDermott[2]





Coupling to sample with finite impedance



PRL **94,** 123602 (2005)

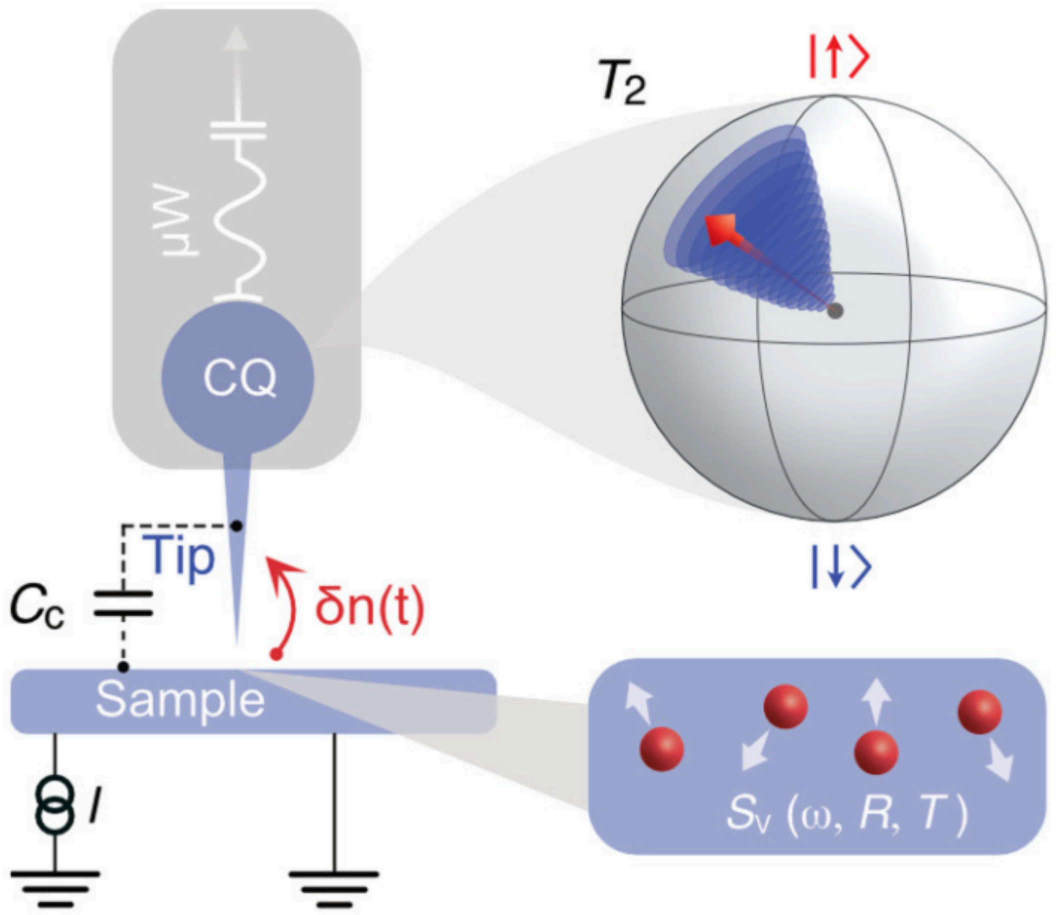
$$\Gamma_{1,i} \propto \left(\frac{C_i}{C_{tot}}\right)^2 \mathrm{Re}[Z_i(\omega_{01})]\,|\langle 0|\hat{n}|1\rangle|^2$$

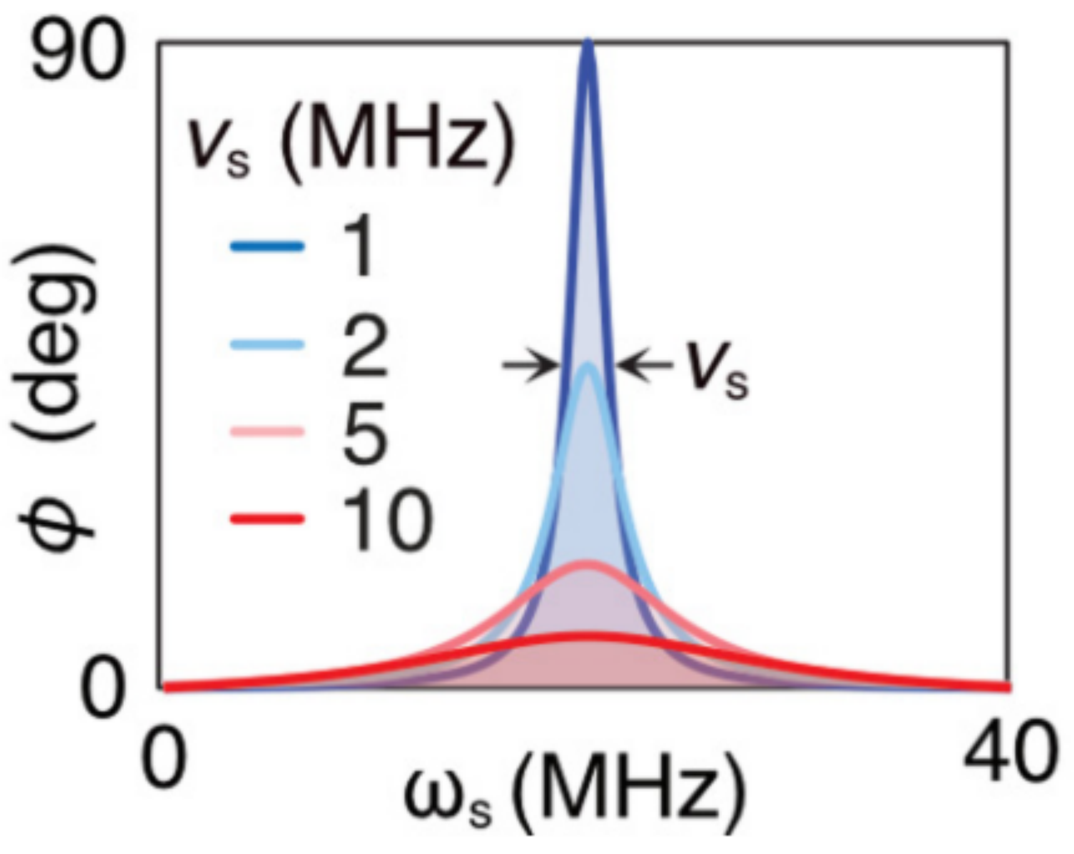
- Want to maximize C_s/C_{tot} so that the sample gates the qubit island effectively
- But capacitive coupling to a lossy sample limits sensitivity via T_1
- Effect is small in CPB regime, but becomes significant as E_J/E_C is increased

Measurement methods

Spectroscopy

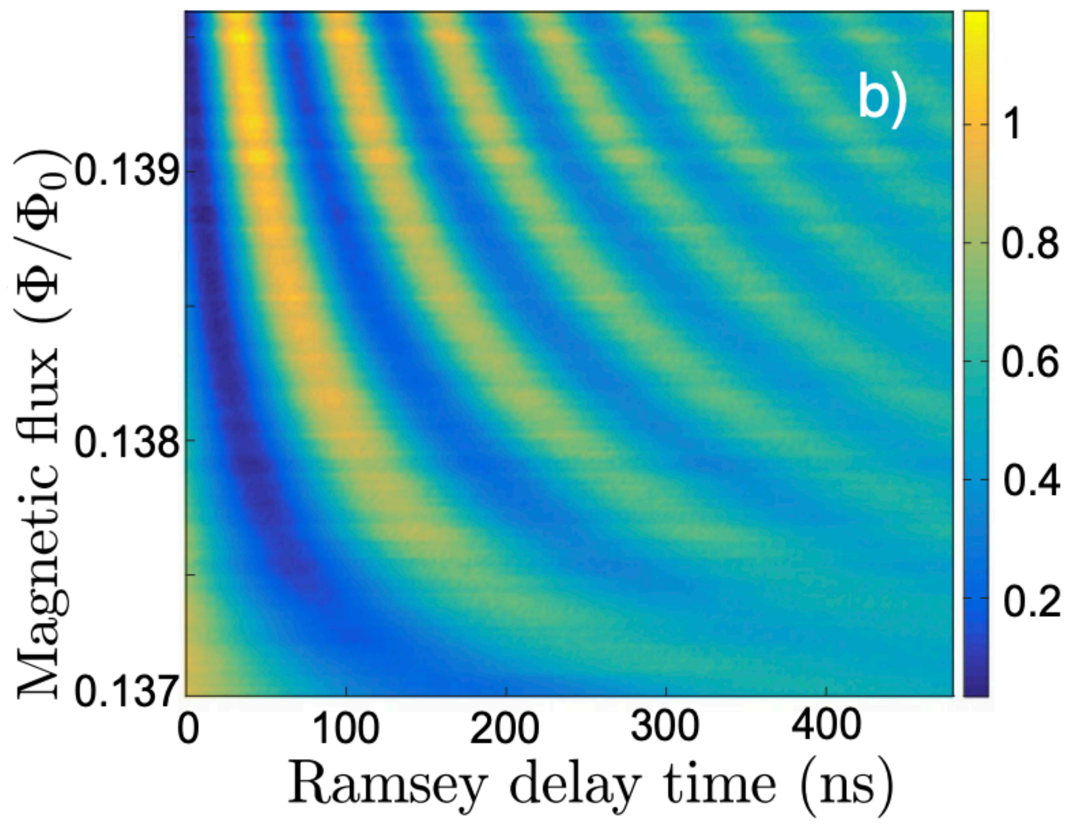
- Can be done with only CW microwave control
- Center frequency measures the mean value of n_g or Φ
- Linewidth measures T_2 but cannot easily be converted into a noise spectrum $S_{n_g}(\omega)$ or $S_\Phi(\omega)$
- Example: Phys. Rev. Res. 2, 043031 (2020)

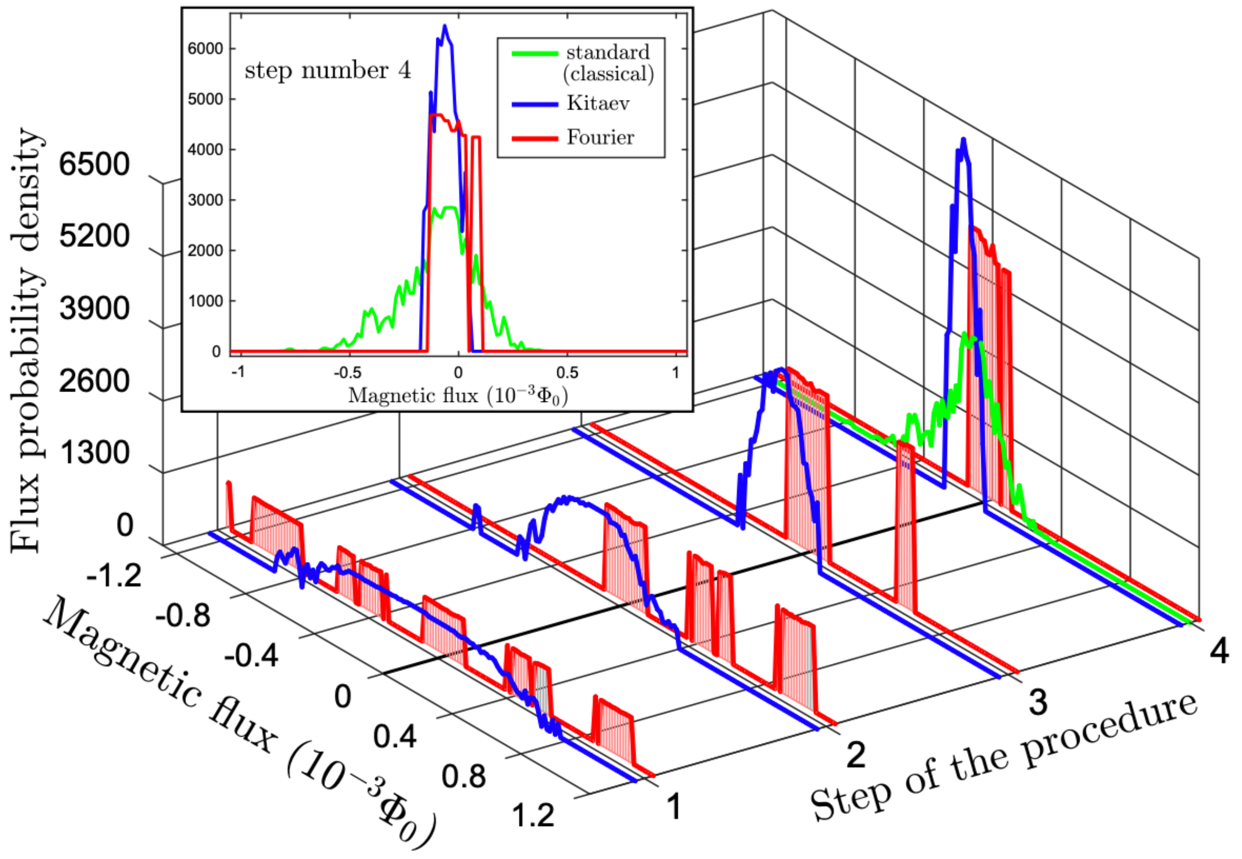




Interferometry

- Enables noise spectroscopy via dynamical decoupling
- Requires time domain control and reasonably high-fidelity readout
- Limited dynamic range due to phase wrapping
- Limited measurement repetition rate:
  - At most 1 bit of information per measurement, then the qubit must be reset to ground state
- Example: npj Quant. Info. 4, 29 (2018)





Can we borrow ideas from SC qubit research without inheriting qubit downsides?

- Requires mK temperatures
- Requires single-photon operation and few-photon readout
- Excess charge noise relative to SETs
- Limited measurement repetition rate
- Limited dynamic range

Fast magnetic imaging/noise spectroscopy

SQUID magnetometer with dispersive readout

- Noise spectroscopy: high BW measurement + FFT
- Compatible with parametric amplifiers
- Faster measurement repetition rate (no reset)
- See:
  - doi:10.1103/PhysRevB.83.134501
  - doi:10.1088/0953-2048/26/5/055015
  - doi:10.1063/1.5030489

Fast potential imaging/noise spectroscopy

Radio-frequency SET

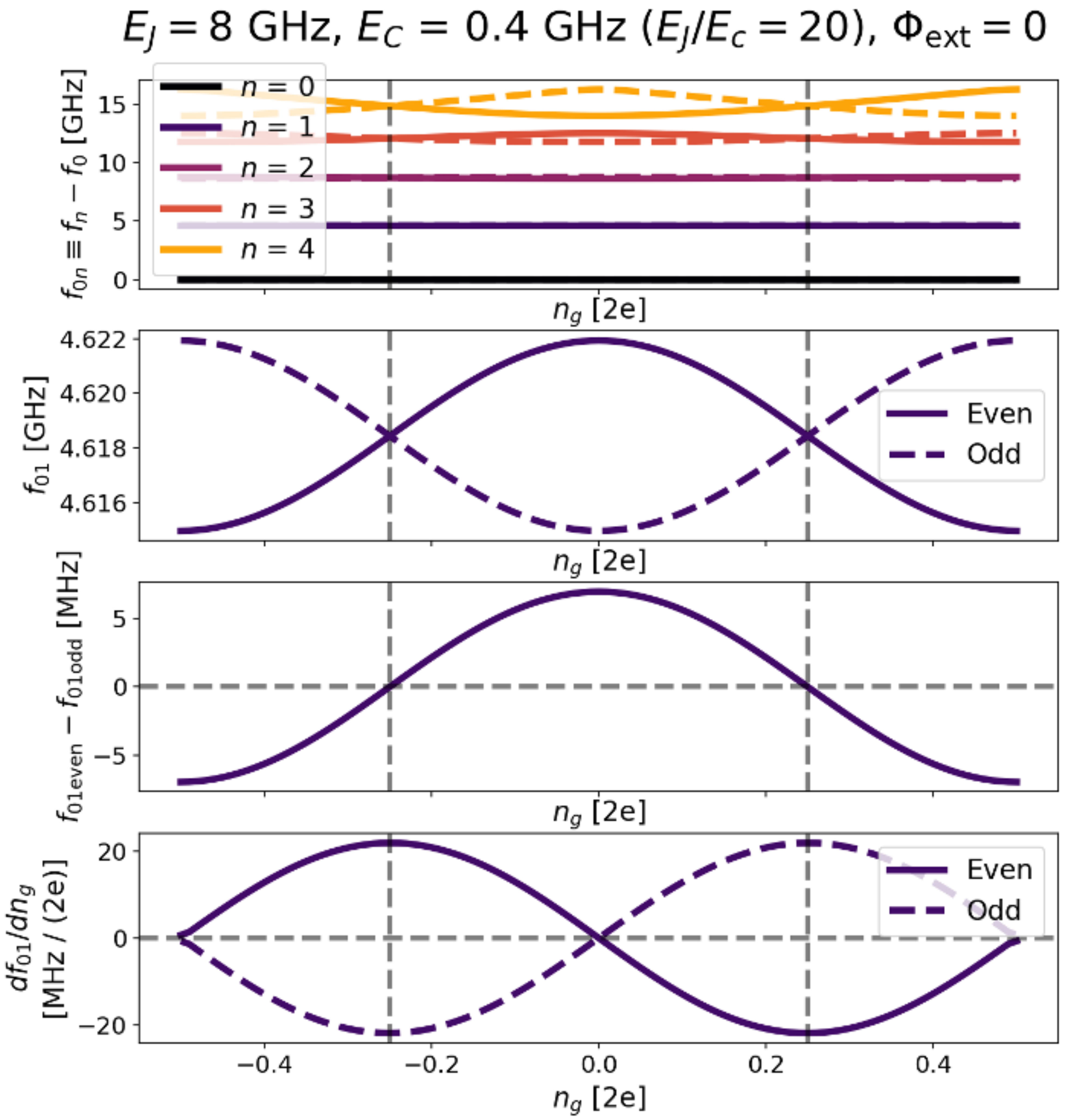
- Noise spectroscopy: high BW measurement + FFT
- Lower charge noise than charge-sensitive qubit
- See:
  - doi:10.1126/science.280.5367.1238

Imaging rf loss in SC circuits

Scanning high-Q SC resonator

- Measure Q vs. position
- Could be frequency-tunable with a SQUID
- See:
  - doi:10.1063/1.4792381
  - doi:10.1103/PhysRevX.6.021044

Goal: Measure qubit frequency $f_{01}(n_g, \Phi)$ to quantify electric potential (via n_g), magnetic field (via Φ), or fluctuations in those parameters (noise spectroscopy).

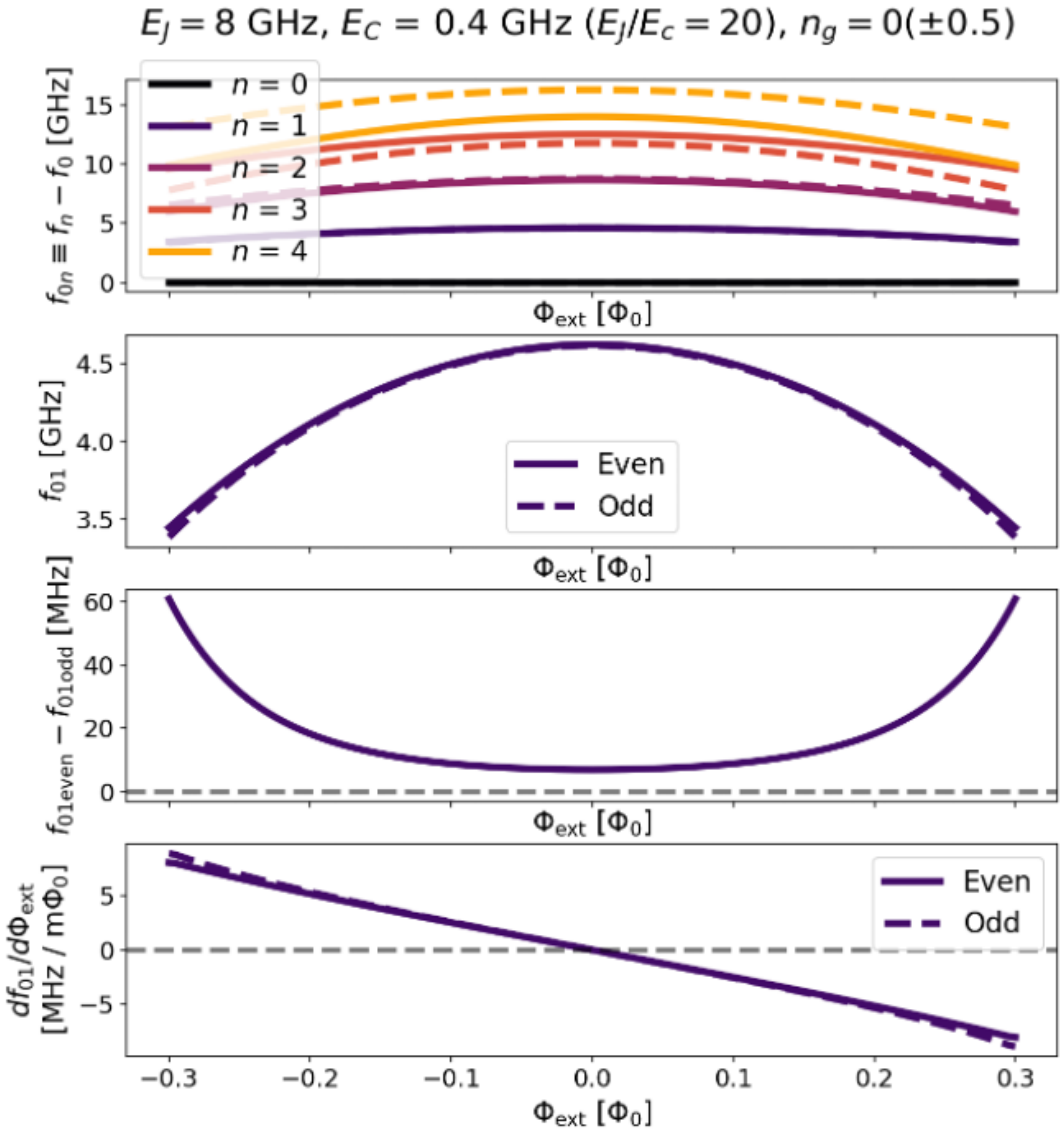


Transition frequencies

Qubit spectrum

Sensitivity to quasiparticle tunneling

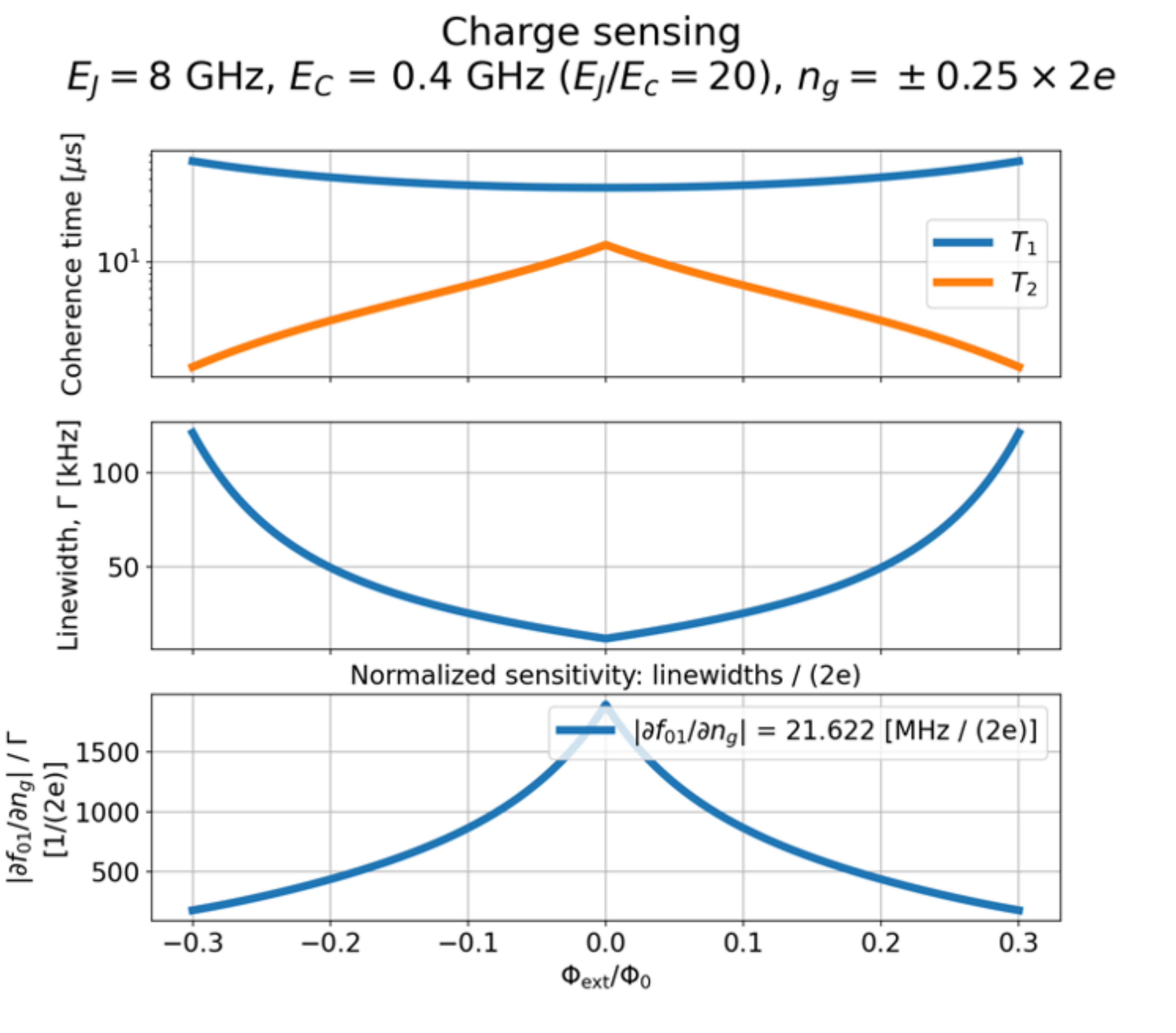
Sensitivity to n_g or Φ

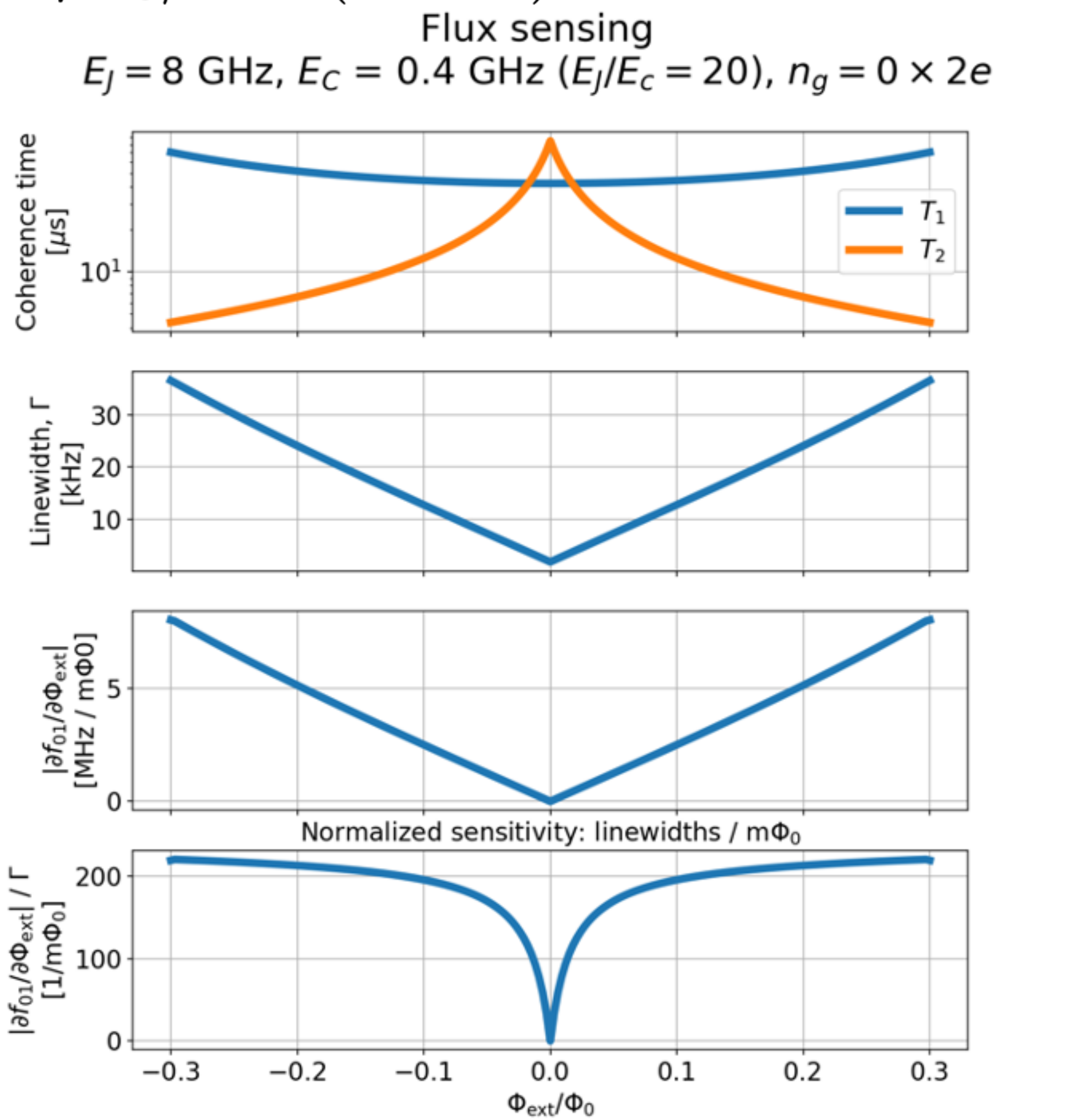


First-order insensitive to Φ

First-order insensitive to n_g

$$A_{n_g} = 10^{-4} e/\sqrt{\mathrm{Hz}},\ A_\Phi = 1\,\mu\Phi_0/\sqrt{\mathrm{Hz}}\ (@\ 1\ \mathrm{Hz})$$

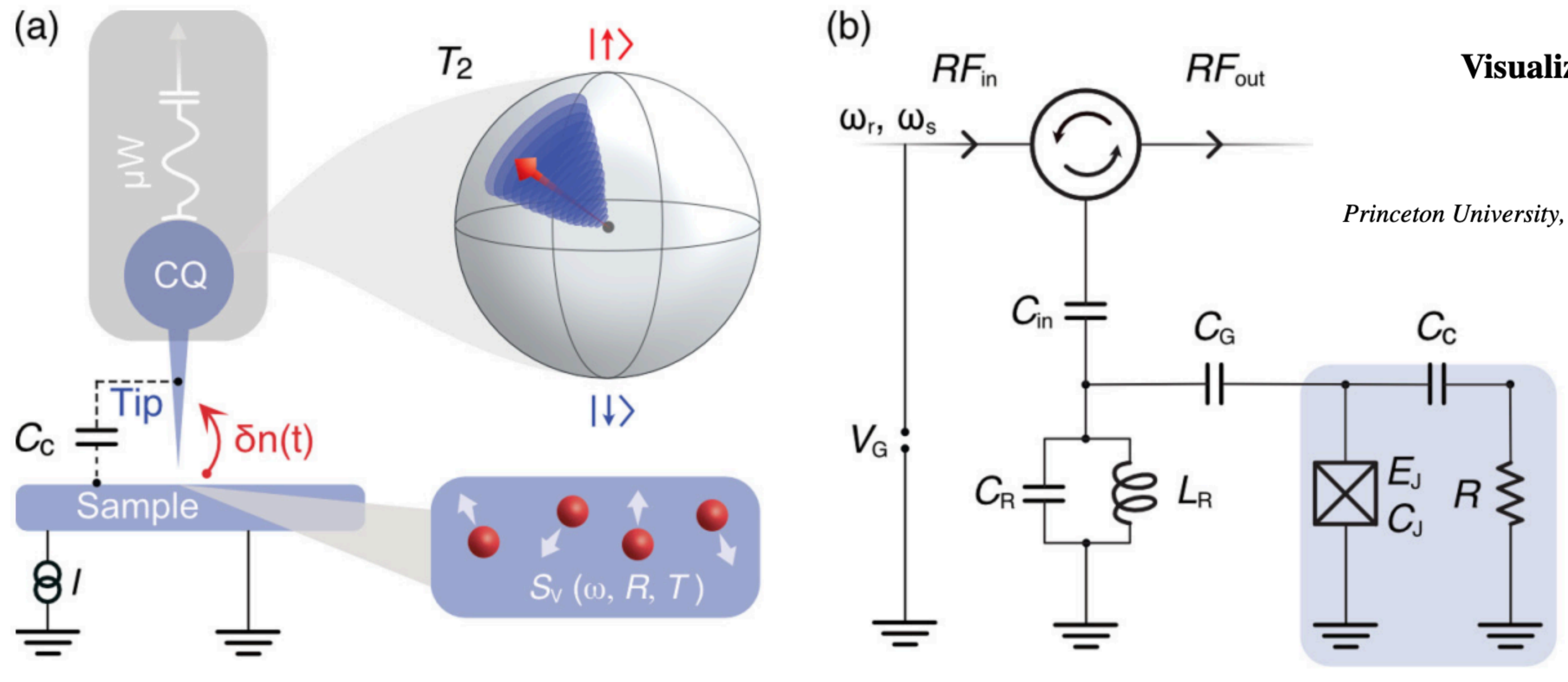




$$S_{n_g} = \frac{1}{\Gamma}\left|\frac{\partial f_{01}}{\partial n_g}\right| = 2\pi T_2 \left|\frac{\partial f_{01}}{\partial n_g}\right|$$

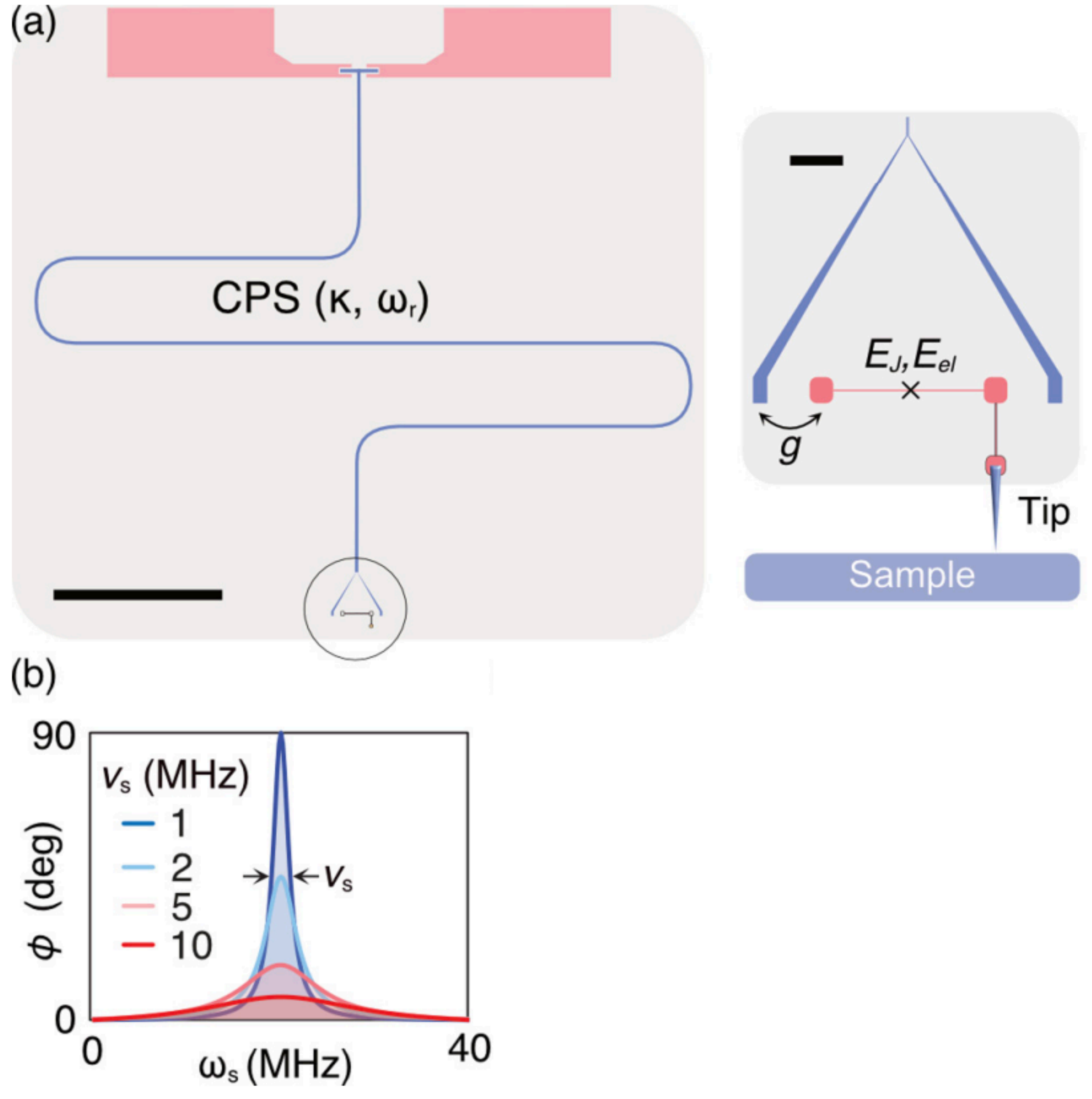
$$S_\Phi = \frac{1}{\Gamma}\left|\frac{\partial f_{01}}{\partial \Phi}\right| = 2\pi T_2 \left|\frac{\partial f_{01}}{\partial \Phi}\right|$$

PHYSICAL REVIEW RESEARCH **2**, 043031 (2020)

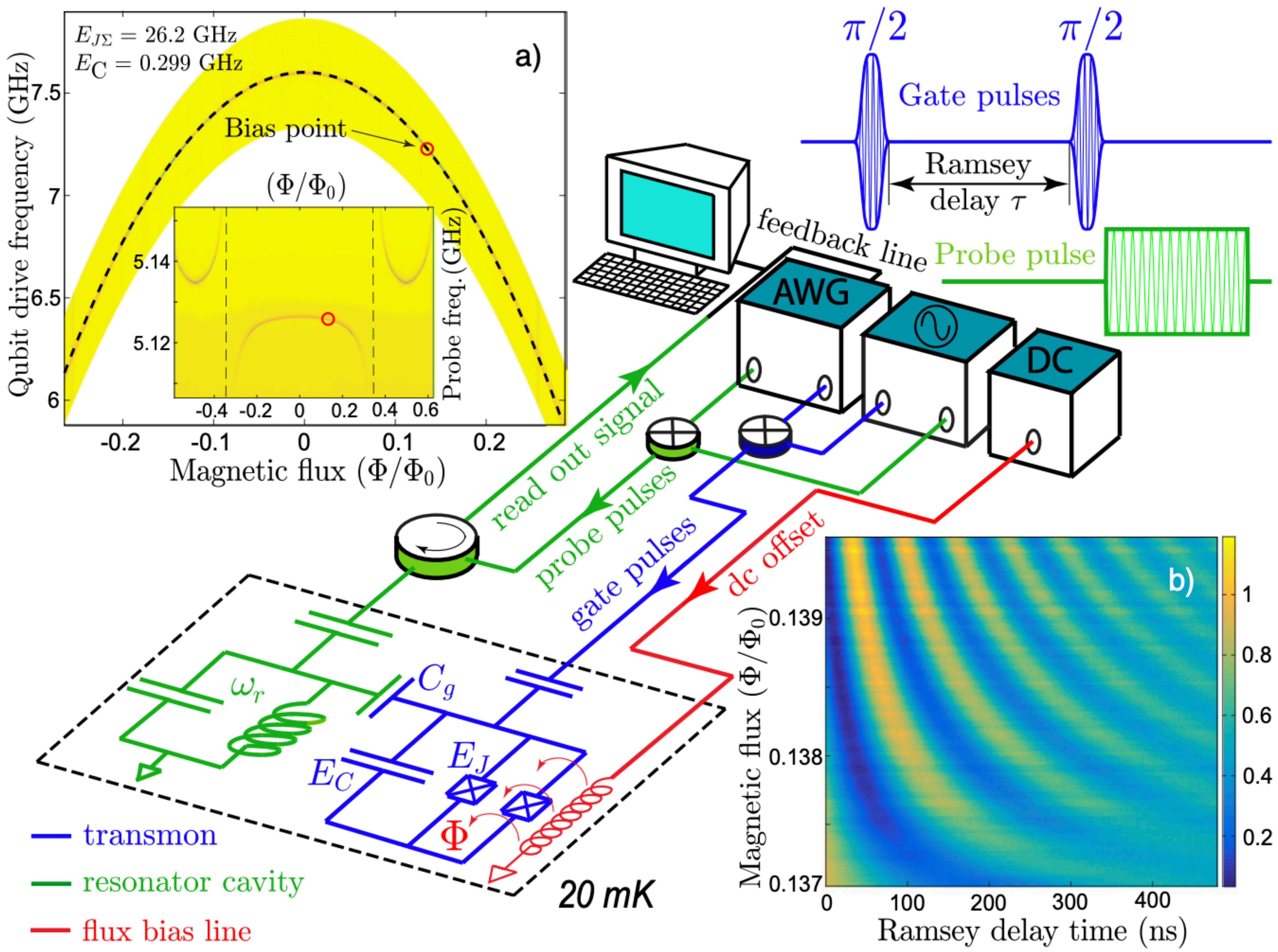


Visualizing dissipative charge-carrier dynamics at the nanoscale with superconducting-charge-qubit microscopy

Berthold Jäck*
Princeton University, Joseph Henry Laboratory at the Department of Physics, Princeton, New Jersey 08544, USA



- Lossy sample capacitively coupled to a Cooper pair box
- Johnson noise from sample causes fluctuating n_g, reducing T_2
- Measure linewidth $1/T_2$ spectroscopically to infer local sample temperature, resistance

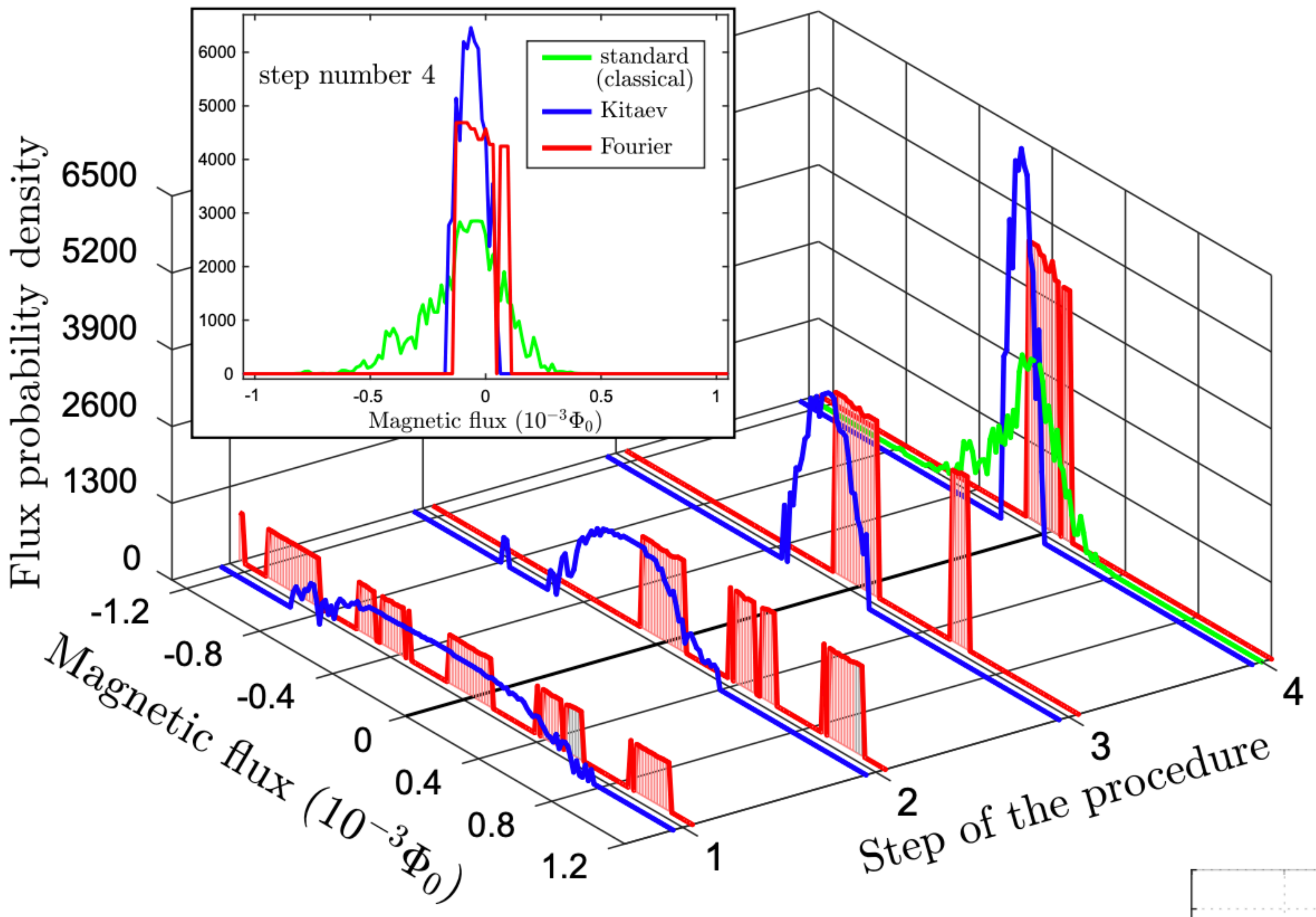


Article | Open Access | Published: 29 June 2018

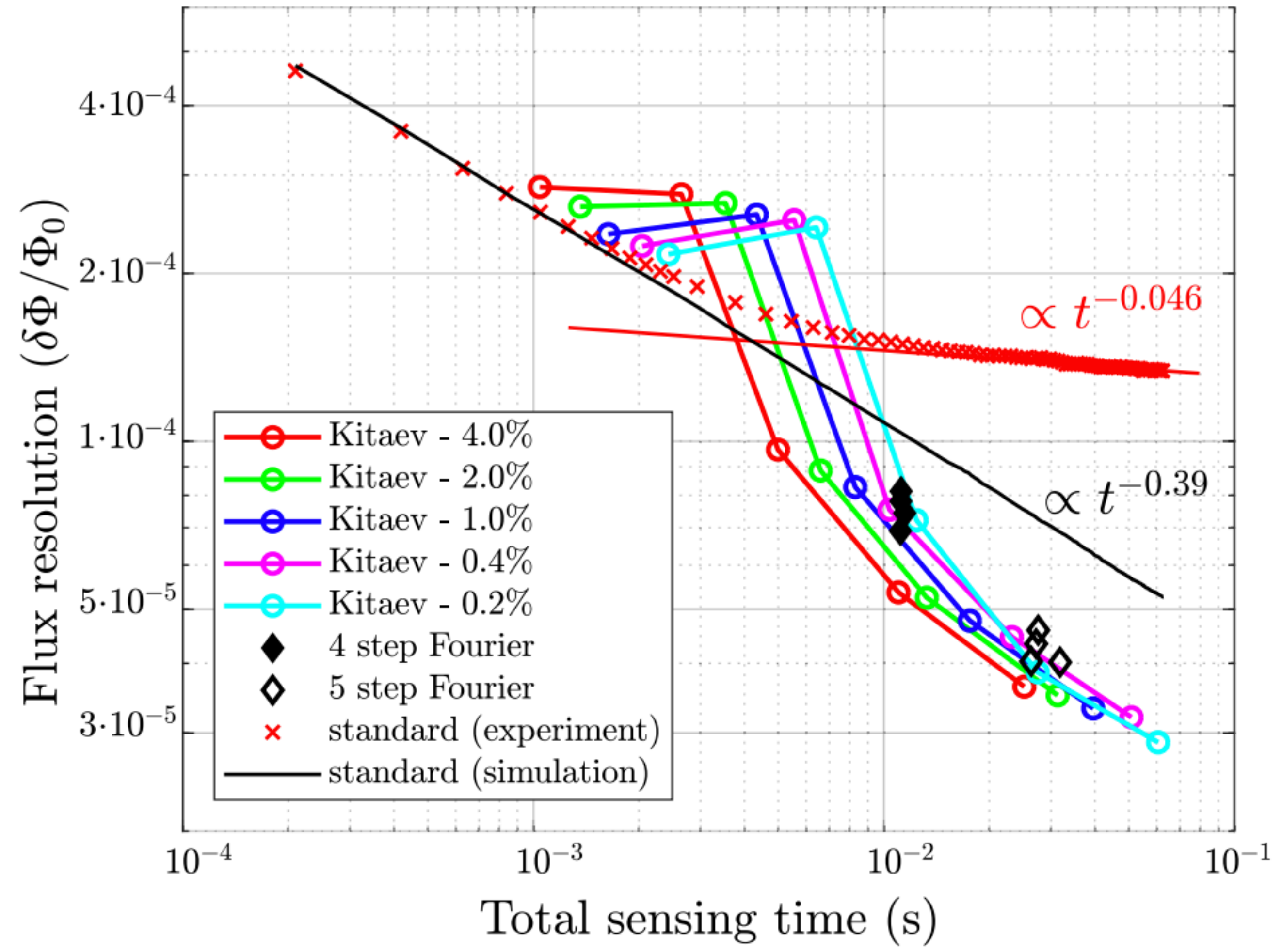
Quantum-enhanced magnetometry by phase estimation algorithms with a single artificial atom

S. Danilin, A. V. Lebedev, A. Vepsäläinen, G. B. Lesovik, G. Blatter & G. S. Paraoanu

npj Quantum Information **4**, Article number: 29 (2018) | Cite this article



- Tunable transmon, $E_J/E_C \approx 90$
- Measure qubit frequency with a Ramsey sequence
- Use phase estimation algorithm to overcome dynamic range issue (phase wrapping)
- Sensitivity still limited by T_2, i.e. 1/f flux noise



Qubit type	DC sensing	T2 noise spectroscopy (dynamical decoupling)	Scanning geometry	Advantages over [X]
Single-junction CPB Ej/Ec ~ 1	**Charge**: Spectroscopy only, limited by 1/f **Flux**: No	**Charge**: Low T2 makes time domain control difficult **Flux**: No	**Charge**: Seems doable **Flux**: --	**Charge** (X = SET): I don't see any **Flux**: --
CPB with SQUID Ej/Ec ~ 1	**Charge, flux**: Spectroscopy only, limited by 1/f, impractical measurement	**Charge, flux**: Low T2 makes time domain control difficult	**Charge + Flux**: Seems pretty hard	**Charge** (X = SET): I don't see any **Flux** (X = SQUID): I don't see any **Charge + Flux** (X = SET + Hall): I don't know
Offset charge-sensitive transmon Ej/Ec ~ 10-20	**Charge:** Spectroscopy or interferometry, limited by sample impedance or 1/f **Flux**: --	**Charge:** Yes, possibly limited by sample impedance **Flux**: --	**Charge**: Seems doable **Flux**: --	**Charge** (X = SET): Noise spectroscopy, can measure SC samples **Flux**: --
Tunable transmon Ej/Ec ~ 50	**Charge**: No **Flux**: Spectroscopy or interferometry	**Charge**: No **Flux**: Yes, requires fast control and readout	**Charge**: -- **Flux**: Seems doable	**Charge**: -- **Flux** (X = SQUID): Noise spectroscopy (is this more useful than a fast SQUID?)
Flux qubit	**Charge**: No **Flux**: Spectroscopy or interferometry	**Charge**: No **Flux**: Yes, requires fast control and readout	**Charge**: -- **Flux**: I don't know	**Charge**: -- **Flux** (X = SQUID): Noise spectroscopy (is this more useful than a fast SQUID?)