Magnifying quantum phase fluctuations with Cooper-pair pairing

Smith et al. PRX 2022

Smith & Borgognoni et al. (in preparation)

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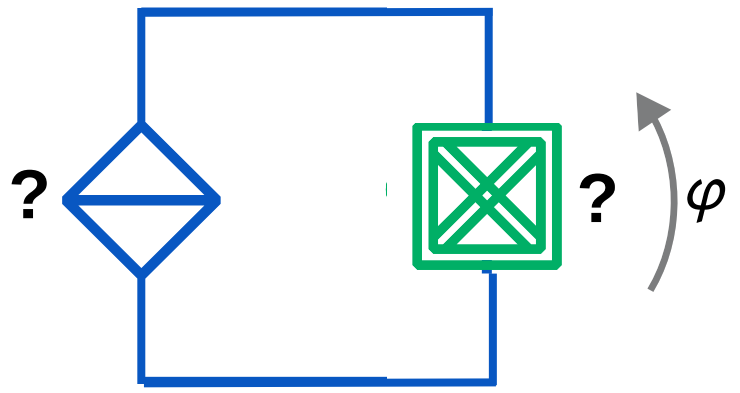
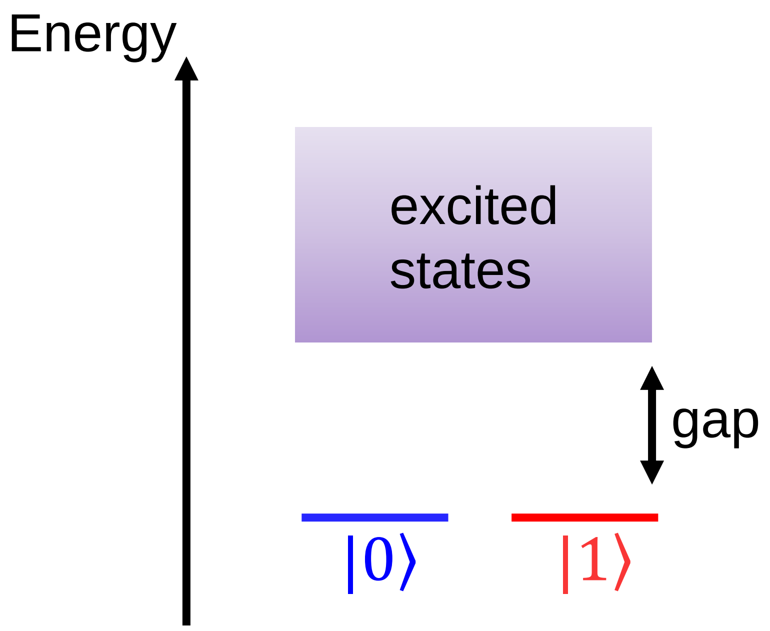
Protected qubit

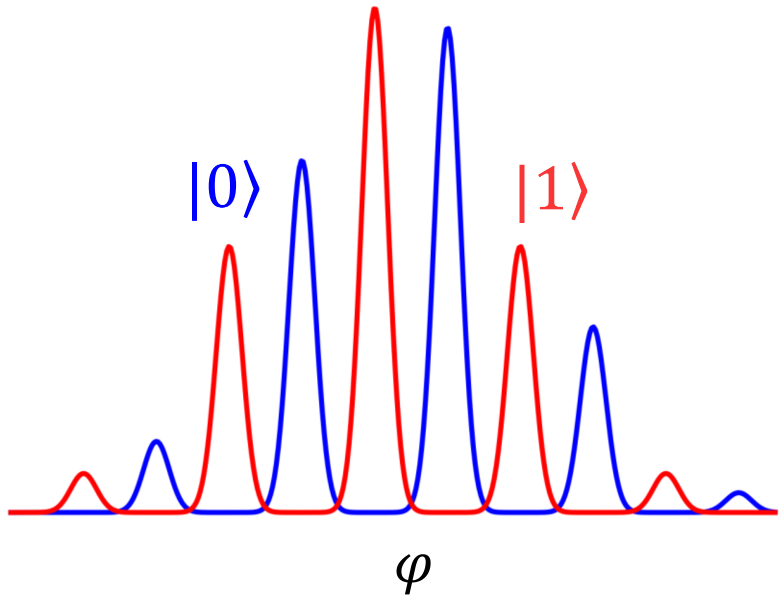
Engineering non-local ground-states

Smith *et. al* PRX 2022

Towards non-local and non-overlapping ground states

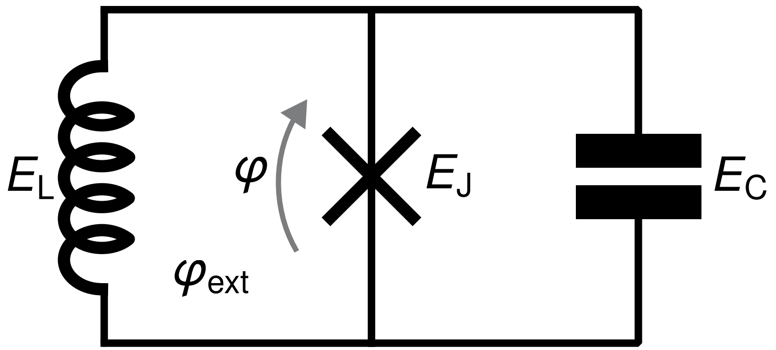




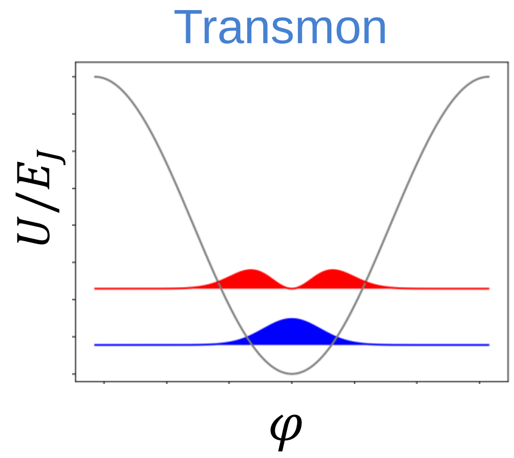


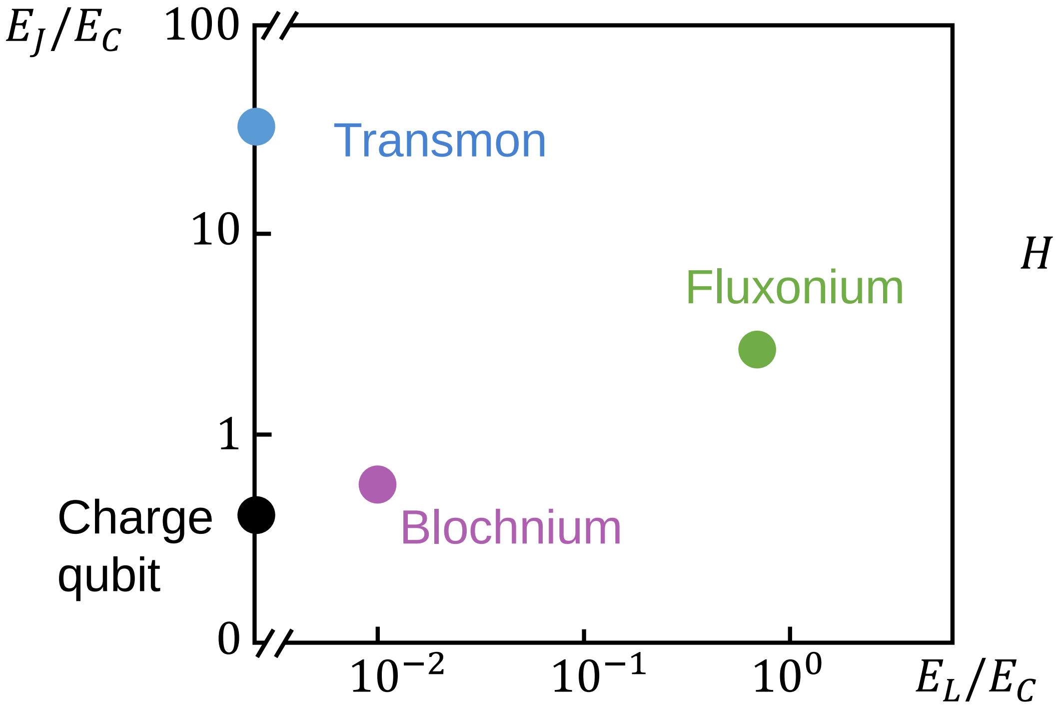
Gottesman PRA (2001), Tahn Le PRA (2019), Kalashnikov PRXQ (2020), Larsen PRL (2020) Gyenis PRXQ (2021)

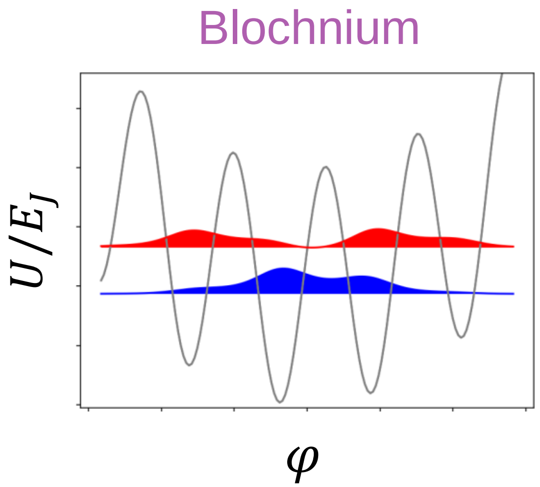
Mendeleev table of artificial atoms

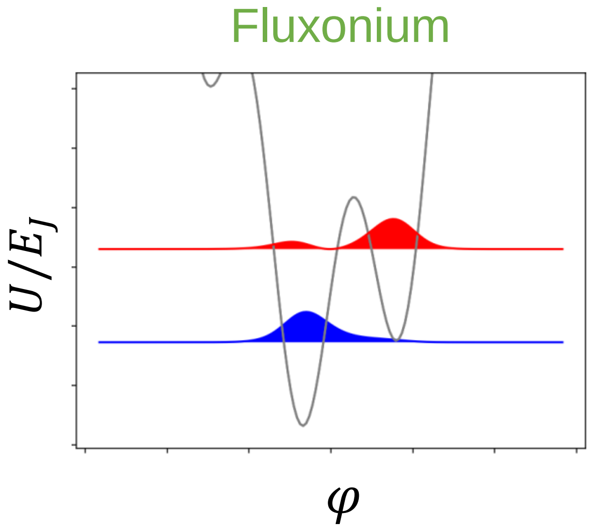


$$H = 4E_C N^2 + \frac{1}{2}E_L(\varphi - \varphi_{ext})^2 - E_J\cos(\varphi)$$



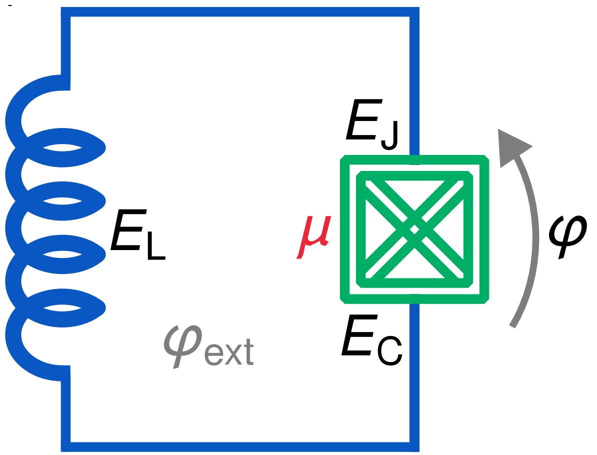


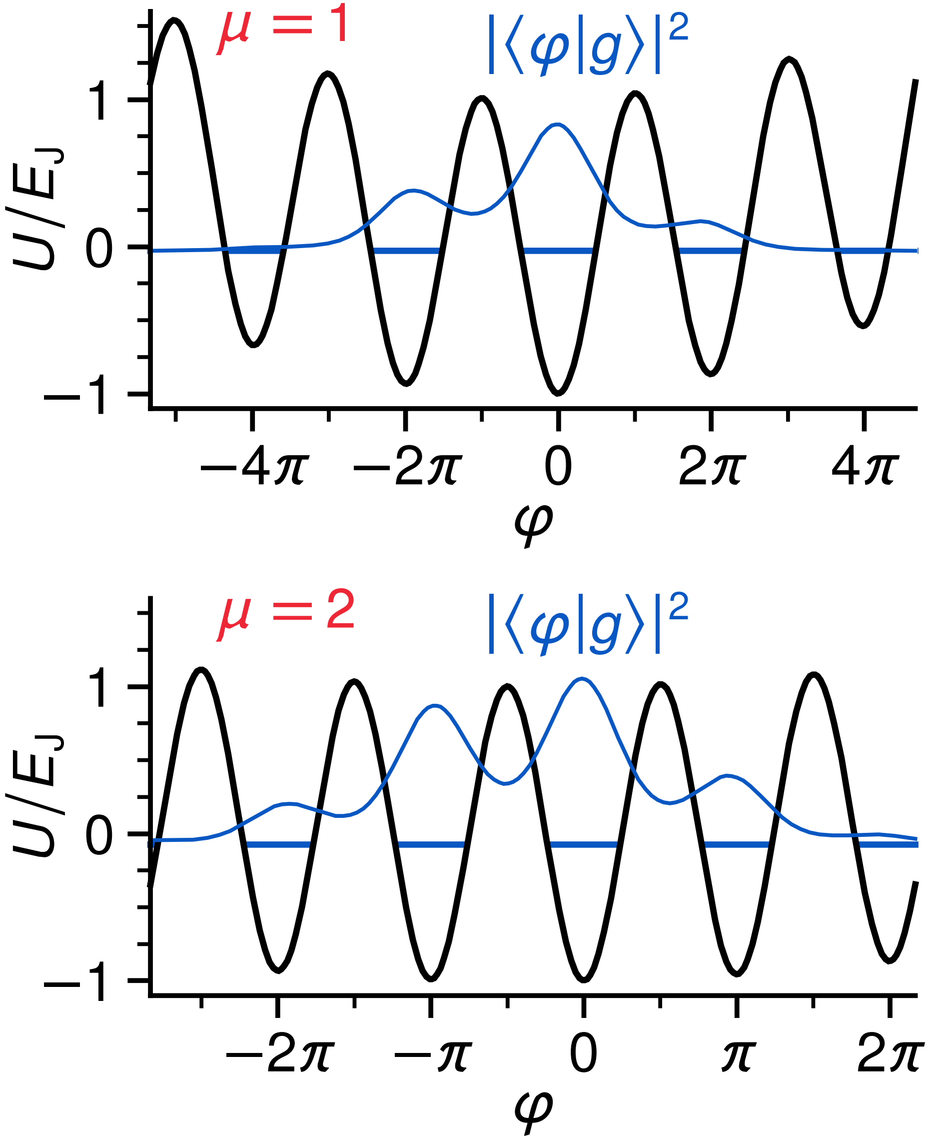




Vion Science 2002, Koch PRA 2007, Manucharyan Science 2009, Pechenezhskiy Nature 2020, Peruzzo PRXQ (2021)

The generalized Josephson element

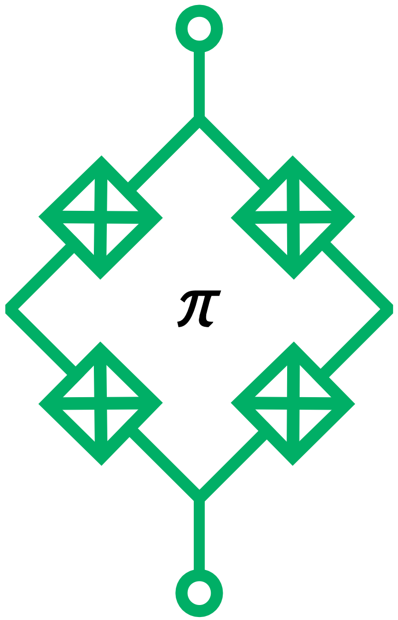




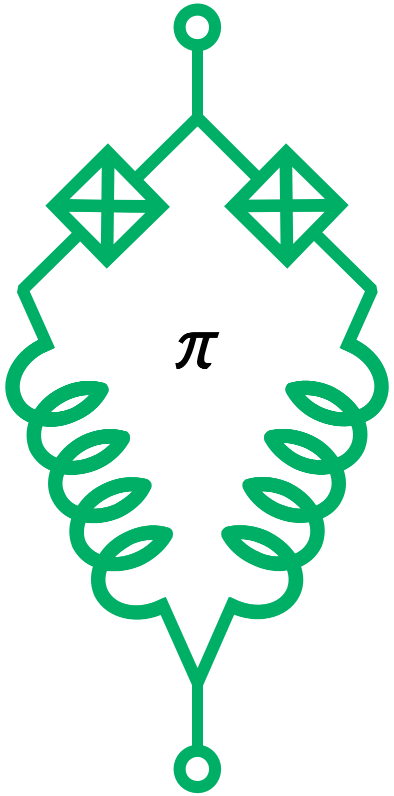
$$H = 4E_C\left(\frac{N}{\mu}\right)^2 + \frac{1}{2}E_L(\varphi - \varphi_{ext})^2 - E_J\cos(\mu\varphi)$$

$$\cos(\mu\varphi) = \frac{1}{2}\sum_{N=-\infty}^{\infty}\left(|N\rangle\langle N+\mu| + |N+\mu\rangle\langle N|\right)$$

Two-Cooper-pair tunneling elements



Rhombus



KITE
(Kinetic Interference
coTunneling Element)

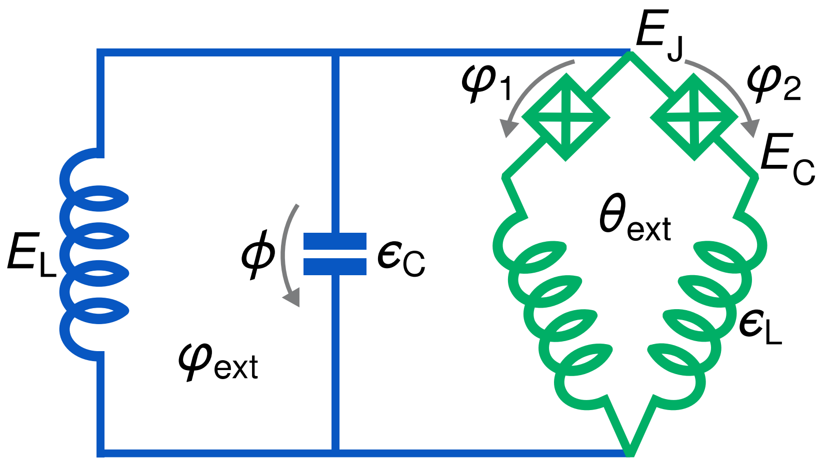
Blatter, Geshkenbein, and Ioffe. *PRB* (2001)
Gladchenko et al. *Nature Physics* (2009)
Douçot and Ioffe. *RPP* (2012)

Bell et al. PRL (2014)
Smith et al. *npj Quantum Info* (2020)

Model reduction: Born-Oppenheimer approximation

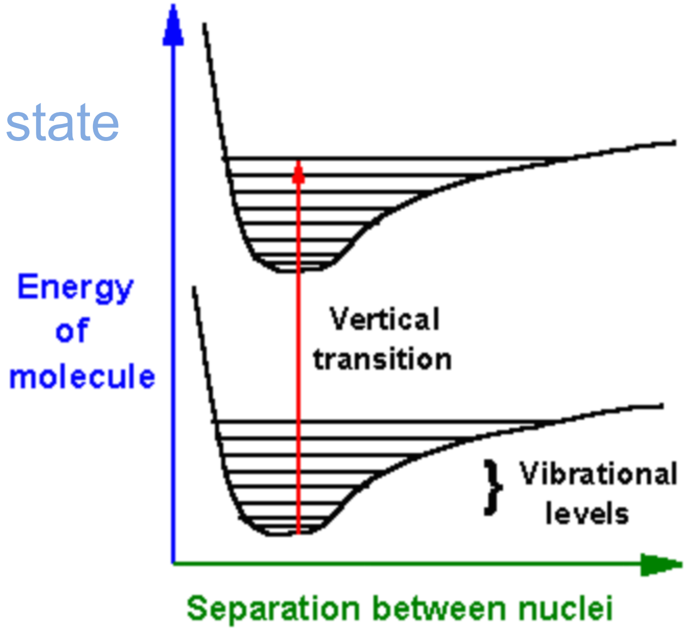
Target regime :

$E_L \lesssim \epsilon_L \ll E_J \approx E_C \lesssim \epsilon_c$



$$\varphi_\Sigma = \tfrac{1}{2}(\varphi_1 + \varphi_2)$$
$$\varphi_\Delta = \tfrac{1}{2}(\varphi_1 - \varphi_2)$$

ϕ: high-frequency "electronic" degree of freedom
→ freeze in quantum ground state

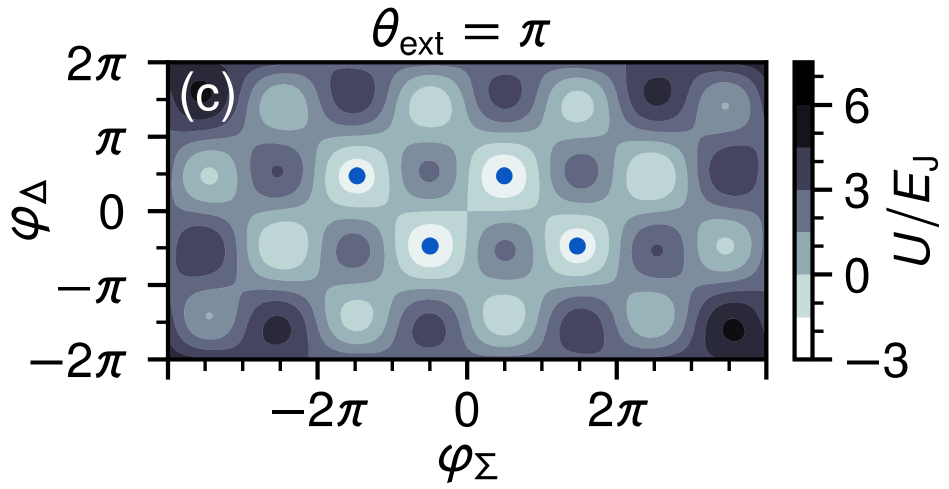


$\varphi_{\Sigma,\Delta}$: low-frequency "nuclear" degrees of freedom
→ temporarily fix to classical values

Model reduction: tight-binding approximation

Low-energy Hamiltonian has two degrees of freedom:

$$H_\mathrm{n} = 2E_\mathrm{C}(N_\Sigma^2 + N_\Delta^2) + \frac{E_\mathrm{L}\epsilon_\mathrm{L}}{E_\mathrm{L} + 2\epsilon_\mathrm{L}}\left(\varphi_\Sigma + \varphi_\mathrm{ext} + \tfrac{1}{2}\theta_\mathrm{ext}\right)^2 + \epsilon_\mathrm{L}\left(\varphi_\Delta - \tfrac{1}{2}\theta_\mathrm{ext}\right)^2$$
$$- 2E_\mathrm{J}\cos\varphi_\Sigma\cos\varphi_\Delta$$

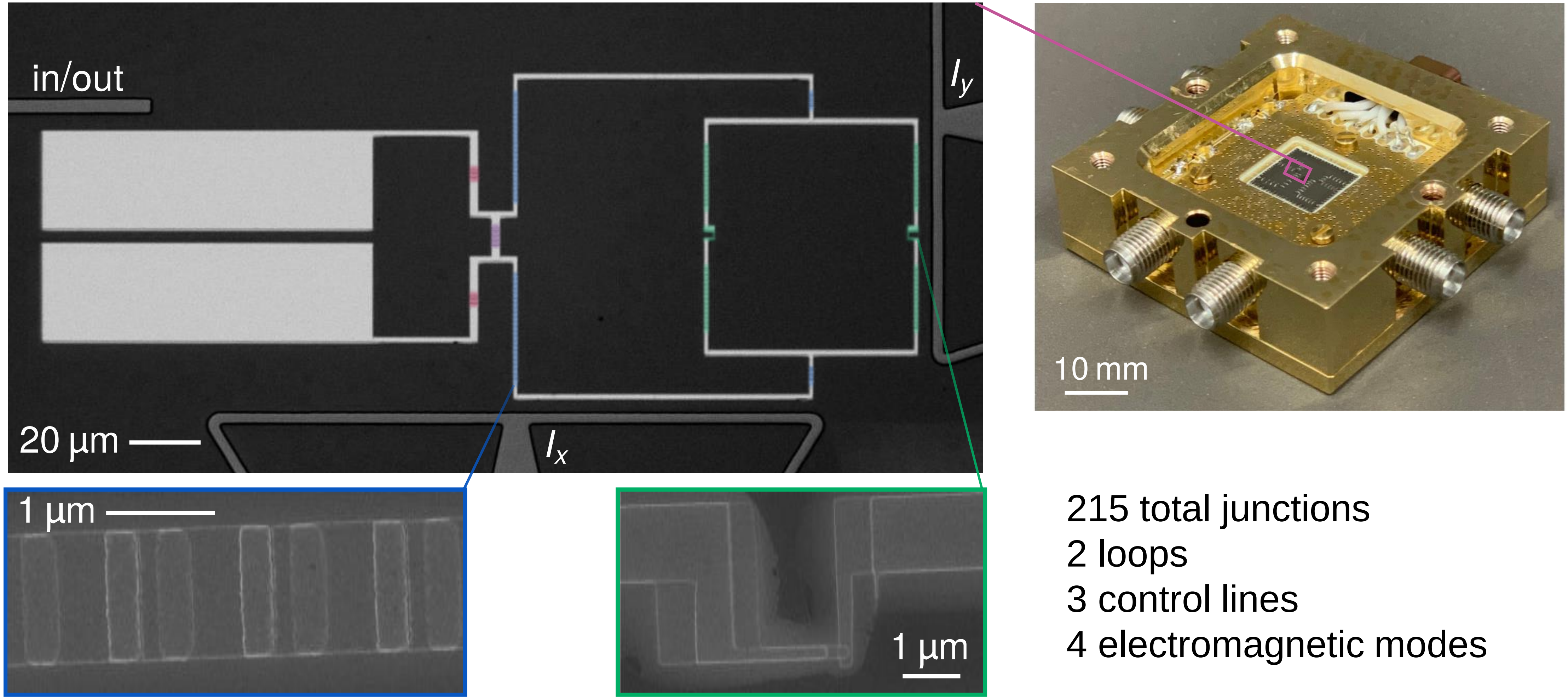


$$H_\pi^\text{tight−binding} = \sum_s \frac{E_\mathrm{L}\epsilon_\mathrm{L}}{E_\mathrm{L} + 2\epsilon_\mathrm{L}}\left(s\pi + \tfrac{\pi}{2} + \varphi_\mathrm{ext}\right)^2 |s\rangle\langle s| + \sum_s \tfrac{1}{2}\Gamma\left(|s\rangle\langle s+1| + |s+1\rangle\langle s|\right)$$

$$H_\pi = E_\mathrm{C}N^2 + \frac{E_\mathrm{L}\epsilon_\mathrm{L}}{E_\mathrm{L} + 2\epsilon_\mathrm{L}}(\varphi + \varphi_\mathrm{ext})^2 + E_\mathrm{J}\cos 2\varphi$$

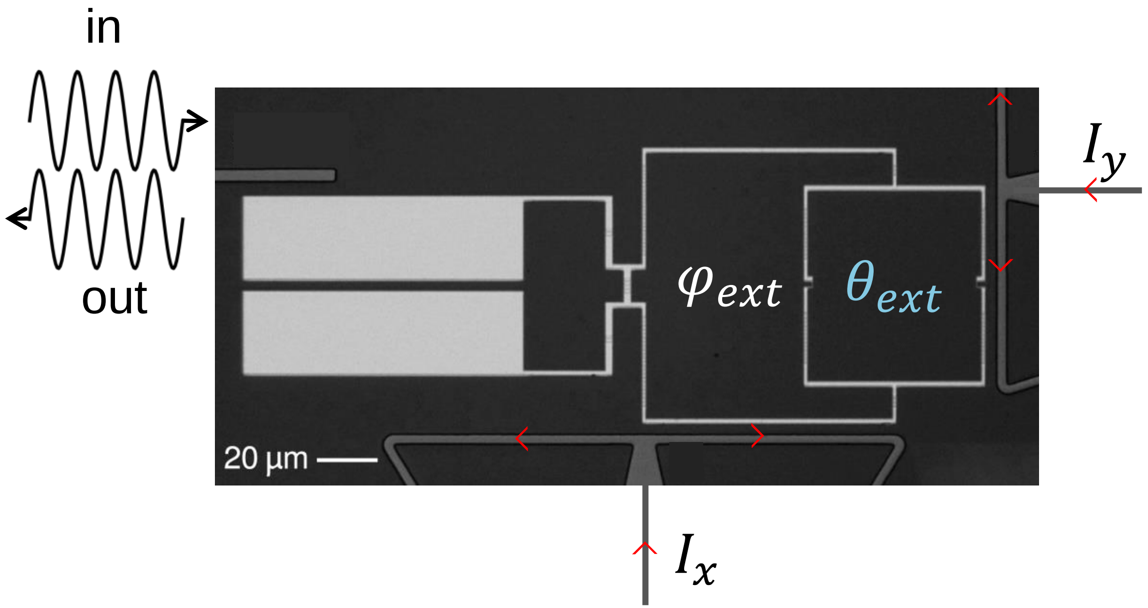
$$\Gamma = \frac{4}{\sqrt{\pi}}(8E_\mathrm{J}^3E_\mathrm{C})^{1/4}\exp\left(-\sqrt{\frac{8E_\mathrm{J}}{E_\mathrm{C}}}\right)$$

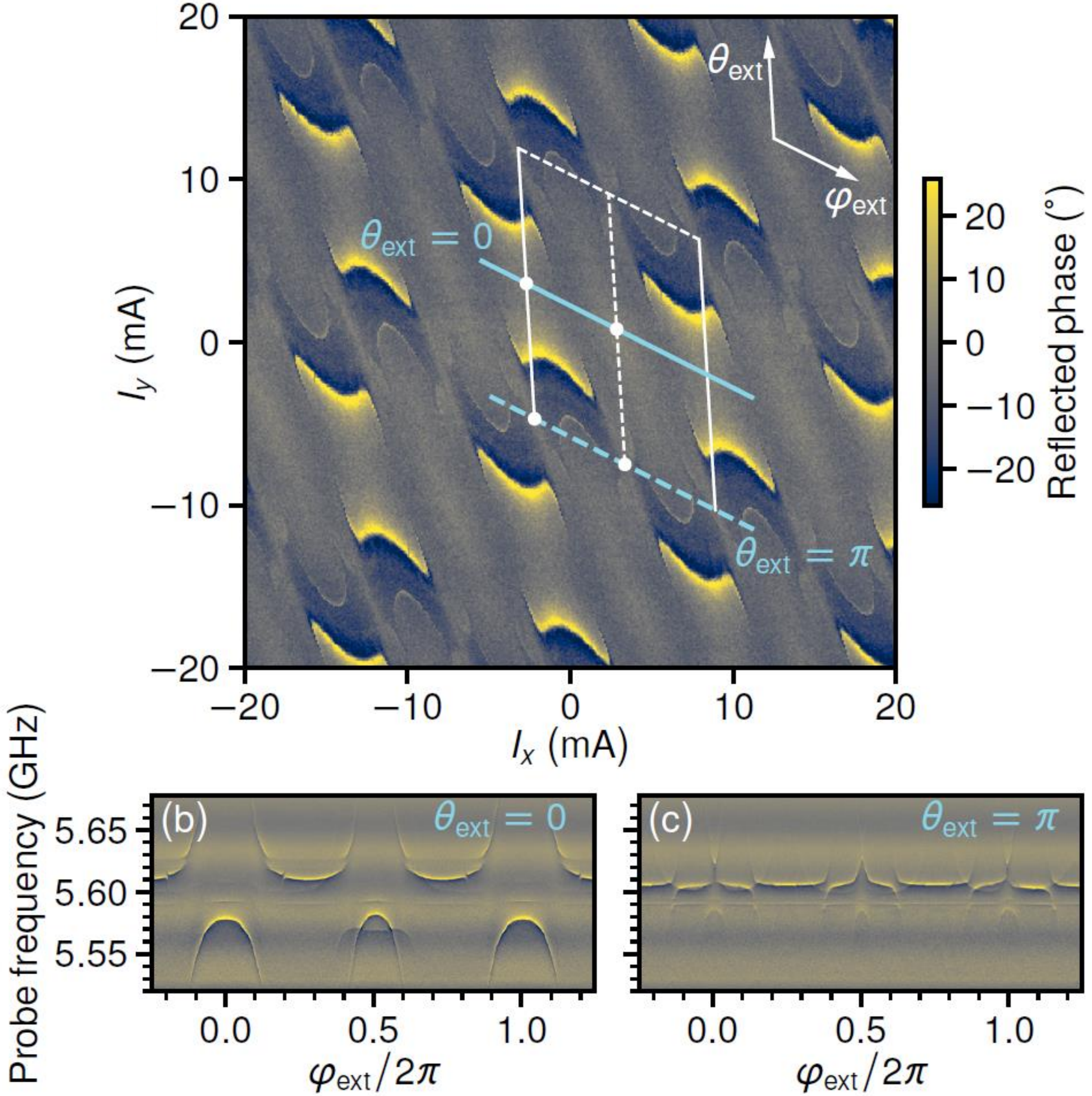
Experimental implementation



215 total junctions
2 loops
3 control lines
4 electromagnetic modes

External flux dependance

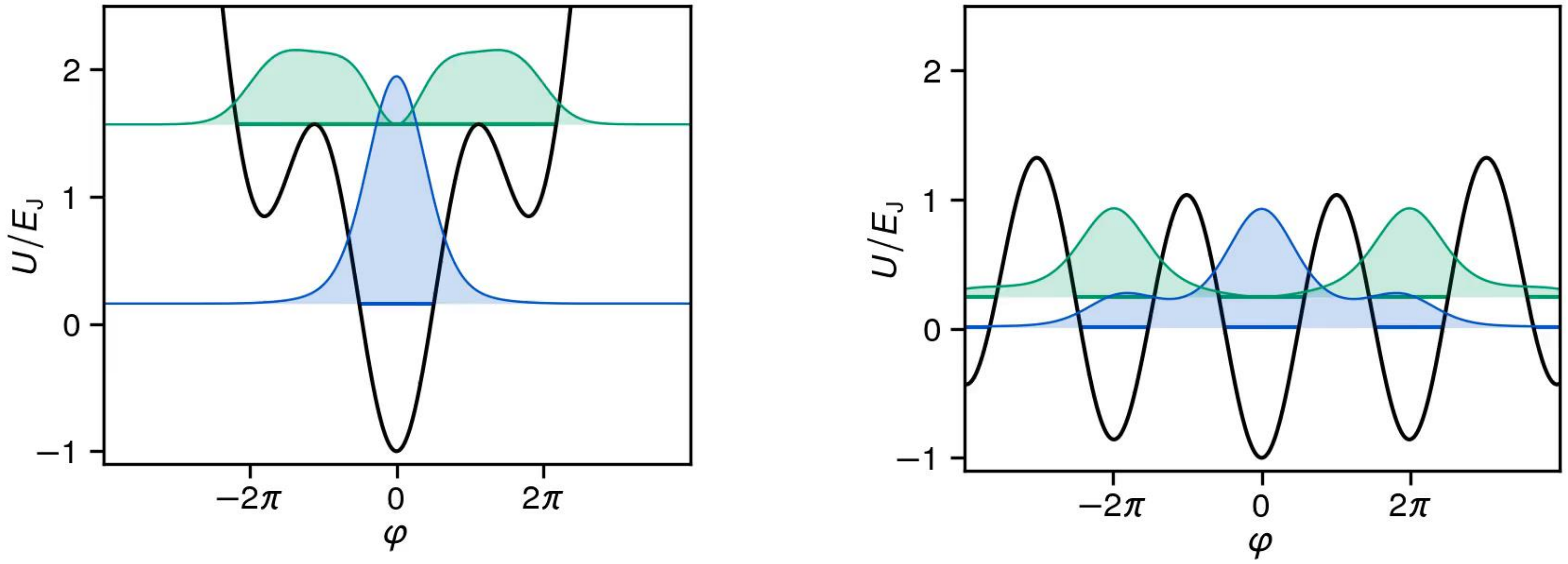




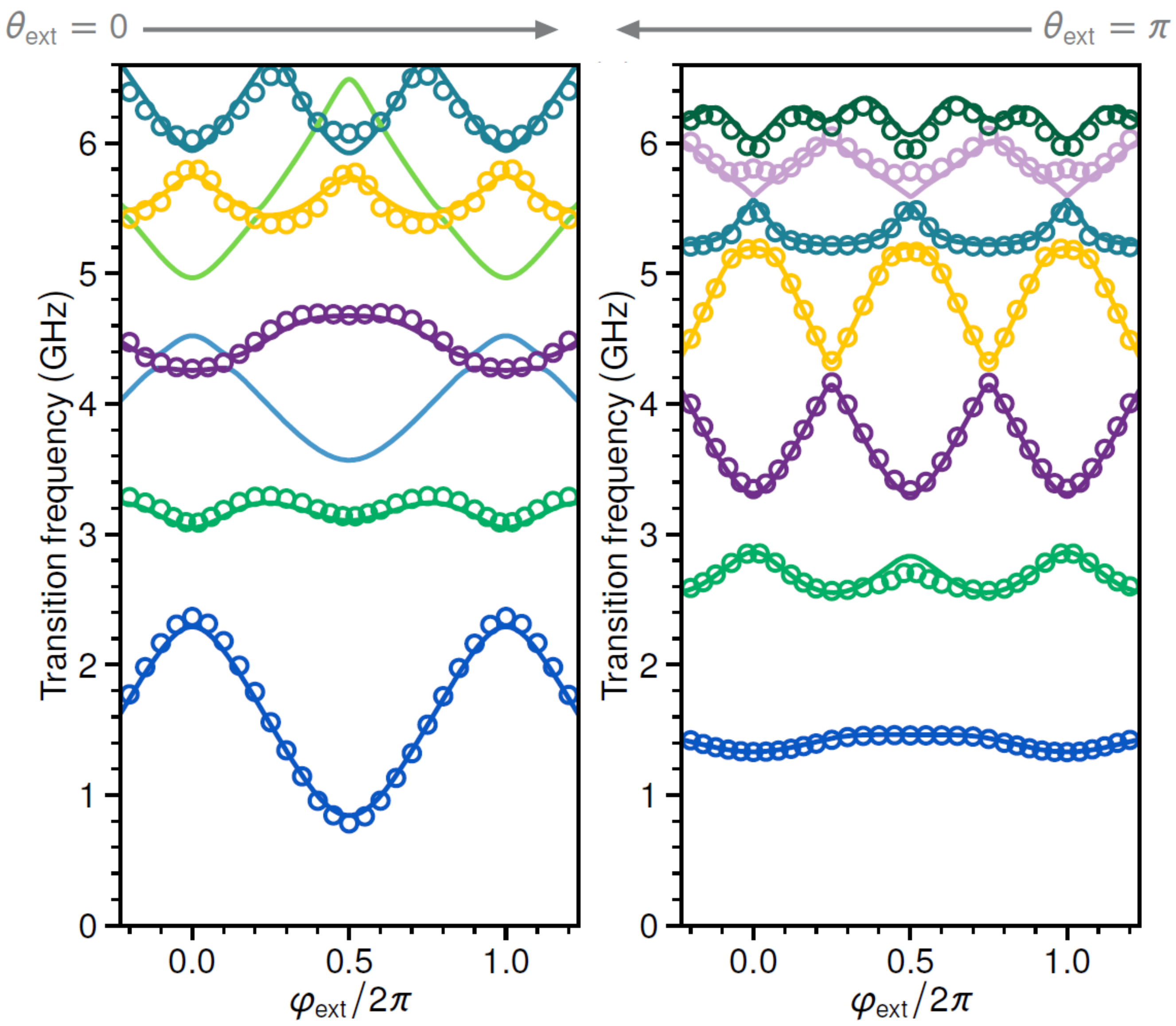
Flux dispersion measures phase fluctuations

$$\varphi_{\mathrm{zpf}} \equiv \left(\frac{2E_C}{E_L}\right)^{1/4}$$

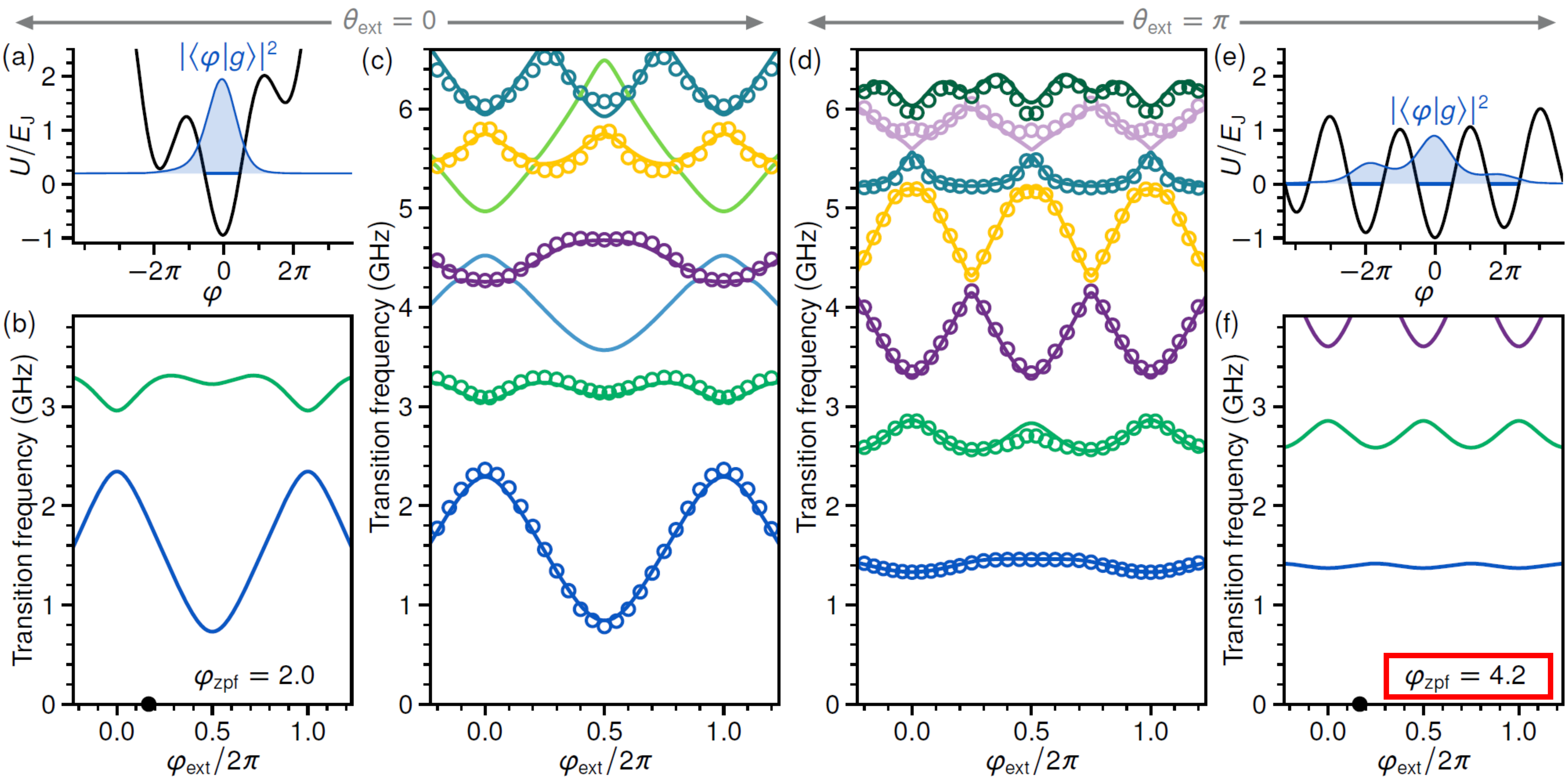
$\varphi_{\mathrm{zpf}} = 2$ $\qquad\qquad$ $\varphi_{\mathrm{zpf}} = 4$



Measured transition energies



Measured transition energies



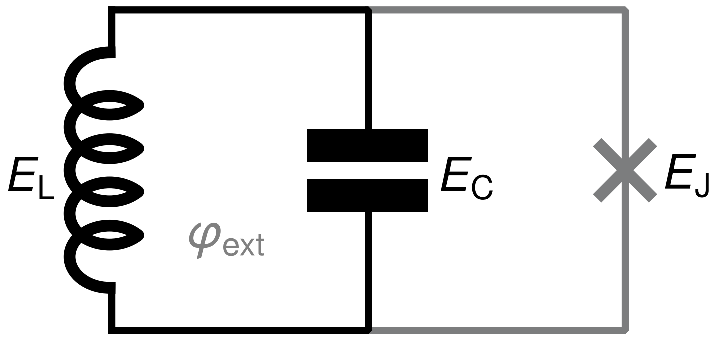
Smith *et. al* PRX 2022

Exploring a new regime of quantum optics

Spectral signature of high-order photon processes

Smith* & Borgognoni* *et. al* in preparation

Nonlinear oscillators in superconducting circuits

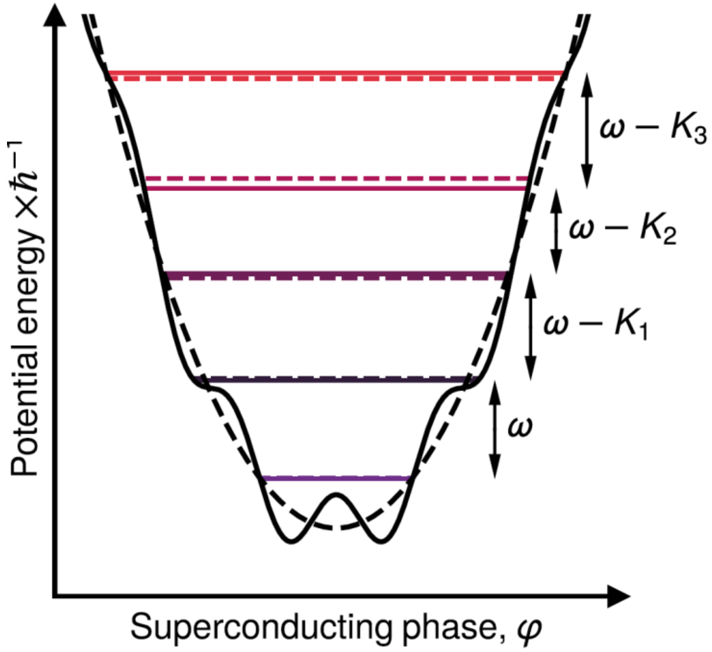


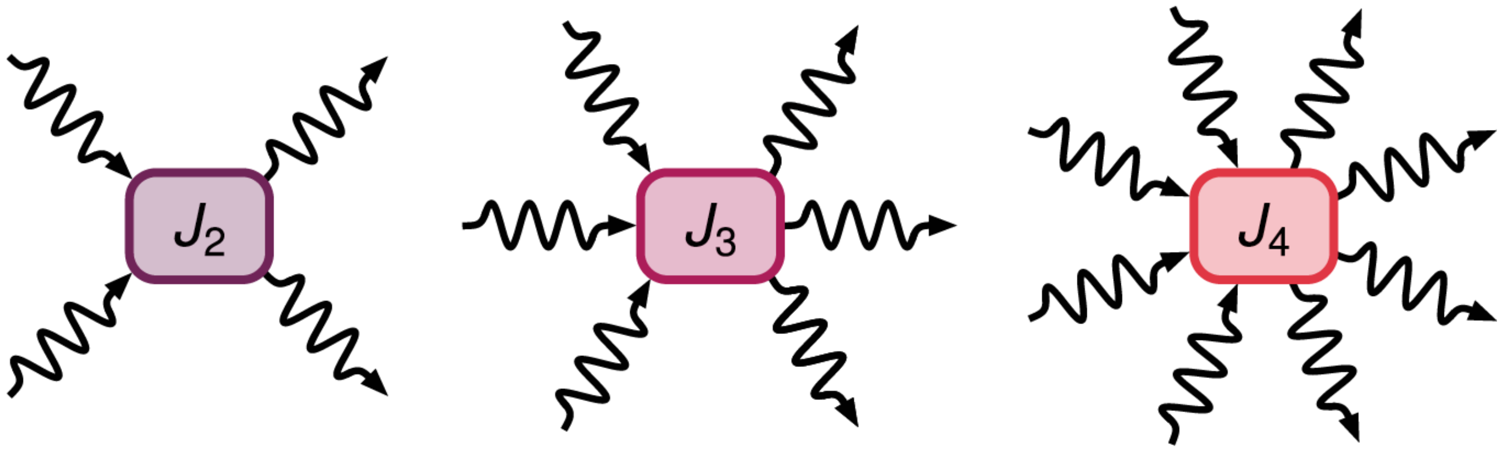
$$H = \hbar\omega_0 a^\dagger a - E_J \cos(\varphi_{zpf}(a + a^\dagger))$$
$$\approx \hbar\omega a^\dagger a + J_2 (a^\dagger)^2 a^2 + J_3 (a^\dagger)^3 a^3 + J_4 (a^\dagger)^4 a^4 + \cdots$$

Small Josephson energy

$E_J \ll \hbar\omega$

$$J_n \propto \varphi_{zpf}^{2n}$$



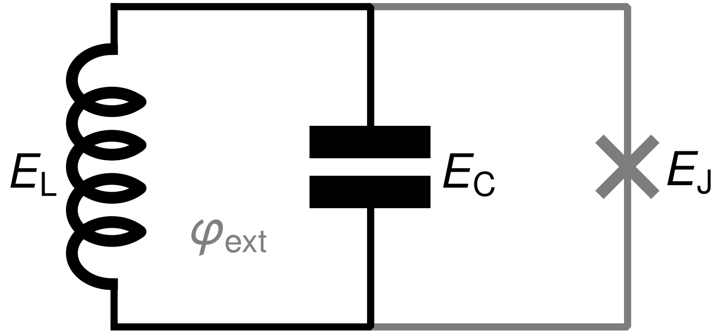


Hriscu & Nazarov PRL (2011), Mehta *et al.* Nature (2023)

Nonlinear oscillators in superconducting circuits

Small Josephson energy

$E_J \ll \hbar\omega$



$$\hbar\omega_0 = \sqrt{8E_L E_C}$$

$$\varphi_{zpf} = \left(\frac{2E_C}{E_L}\right)^{1/4}$$

$$H = \hbar\omega_0 a^\dagger a - E_J \cos(\varphi_{zpf}(a + a^\dagger))$$

Transmon
Amplifiers,
Non-linear crystals

0 — 1 — φ_{zpf}

Kerr interaction

$$H \approx \hbar\omega a^\dagger a + J_2 (a^\dagger)^2 a^2$$

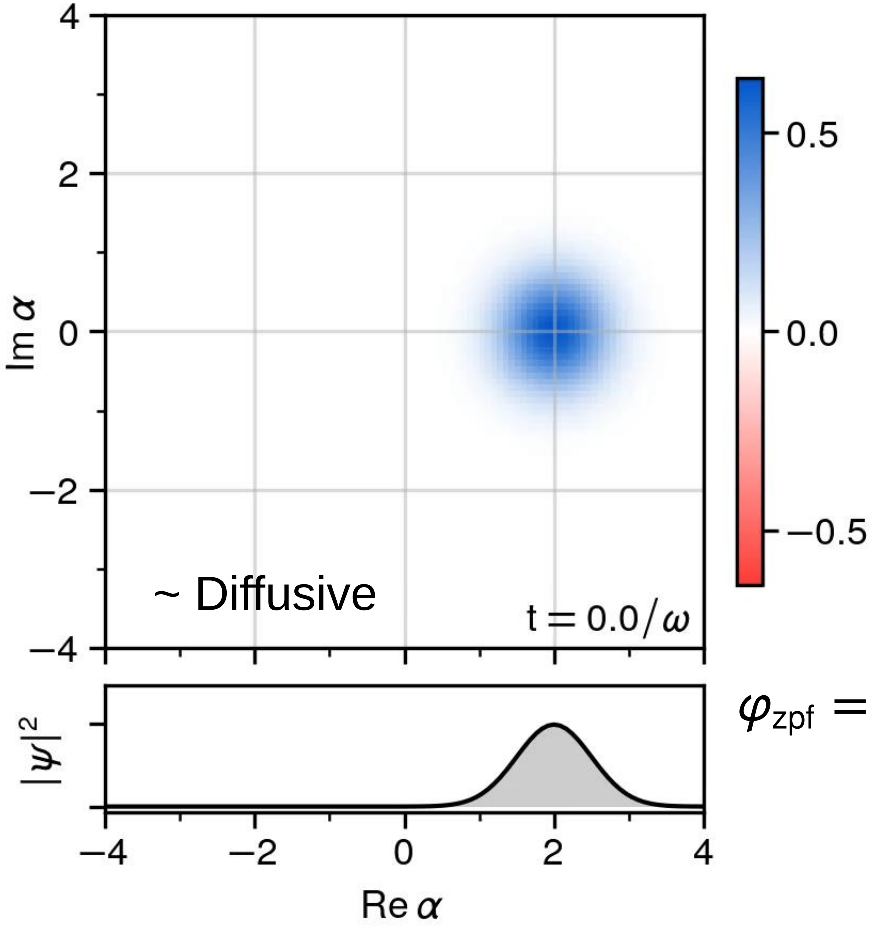
High order photon-photon interactions

$$H \approx \hbar\omega a^\dagger a + \sum_n J_n (a^\dagger)^n a^n$$

Time evolution of an initial coherent state

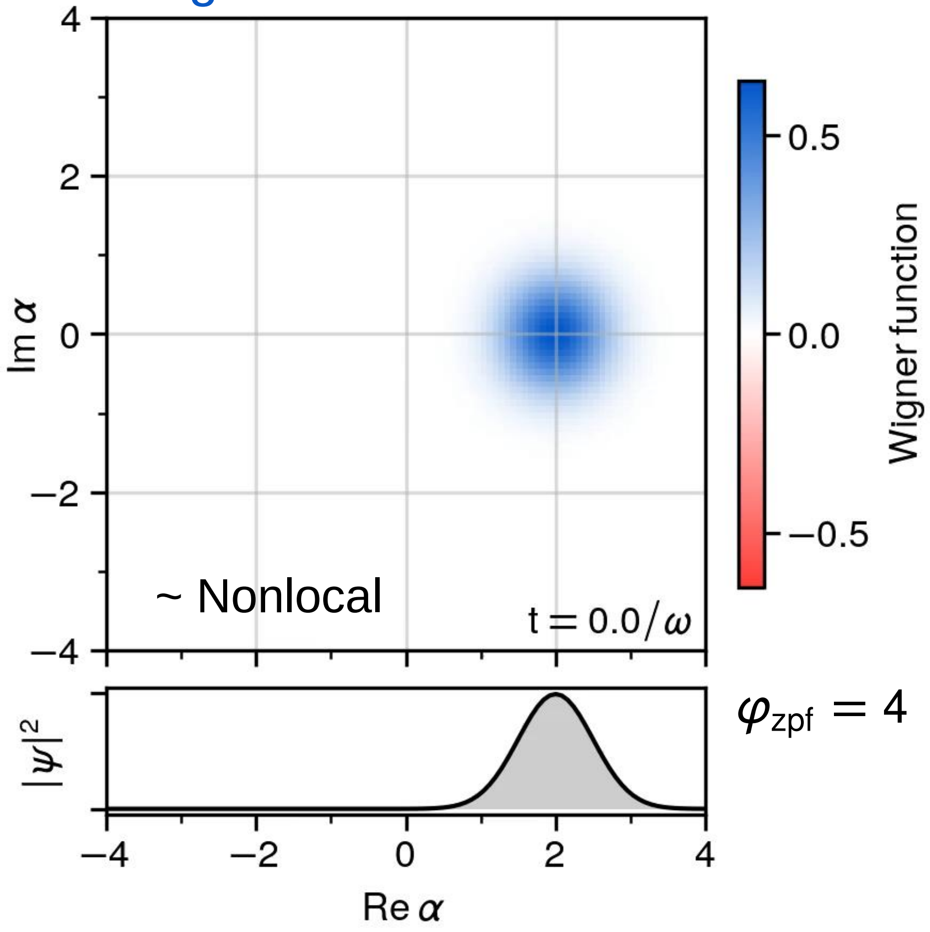
$E_{\mathrm{J}} = \hbar\omega/100$

Kerr interaction



$\varphi_{\mathrm{zpf}} = 0.2$

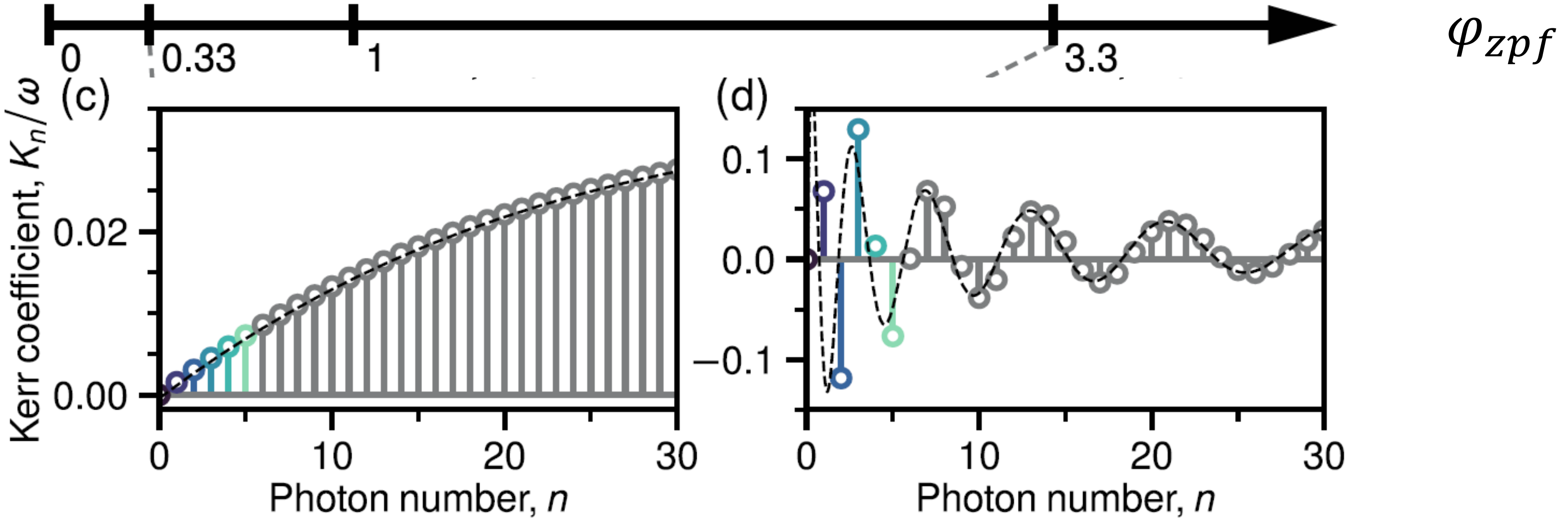
High-order interactions



$\varphi_{\mathrm{zpf}} = 4$

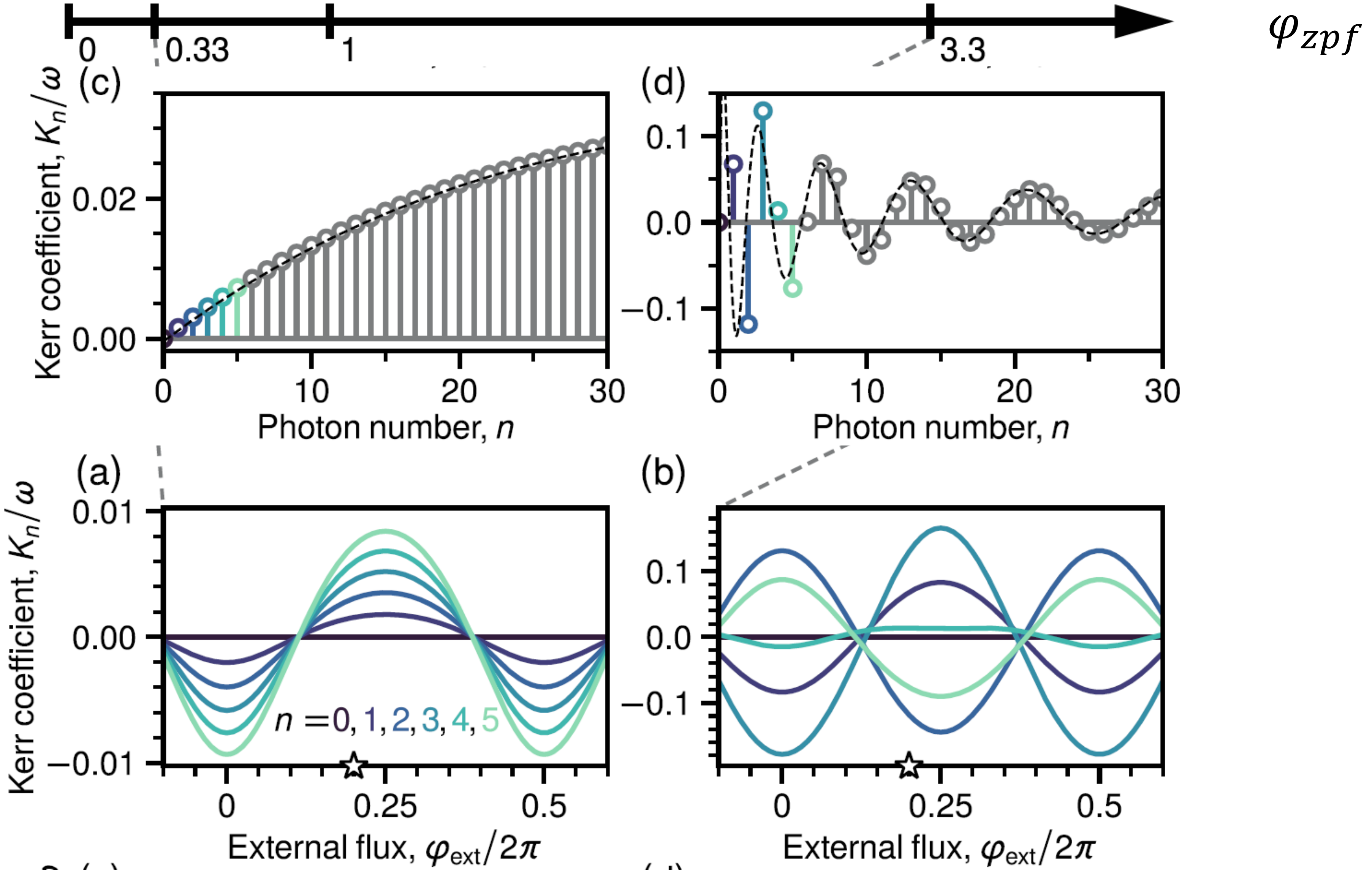
Kirchmair et al. *Nature* (2013)

Spectra of nonlinear oscillators



Hriscu & Nazarov PRL (2011)

Spectra of nonlinear oscillators



Hriscu & Nazarov PRL (2011)

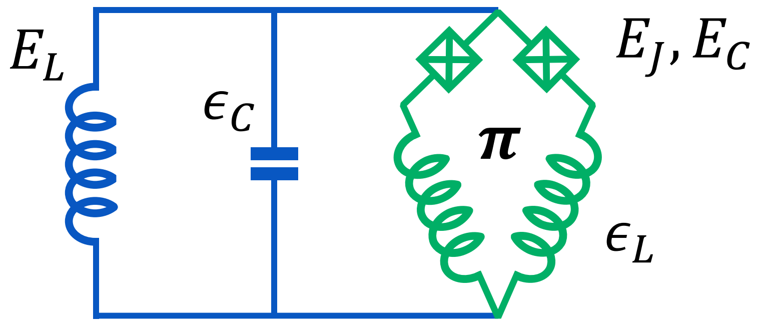
Experimental realization: two technical challenges

1. Large $\varphi_{\text{zpf}} \to$ ultra-high impedance

2. Small $E_J \to$ ultra-small junction

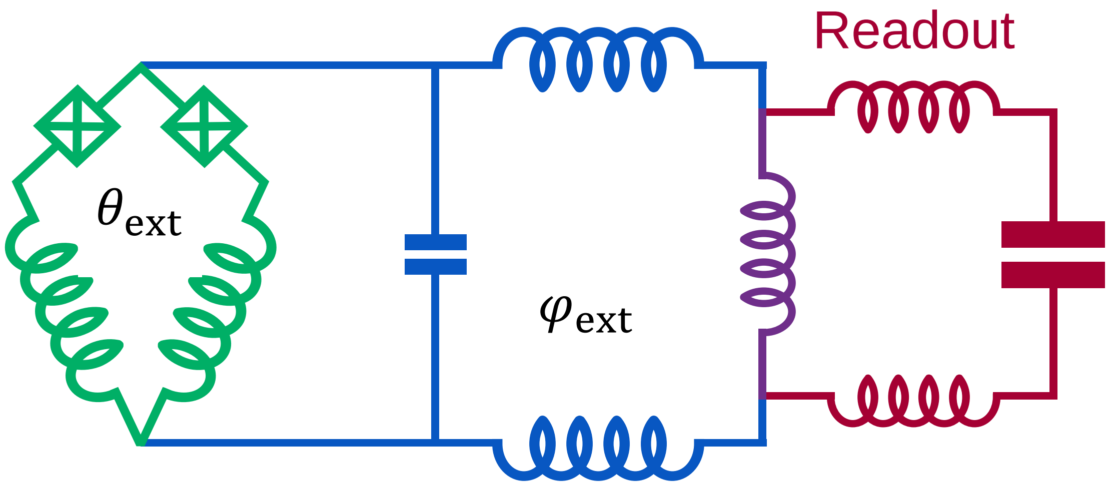
KITE in the dc-SQUID-like regime* $\epsilon_L \gtrsim E_J$

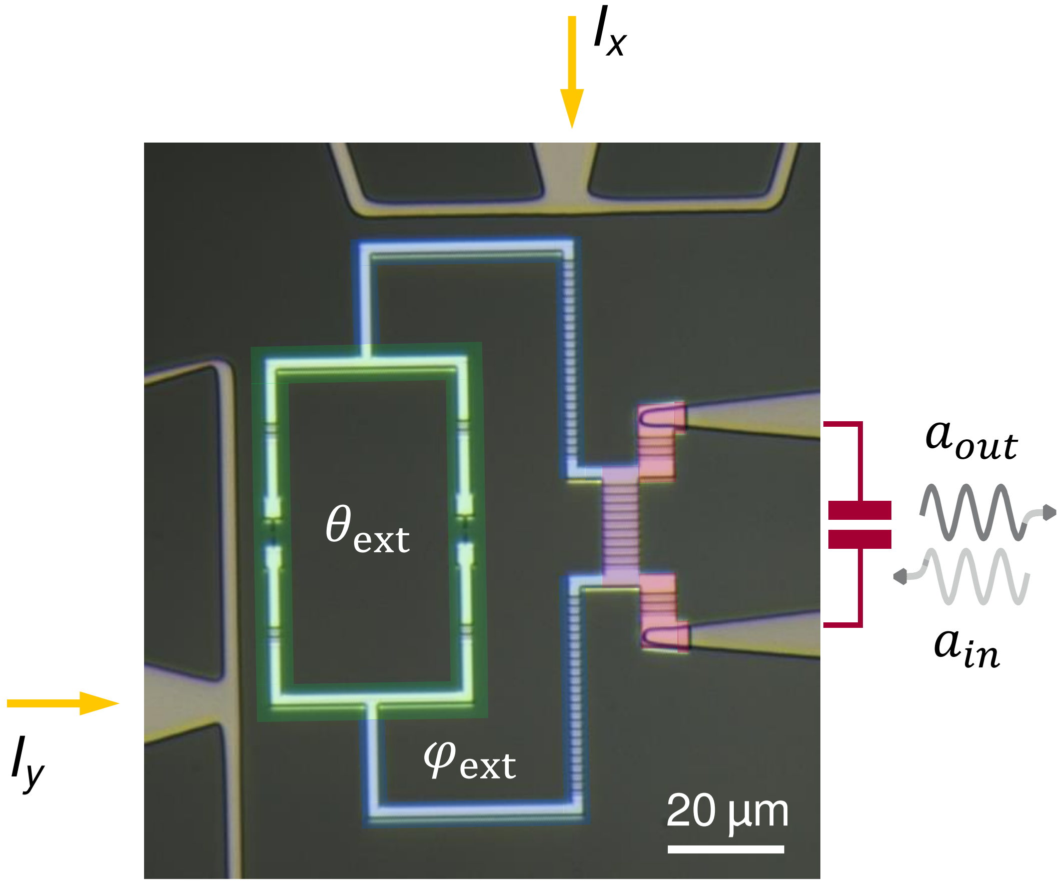
$$\to \frac{1}{2}\frac{E_J^2}{\epsilon_L}\cos(2\varphi)$$



*opposite regime $\epsilon_L \ll E_J$ explored in Smith *et al.* PRX (2022)

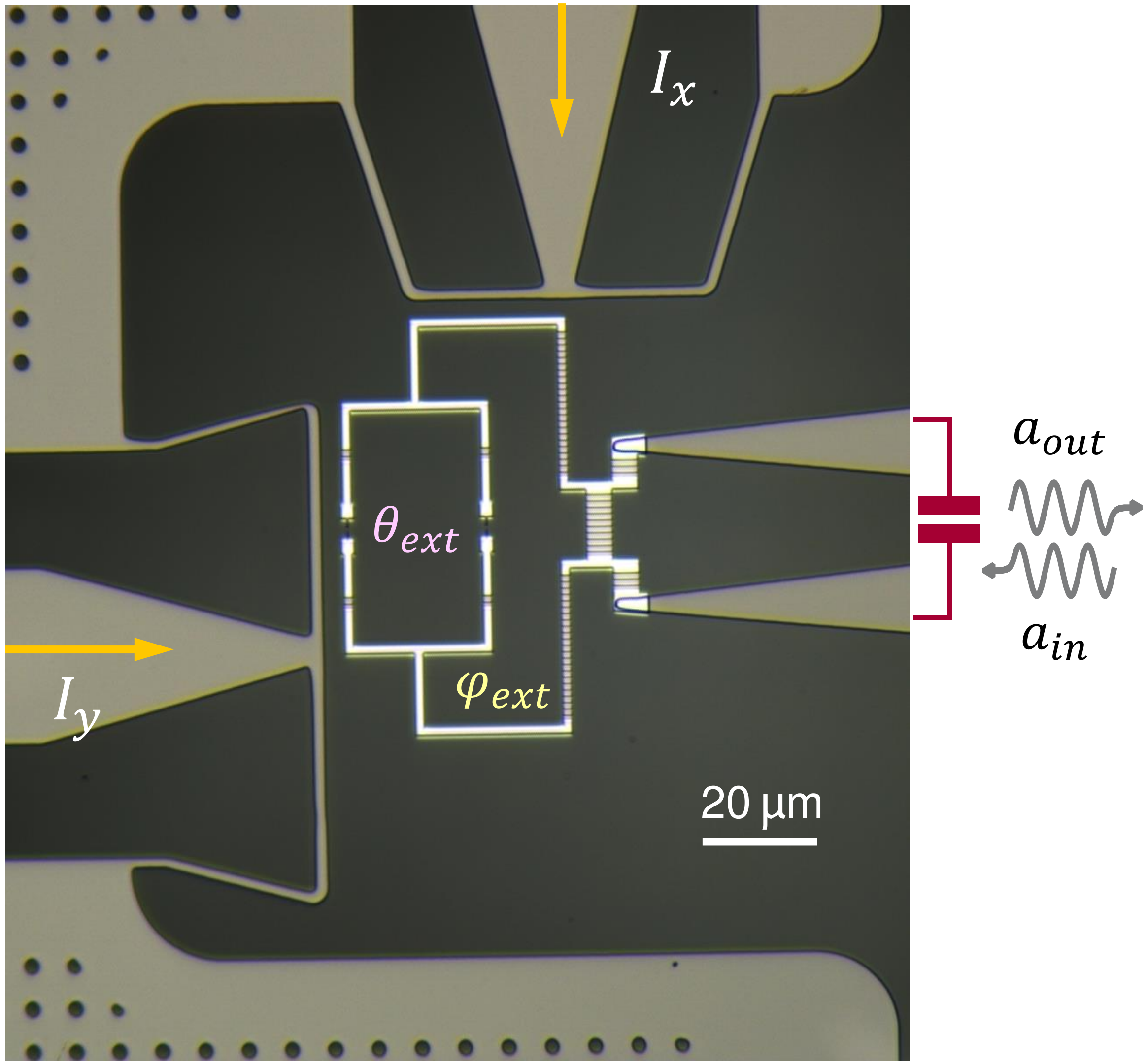
Experimental realization: physical device

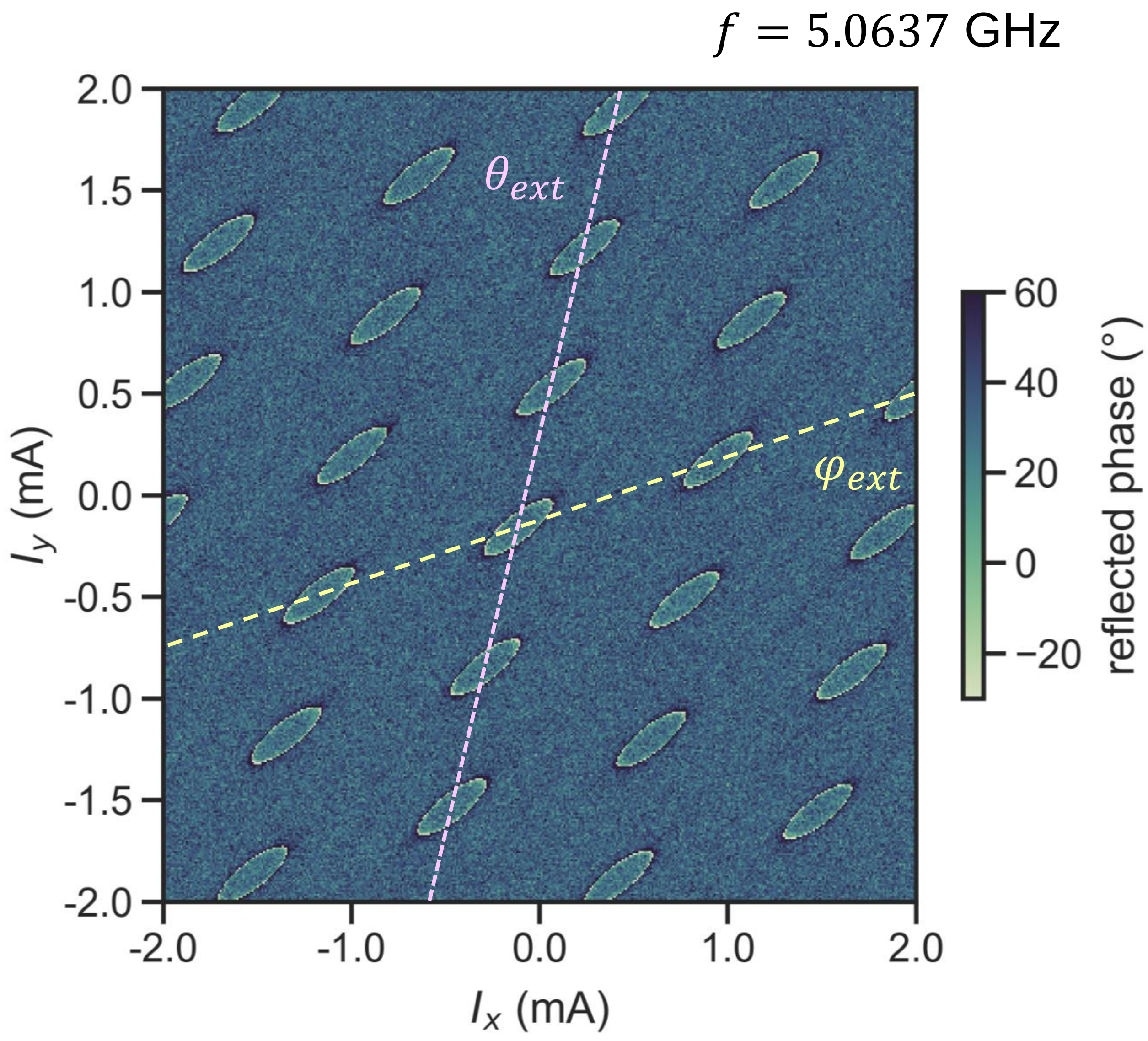




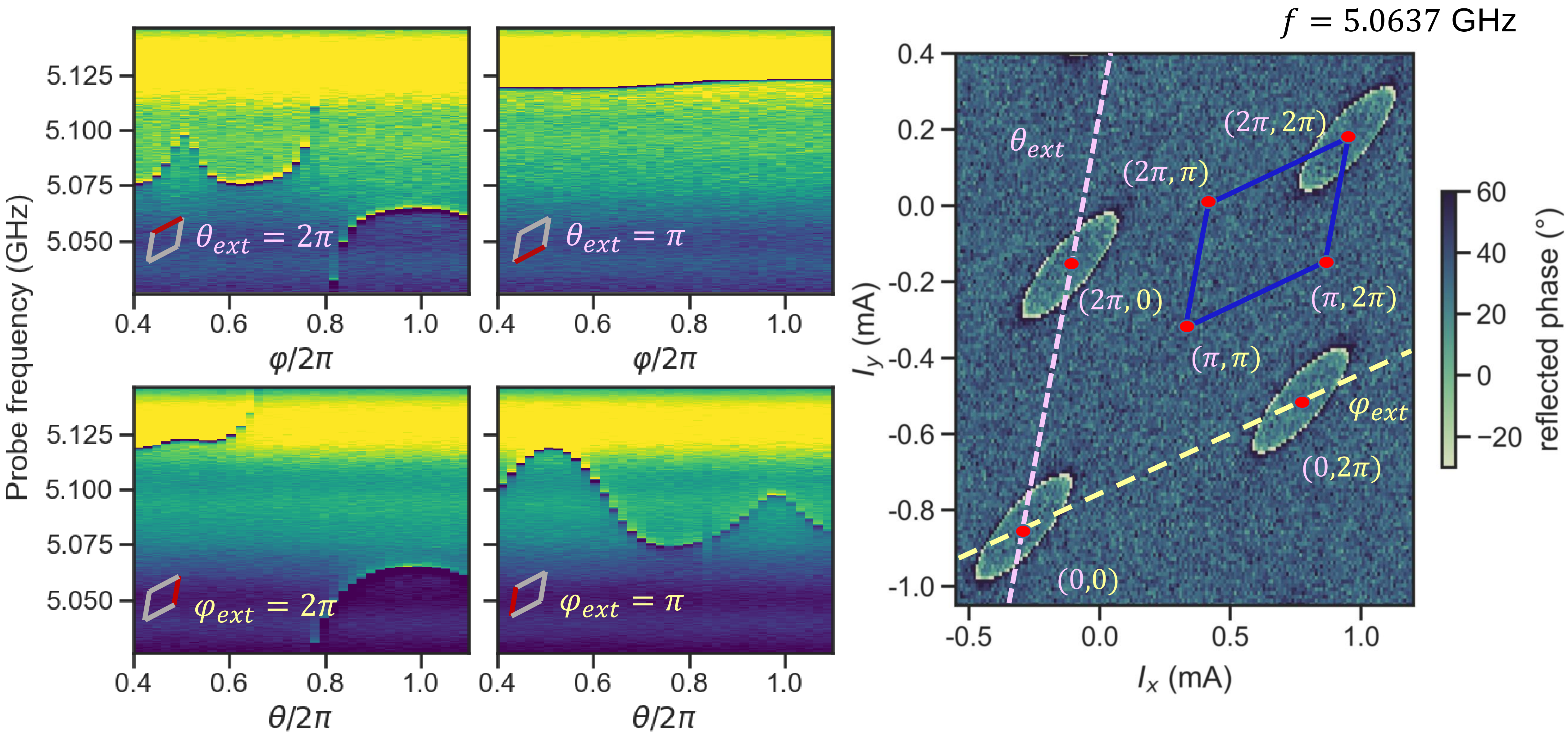
One aluminum double-angle deposition

Readout resonator vs. flux

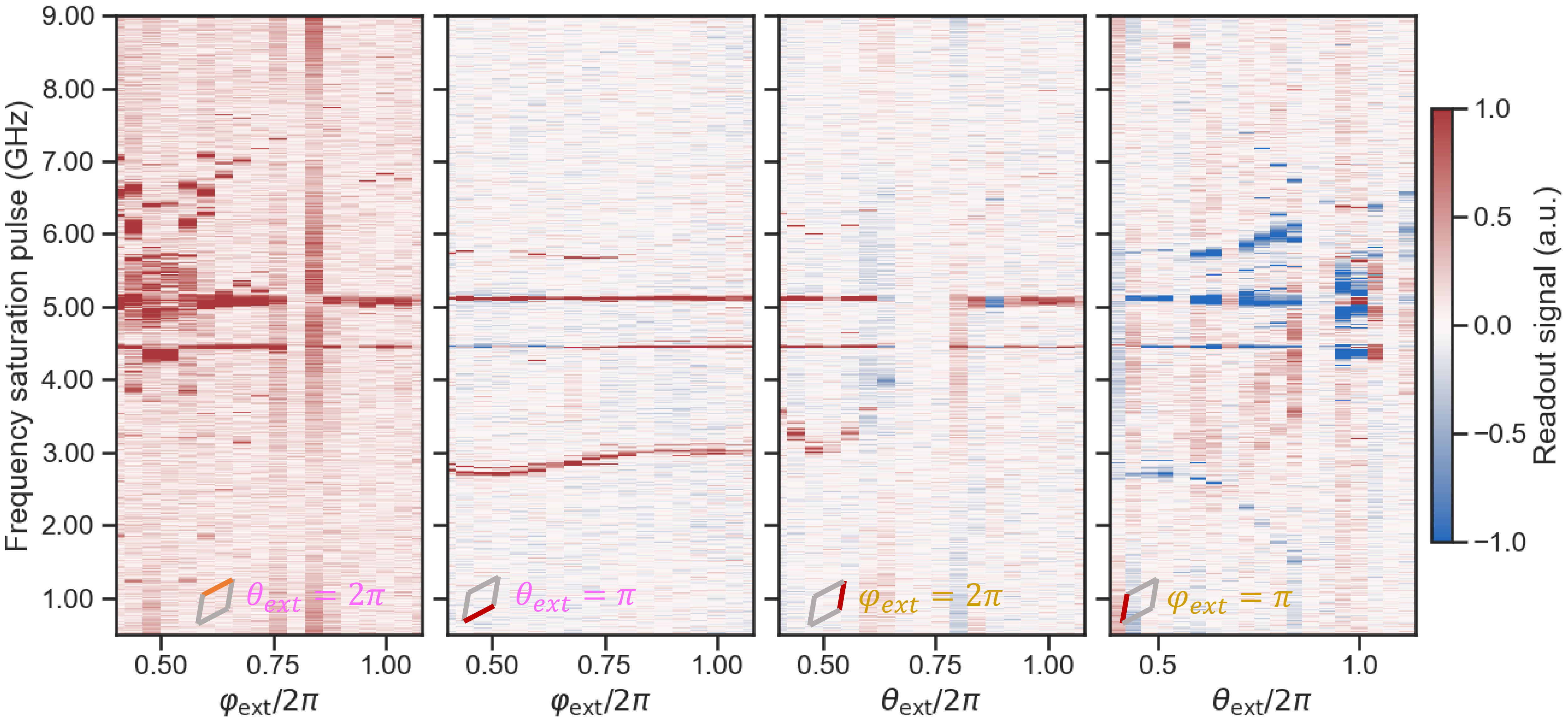




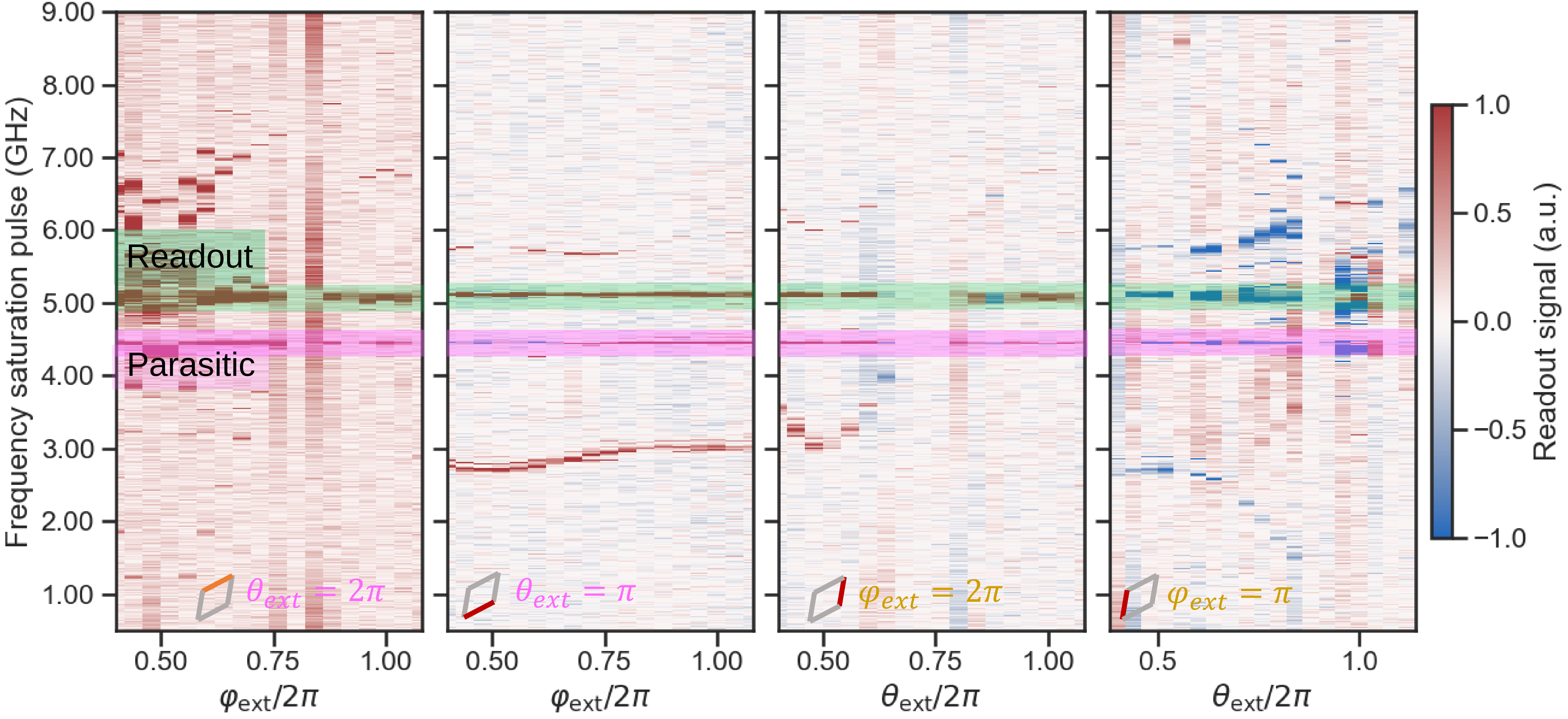
Readout resonator vs. flux



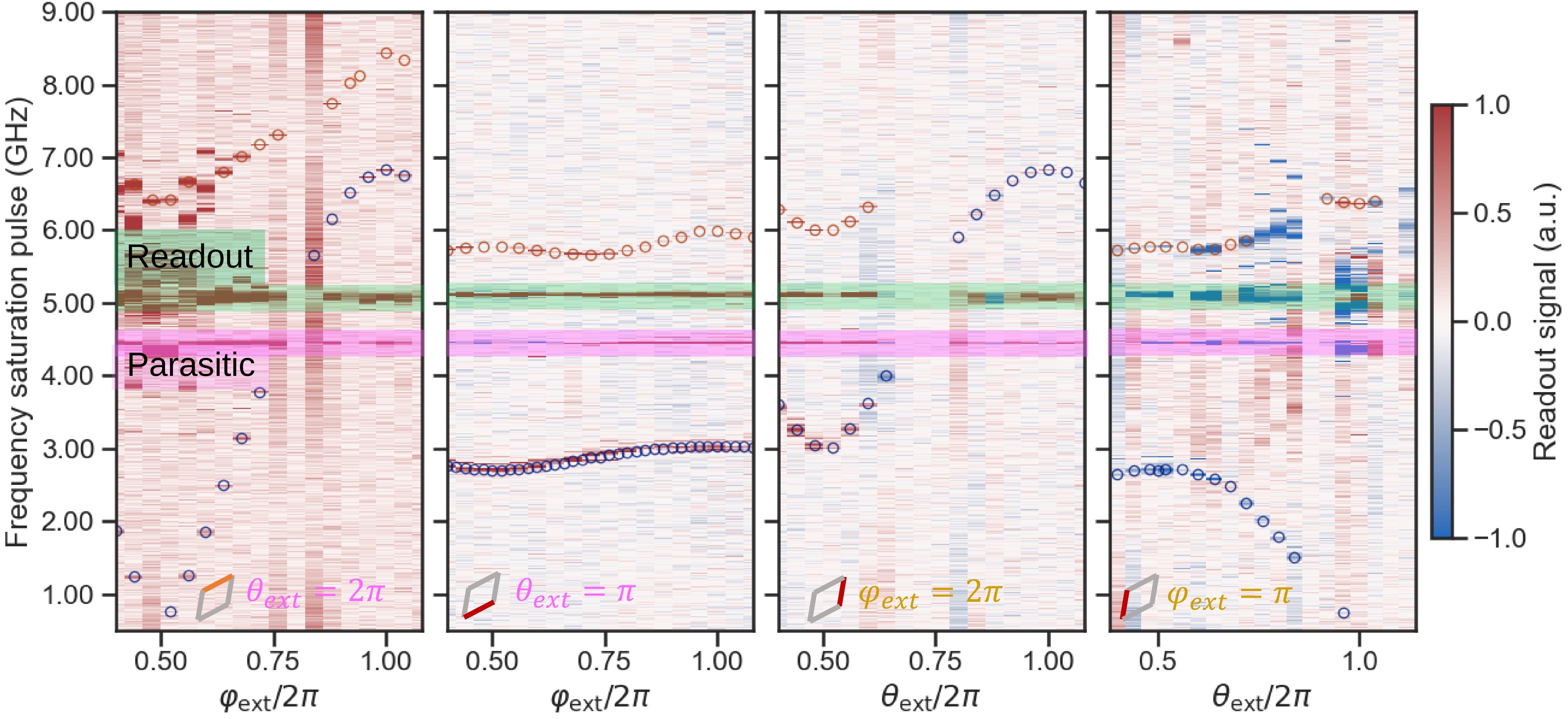
Transition frequencies vs. flux



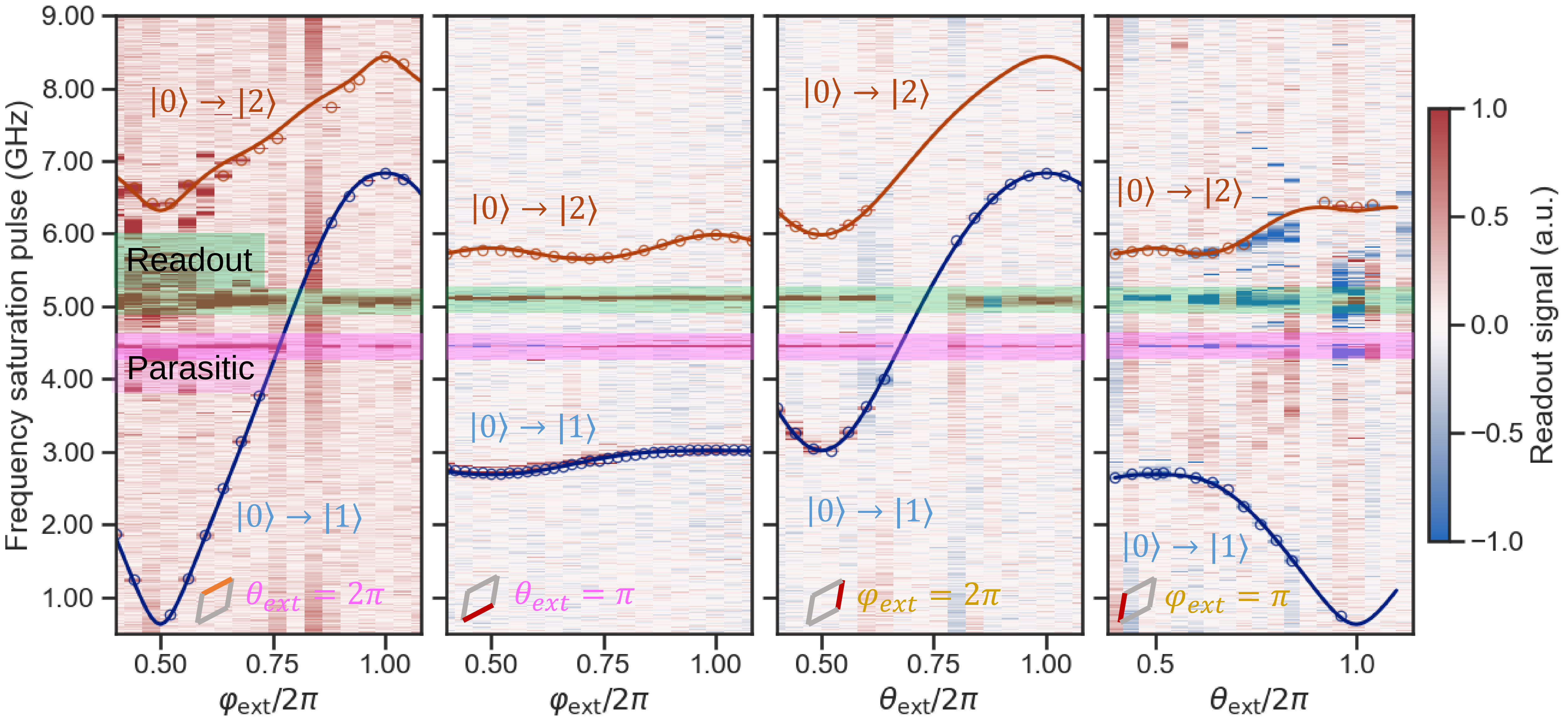
Transition frequencies vs. flux



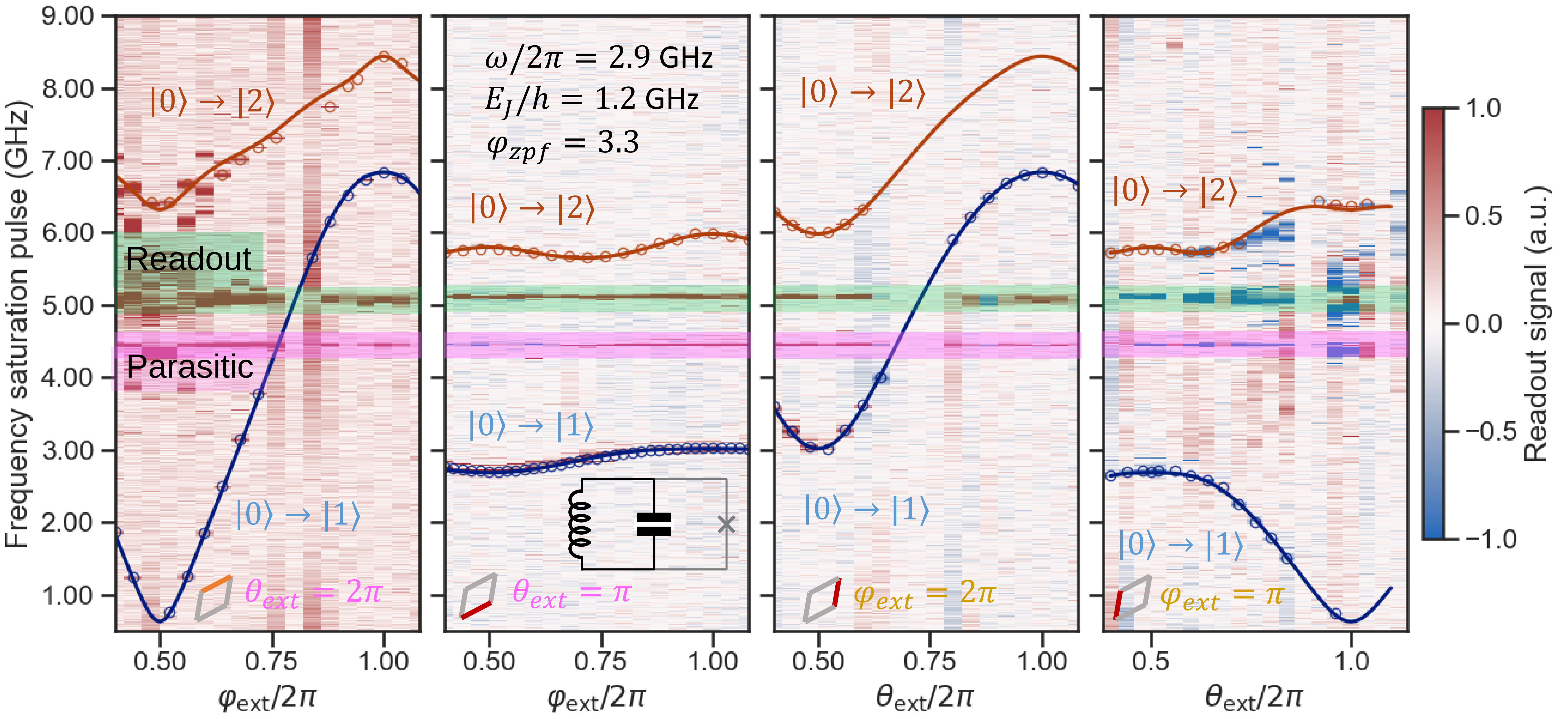
Transition frequencies vs. flux



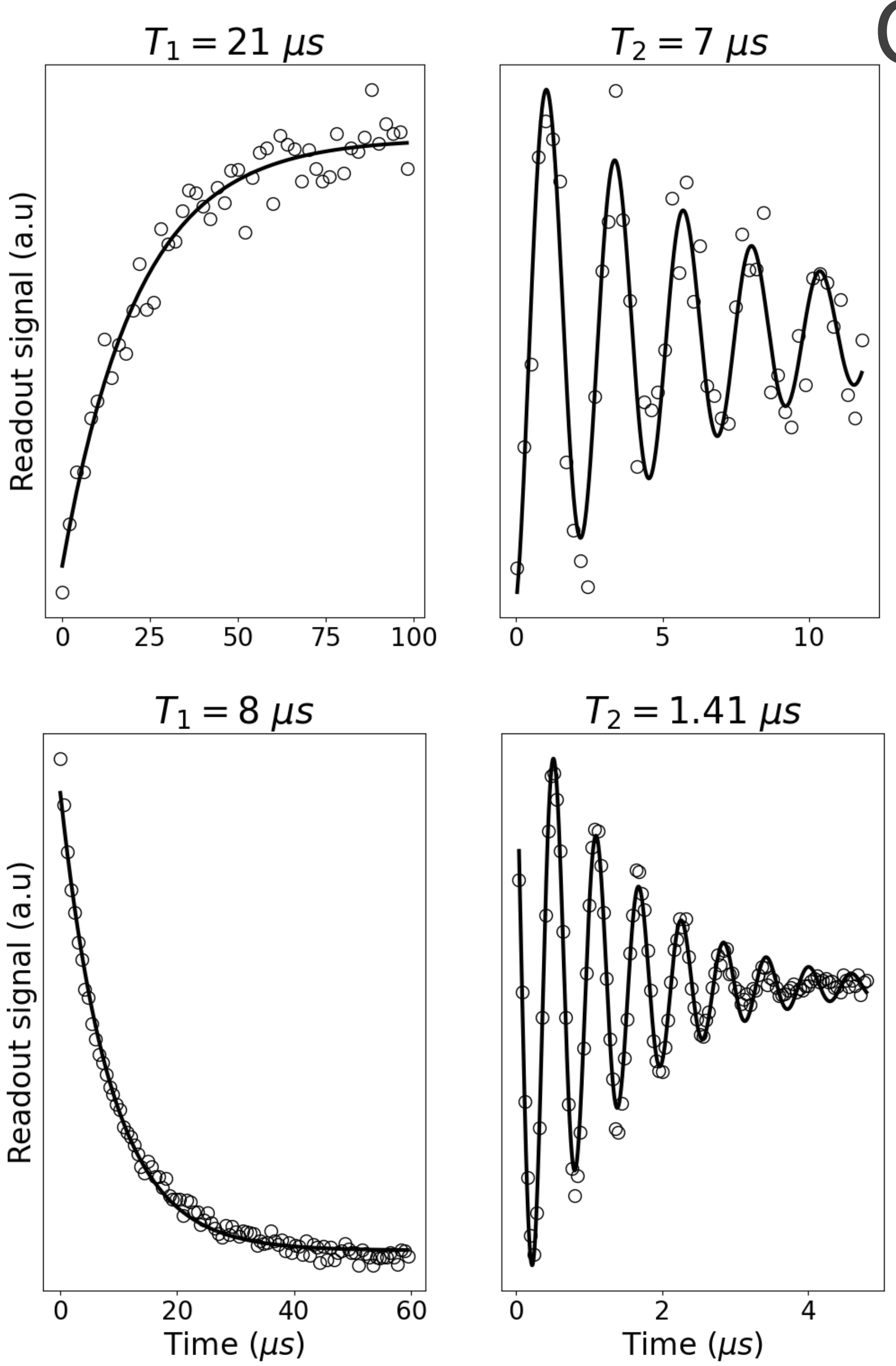
Transition frequencies vs. flux

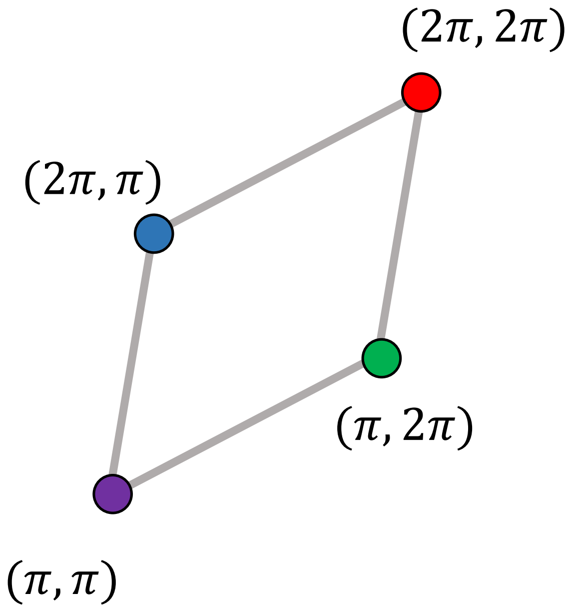


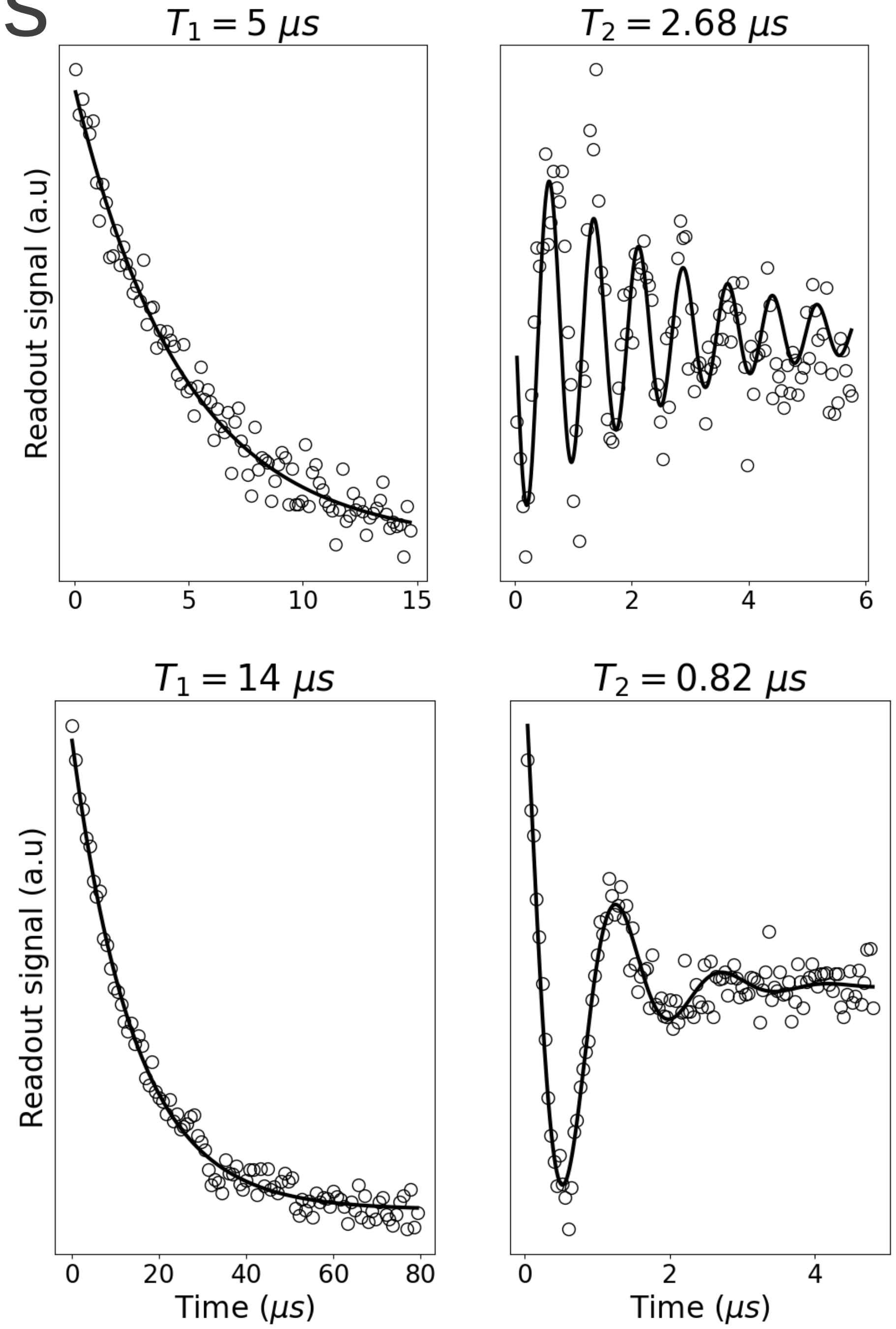
Transition frequencies vs. flux



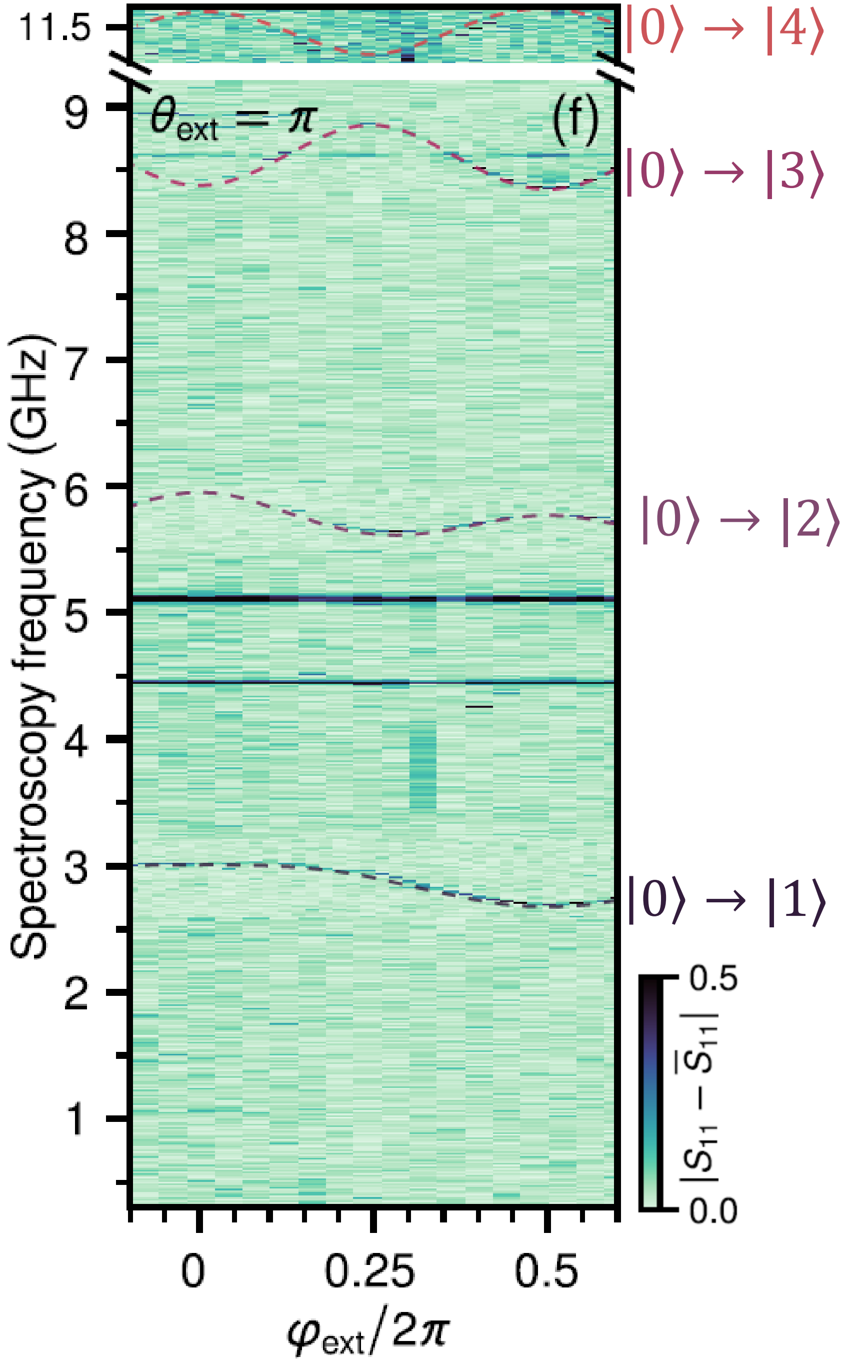
Coherence times

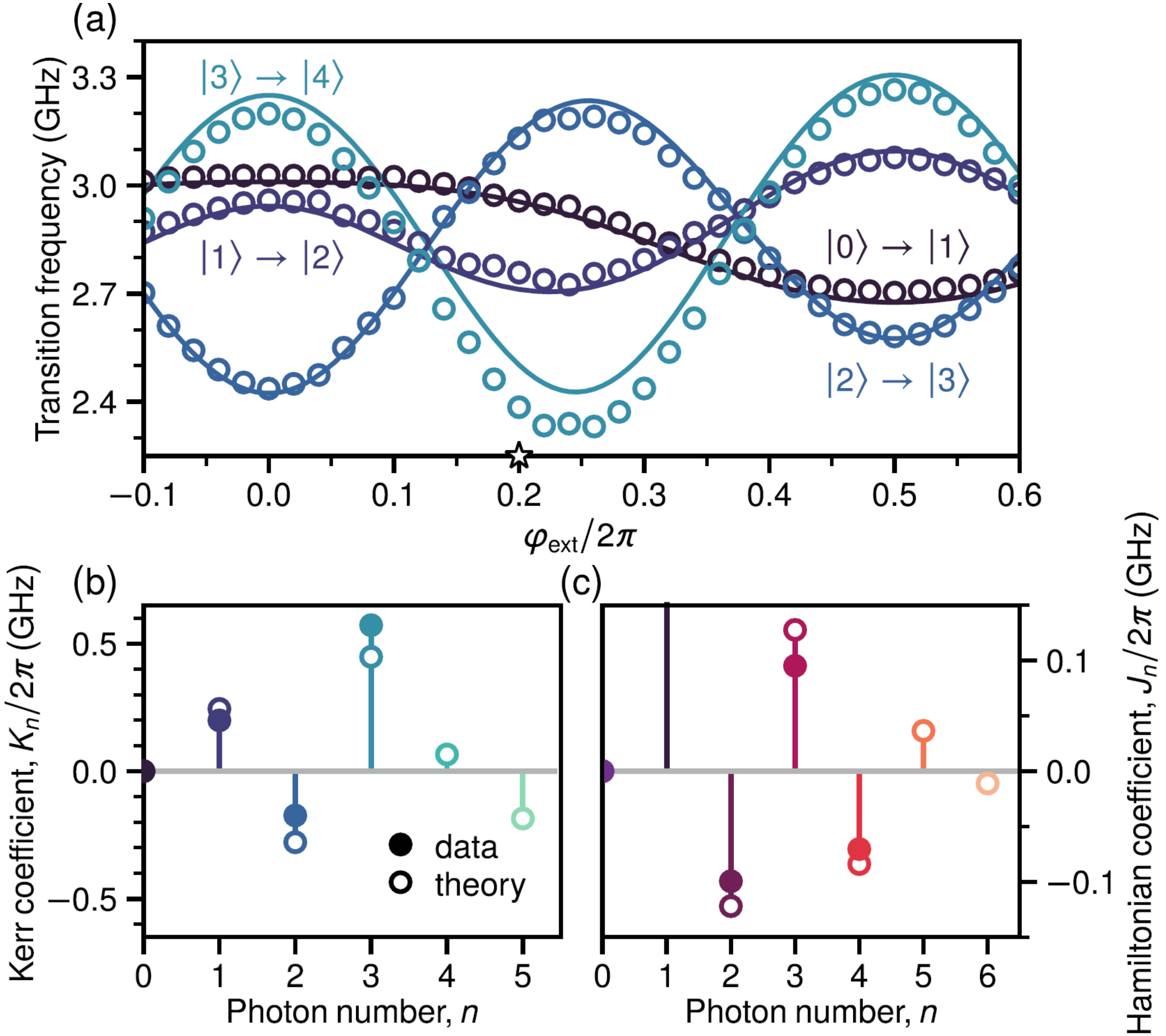






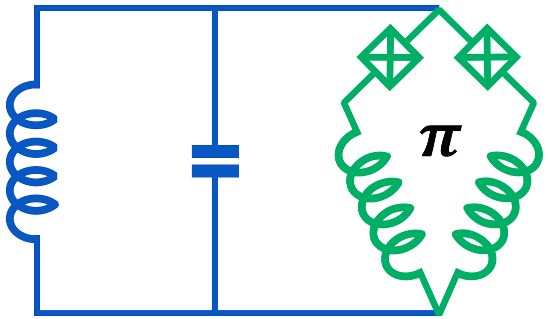
Flux dependence of $|0\rangle \rightarrow |n\rangle$ at $\theta_{ext} = \pi$





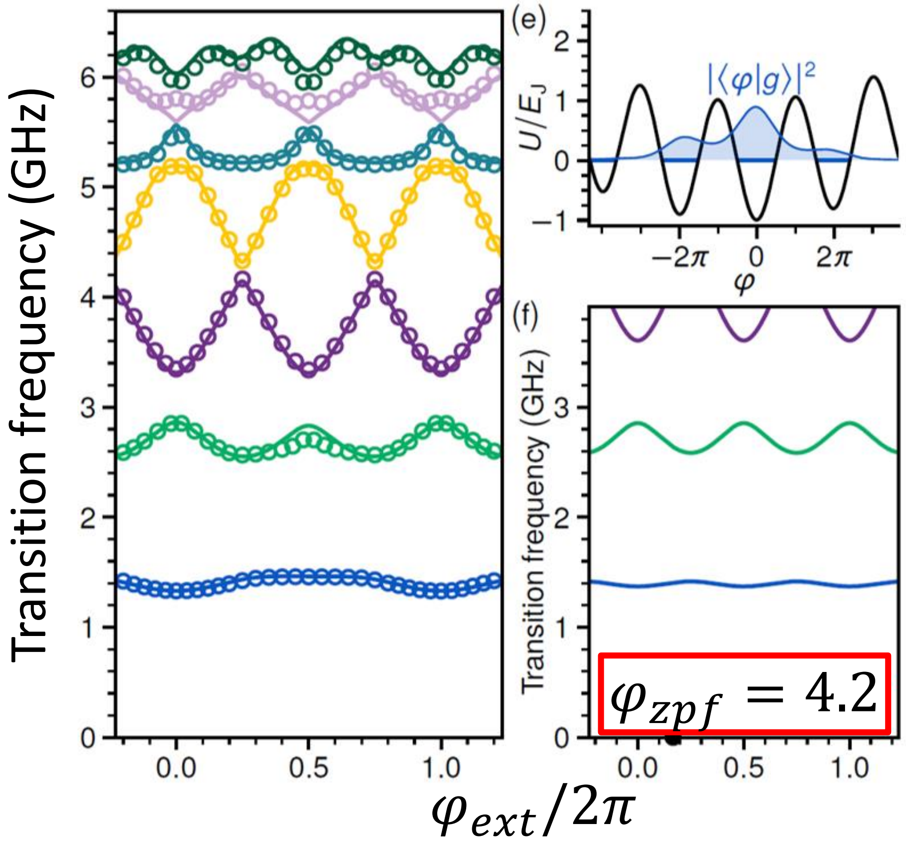
Conclusion and perspectives

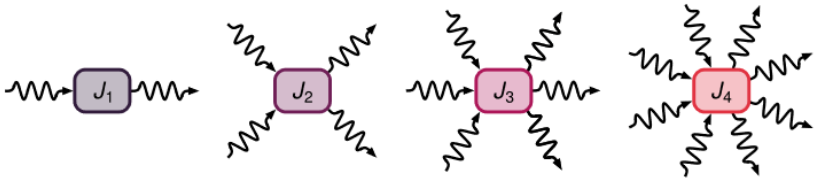
Conclusion

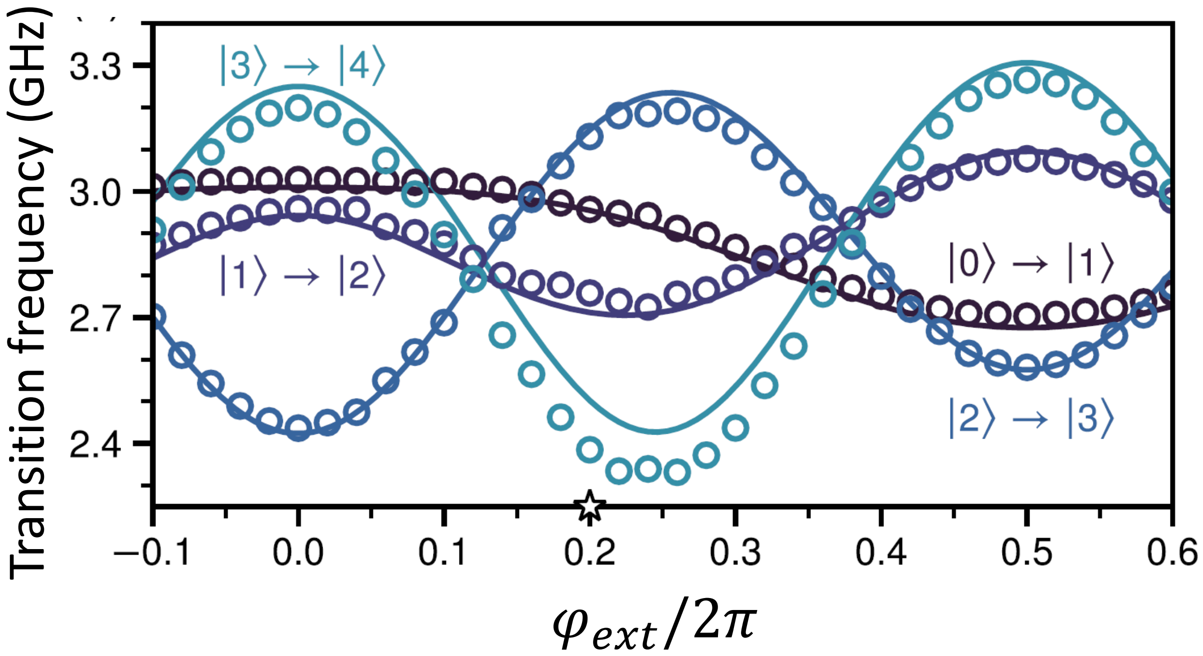


$\epsilon_L \ll E_J$

$\epsilon_L \gtrsim E_J$







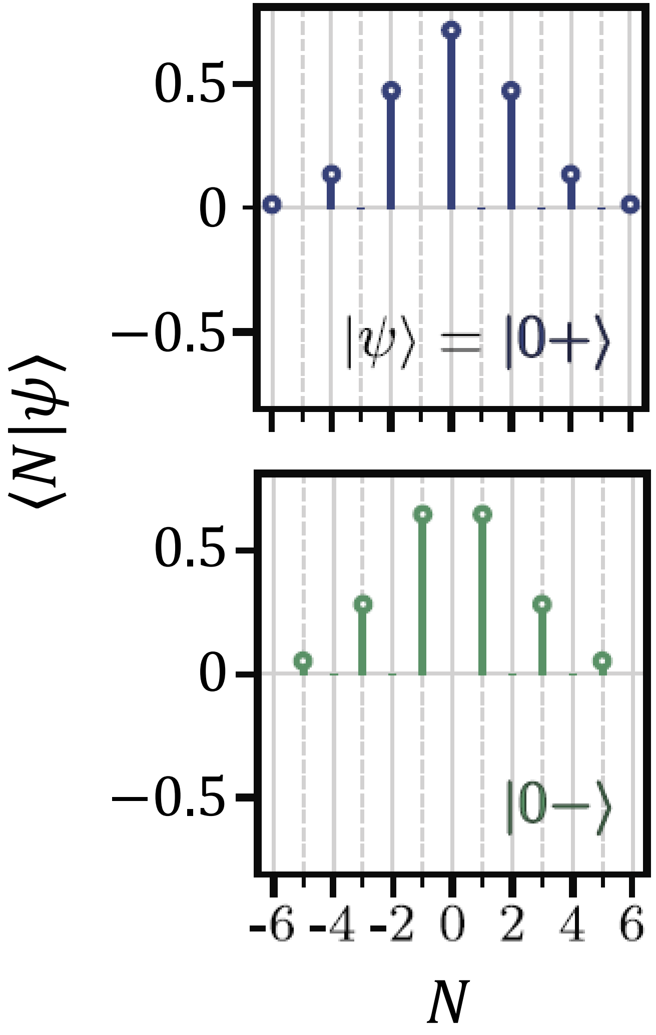
× 10 reduction in flux sensitivity

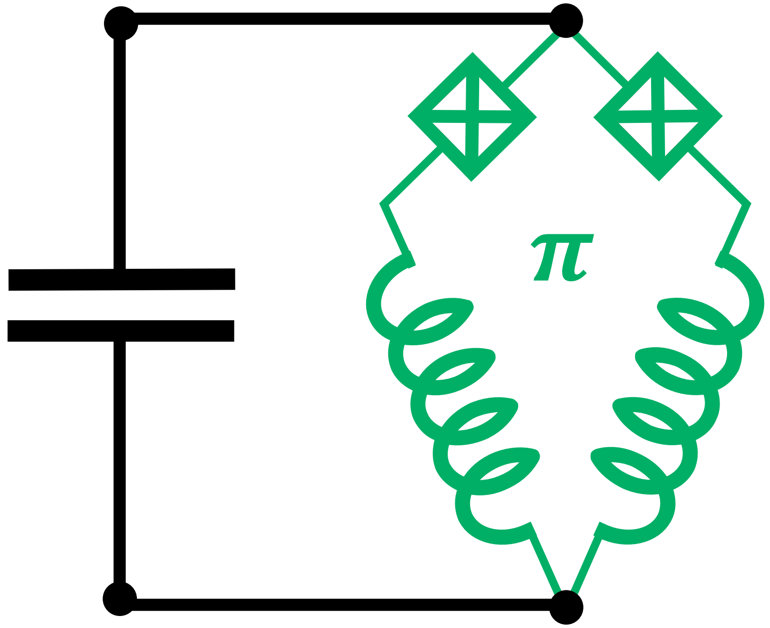
× 2 magnification of phase fluctuations

→ Interlacing spectra

→ High order photon-photon interactions

Qubit protected by Cooper-pair pairing **(open position)**

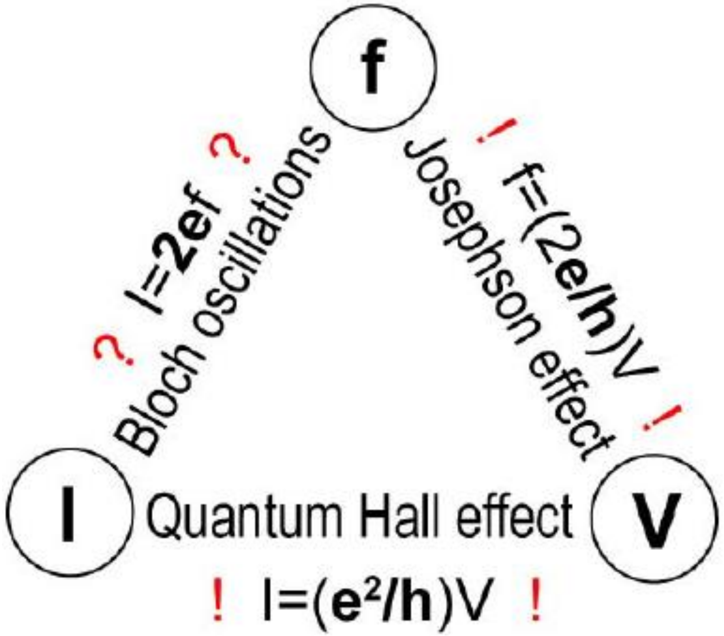


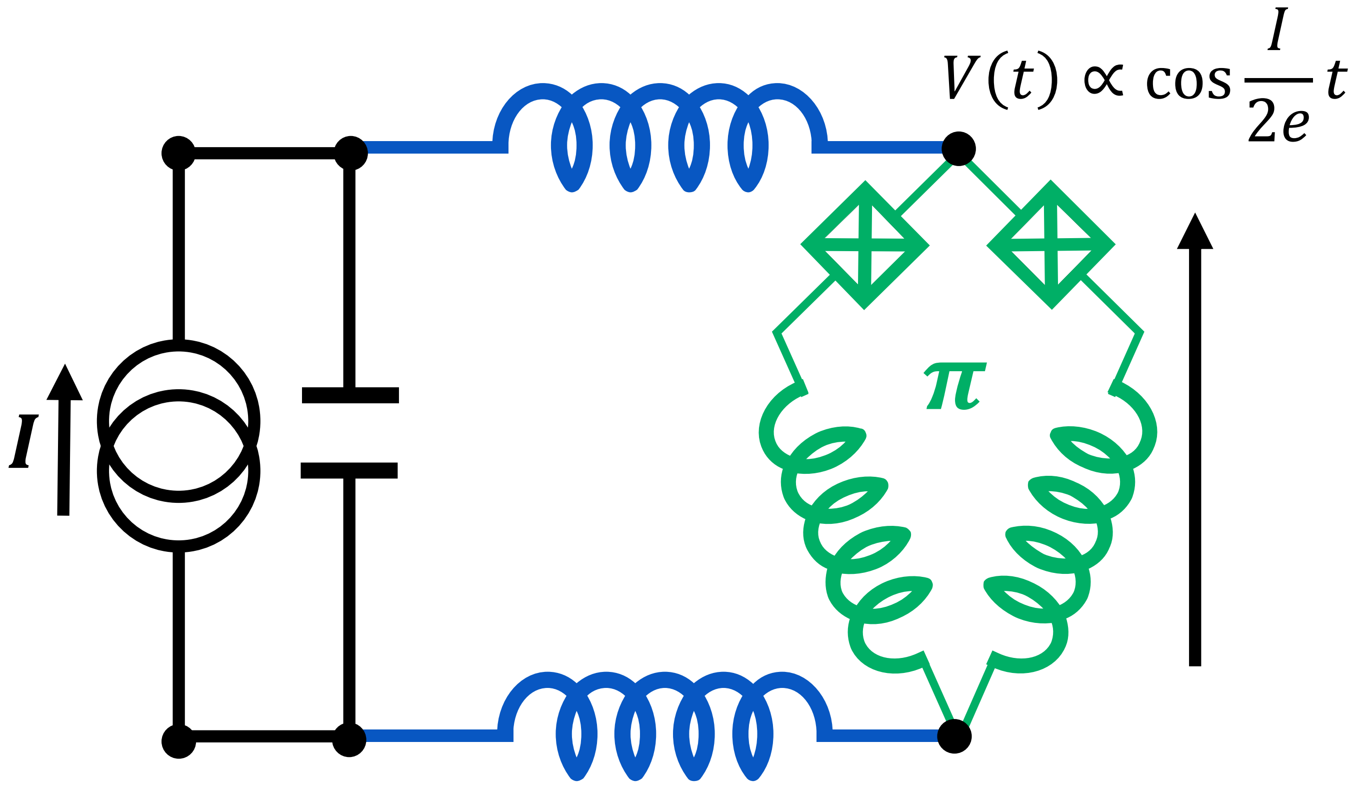


Smith *et al.* NPJQI (2020)

Dodge *et al.* arXiv:2303.00625

Closing the metrological triangle





Manucharyan PhD thesis (2012), Shaikhaidarov *et al.* Nature (2022), Crescini *et al.* Nature Phys (2023)

The QUANTIC team