Quantum Effects in Josephson Junctions - Part 1

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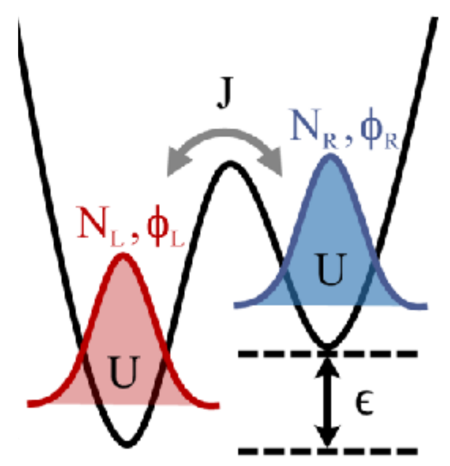
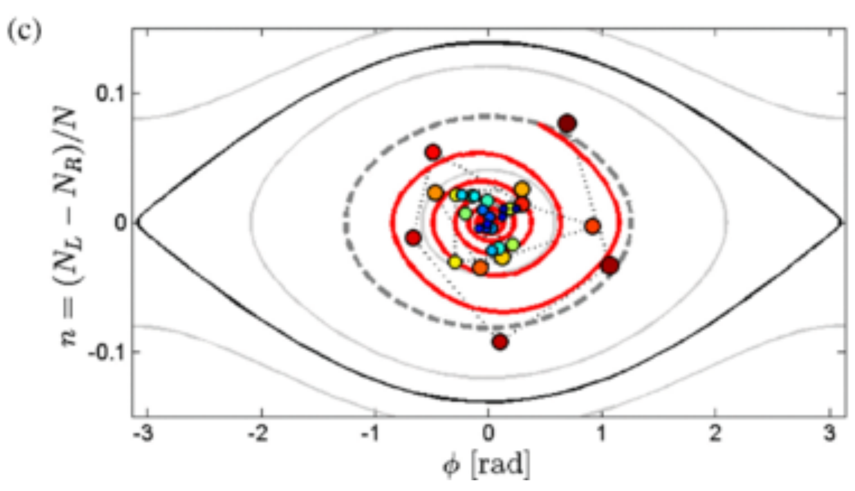
Introduction

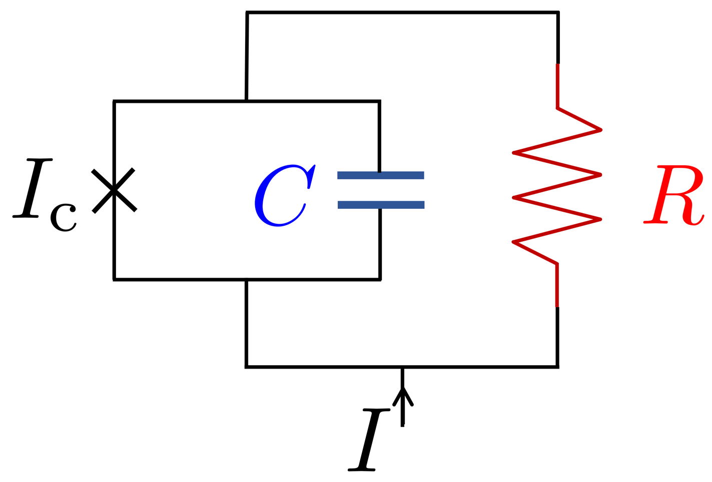
✓ Damped dynamics in a Bose Josephson junction

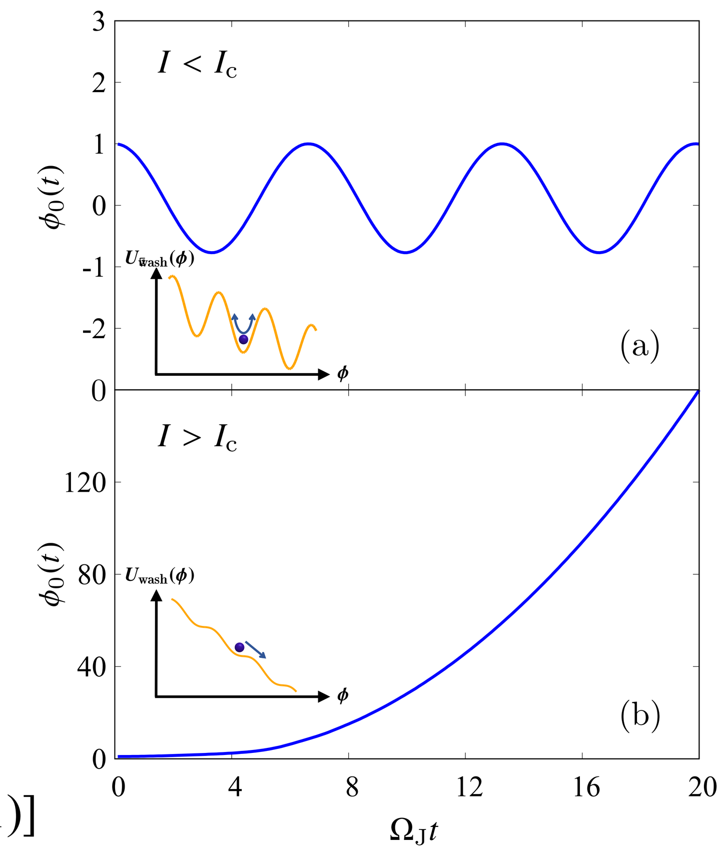




[M. Pigneur *et al.*, Phys. Rev. Lett. **120**, 173601 (2018)]

✓ Resistively & capacitively shunted Josephson circuit





[KF and L. Salasnich, Phys. Rev. B **104**, 014519 (2021)]

Our work

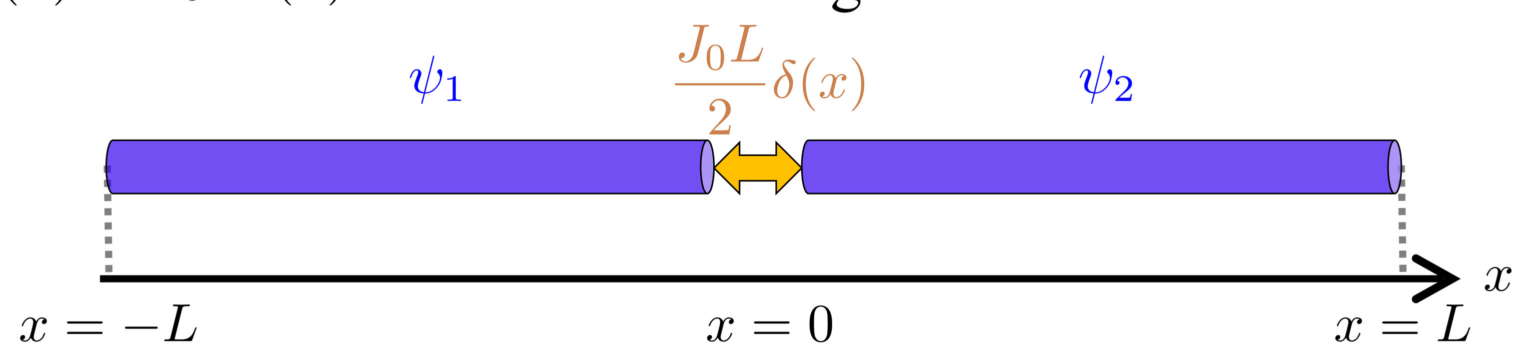
We clarify the damped dynamics of correlation functions in Josephson junctions subject to quantum noise.

1D Bose Josephson junction

[F. Binanti, KF, and L. Salasnich, Phys. Rev. A **103**, 063309 (2021)]

$$\mathcal{L} = \sum_{j=1,2}\left[i\hbar\psi_j^*\partial_t\psi_j - \frac{\hbar^2}{2m}|\partial_x\psi_j|^2 - \frac{g}{2}|\psi_j|^4\right] + \frac{J(x)}{2}\left[\psi_1^*\psi_2 + \psi_2^*\psi_1\right]$$

$J(x) = J_0 L\delta(x)$: head-to-tail configuration



▶ **Effective Hamiltonian for Josephson mode**

$\psi_j = \sqrt{\rho_j}e^{i\phi_j}$ $\quad \phi \equiv \phi_1 - \phi_2$ $\quad \zeta \equiv (\rho_1 - \rho_2)/(2\bar{\rho})$ $\quad \bar{\rho} \equiv (\rho_1 + \rho_2)/2$

$\phi(x,t) = \frac{1}{\sqrt{L}}\sum_{n=0}^{\infty}\Phi_n(x)q_n(t)$ $\quad \phi_0(t) \equiv \phi(0,t)$ $\quad Q_n(t) \equiv q_n(t)$

$$H = \frac{P_0^2}{2M} - J_0 L\bar{\rho}\cos\phi_0 + \sum_{n=1}^{\infty}\left[\frac{(P_n + P_0)^2}{2M} + \frac{M\omega_n^2}{2}Q_n^2\right]$$

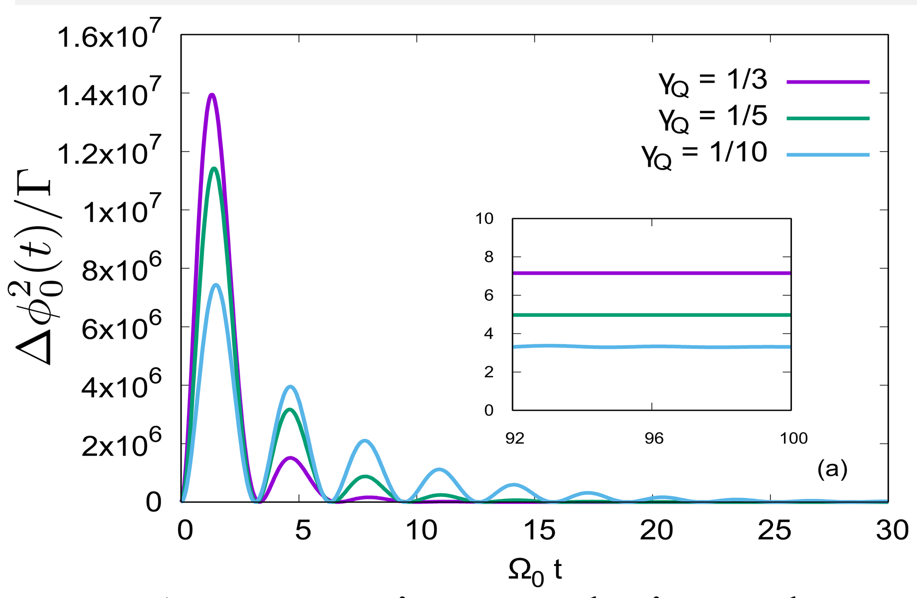
$$\begin{cases} \ddot{\phi}_0 + \gamma\dot{\phi}_0 + \Omega^2\phi_0 = \xi_\phi \\ \ddot{\zeta}_0 + \gamma\dot{\zeta}_0 + \Omega^2\zeta_0 = \xi_\zeta \end{cases}$$

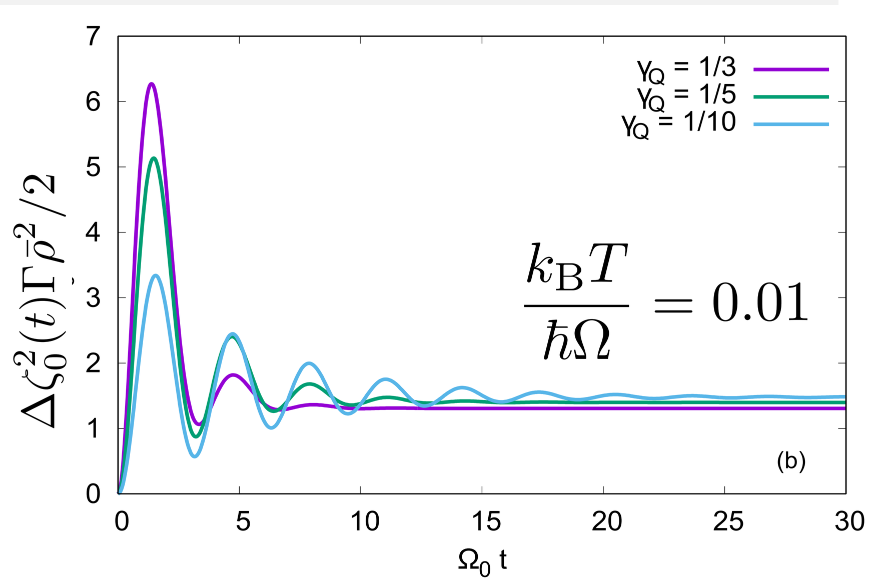
Intrinsic coupling with bath modes (Velocity-coupling model)

Generalized Langevin equations for Josephson mode

$M = \frac{\hbar^2}{2gL}$ $\quad \omega_n = ck_n$ $\quad \langle\{\xi_\phi(t), \xi_\phi(0)\}\rangle = \frac{2\gamma}{ML^2\Omega^2}\int\frac{d\omega}{2\pi}e^{i\omega t}\hbar\omega^3\coth\left(\frac{\hbar\omega}{2k_BT}\right)$

$c = \sqrt{\frac{g\bar{\rho}}{m}}$ $\quad \omega_{\rm cut} = c\frac{\pi N}{L}$ $\quad \langle\{\xi_\zeta(t), \xi_\zeta(0)\}\rangle = \frac{2M\Omega^2\gamma}{\hbar^2\bar{\rho}^2L^2}\int\frac{d\omega}{2\pi}e^{i\omega t}\hbar\omega\coth\left(\frac{\hbar\omega}{2k_BT}\right)$





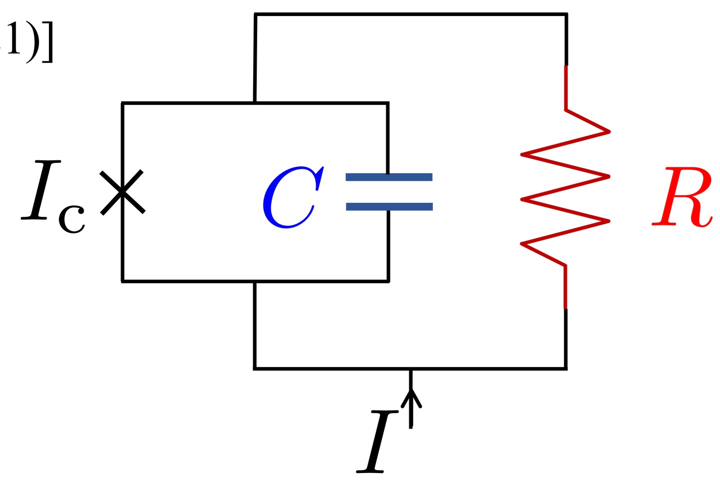
- Asymptotic correlations depend on $\gamma = \bar{\rho}J_0/(Mc)$.
- Phase correlation is strongly enhanced.
- In-phase oscillations.

$\Gamma = \frac{2\hbar}{M\Omega}$ $\quad \gamma_Q \equiv \frac{\gamma}{2\Omega}$

RCSJ junction

[KF and L. Salasnich, Phys. Rev. B **104**, 014519 (2021)]

$$\begin{cases} C\dot{V} + \frac{V}{R} + I_c\sin\phi = I + \xi \\ \dot{\phi} = \frac{2e}{\hbar}V \end{cases}$$



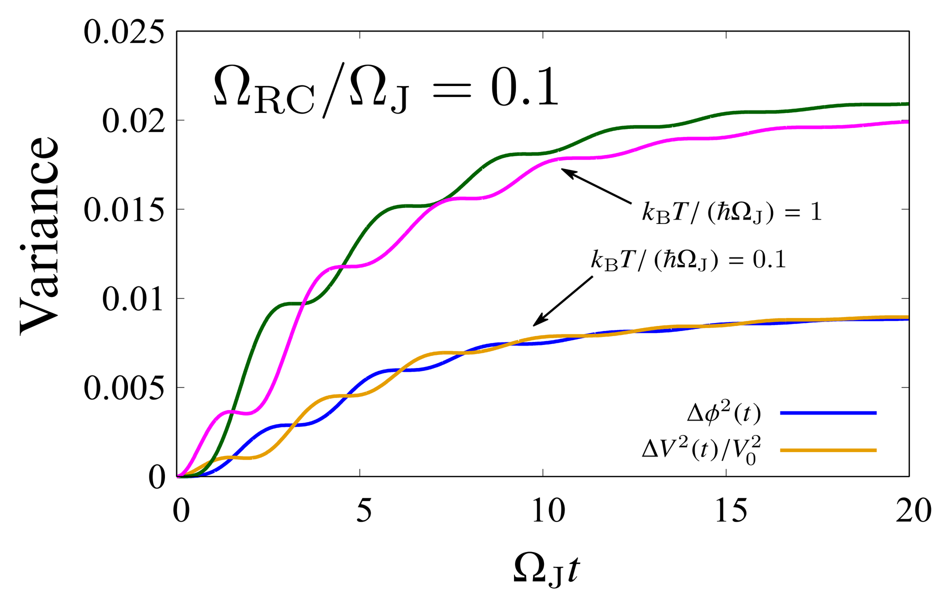
$$\ddot{\phi} + 2\Omega_{\rm RC}\dot{\phi} + \Omega_J^2\phi = \Omega_J^2\left(\frac{I}{I_c} + \frac{\xi}{I_c}\right)$$

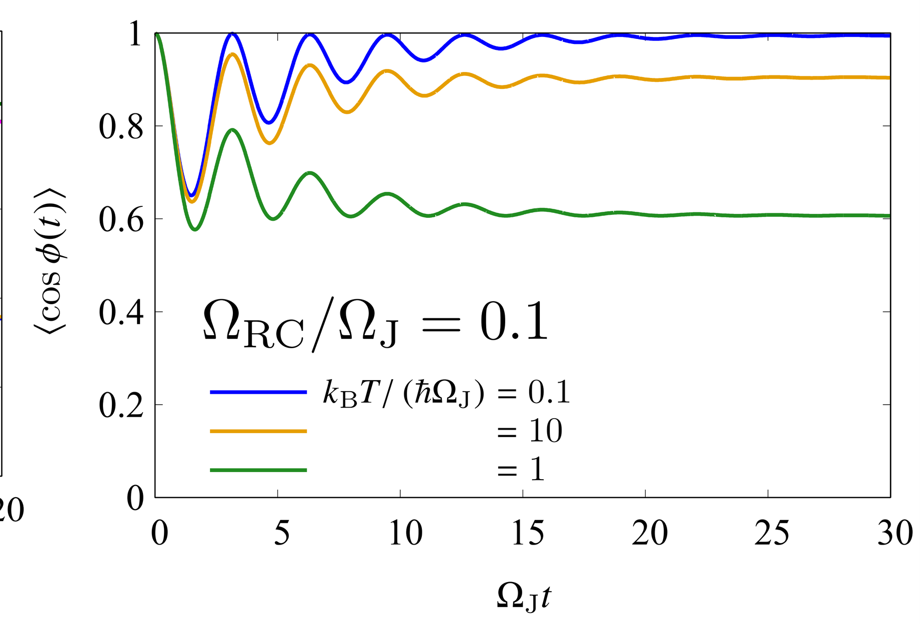
$\Omega_J = \sqrt{\frac{2eI_c}{\hbar C}}$ $\quad \Omega_{\rm RC} = \frac{1}{2RC}$

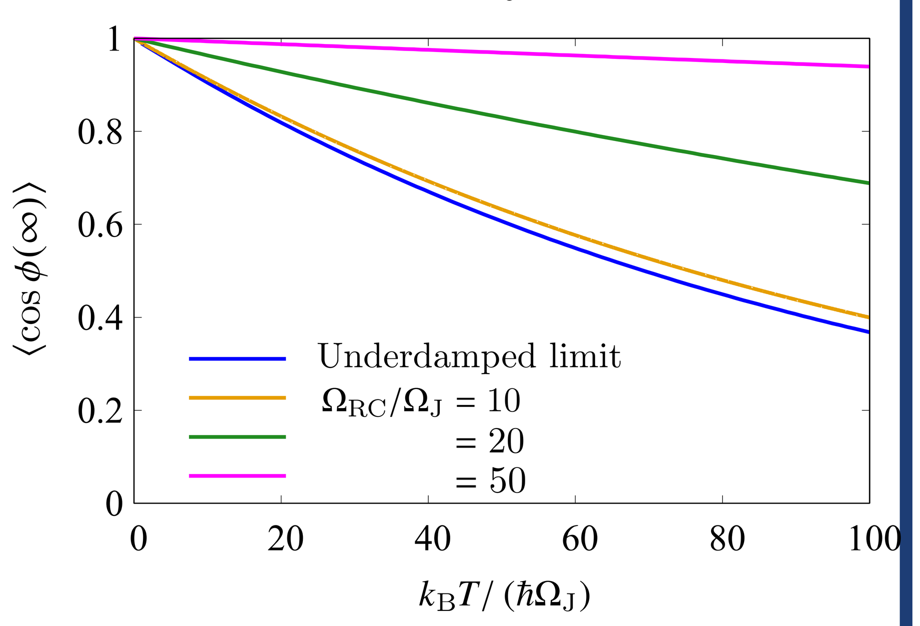
$\langle\xi(t)\xi(0)\rangle = \frac{2}{R}\int\frac{d\omega}{2\pi}e^{i\omega t}\hbar\omega\coth\left(\frac{\hbar\omega}{2k_BT}\right)$

$\frac{2e\Omega_J}{I_c} = 0.01$ $\quad \omega_{\rm cut} = \Delta(T)/\hbar$ $\quad \Delta(T)$: superconducting gap

[M. H. Devoret, J. M. Martinis, and J. Clarke, Phys. Rev. Lett. **55**, 1908 (1985)]







- Out-of-phase oscillations of phase & voltage variances.
- Coherence decay earlier at a higher temperature.
- Coherence decay earlier with smaller damping $\Omega_{\rm RC}$.

Summary

Bose Josephson junction

Intrinsic coupling through momenta

- Enhancement of $\langle\phi_0^2(t)\rangle$
- In-phase oscillations of $\Delta\phi_0^2(t)$ and $\Delta\zeta_0^2(t)$

RCSJ junction

Current noise & friction generated by a resistor

- Same order of $\langle\phi^2(t)\rangle$ and $\langle V^2(t)\rangle$
- Out-of-phase oscillations of $\Delta\phi^2(t)$ and $\Delta V^2(t)$

- Correlations in the long-time limit depend on the damping (friction) constant in the quantum regime.