Atomtronic implementation of SQUIDs and Josephson junctions

Ludwig Mathey

SFB
SFB 925: Light induced dynamics and control of strongly correlated quantum systems

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

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Zentrum für Optische Quantentechnologien

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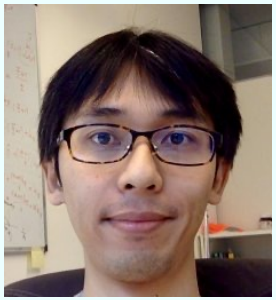

Junichi Okamoto

Vijay Singh

Jayson Cosme

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Recent and current collaborators

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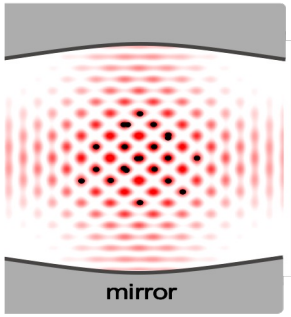
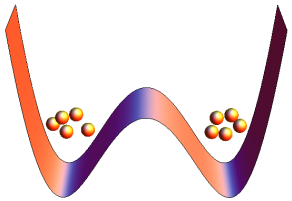
Wanzheng Hu
Jean Dalibard
Markus Heyl
Jan Budich
Darrick Chang
Eite Tiesinga

Research interests

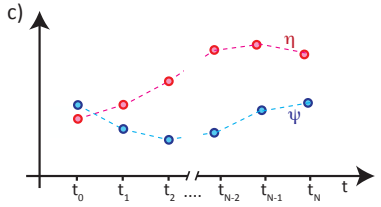
Atom-photon systems

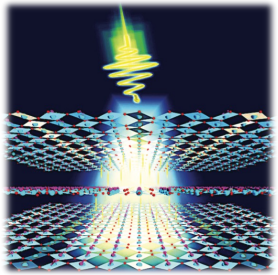


Cold atom dynamics

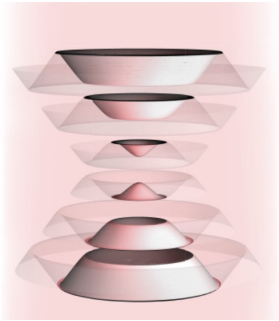


Path integrals

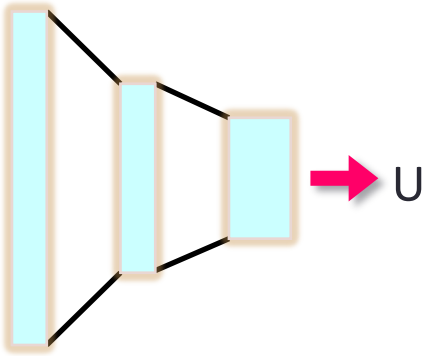




Superconductors



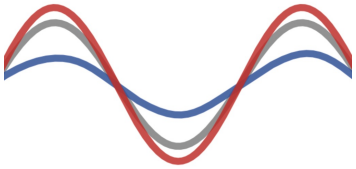
Graphene dynamics



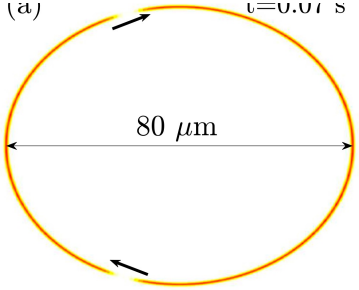
Quantum machine learning

SQUIDs and Josephson junctions

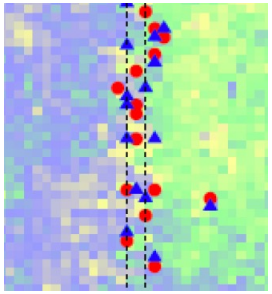
Dynamical control



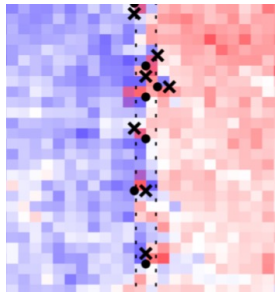
quasi-1d SQUID



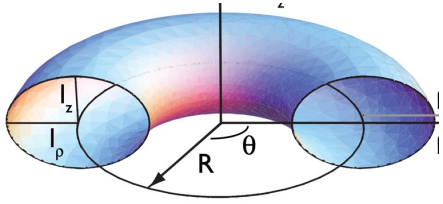
JJ dynamics, th



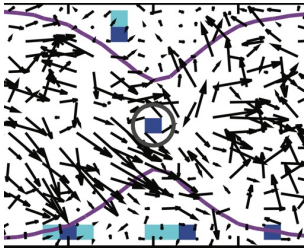
JJ dynamics, exp



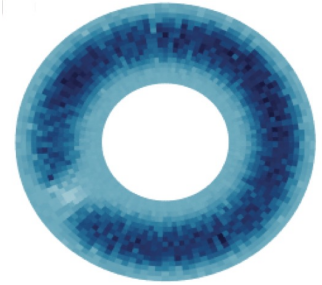
Phase fluctuations



Phase dynamics

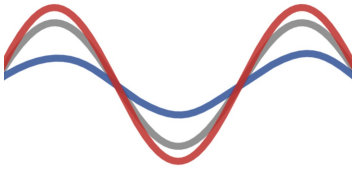


3D SQUID

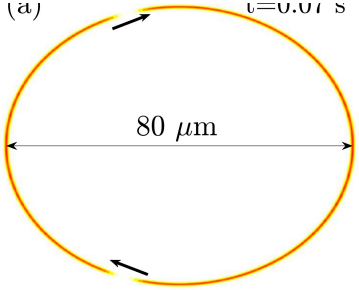


SQUIDs and Josephson junctions

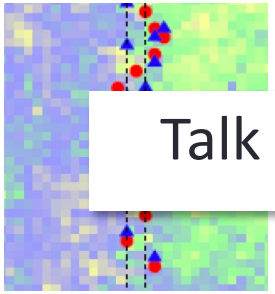
Dynamical control



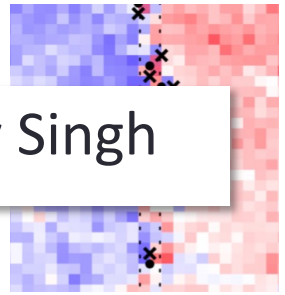
quasi-1d SQUID



JJ dynamics, th

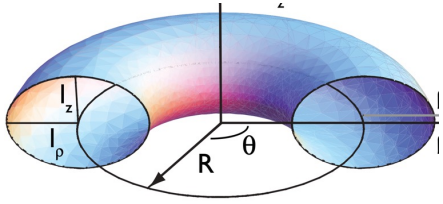


JJ dynamics, exp

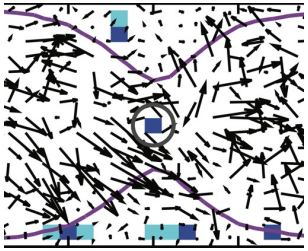


Talk by Vijay Singh

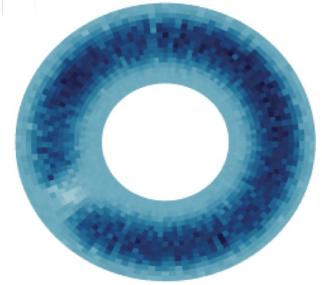
Phase fluctuations



Phase dynamics



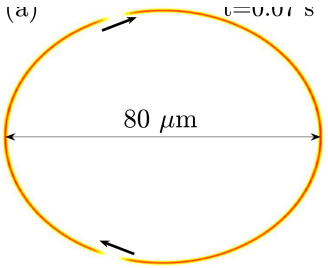
3D SQUID



Overview

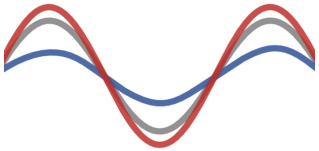
Implementation of an atomtronic SQUID in a strongly Confined toroidal condensate

Hannes Kiehn, Vijay Singh, LM



Dynamical control of an atomic Josephson junction

Beilei Zhu, Vijay Singh, Junichi Okamoto, LM



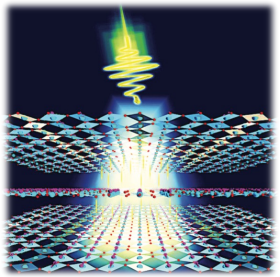
C-field methods / Truncated Wigner

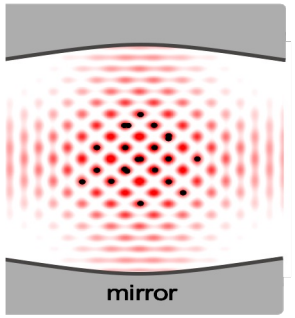
Heisenberg/Langevin

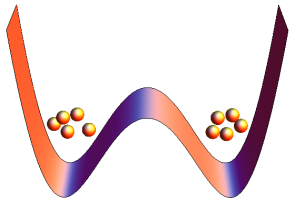
$W(\psi, \psi^*)$ $\langle O(\psi, \psi^*)\rangle$

Wigner distribution Propagation Observables

Physical systems:







Overview

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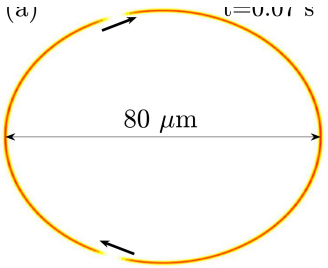

Dynamical control of an atomic Josephson junction

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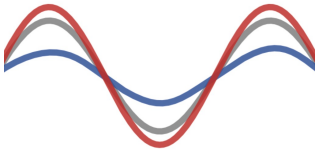
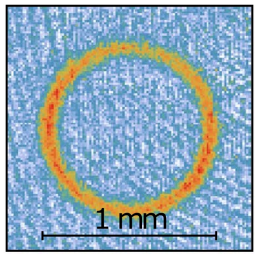
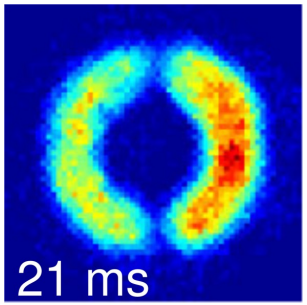


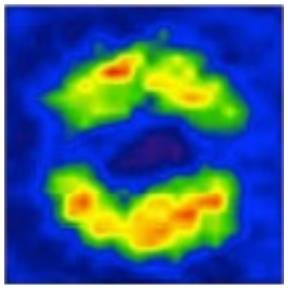
Toroidal condensates



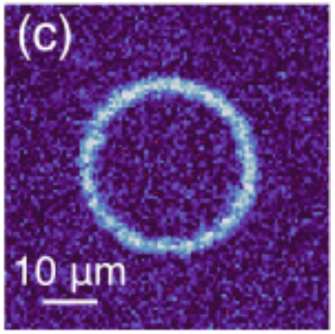
von Klitzing



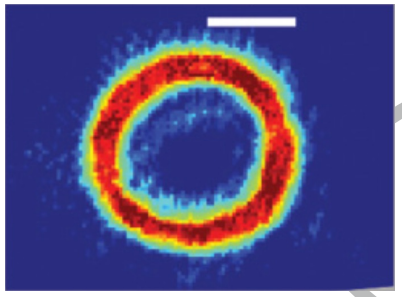
Campbell



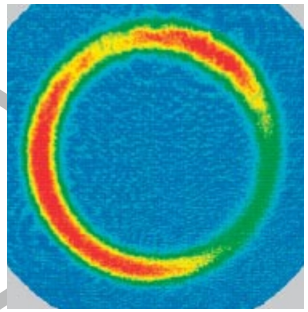
Boshier



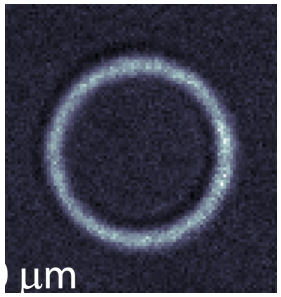
Roati



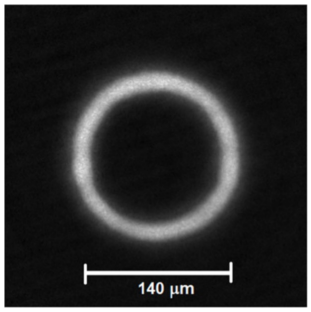
Hadzibabic



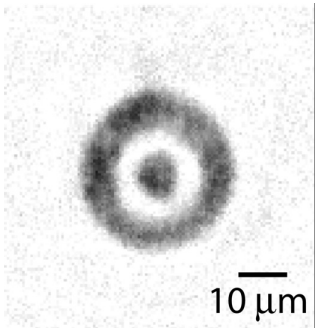
Stamper-Kurn



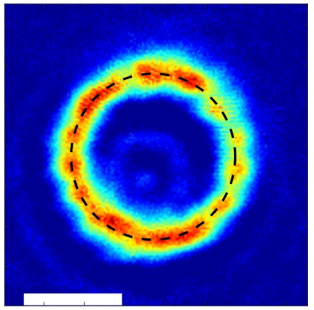
Wright



Rubinsztein-Dunlop



Dalibard

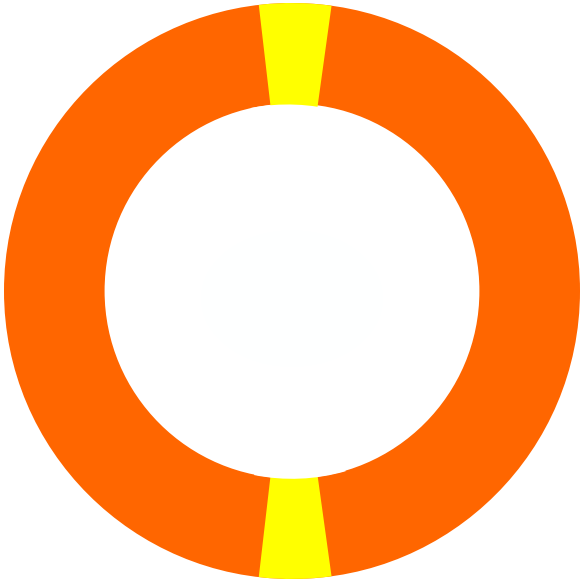


Perrin

SQUIDs

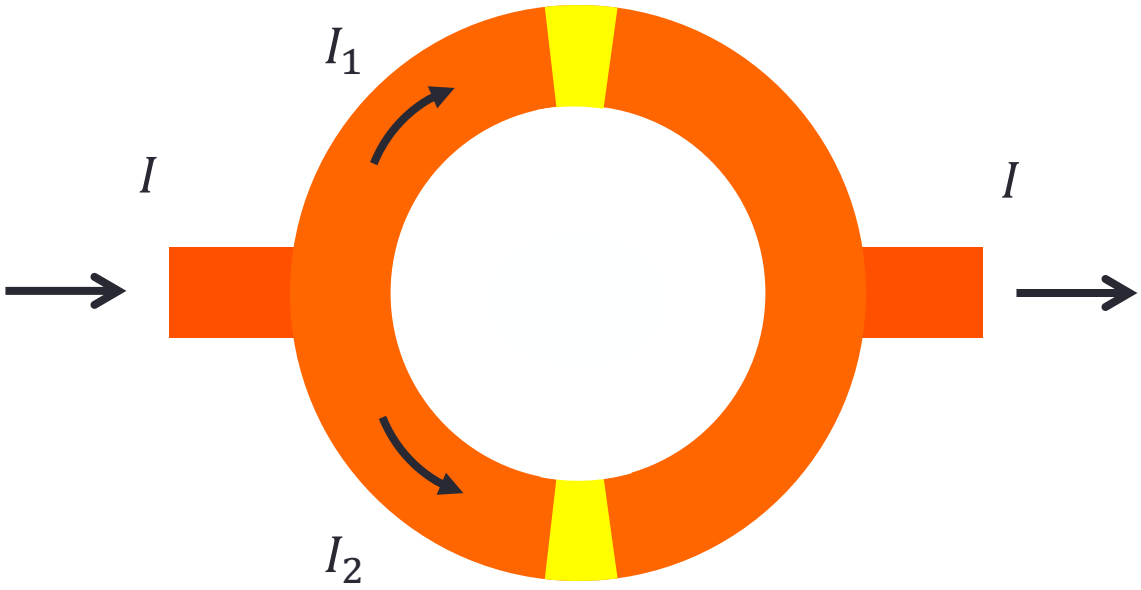
Superconducting ring

SQUIDs



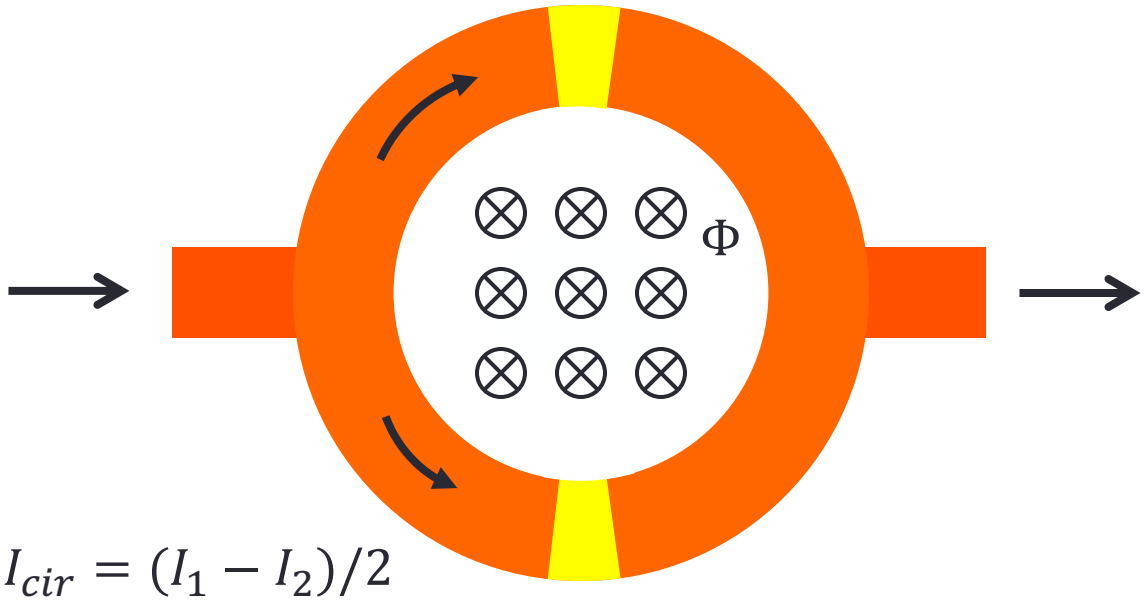
Josephson junctions

SQUIDs



Leads

SQUIDs

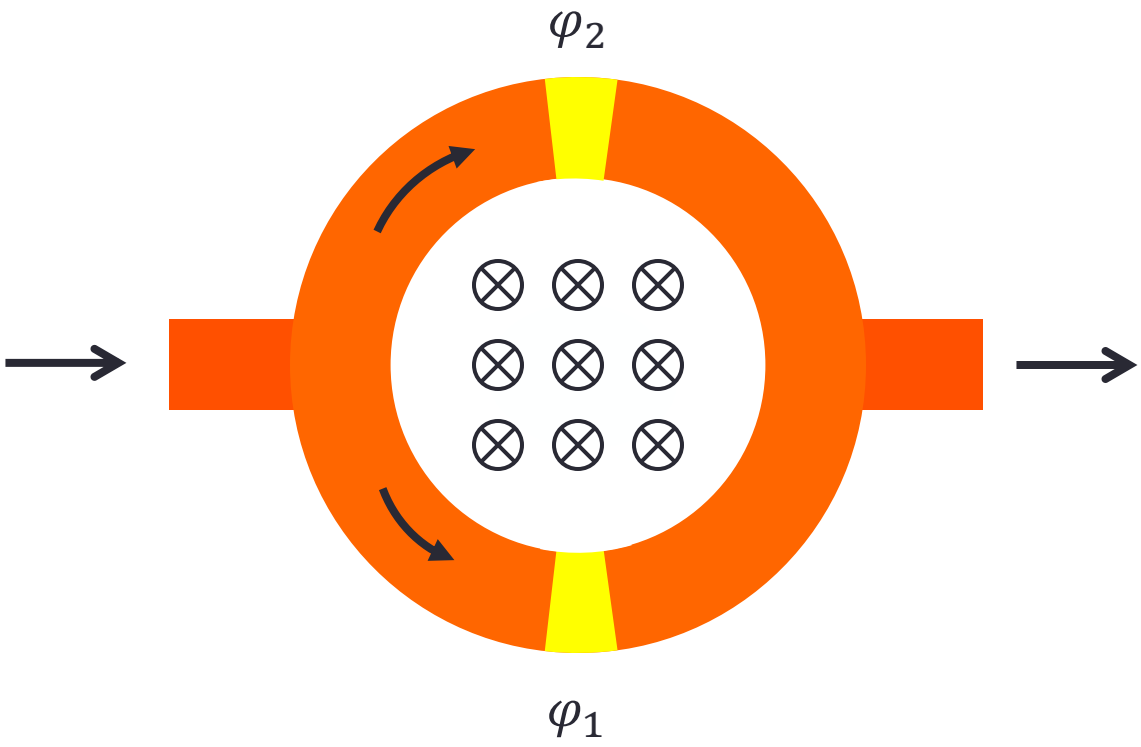


$I_{cir} = (I_1 - I_2)/2$

Magnetic flux

SQUIDs

$$2\pi n = \varphi_2 - \varphi_1 - 2\pi \frac{\Phi}{\Phi_0} - 2\pi \frac{LI_{cir}}{\Phi_0}$$



Phase winding

SQUIDs

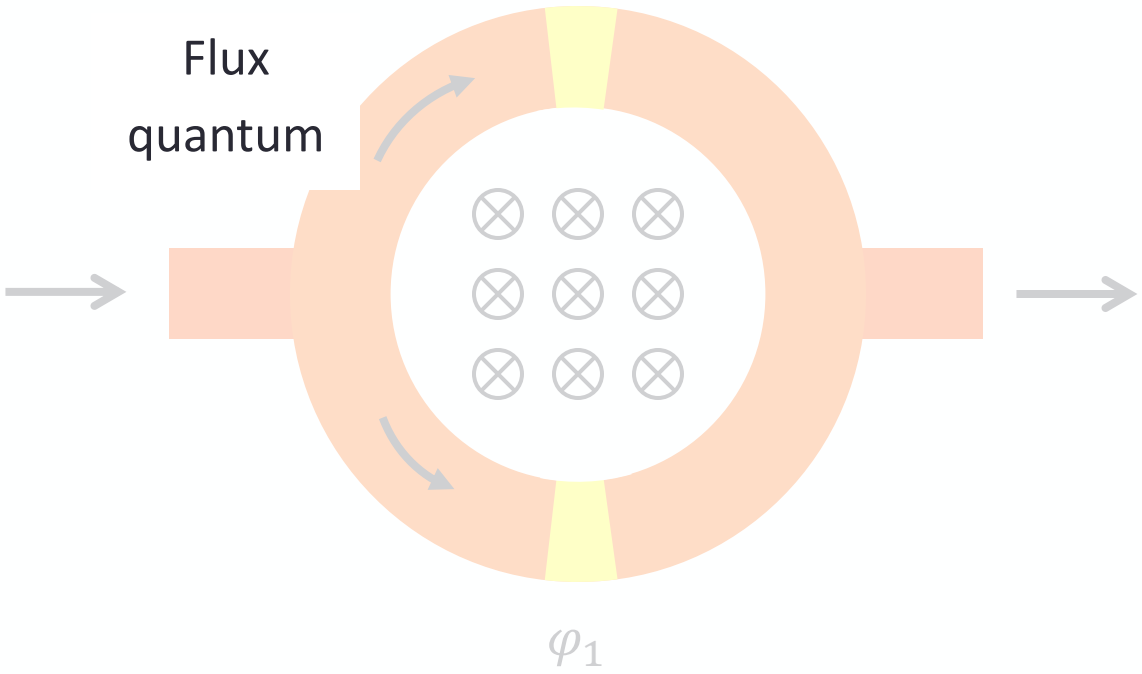
$$2\pi n = \varphi_2 - \varphi_1 - 2\pi\frac{\Phi}{\Phi_0} - 2\pi\frac{LI_{cir}}{\Phi_0}$$

$$\Phi_0 = \frac{\pi\hbar}{e}$$

Flux quantum

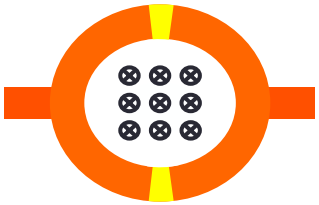
$$\beta_L = \frac{LI_{cir}}{\Phi_0}$$

Screening parameter



Phase winding

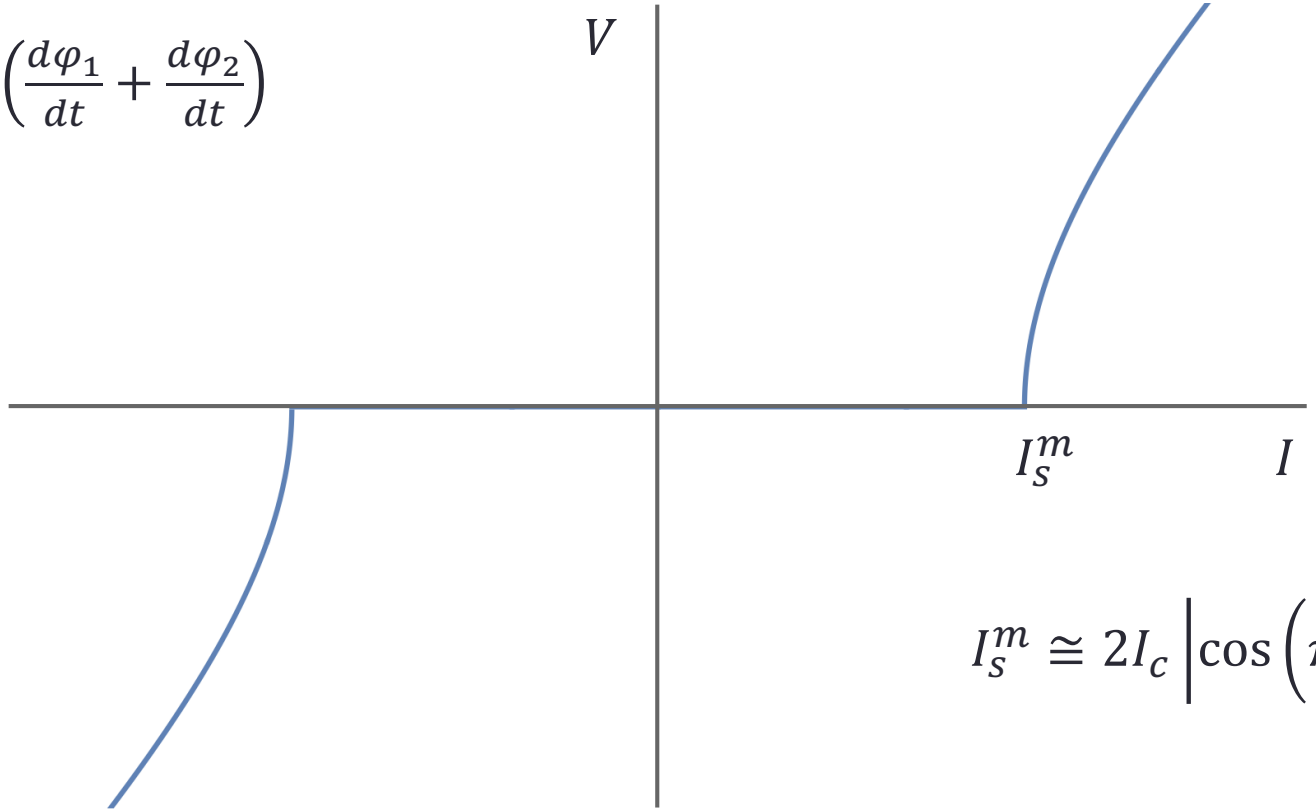
SQUIDs



$$\frac{I}{2} = \frac{\hbar C}{2e}\frac{d^2\varphi_1}{dt^2} + \frac{\hbar}{2eR_N}\frac{d\varphi_1}{dt} + I_c \sin\varphi_1 - I_{cir}$$

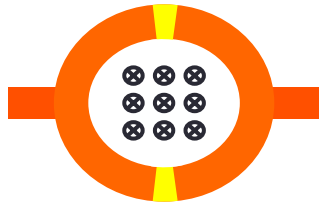
$$\frac{I}{2} = \frac{\hbar C}{2e}\frac{d^2\varphi_2}{dt^2} + \frac{\hbar}{2eR_N}\frac{d\varphi_2}{dt} + I_c \sin\varphi_2 + I_{cir}$$

$$V = \frac{\Phi_0}{4\pi}\left(\frac{d\varphi_1}{dt} + \frac{d\varphi_2}{dt}\right)$$



$$I_s^m \cong 2I_c \left|\cos\left(\pi\frac{\Phi}{\Phi_0}\right)\right|$$

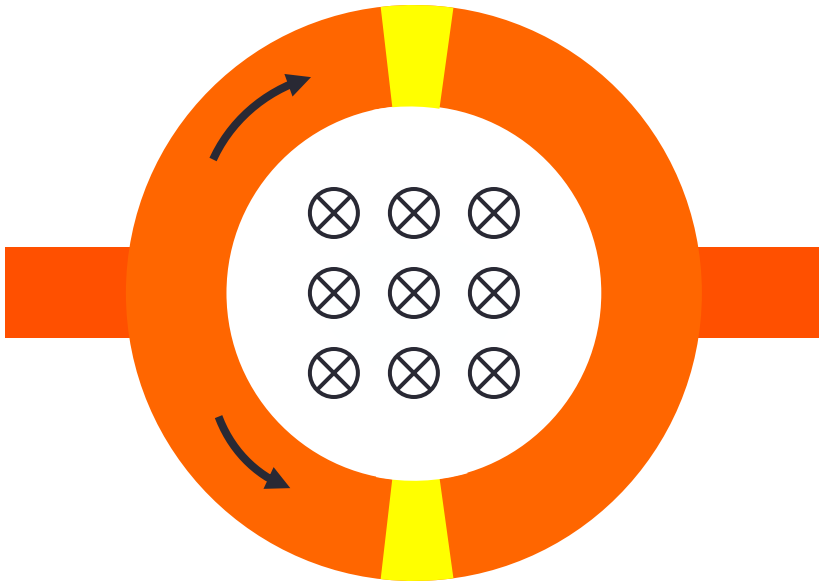
SQUIDs

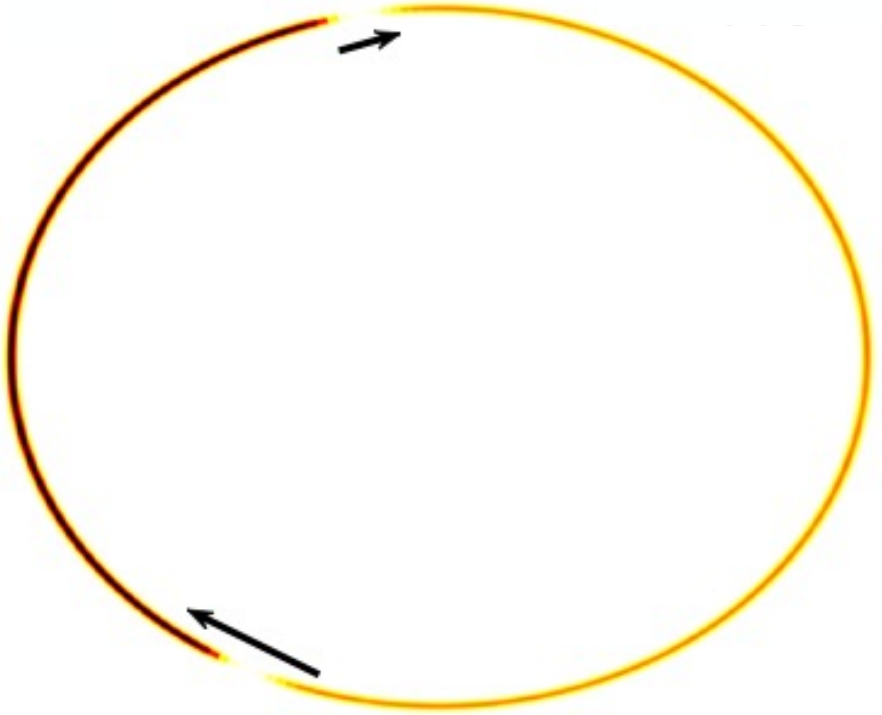


Overdamped limit

$$\langle V(t)\rangle = I_c R_N \sqrt{\frac{I}{2I_c} - \left(\cos\left(\pi\frac{\Phi}{\Phi_0}\right)\right)^2}$$

Atomtronic realization





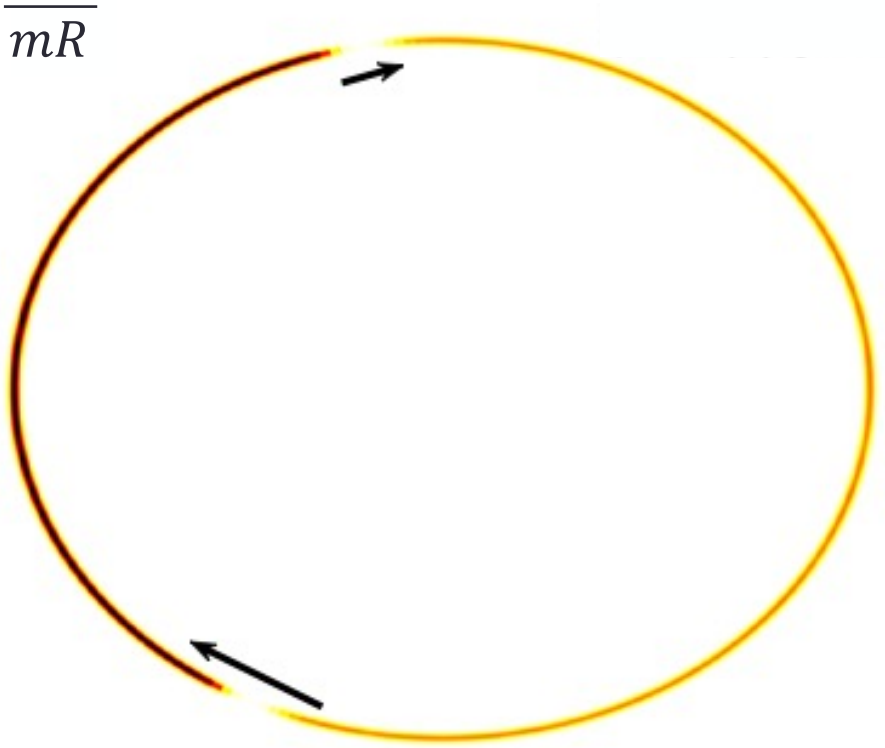
Atomtronic realization

$$v_0 = \frac{2\pi\hbar}{mR}$$

$$\frac{\Phi}{\Phi_0} \rightarrow \frac{v_\Phi}{v_0}$$

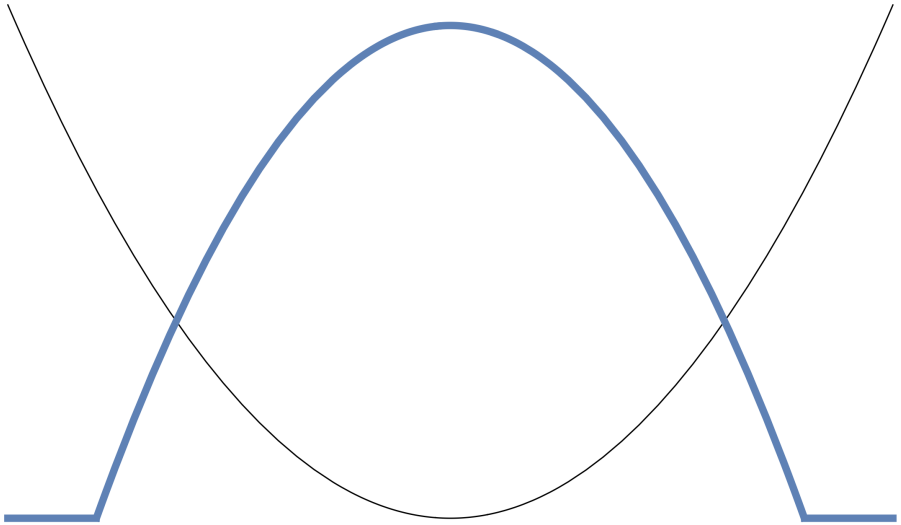
$$v_{bias} \rightarrow \Delta n \rightarrow V$$

$$\frac{d\Delta n}{dt} \rightarrow I$$

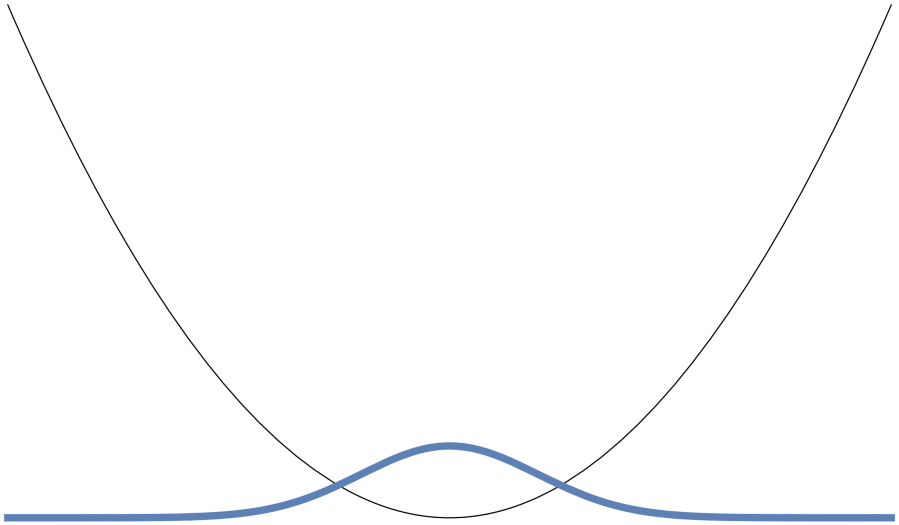


Boshier group, Nat. Comm. 11, 3338 (2020)

Dimensionality

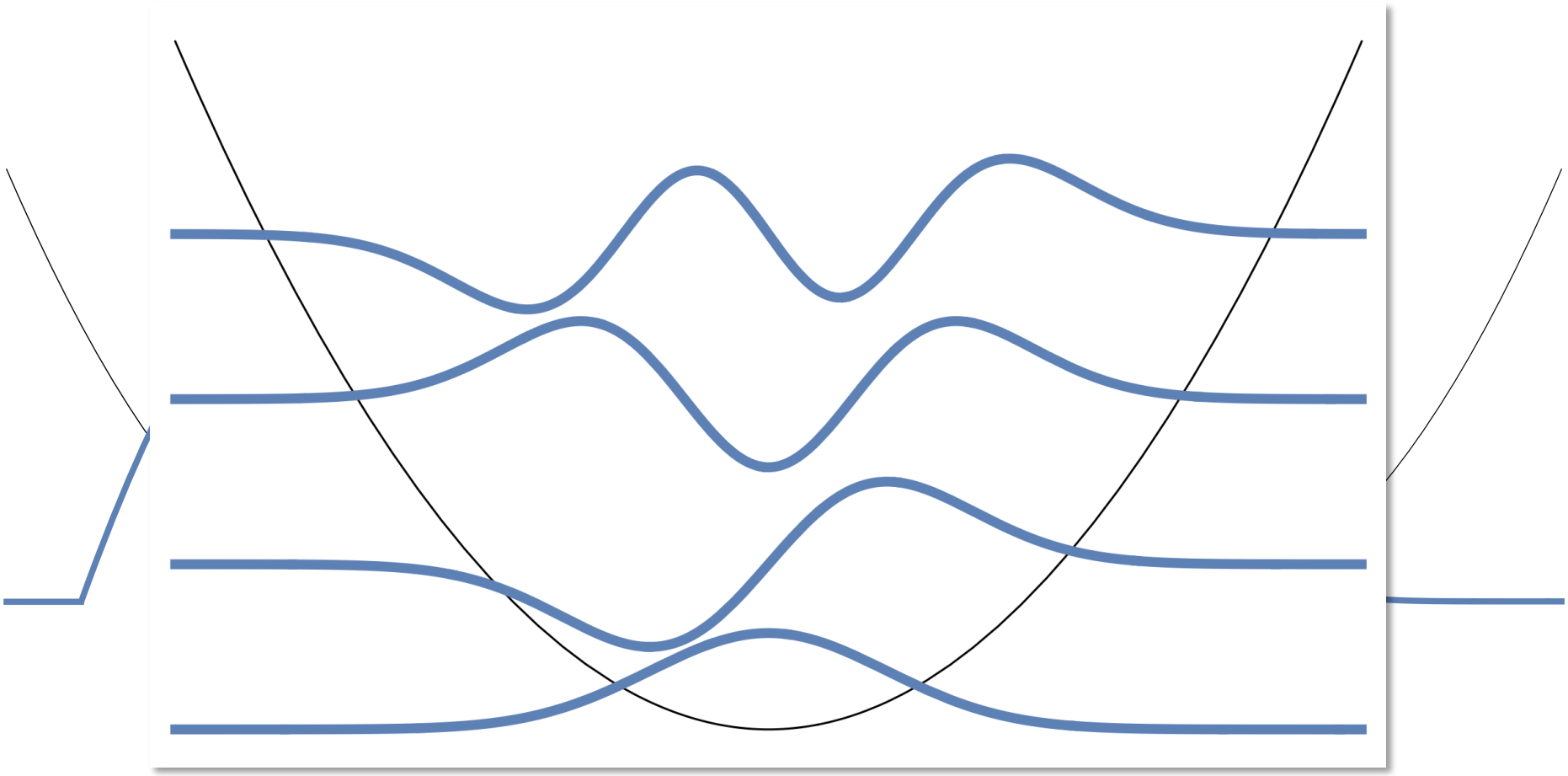


3D



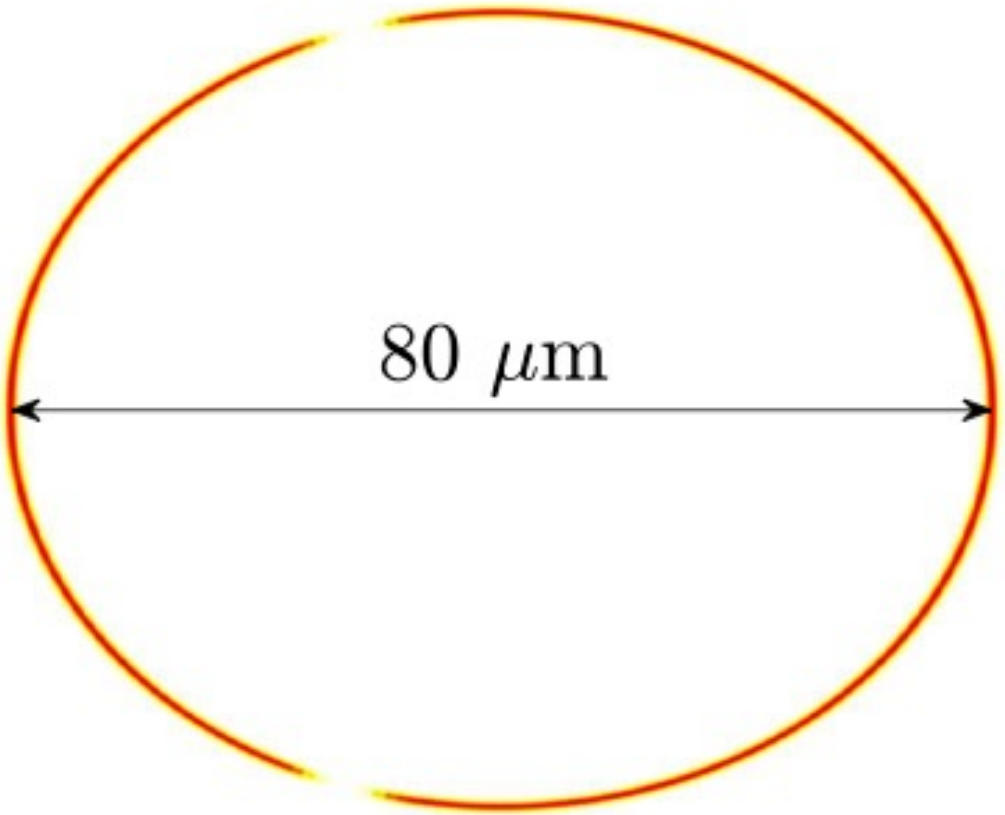
1D

Dimensionality

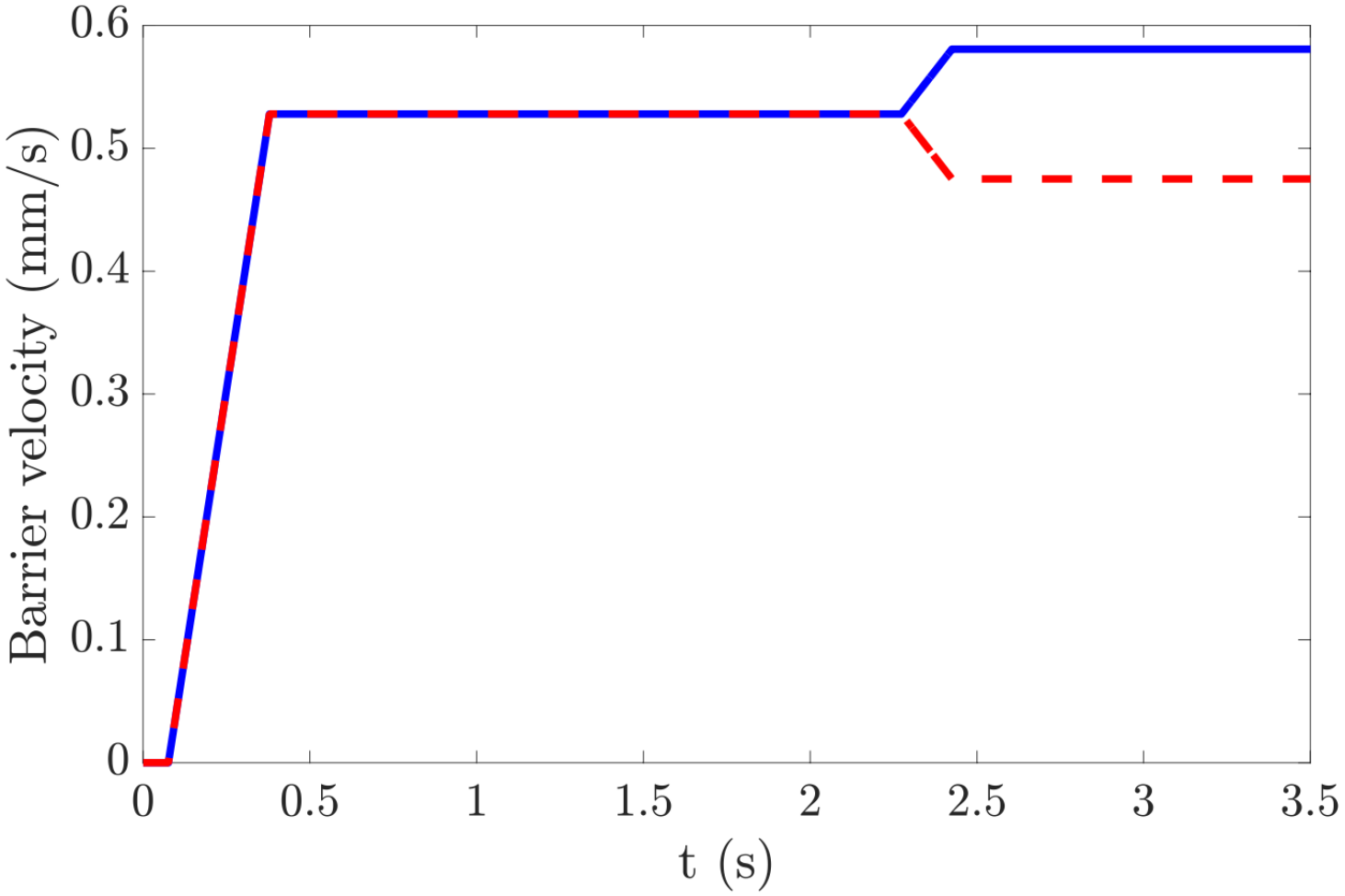


Quasi-1D

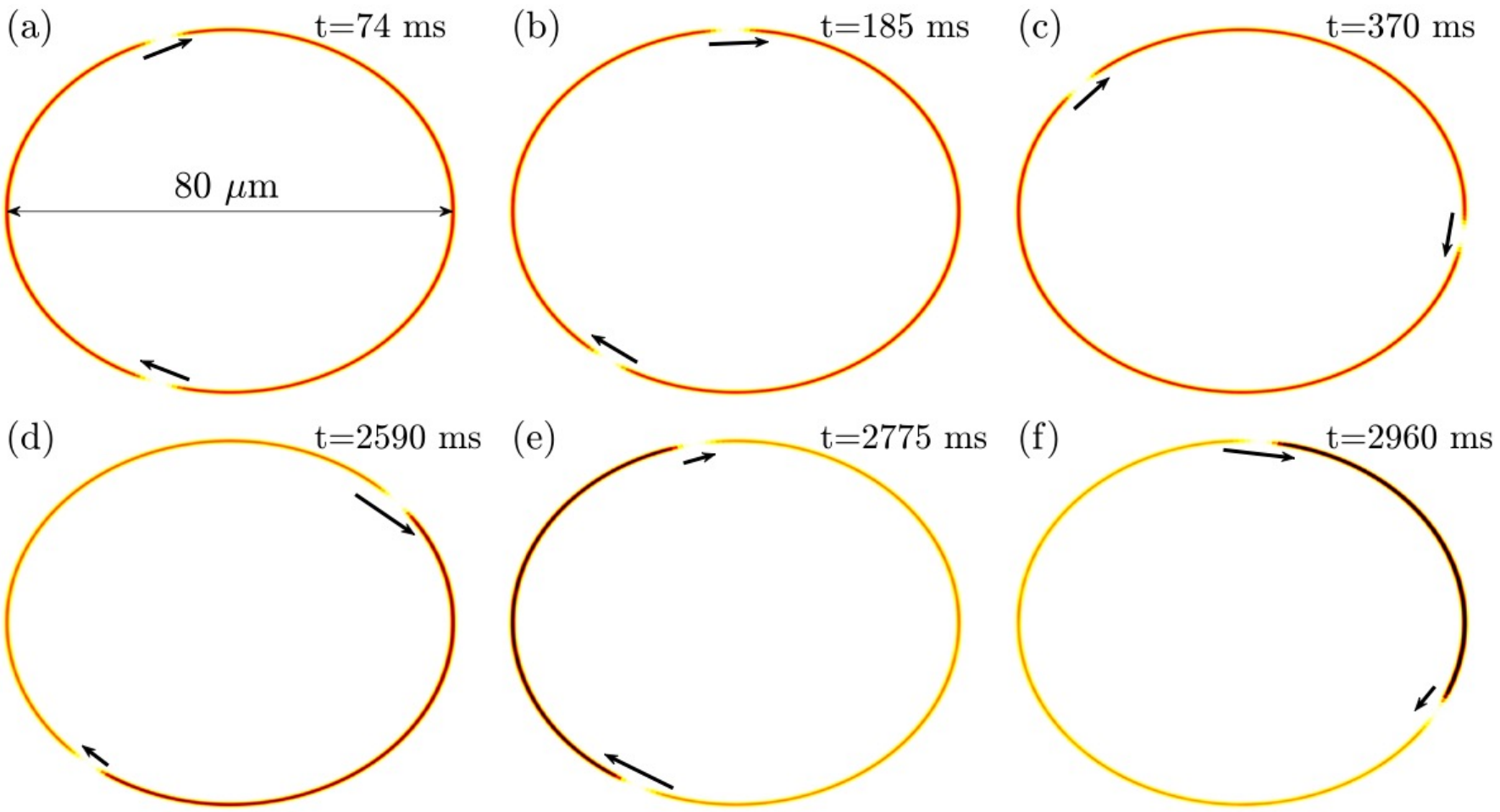
Quasi-1D condensates



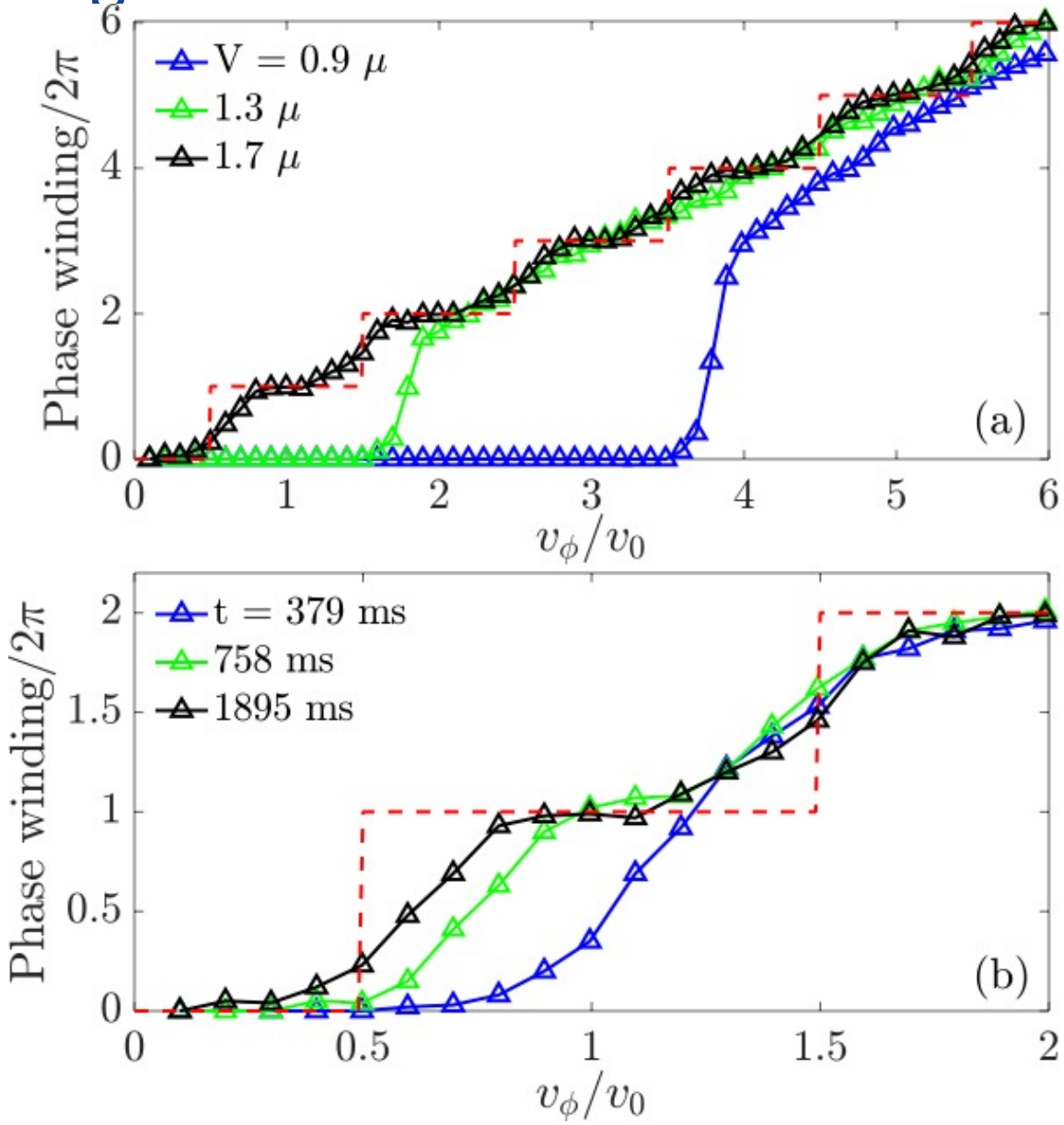
Protocol



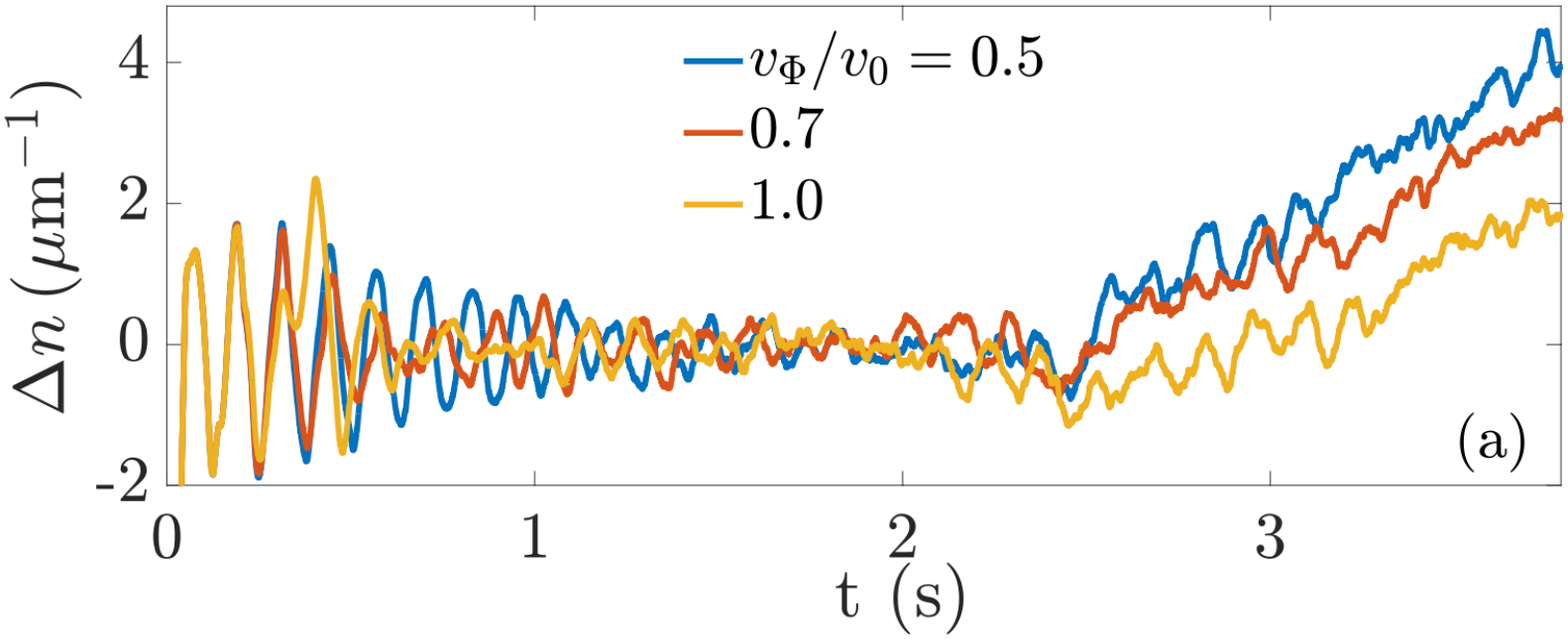
SQUID dynamics



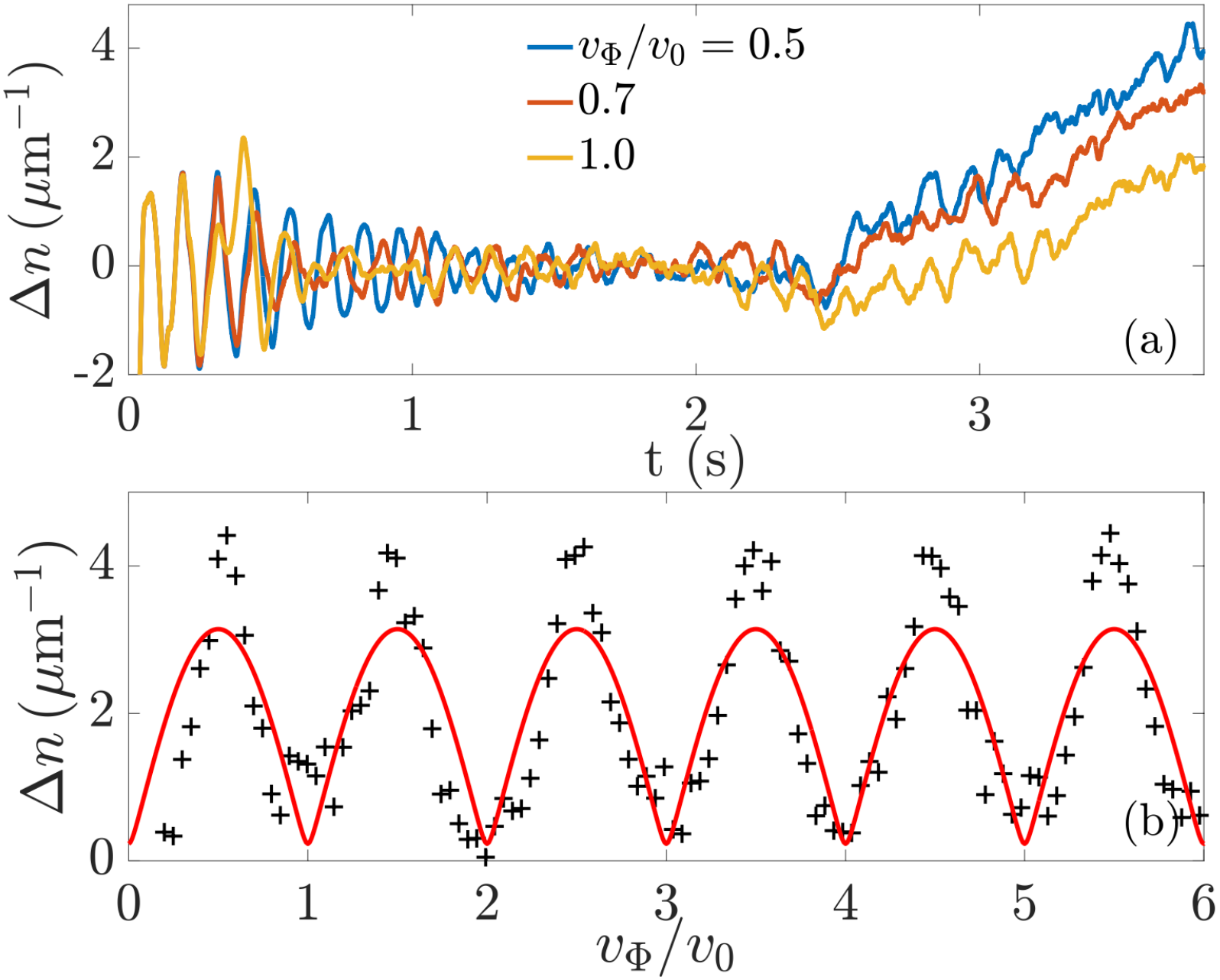
Phase winding



Density imbalance



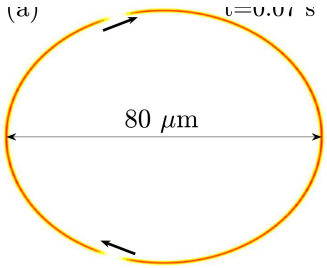
Voltage-flux relation



Overview

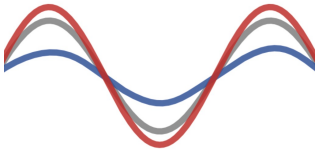
Implementation of an atomtronic SQUID in a strongly Confined toroidal condensate

Hannes Kiehn, Vijay Singh, LM

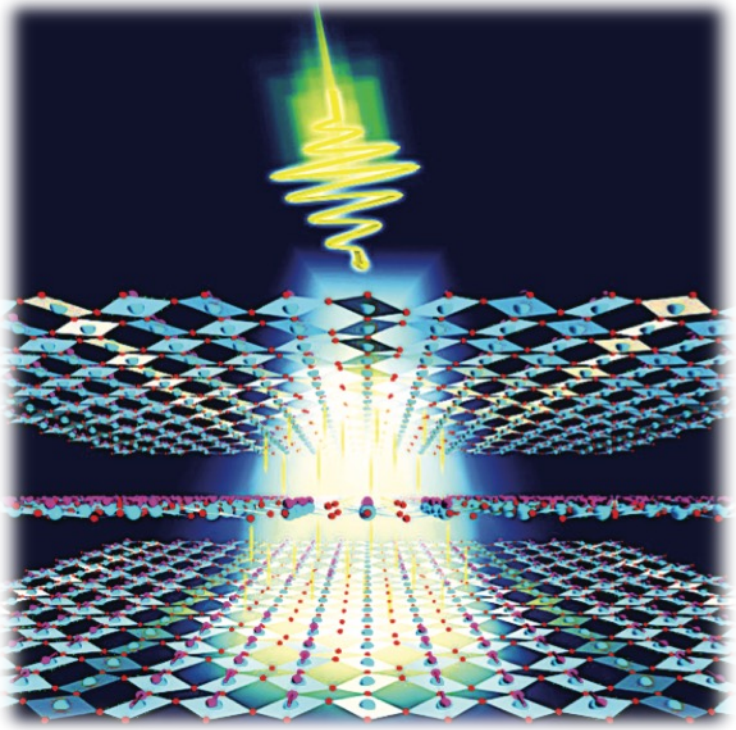


Dynamical control of an atomic Josephson junction

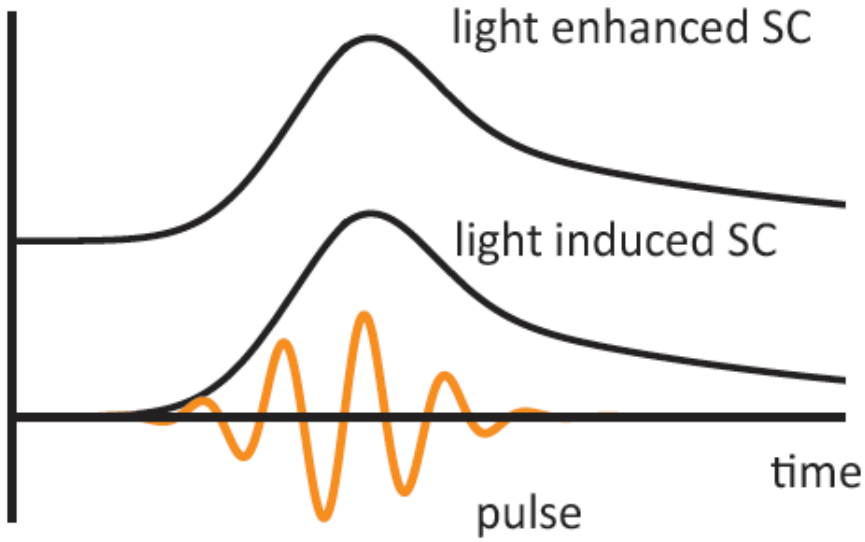
Beilei Zhu, Vijay Singh, Junichi Okamoto, LM



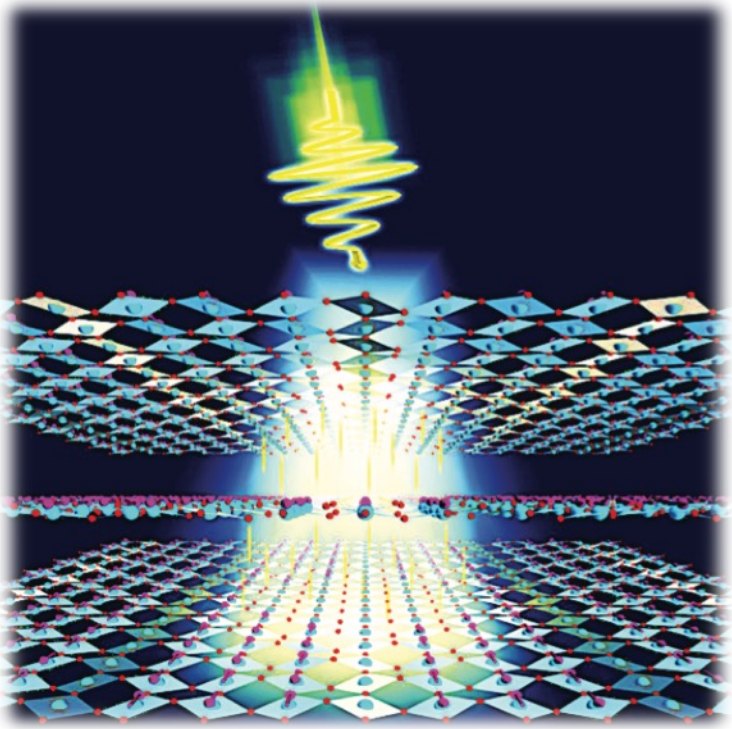
Light-induced dynamics

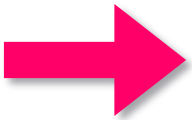


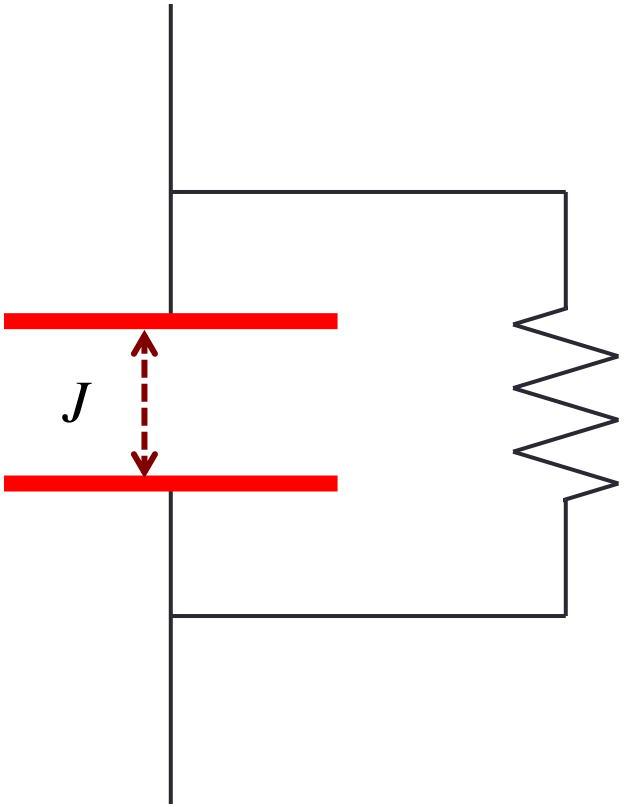
Pump-probe experiments



Parametric Control

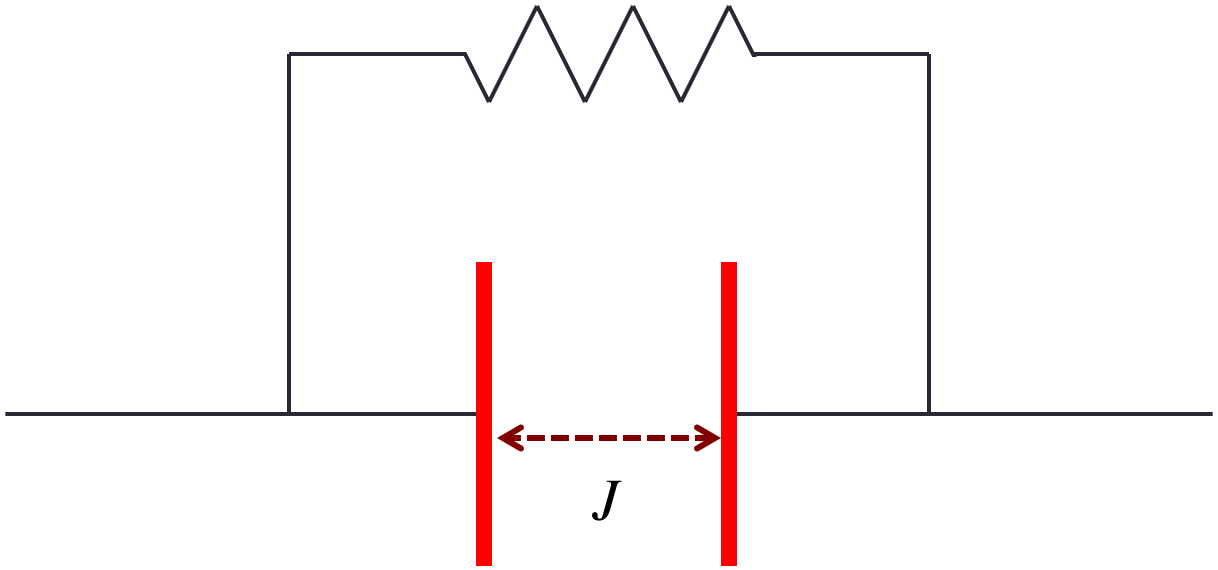






Okamoto, Cavalleri, LM, PRL 117, 227001, ’16

Resistively and capacitively shunted Josephson junction

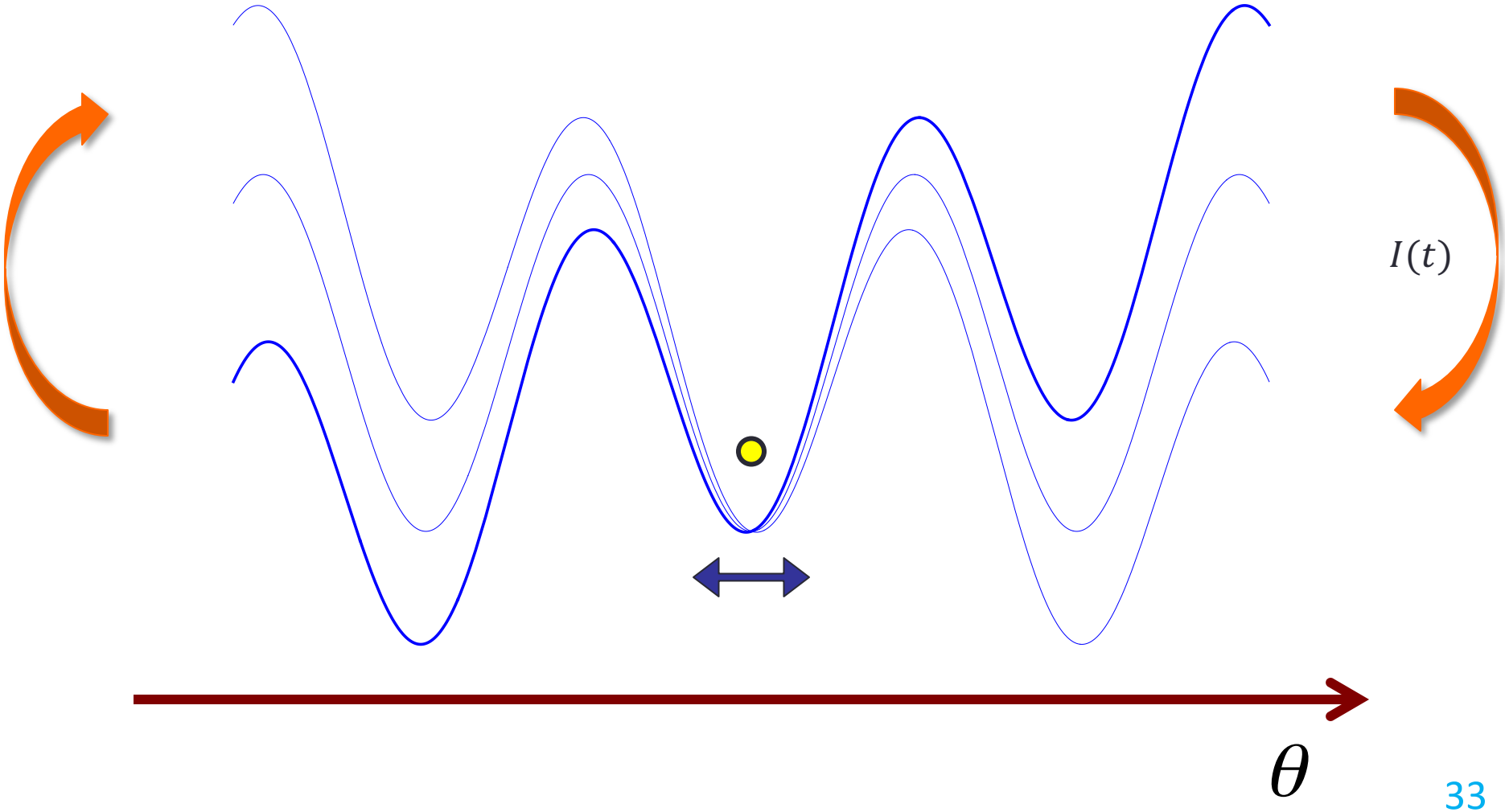


$$I(t) = Jn_0 \sin(\theta) + \frac{\hbar}{qR}\dot{\theta} + \frac{\hbar C}{q}\ddot{\theta}$$

$$\dot{\theta} = \dot{\theta}_2 - \dot{\theta}_1 = \frac{qV(t)}{\hbar} \propto E(t)$$

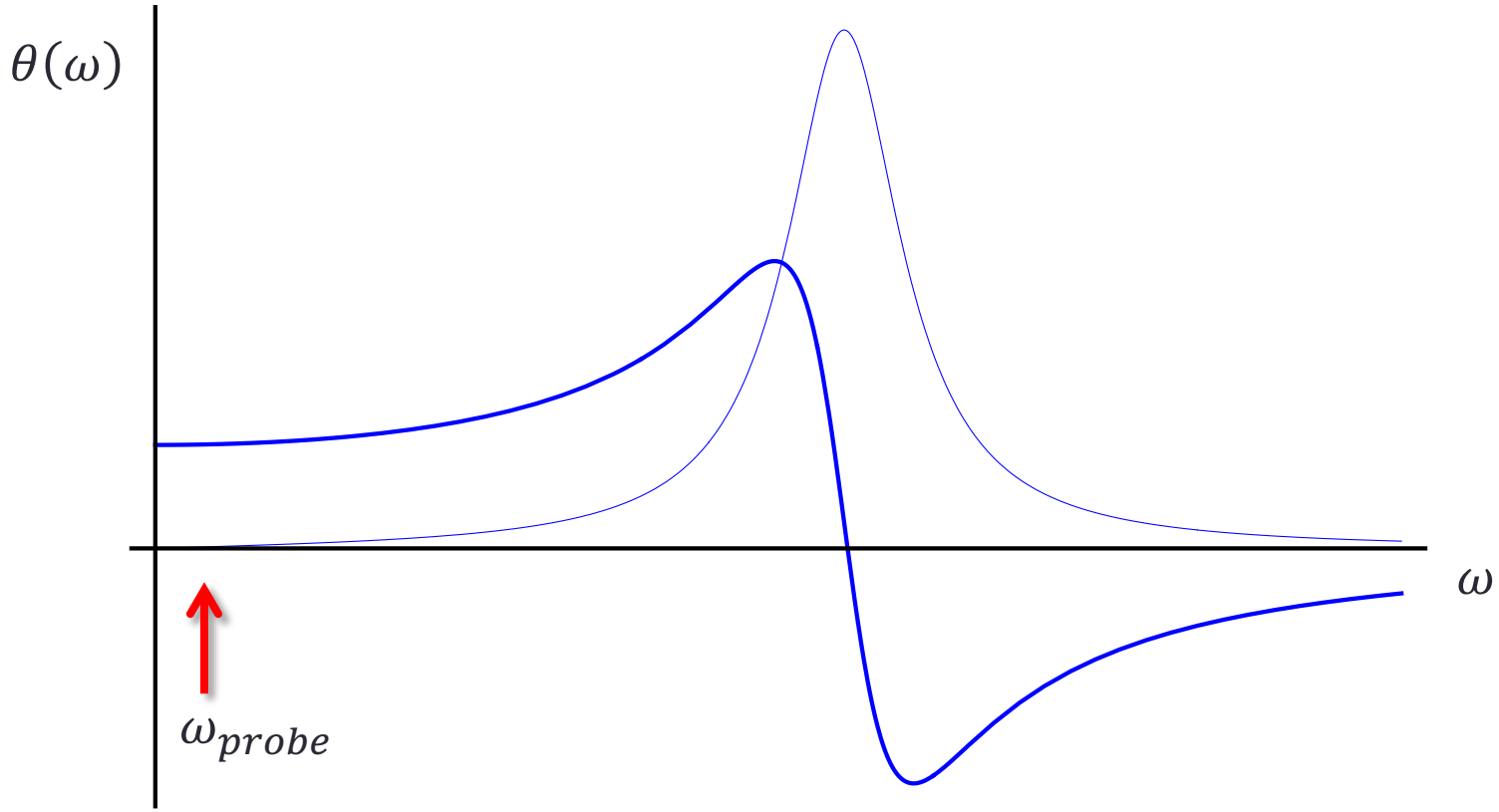
Washboard potential

$$I(t) = Jn_0 \sin(\theta) + \frac{\hbar}{qR}\dot{\theta} + \frac{\hbar C}{q}\ddot{\theta}$$



Phase-current relation

$$I(t) \sim J n_0 \theta + \frac{\hbar}{qR}\dot{\theta} + \frac{\hbar C}{q}\ddot{\theta} \quad \Rightarrow \quad \theta(\omega) \propto \frac{I(\omega)}{\omega_0^2 - i\gamma\omega - \omega^2}$$

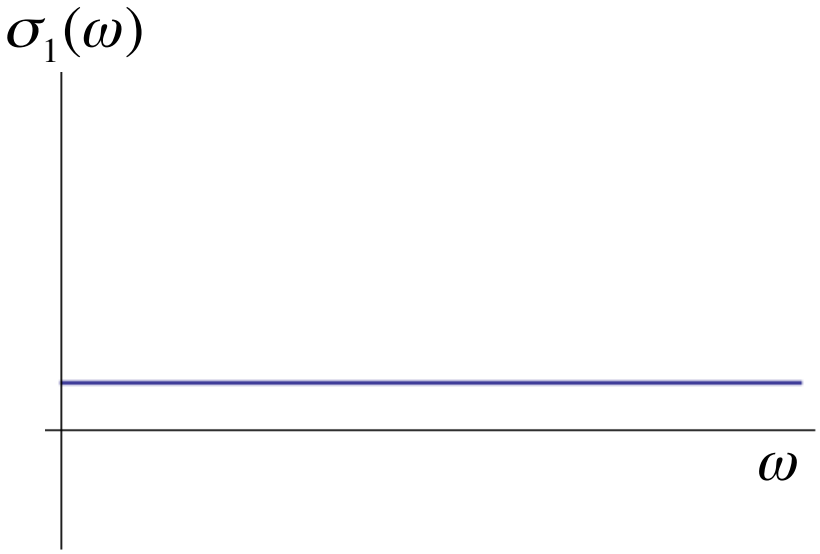


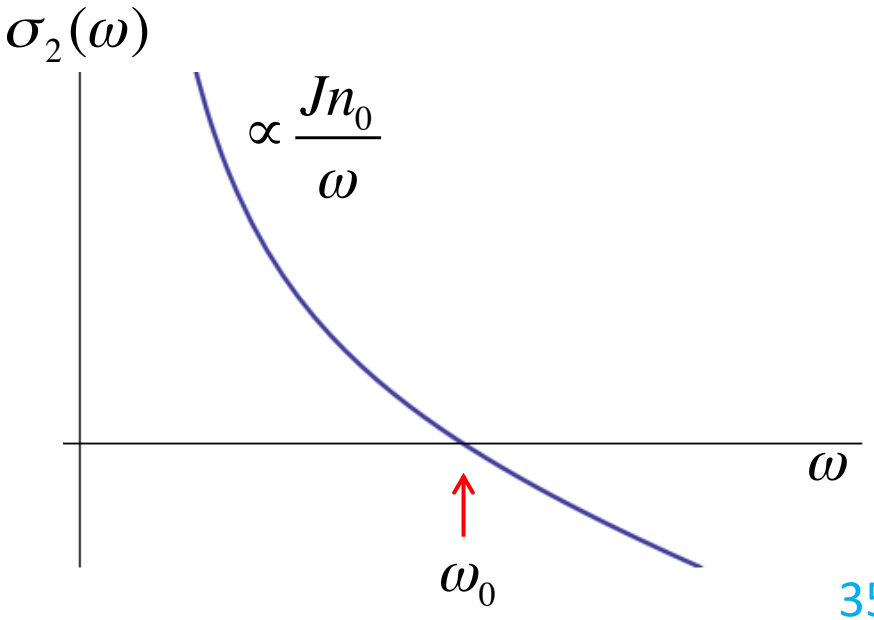
Conductivity

$$E(\omega) \propto -i\omega\theta(\omega) \propto \frac{i\omega I(\omega)}{\omega_0^2 - i\gamma\omega - \omega^2}$$

$$\underbrace{\frac{\omega_0^2 - i\gamma\omega - \omega^2}{-i\omega}} E(\omega) \propto I(\omega)$$

$$\sigma(\omega) = \sigma_1(\omega) + i\sigma_2(\omega)$$

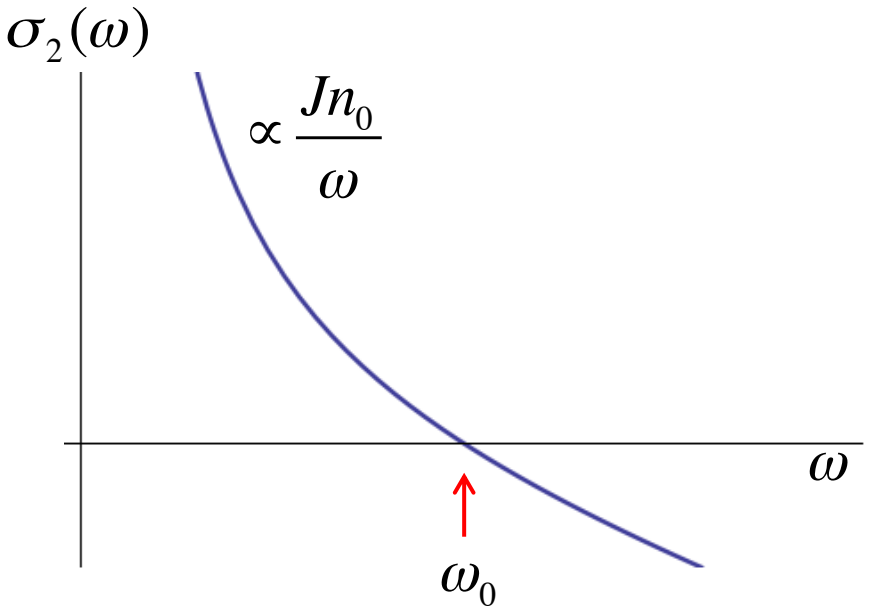




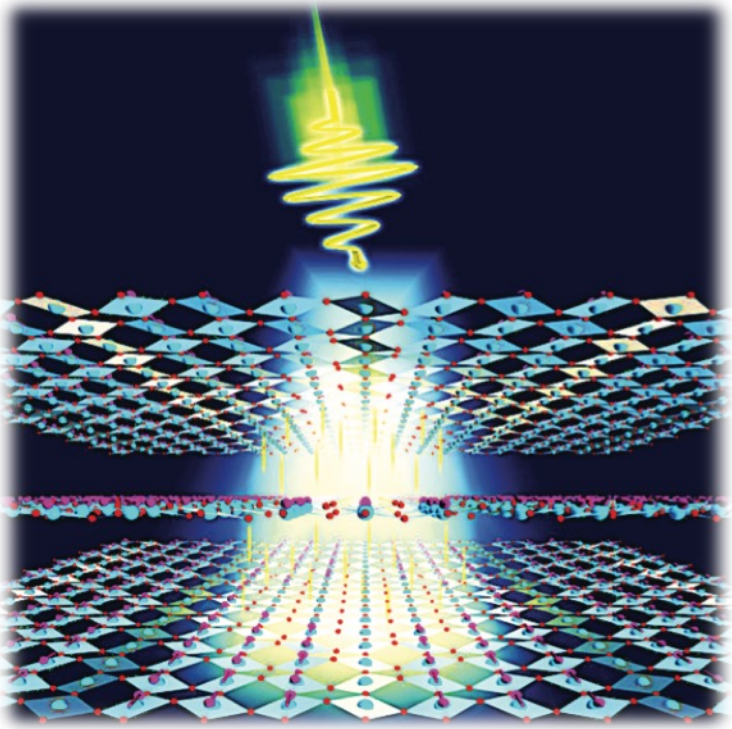
Comparison to Drude model

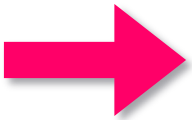
perfect conductor

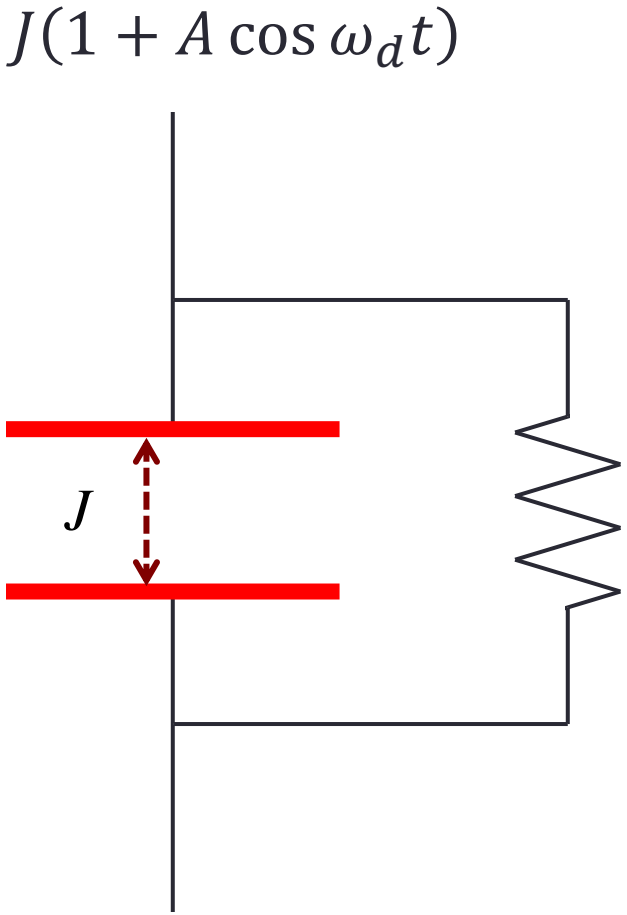
$$\sigma(\omega) = \frac{ne^2}{m}\frac{1}{1/\tau - i\omega} \quad \xrightarrow{\tau \to \infty} \quad \sigma(\omega) = i\frac{ne^2}{m}\frac{1}{\omega} = i\sigma_2(\omega)$$



Parametrically driven junction

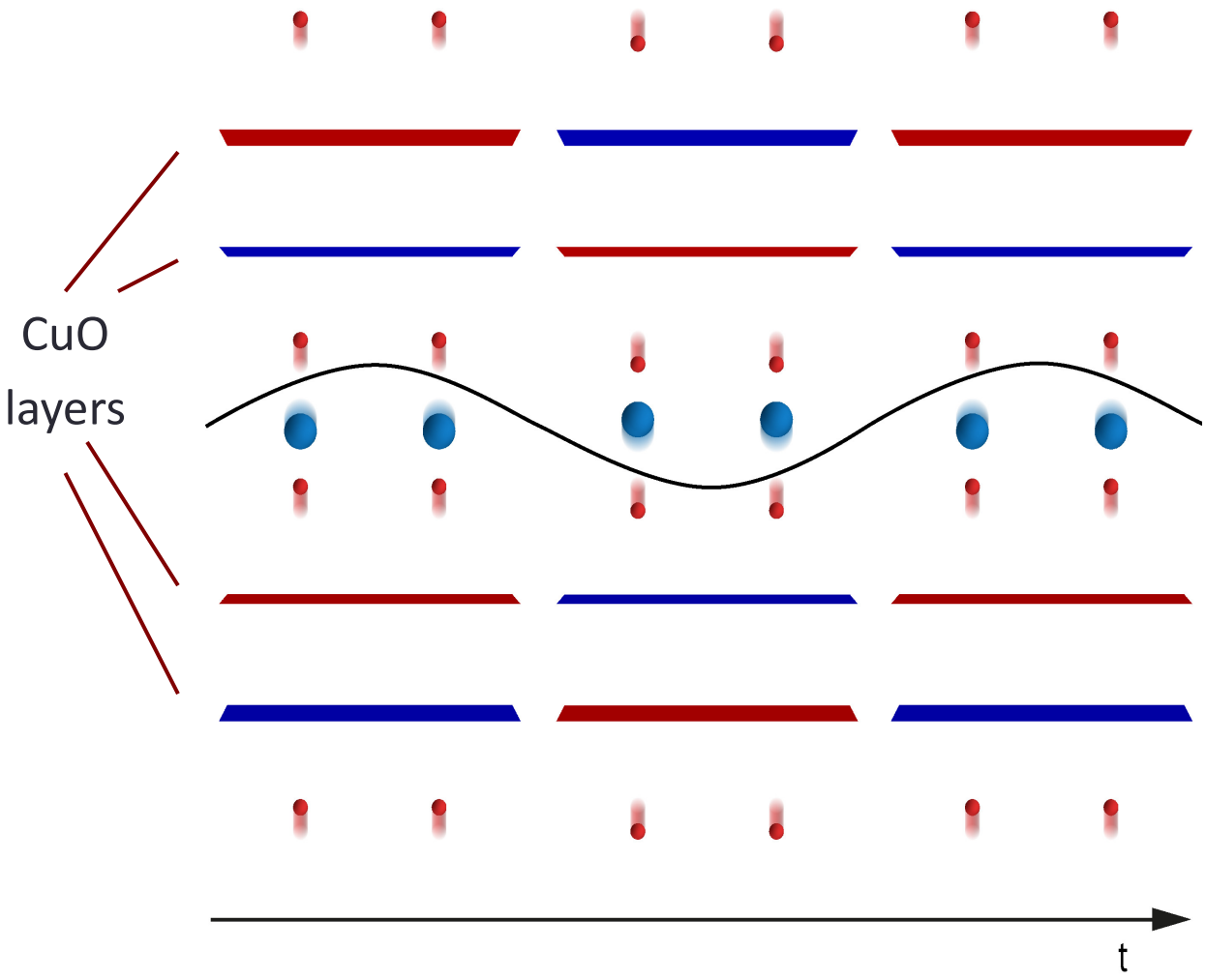






Okamoto, Cavalleri, LM, PRL 117, 227001, ’16

Phonon-induced modulation



$J_w(1 + A_w \cos \omega_d t)$

$J_s(1 - A_s \cos \omega_d t)$

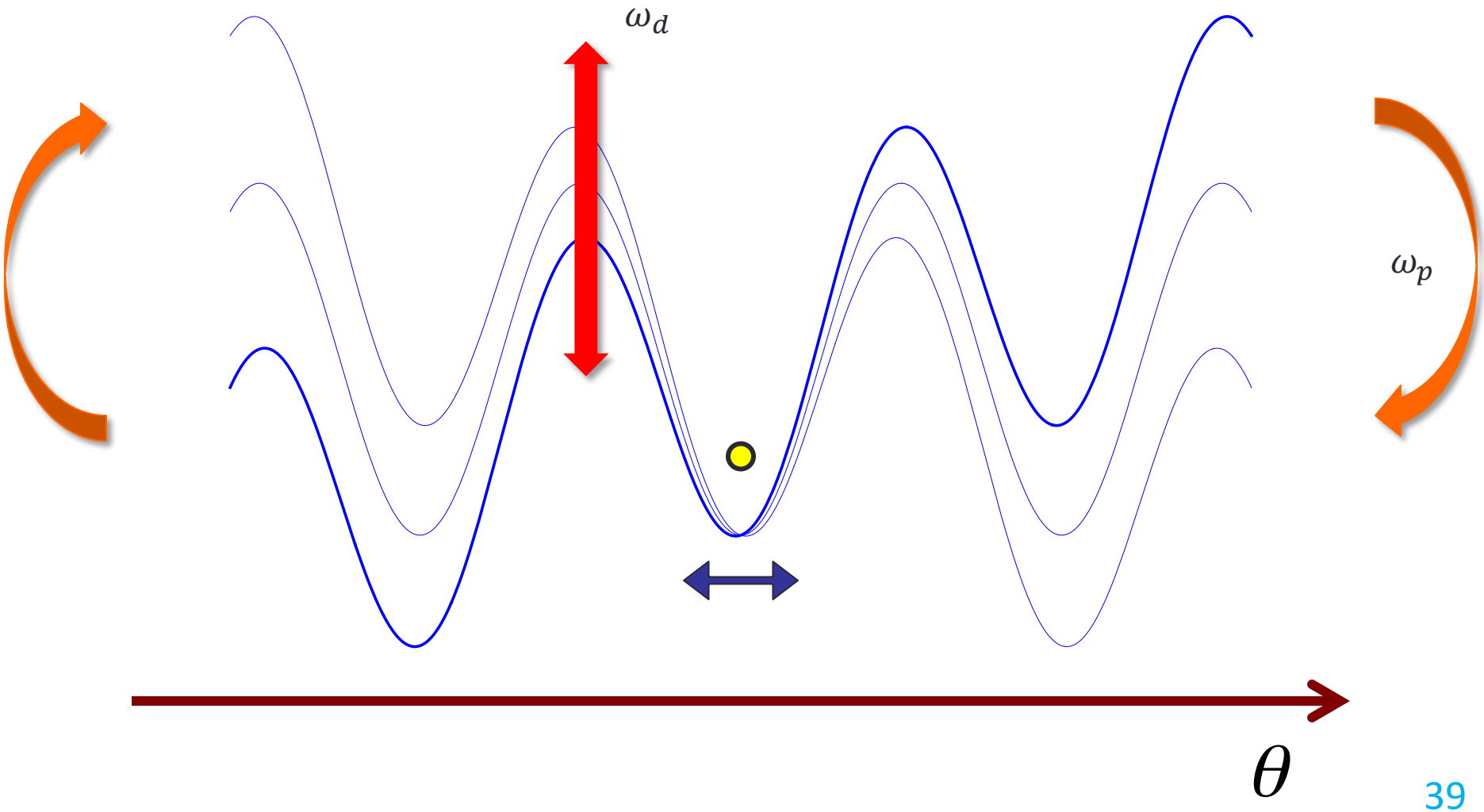
$J_w(1 + A_w \cos \omega_d t)$

$J_s(1 - A_s \cos \omega_d t)$

$J_w(1 + A_w \cos \omega_d t)$

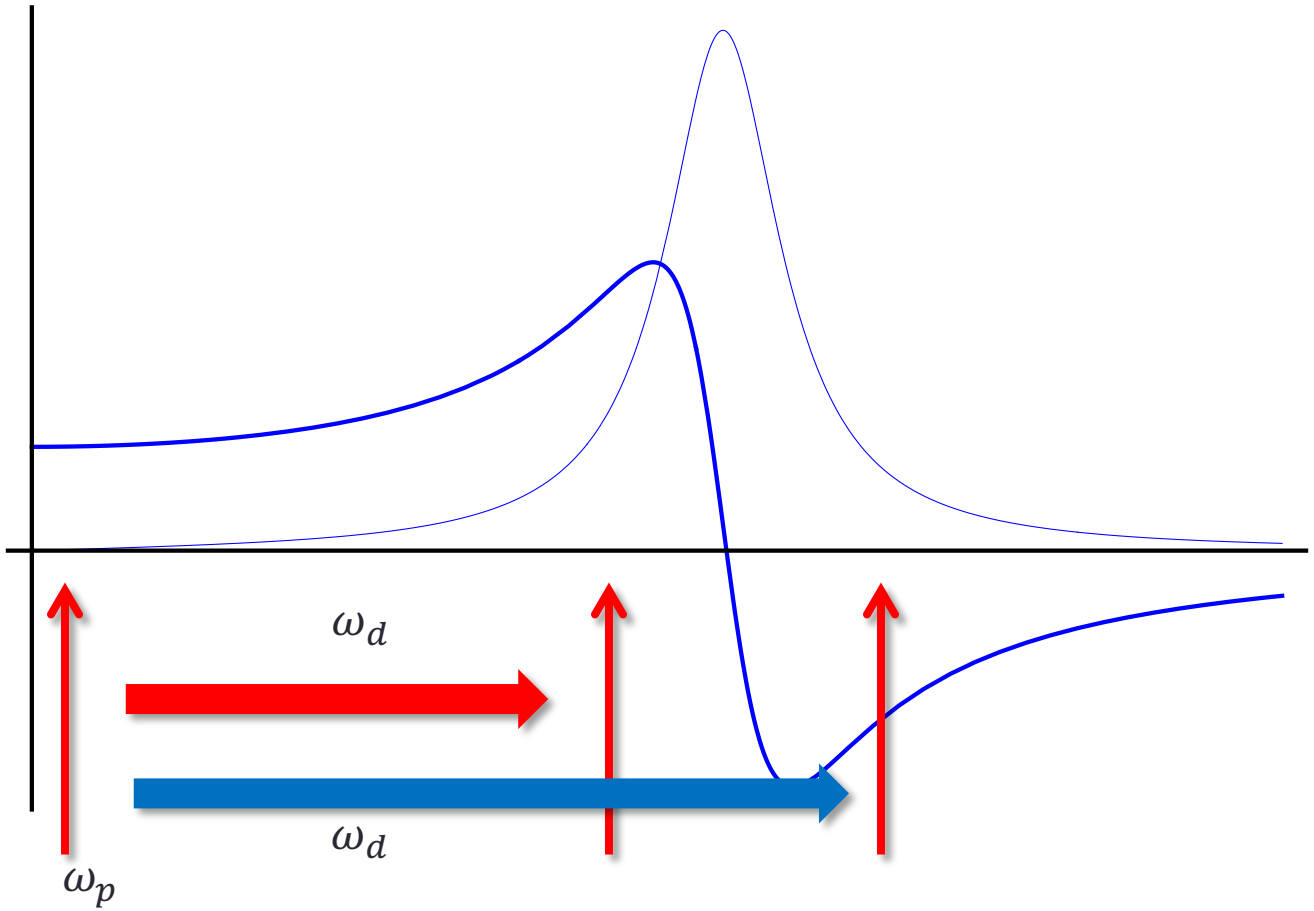
Parametrically modulated washboard potential

$$\omega_0^2(1 + A\cos\omega_d t)\theta + \gamma\dot{\theta} + \ddot{\theta} \propto I(t)$$



First order correction

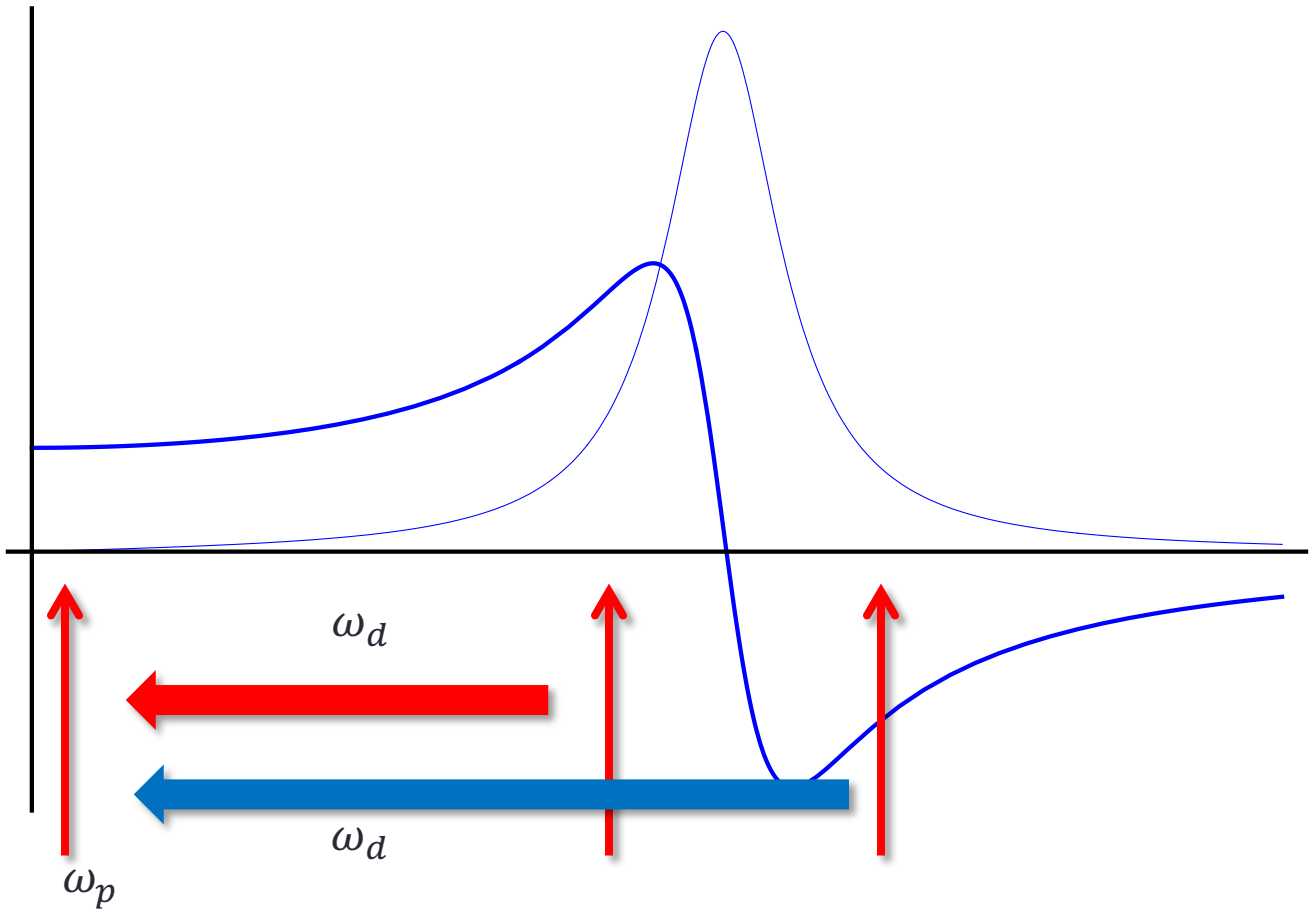
$$\theta_0 + A\theta_1 + A^2\theta_2$$



$$\theta_1(t) \propto -e^{-i\omega t} \cos \omega_d t \frac{\omega_0^2 - \omega_d^2}{(\omega_0^2 - \omega_d^2)^2 - \gamma^2 \omega_d^2}$$

Second order correction

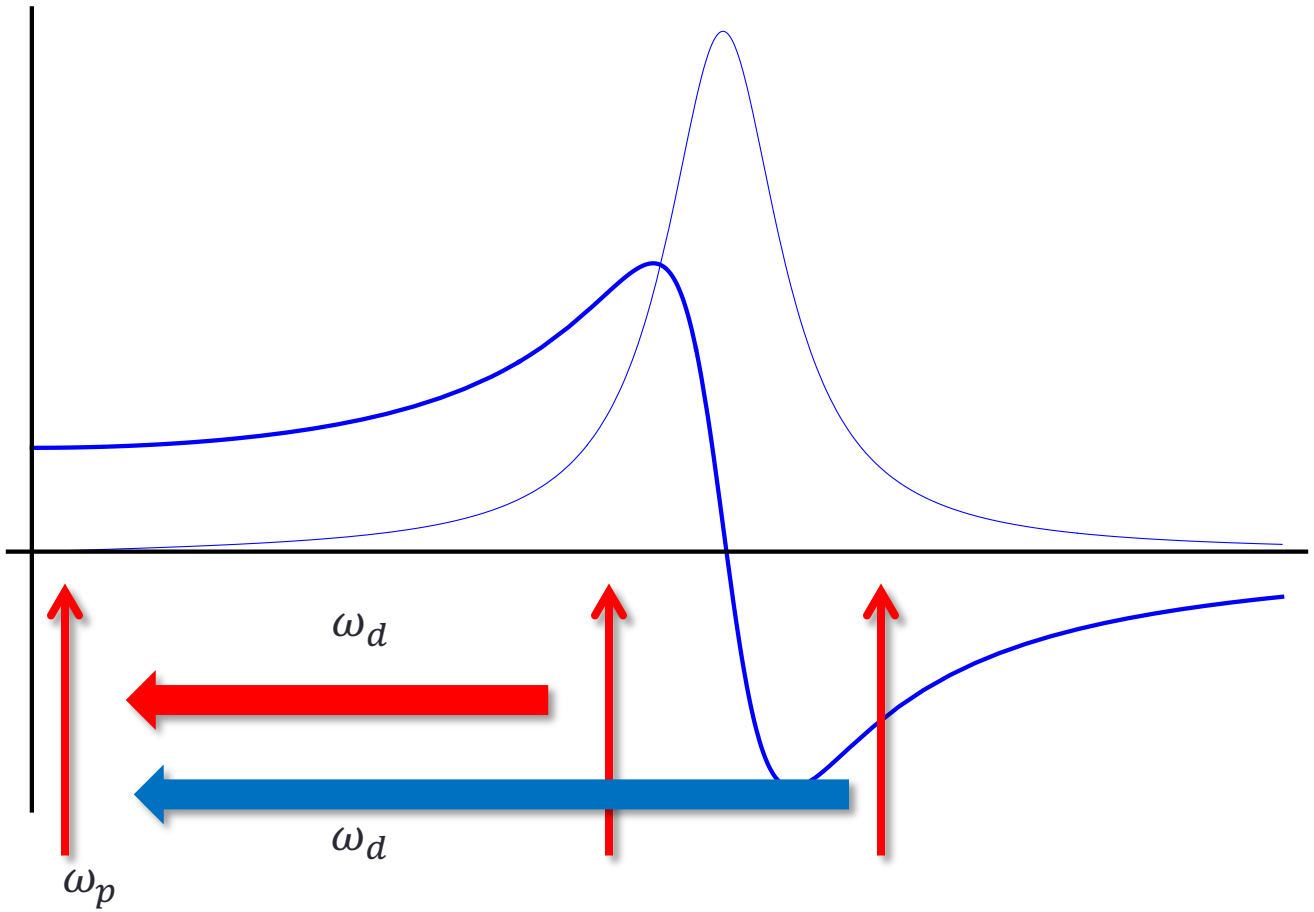
$$\theta_0 + A\theta_1 + A^2\theta_2$$



$$\theta_2(t) \propto e^{-i\omega t}(\cos\omega_d t)^2 \frac{\omega_0^2 - \omega_d^2}{(\omega_0^2 - \omega_d^2)^2 + \gamma^2\omega_d^2}$$

Second order correction

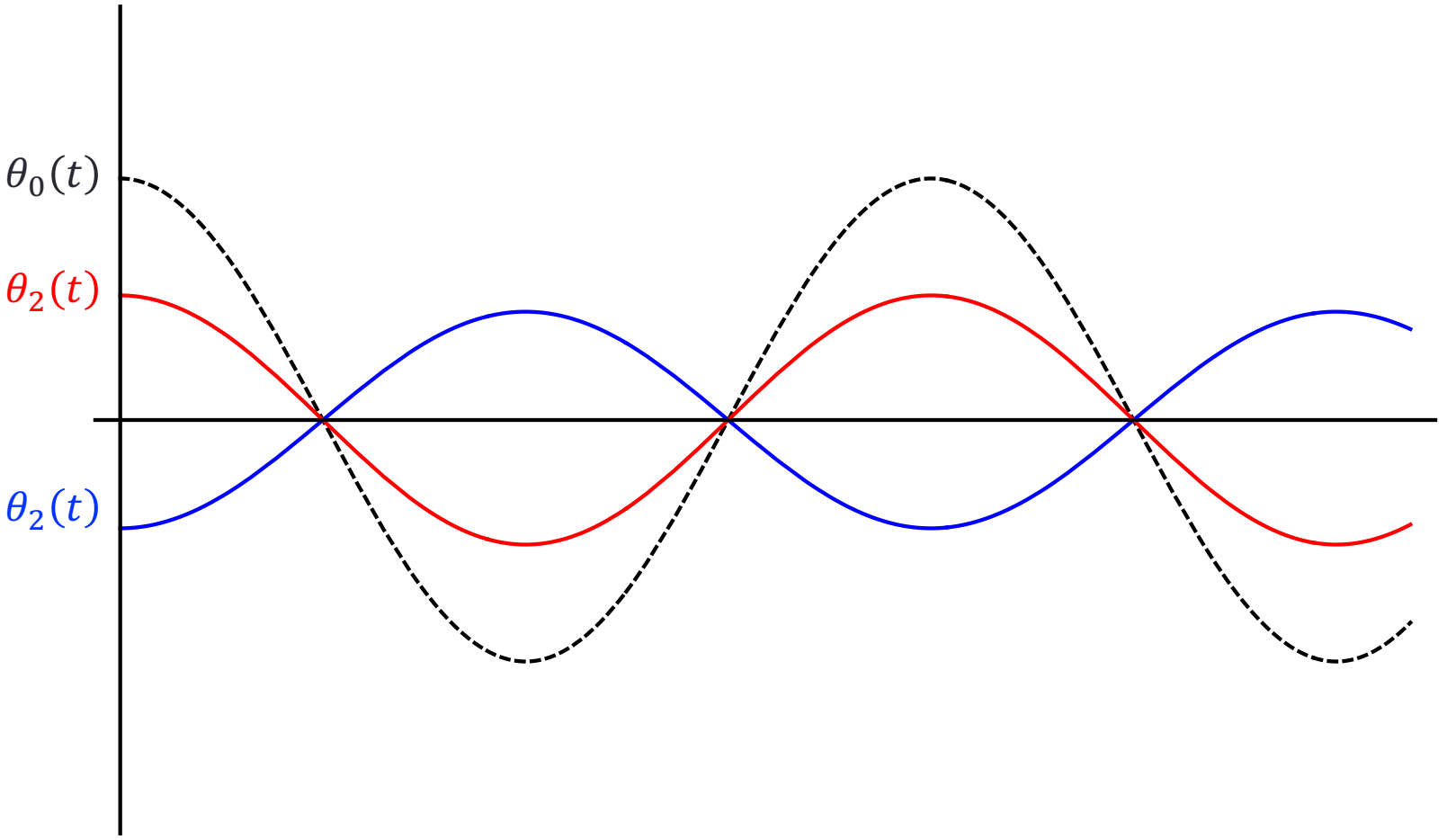
$$\theta_0 + A\theta_1 + A^2\theta_2$$



$$\theta_2(t) \propto e^{-i\omega t}\frac{1}{2}\frac{\omega_0^2 - \omega_d^2}{(\omega_0^2 - \omega_d^2)^2 + \gamma^2\omega_d^2}$$

Second order correction

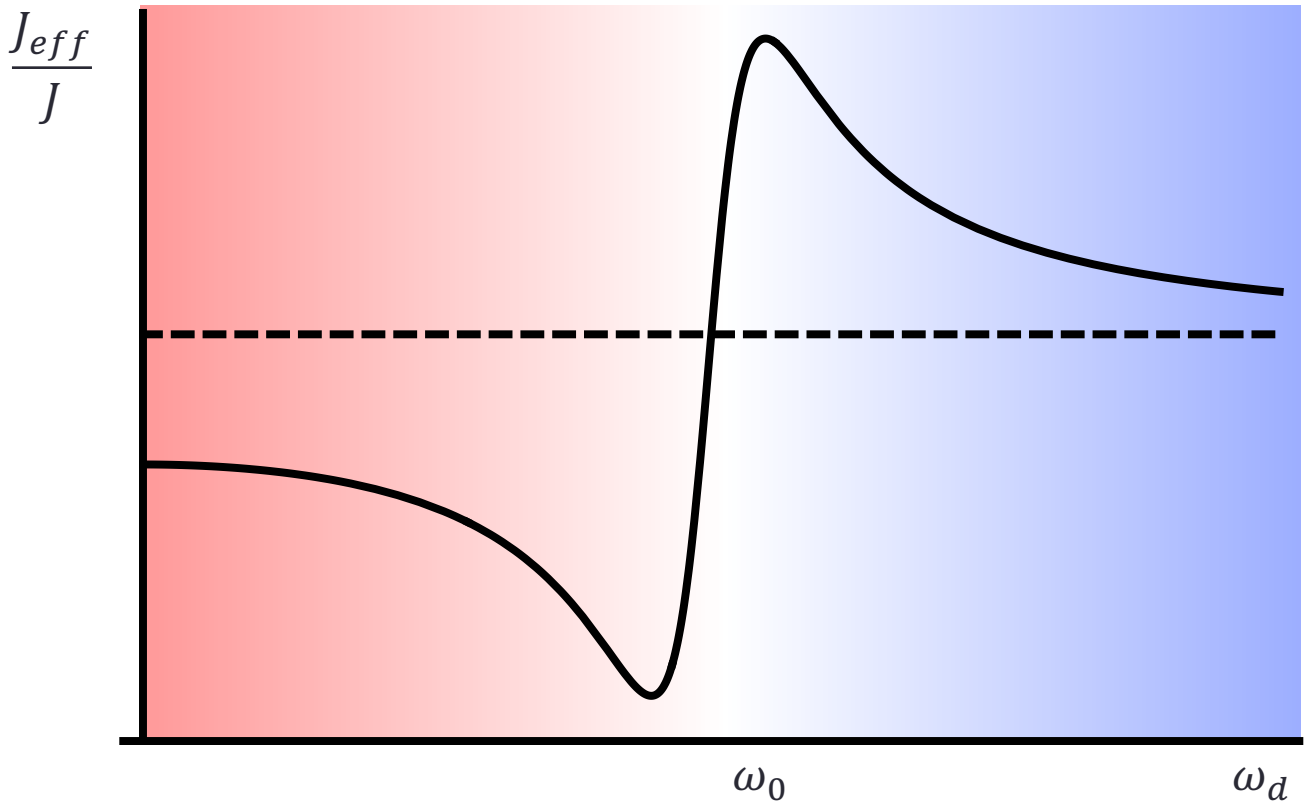
$$\theta_0 + A\theta_1 + A^2\theta_2$$



Red detuning: destabilization

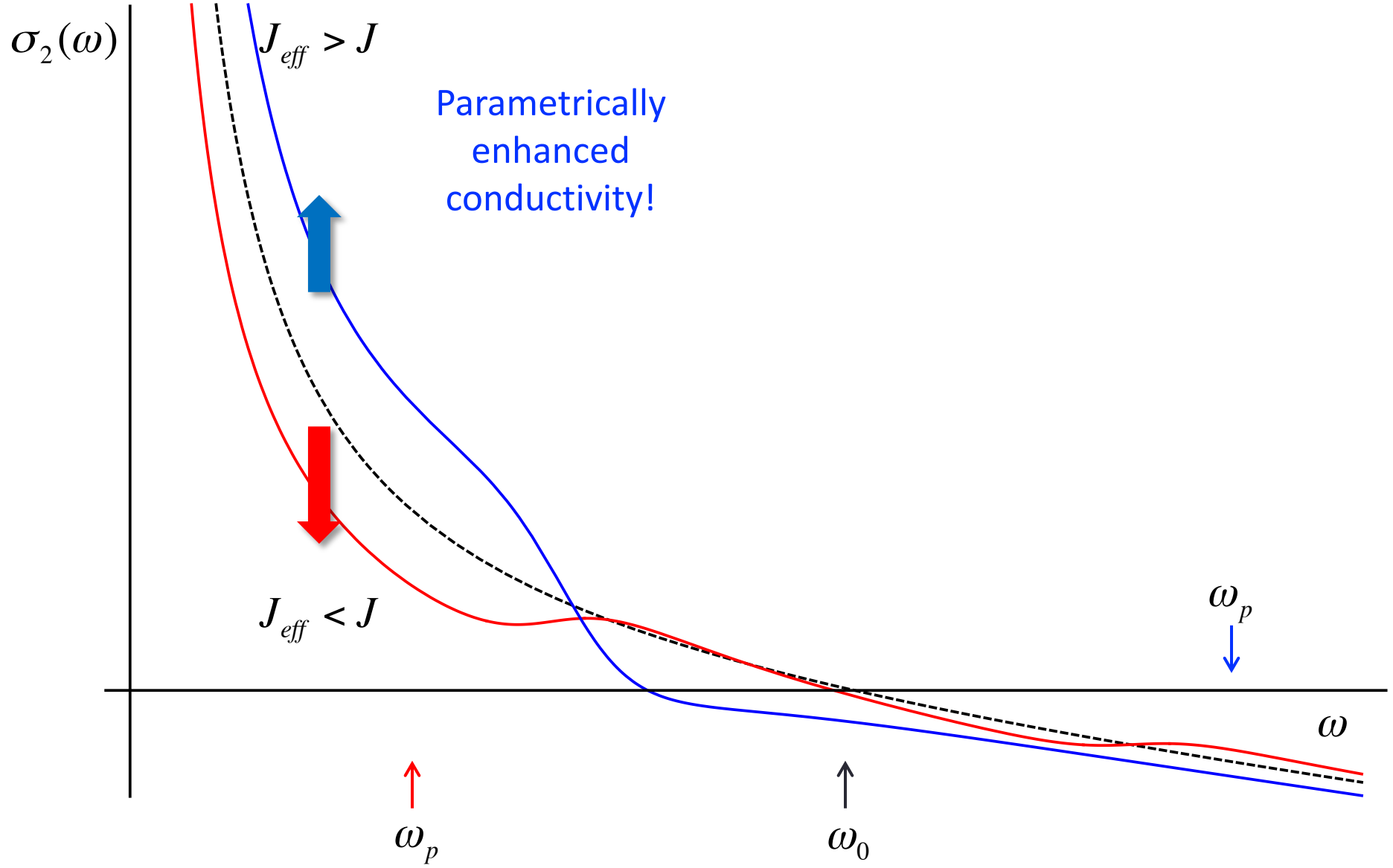
Blue detuning: stabilization

Effective Josephson energy

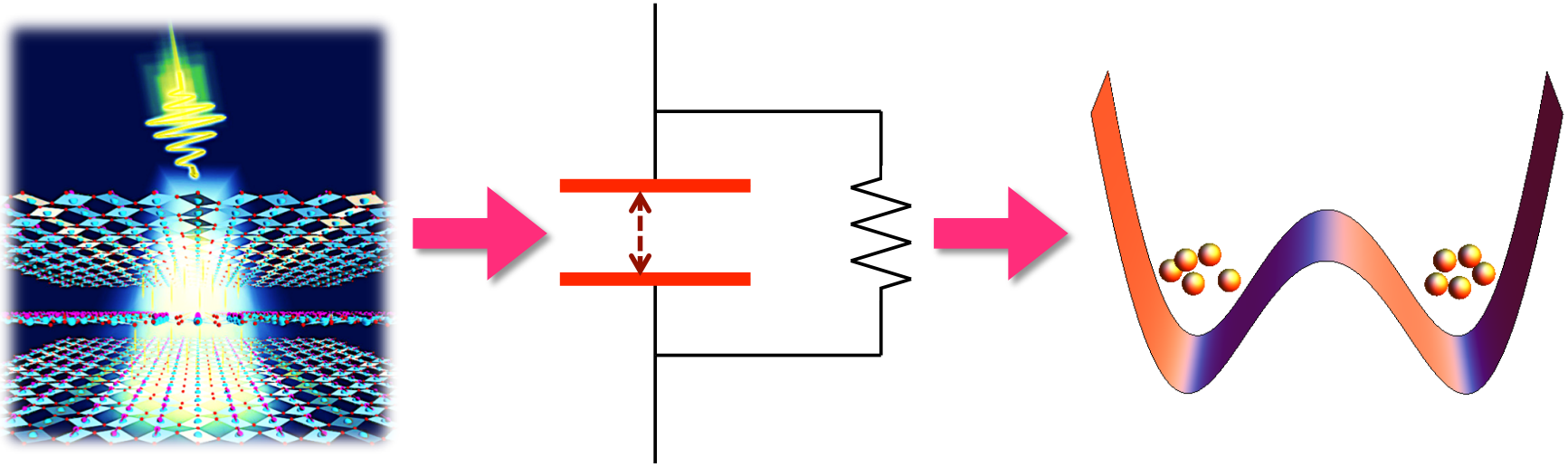


$$\frac{J_{eff}}{J} \propto 1 - \frac{A^2}{2} \frac{\omega_0^2(\omega_0^2 - \omega_d^2)}{(\omega_0^2 - \omega_d^2)^2 - \gamma^2 \omega_d^2}$$

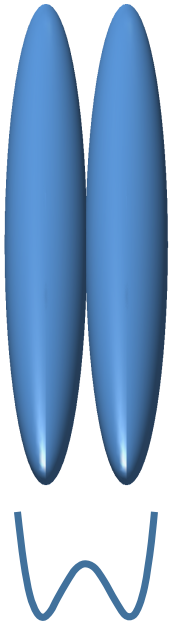
Conductivity of the driven state



Atomic Josephson junction

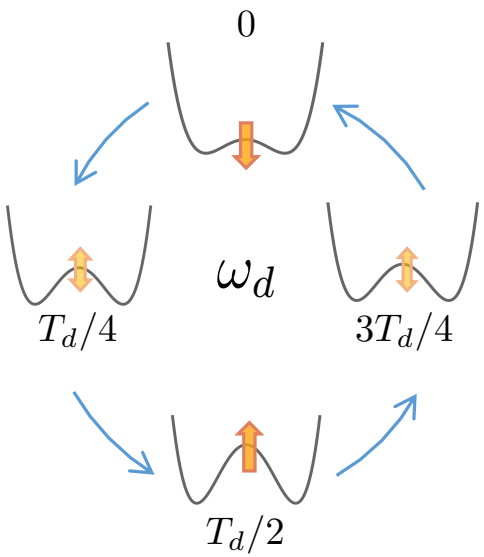


Atomic Josephson junction

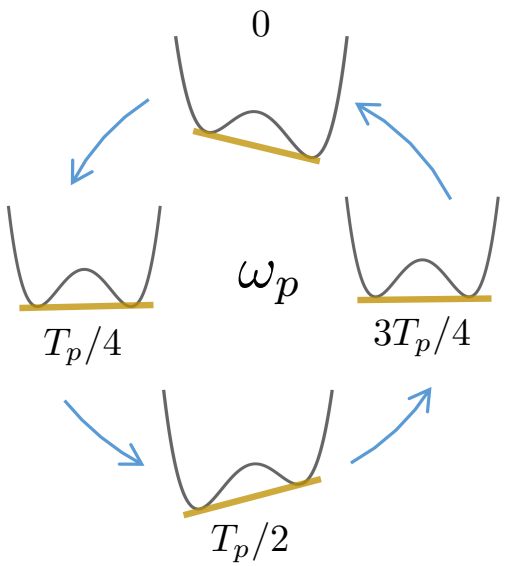


Condensates in a double-well

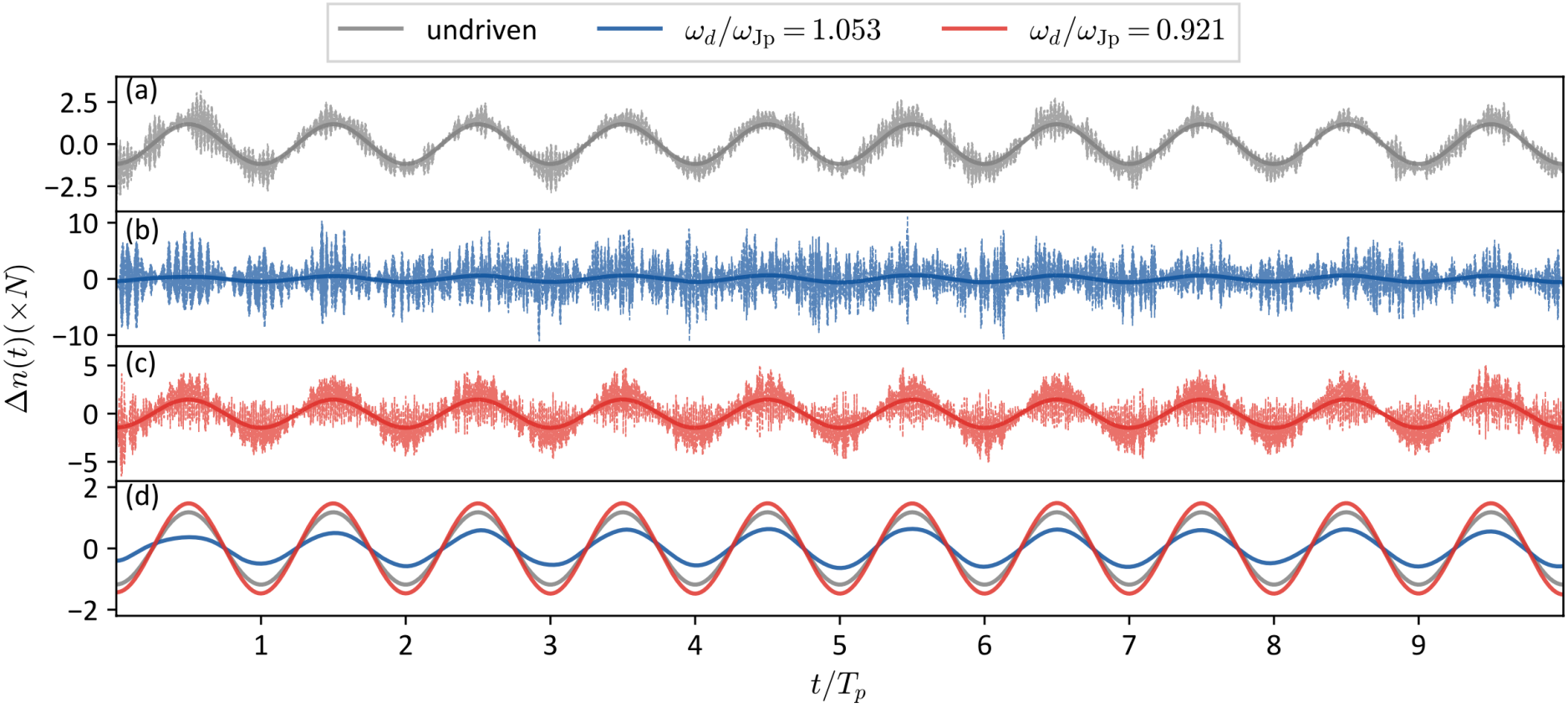
driving



probe



Density response



Neutral particles

$$-\dot{V}(t) \sim \omega_J^2 \theta + \gamma \dot{\theta} + \ddot{\theta}$$

$$\sigma^n(\omega) = \frac{j(\omega)}{V(\omega)}$$

$$\sigma^n(\omega) \sim \frac{i\omega}{\omega^2 - \omega_J^2 + i\gamma\omega}$$

Charged particles

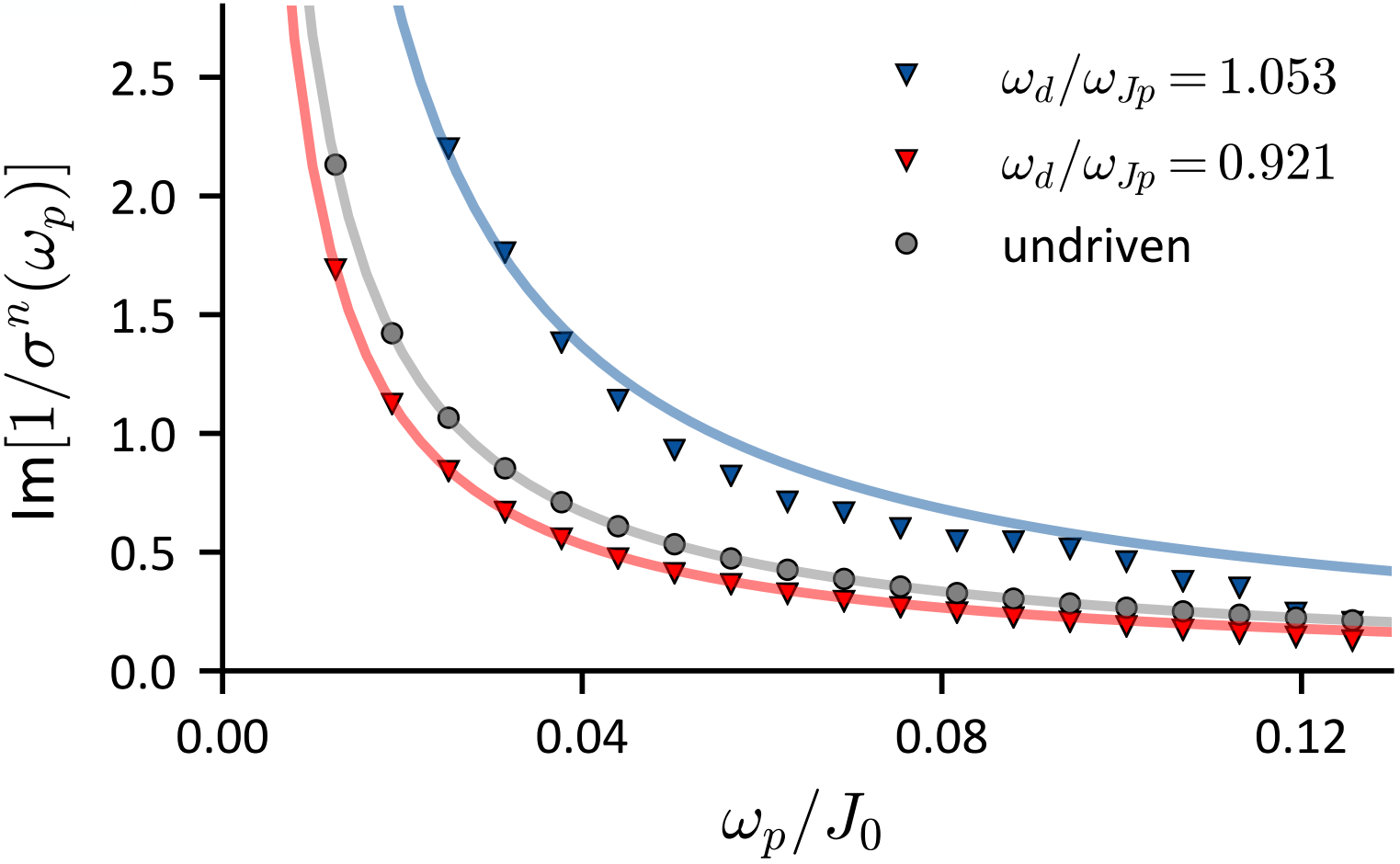
$$I(t) \sim J n_0 \theta + \frac{\hbar}{qR}\dot{\theta} + \frac{\hbar C}{q}\ddot{\theta}$$

$$\sigma^c(\omega) = \frac{j(\omega)}{E(\omega)}$$

$$\sigma^c(\omega) \sim \frac{\omega^2 - \omega_J^2 + i\gamma\omega}{i\omega}$$

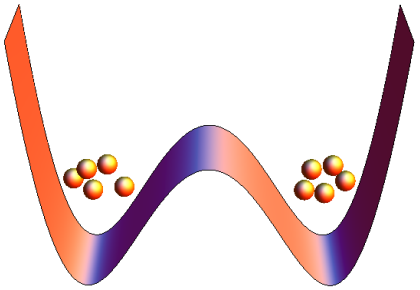
$$\frac{1}{\sigma^n(\omega)} \sim \sigma^c(\omega)$$

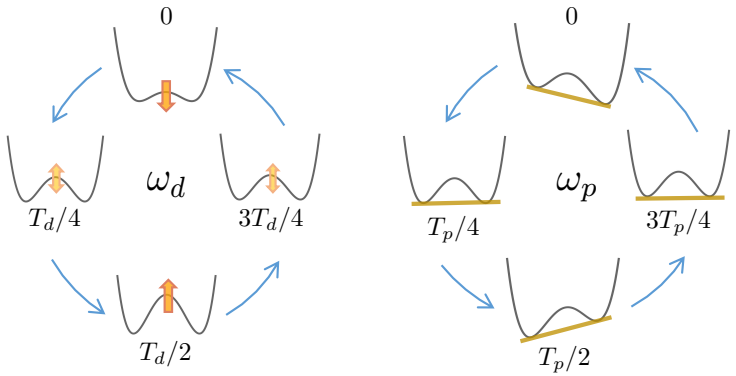
Conductivity



Conclusions on atomic Josephson junctions

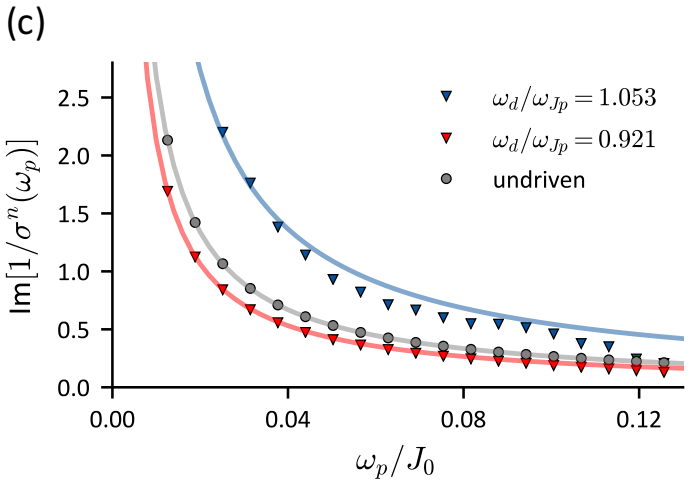
Atomic junction of coupled condensates





Implementation of pump and probe mechanism

Parametric control of conductivity



PRR 3, 013111 (2021)

Overview

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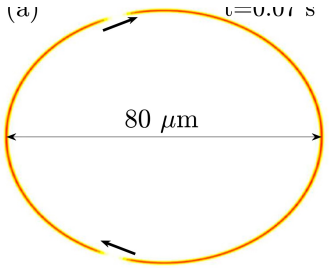
Hannes Kiehn, Vijay Singh, LM

arXiv:2204.03000



Dynamical control of an atomic Josephson junction

Beilei Zhu, Vijay Singh, Junichi Okamoto, LM

PRR 3, 013111, ‘21