

Twisted by dissipation

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NCCR QSIT, SNF
www.quantumoptics.ethz.ch

Twisted by dissipation

Driven

Dissipative

Interacting

Quantum many-body system

Twisted by dissipation

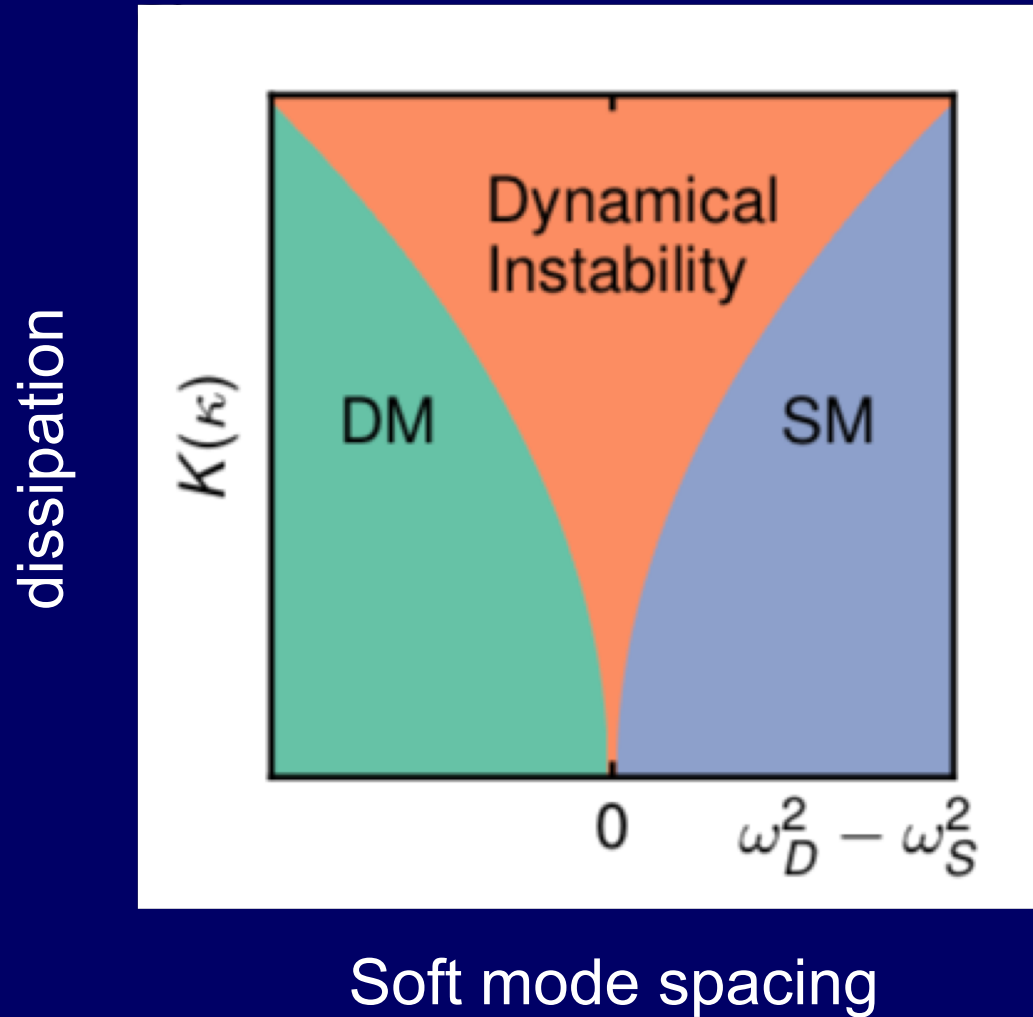
Driven

Dissipative

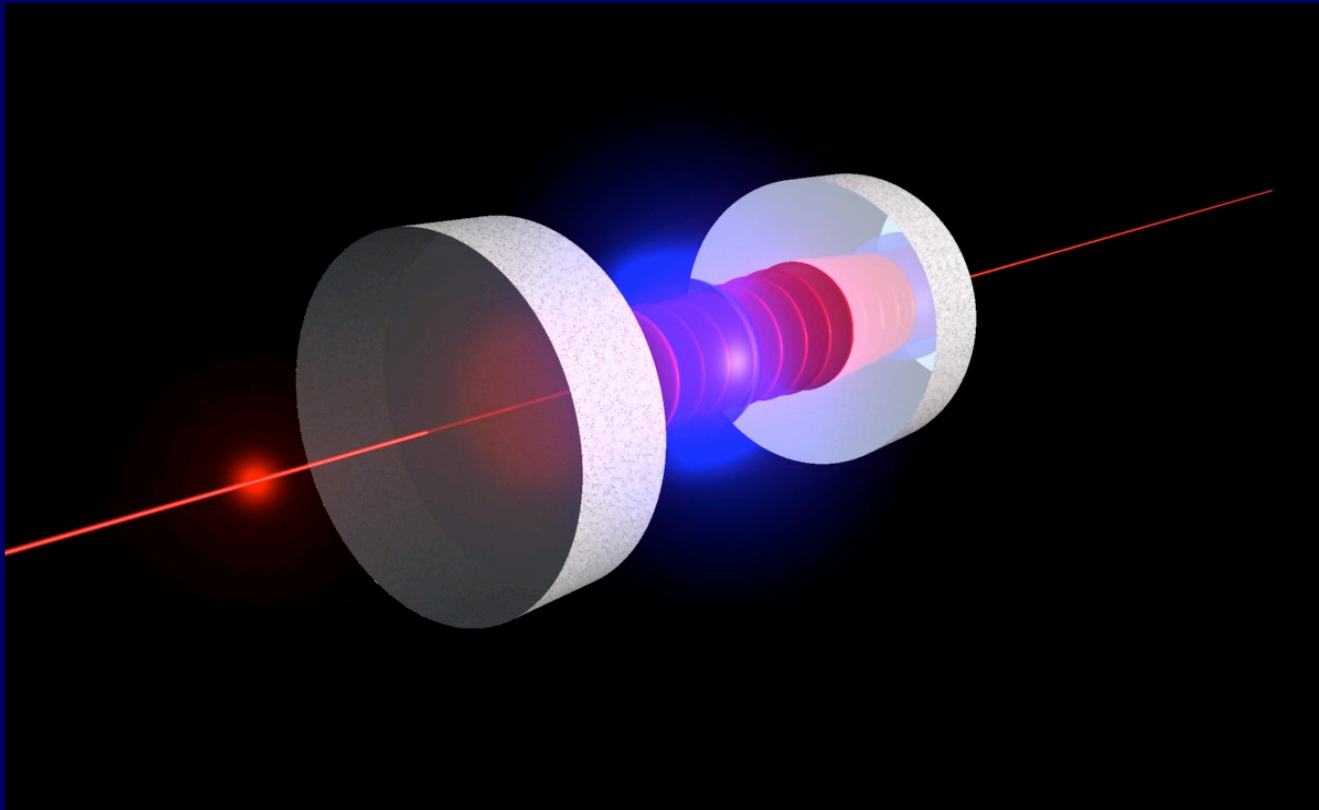
Interacting

Quantum many-body system

Twisted by dissipation

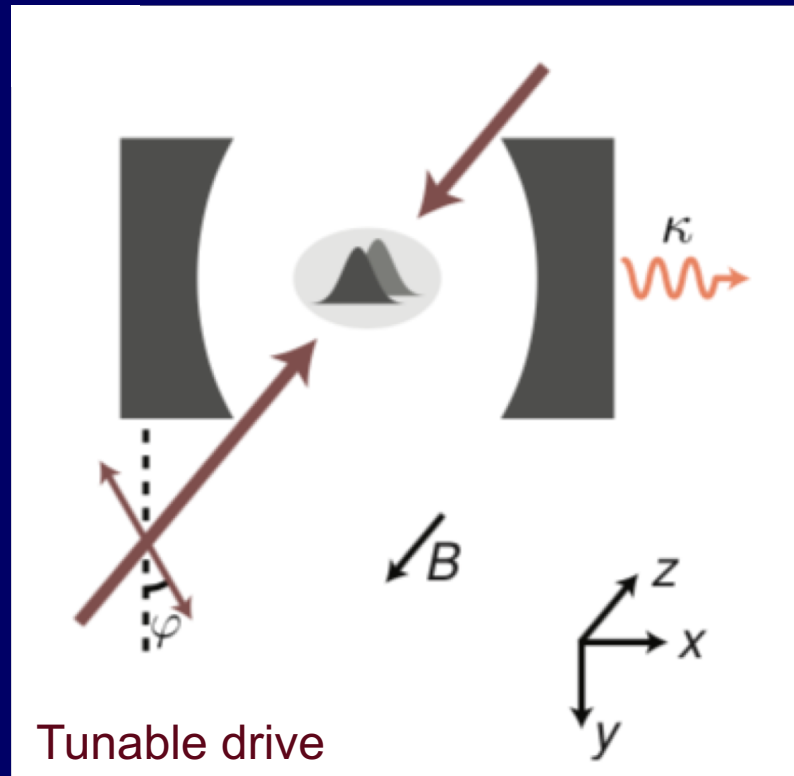


Let's build the system



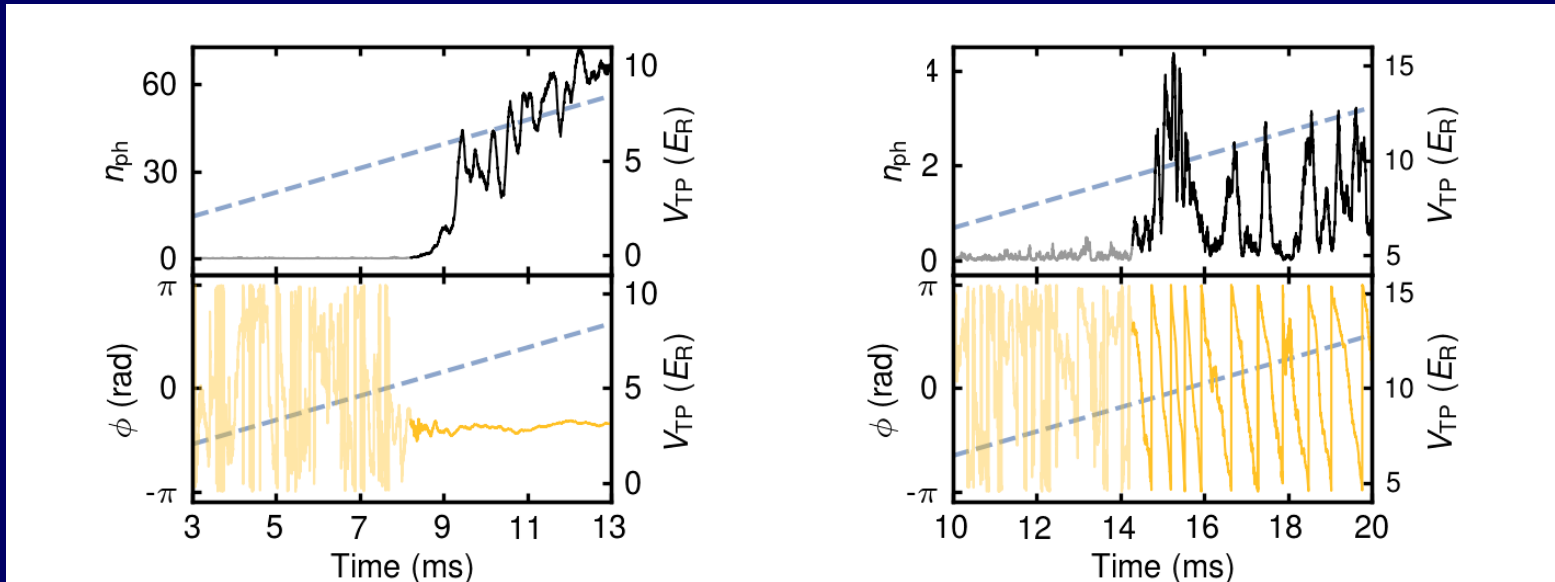
Let's build such a system

Spinor condensate



Dissipation & observation

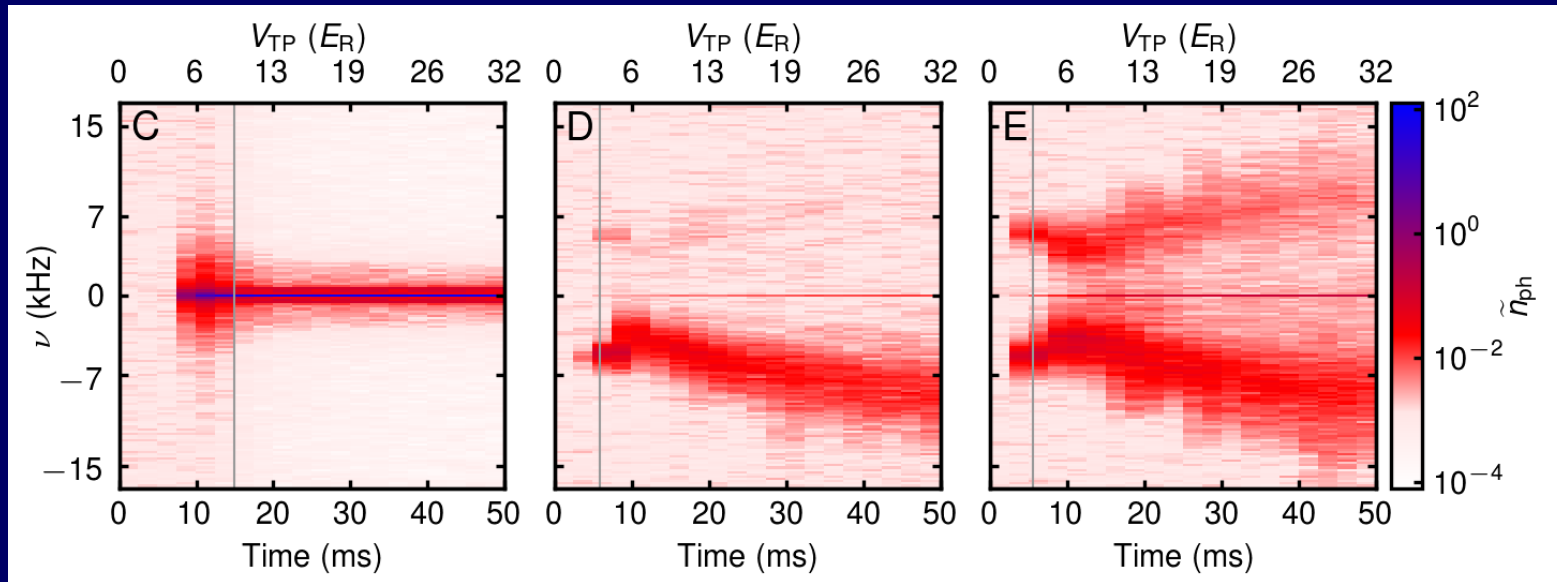
Observations



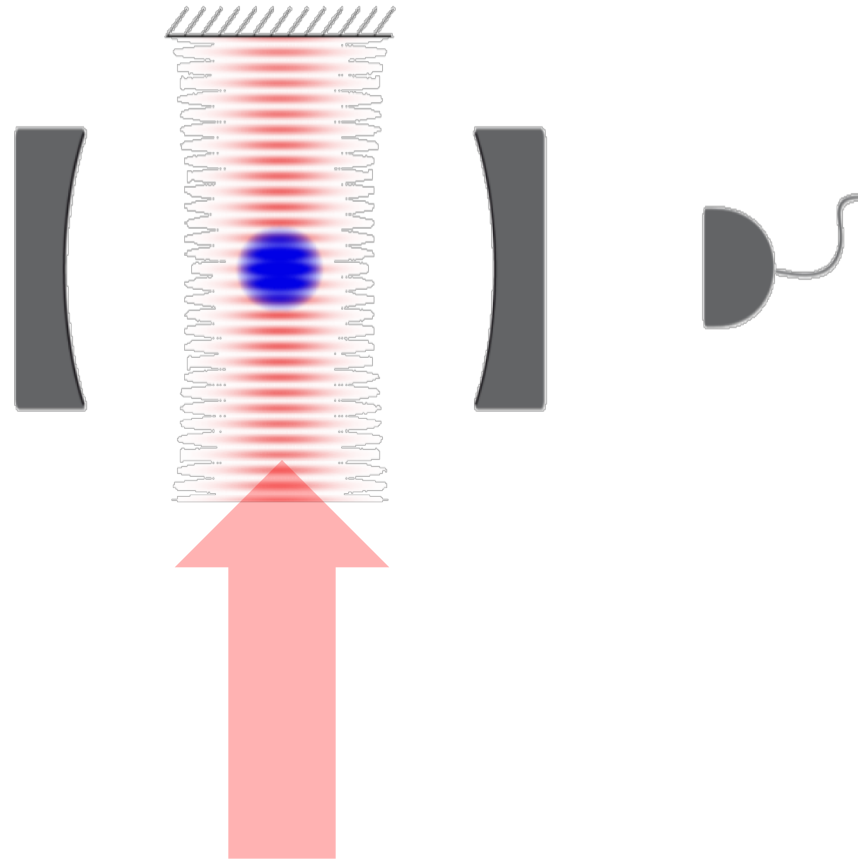
Running phase

Observations

???

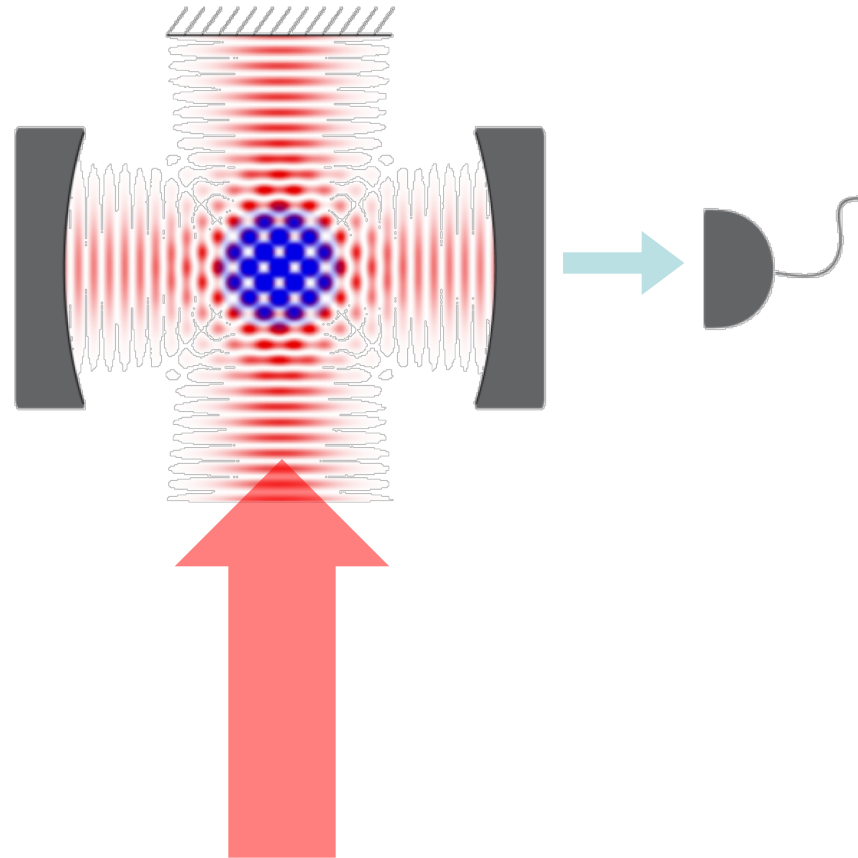


Reminder



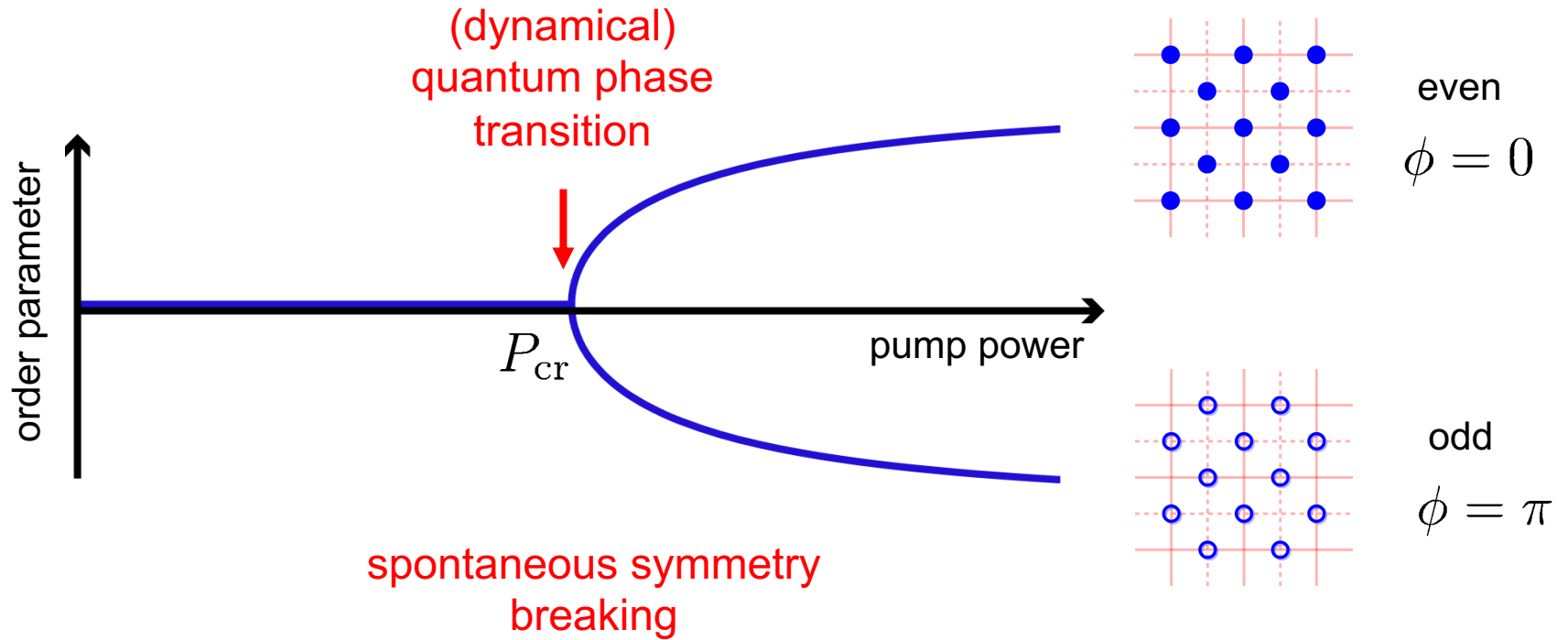
Theory: H. Ritsch, P. Domokos, Carmichael, Keeling, Morigi,
Gopalakrishnan, Strack, Mekhov, Kollath, ...
Exp. V. Vuletic, ETH, Tübingen, NUS, Stanford, ...

Phase Transition

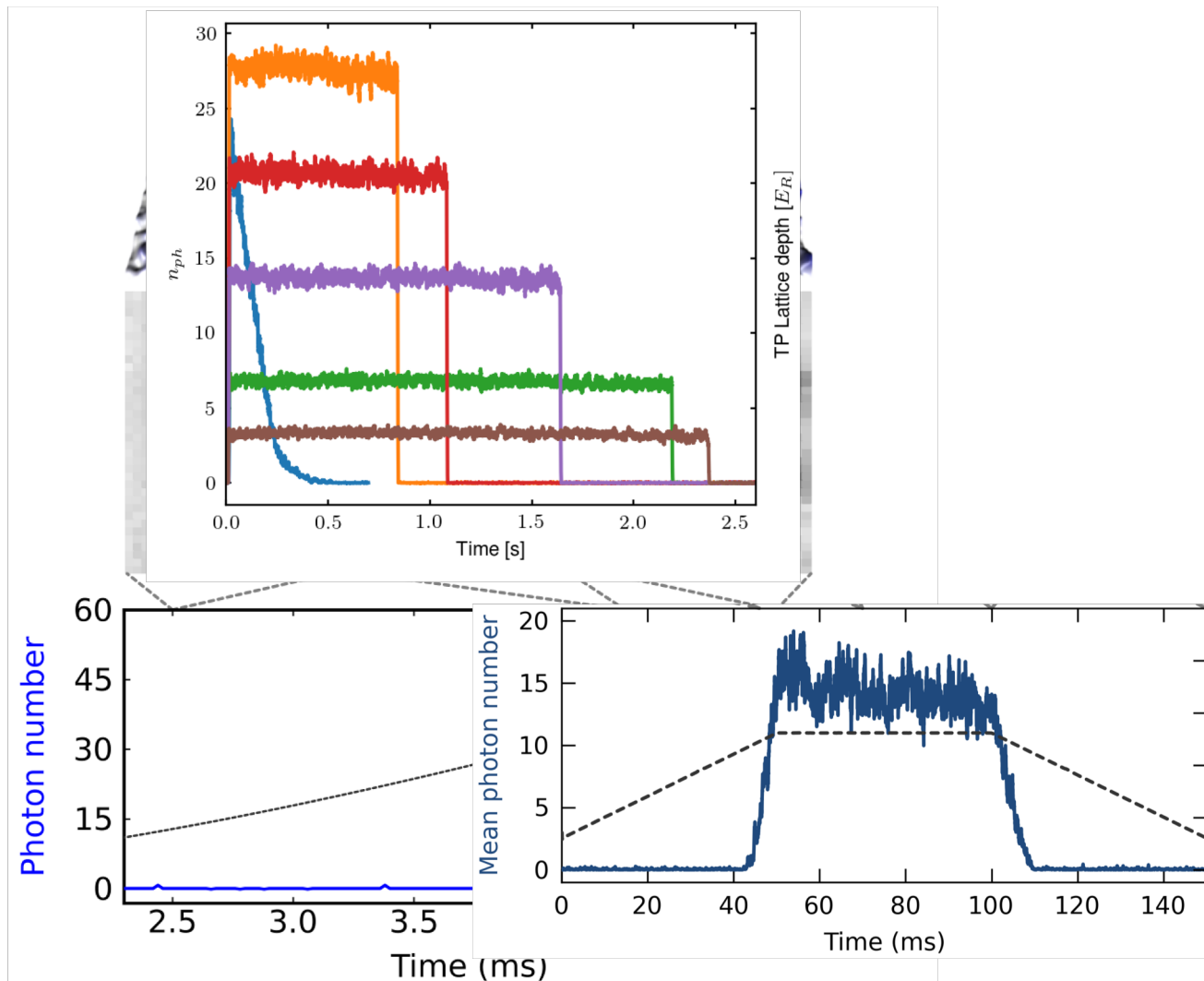


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Exp. V. Vuletic, ETH, Berkeley, Tübingen, NUS, Stanford, ...

zero point motion \longleftrightarrow potential energy

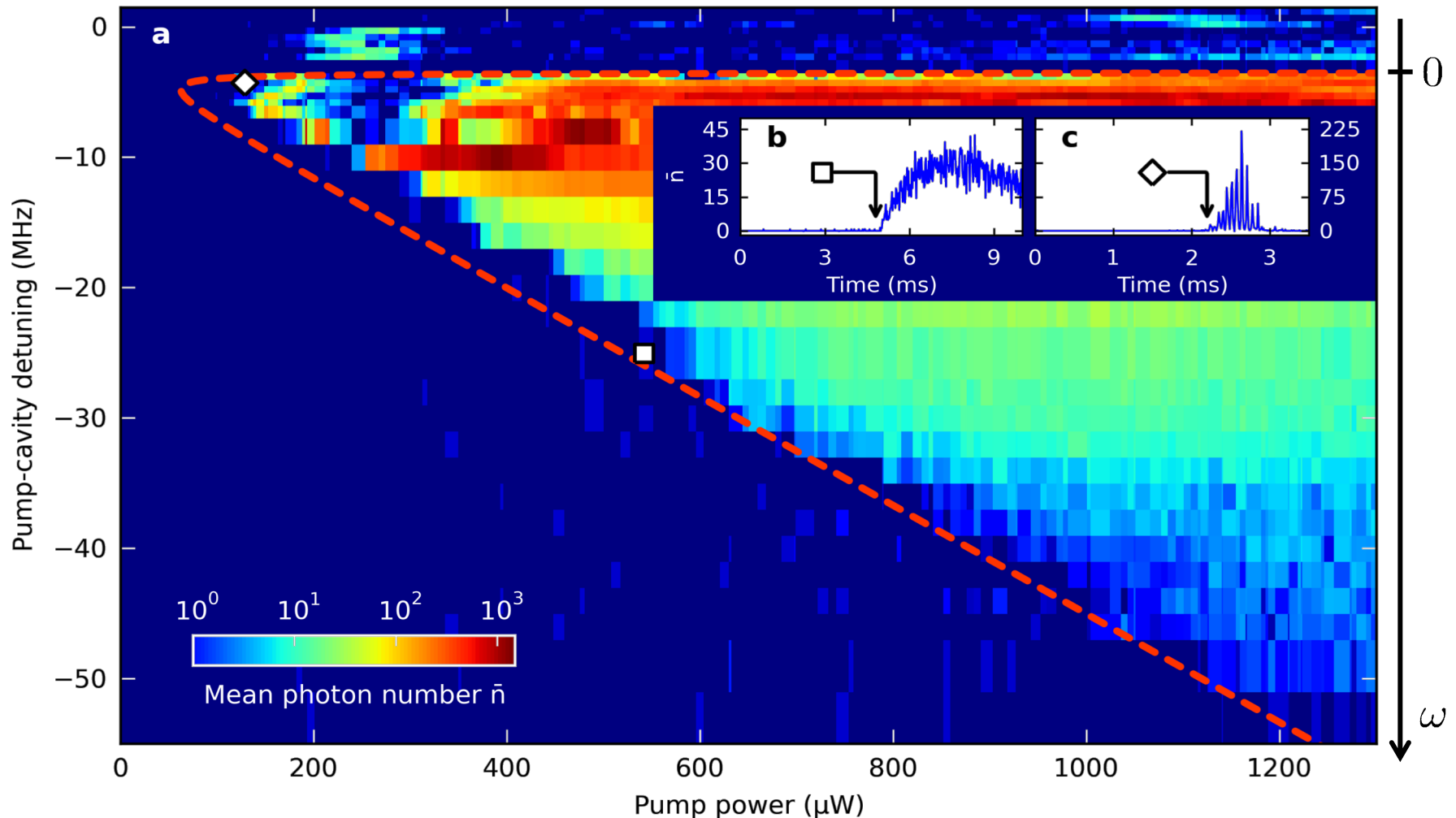


Observing Self-Organization



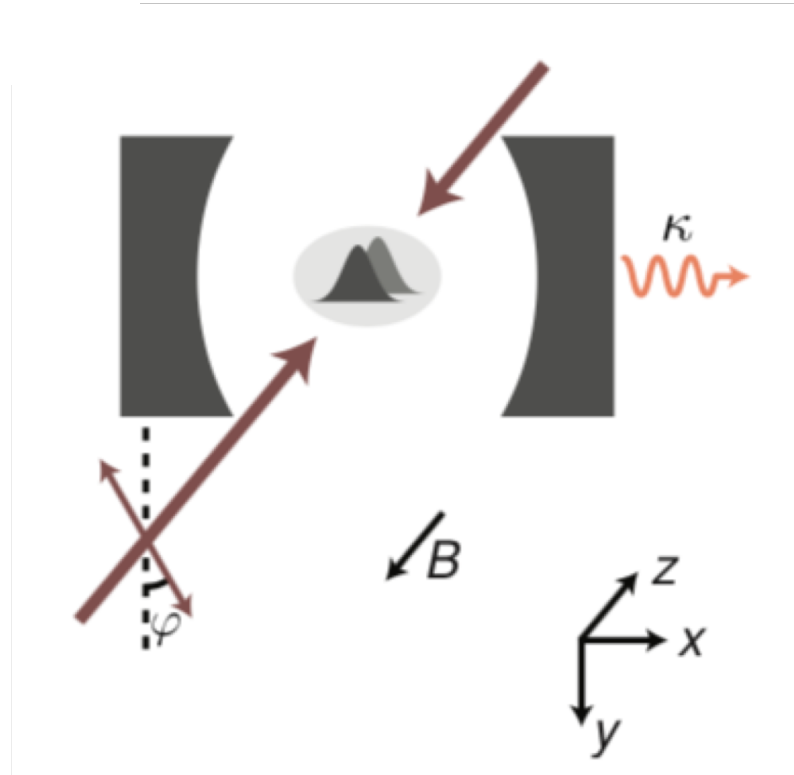
K. Baumann, C. Guerlin, F. Brennecke, and T. Esslinger. Nature 464, 1301 (2010)

Zero Temperature Phase Diagram

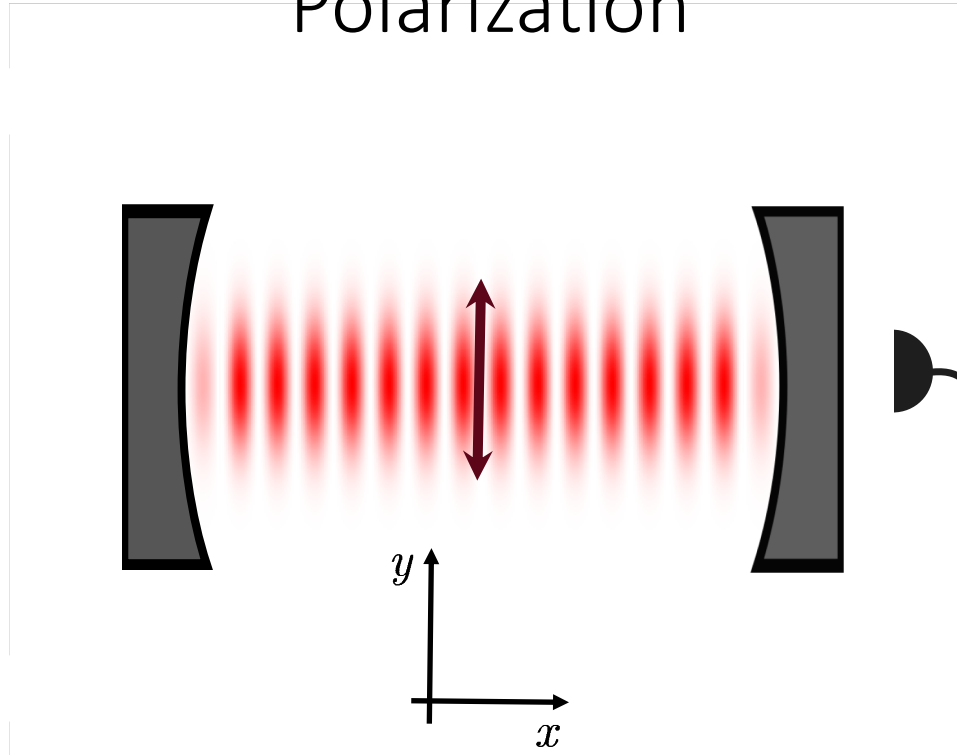
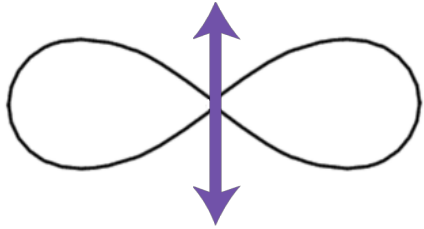


K. Baumann, C. Guerlin, F. Brennecke, and T. Esslinger. Nature 464, 1301 (2010)

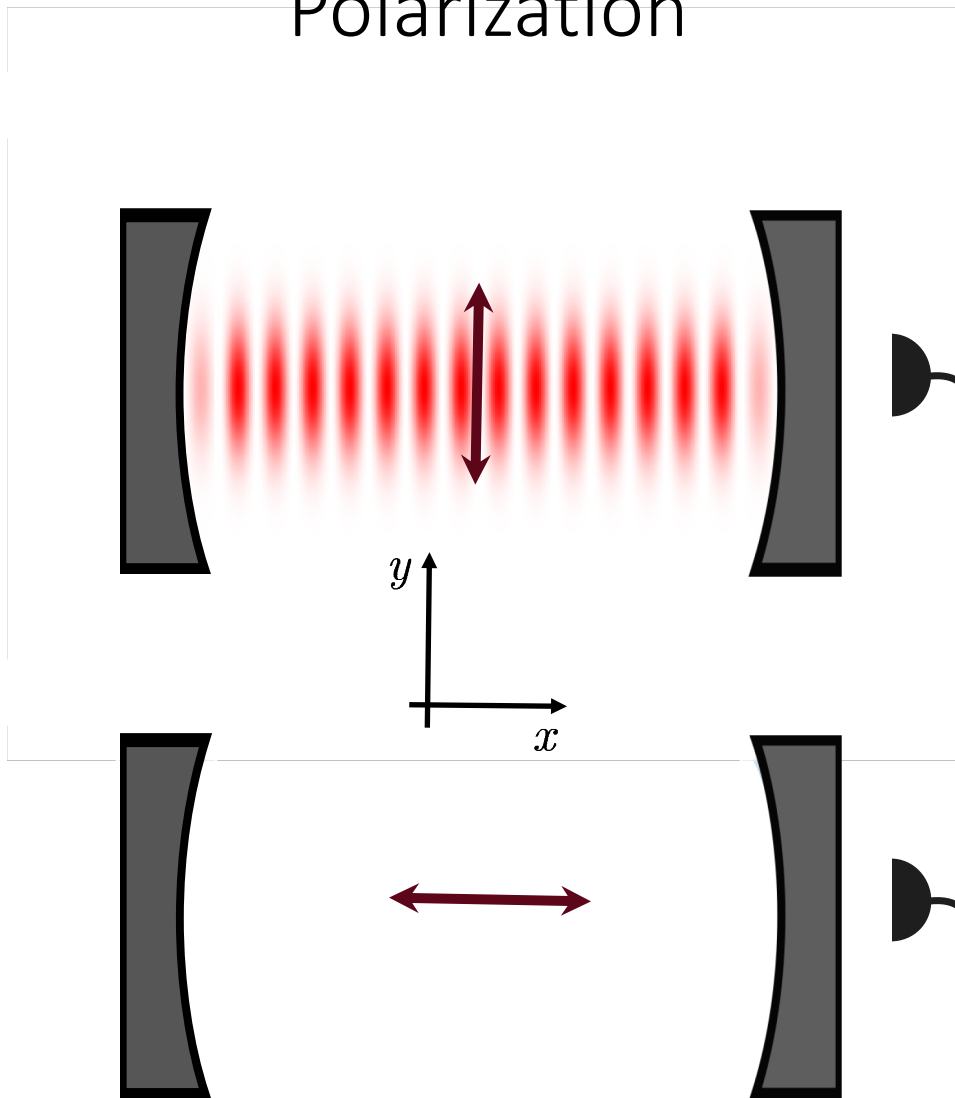
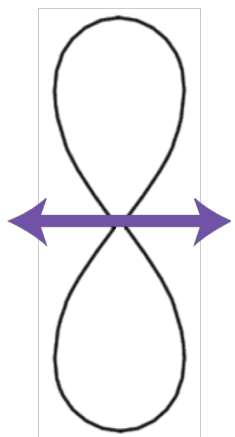
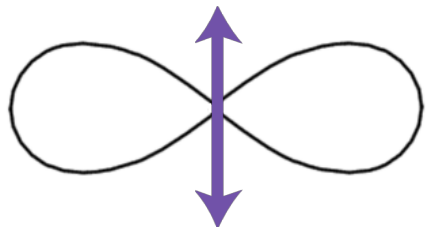
Polarization



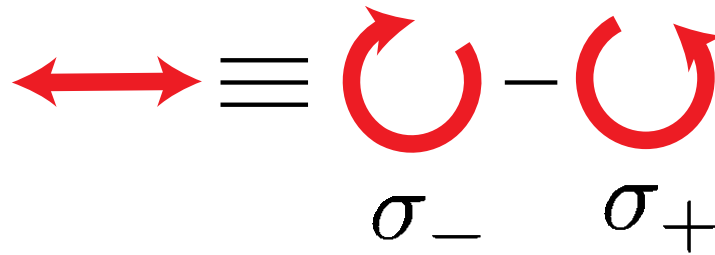
Polarization



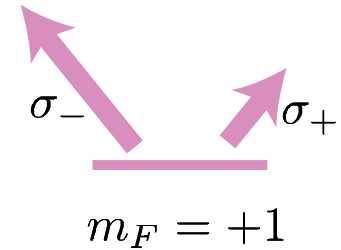
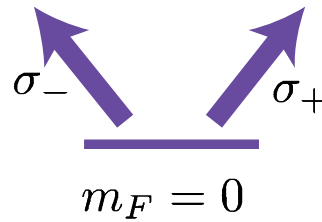
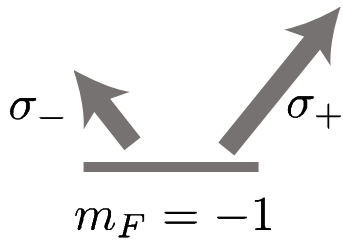
Polarization



Polarization



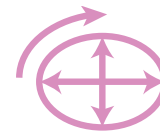
$B \odot$



Rotating dipole



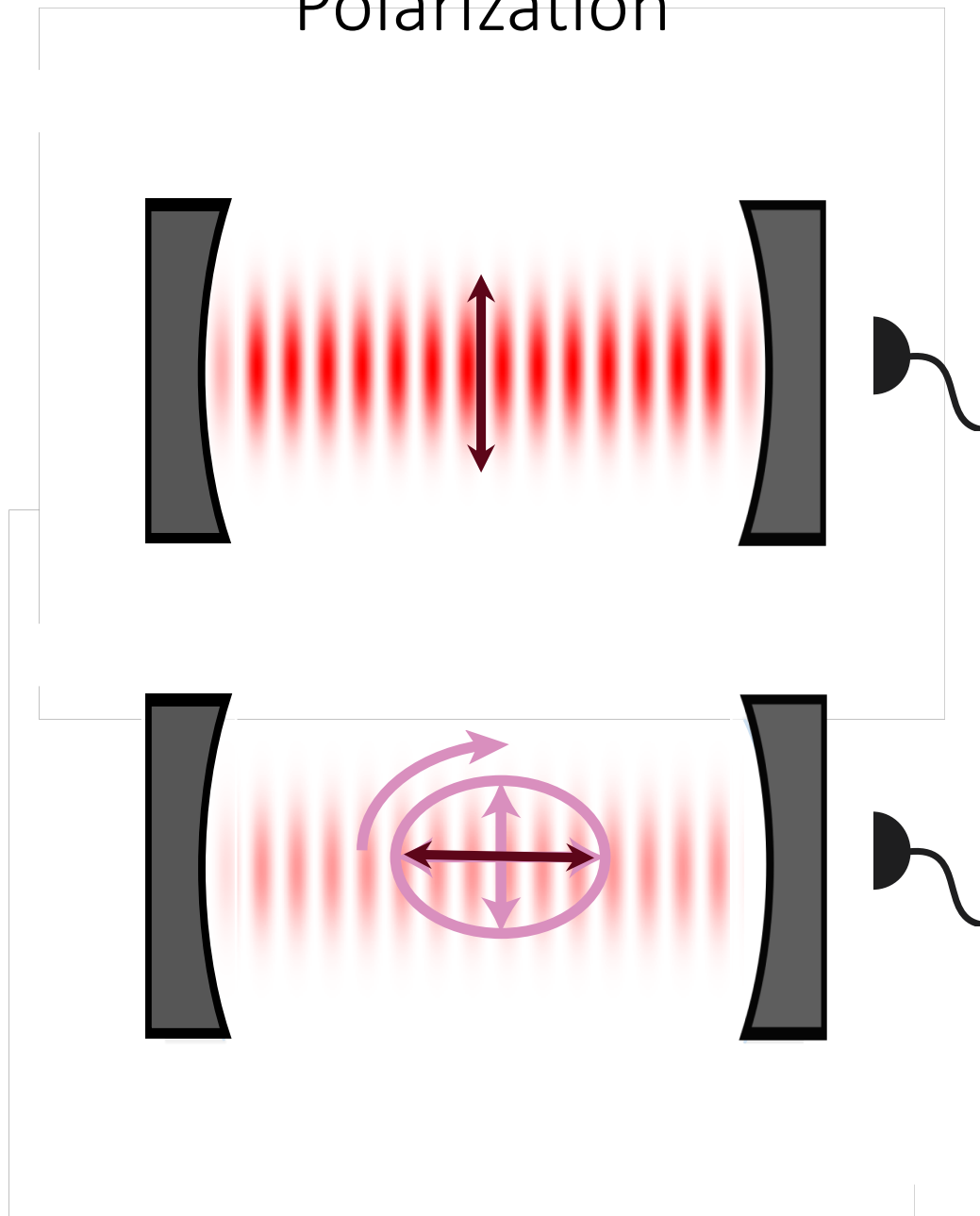
Oscillating dipole



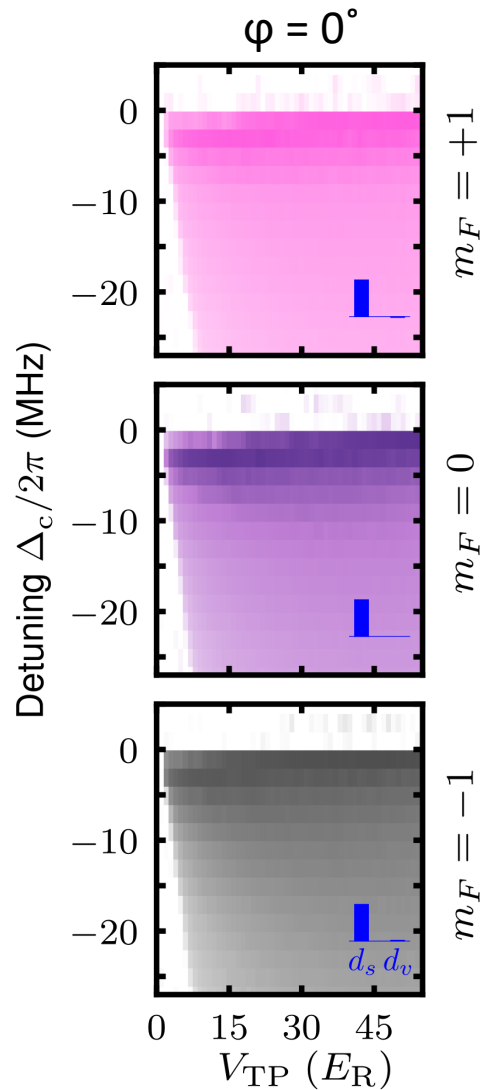
Rotating dipole

$$\hat{\mathbf{d}} = \hat{\mathbf{d}}_s + i\hat{\mathbf{d}}_v = -\frac{\alpha_s}{2}\hat{\mathbf{E}} + i\frac{\alpha_v}{4F}\hat{\mathbf{F}} \times \hat{\mathbf{E}}$$

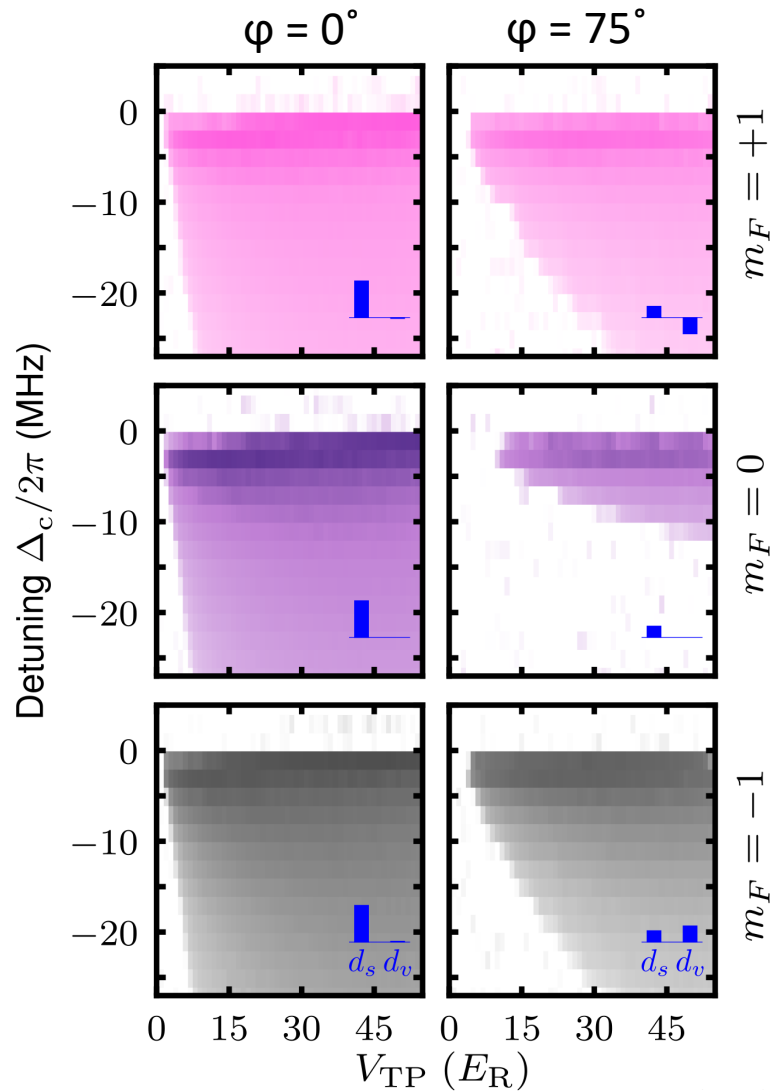
Polarization



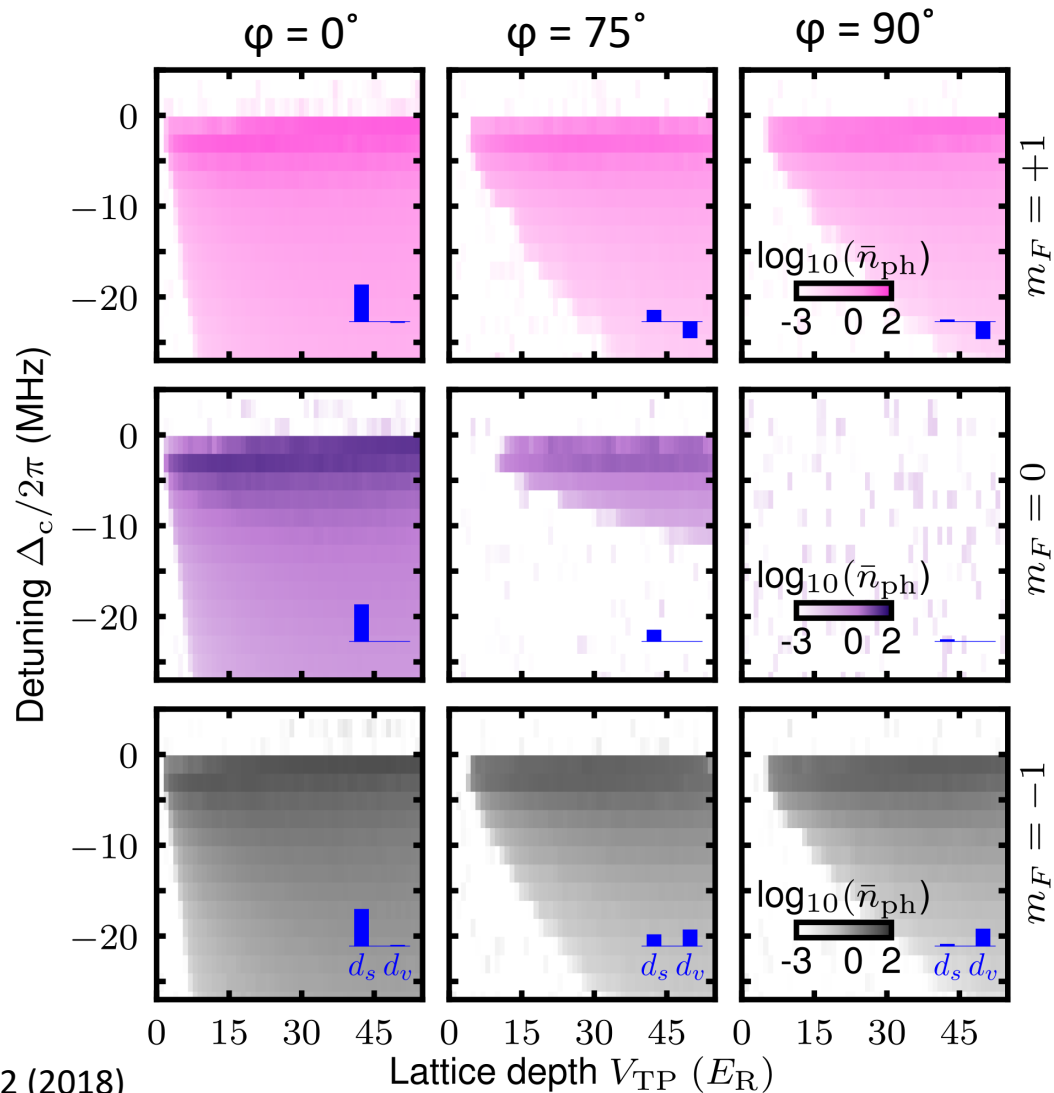
Constructing the phase diagram – y polarization



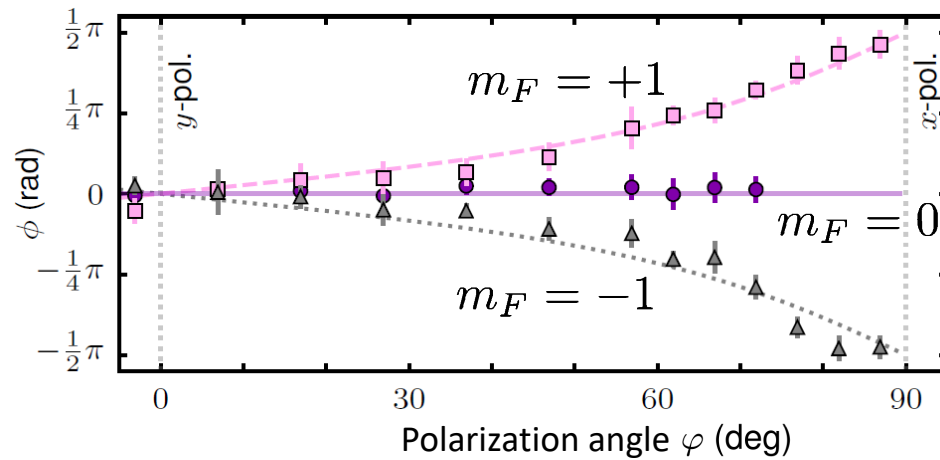
Constructing the phase diagram – xy polarization



Constructing the phase diagram – x polarization

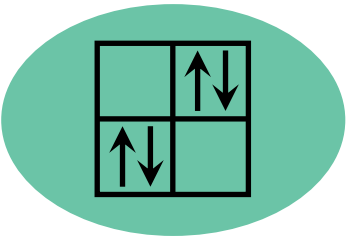


Phase of scattered light

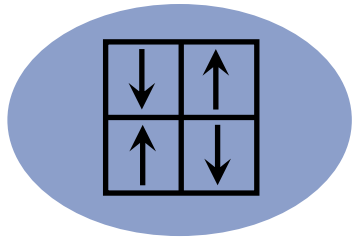
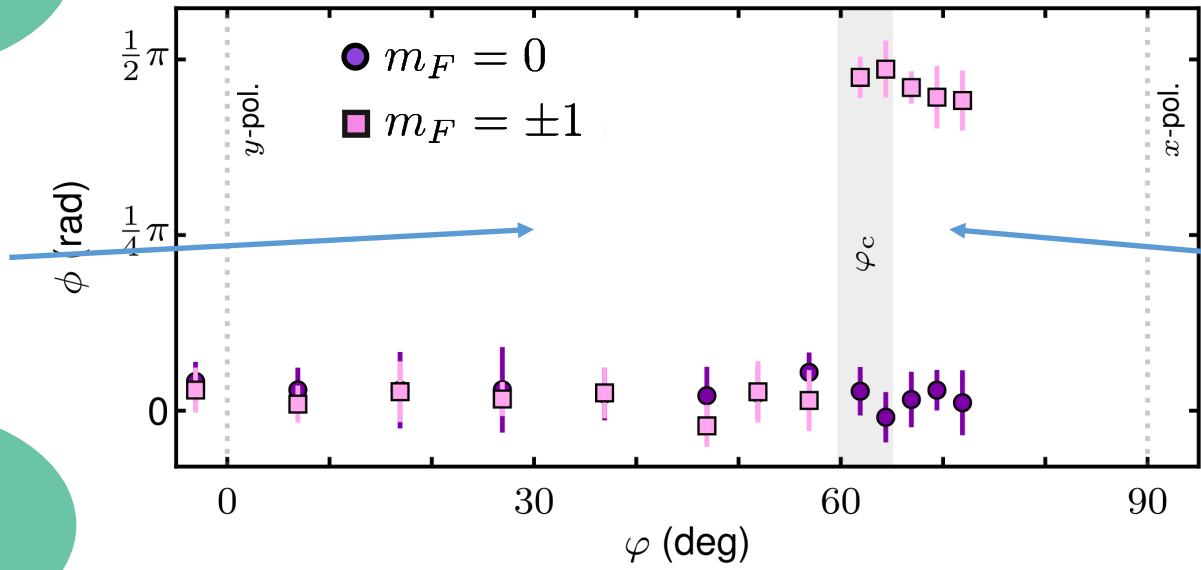
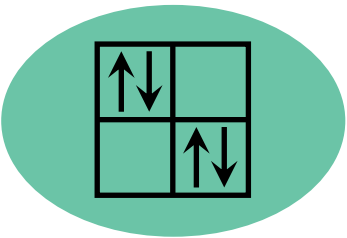


Spin mixture: $m_F = \pm 1$ vs $m_F = 0$

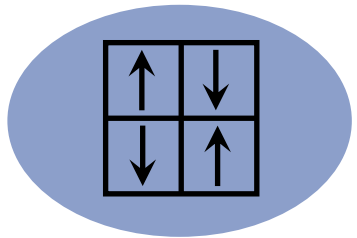
Spin mixture: $m_F = \pm 1$ vs $m_F = 0$



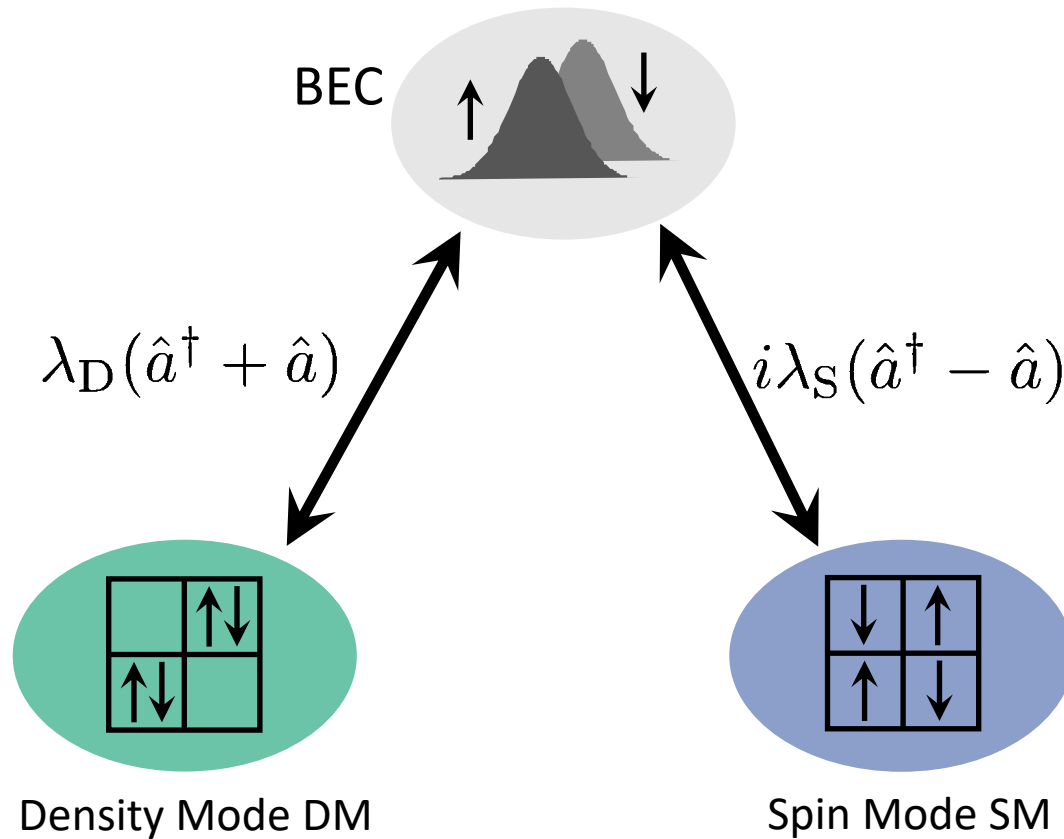
Spin mixing



Spin texture

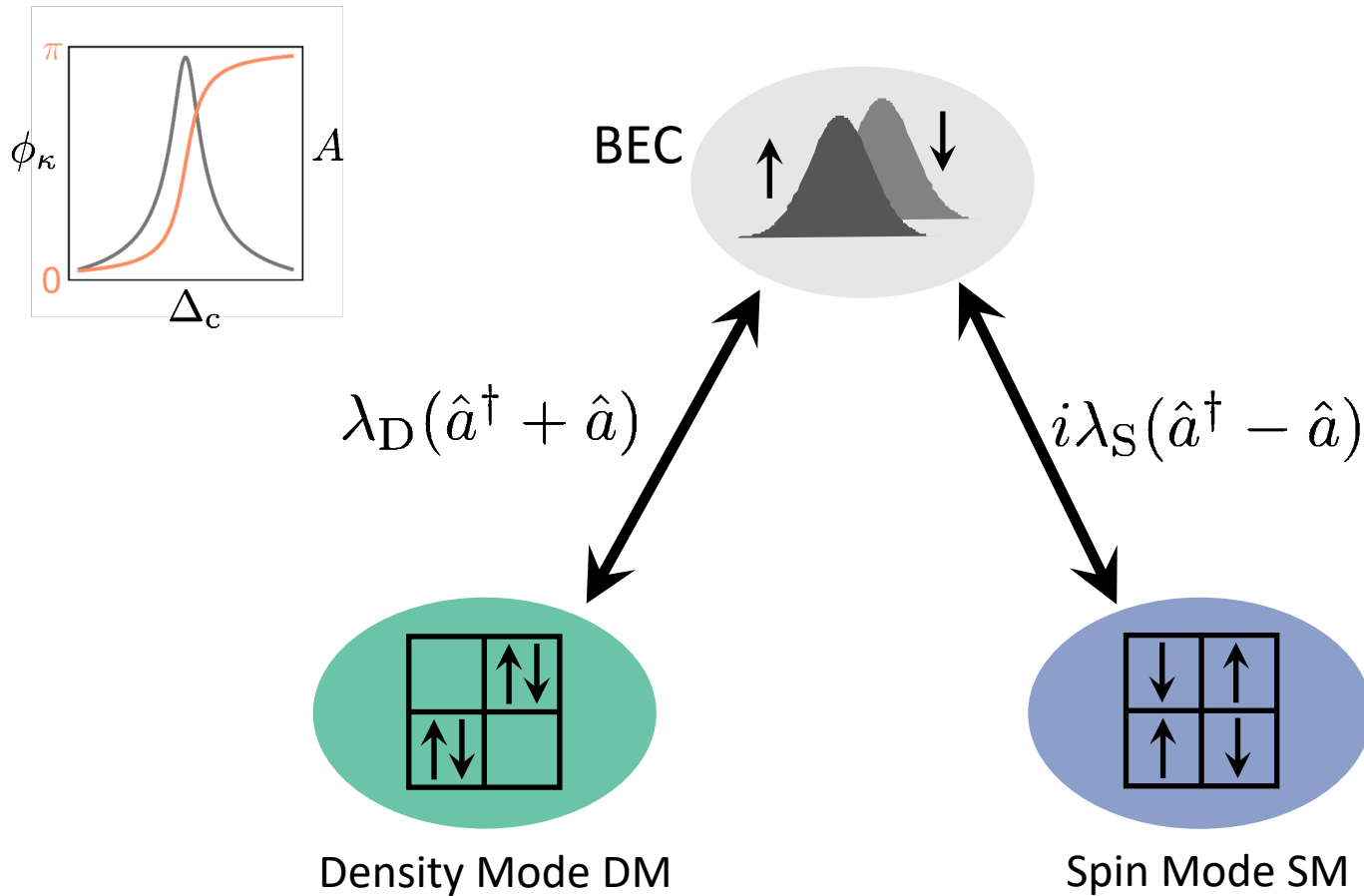


Coherent coupling to density and spin mode

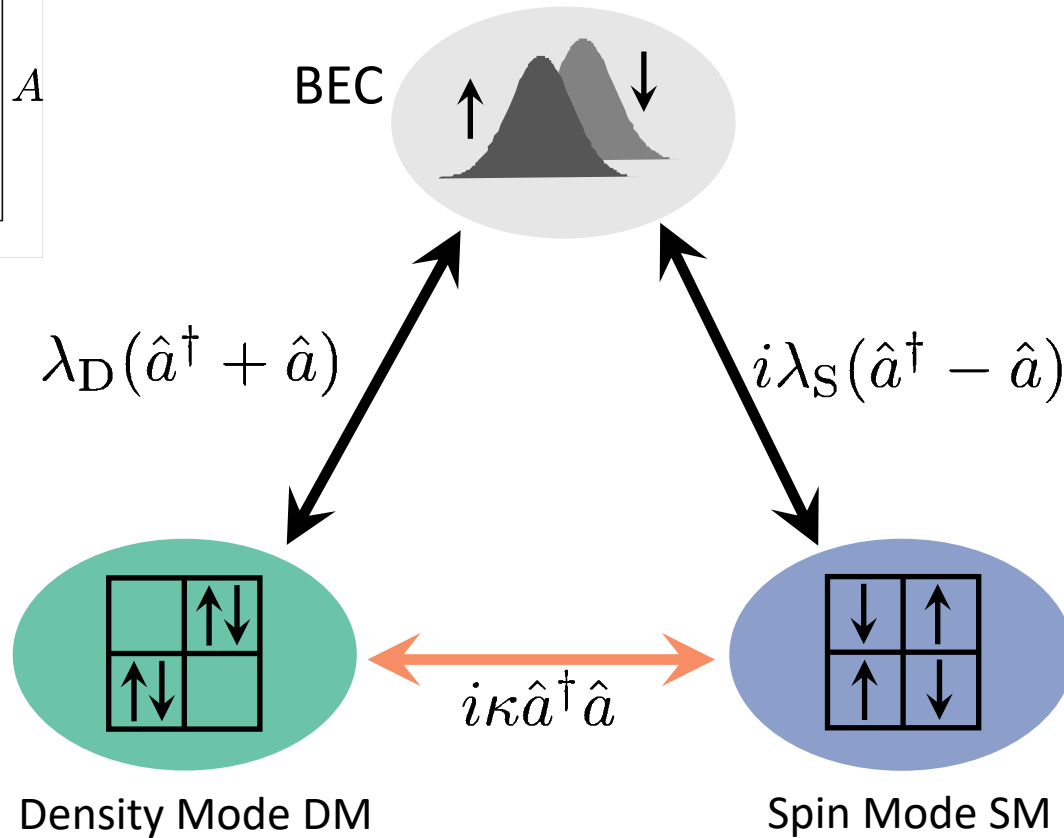
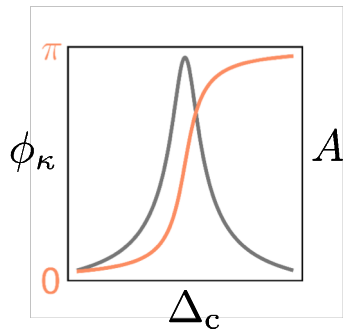


- Coupling via in-phase or out-of-phase quadrature.
- Control via power and polarization of pump

Coherent coupling to density and spin mode



Coherent coupling to density and spin mode



Many-body description of the system

$$\hat{H} = \hbar(-\Delta_c - i\kappa)\hat{a}^\dagger\hat{a} + \hbar\omega_0(\hat{J}_{z,+} + \hat{J}_{z,-}) + \frac{\hbar}{\sqrt{N}} \left[\lambda_D(\hat{a}^\dagger + \hat{a})(\hat{J}_{x,+} + \hat{J}_{x,-}) + i\lambda_S(\hat{a}^\dagger - \hat{a})(\hat{J}_{x,+} - \hat{J}_{x,-}) \right]$$

Density Mode:

$$x_D = \frac{1}{N} (\langle \hat{J}_{x,+} \rangle + \langle \hat{J}_{x,-} \rangle)$$

Coupling strengths

$$\lambda_D \propto \sqrt{V_{\text{TP}}} \cos \varphi$$

Spin Mode:

$$x_S = \frac{1}{N} (\langle \hat{J}_{x,+} \rangle - \langle \hat{J}_{x,-} \rangle)$$

$$\lambda_S \propto \sqrt{V_{\text{TP}}} \sin \varphi$$

Adiabatically eliminated cavity field

$$\frac{d^2}{dt^2} \begin{pmatrix} x_D \\ x_S \end{pmatrix} = \begin{pmatrix} -\omega_D^2 & -K^2 \\ K^2 & -\omega_S^2 \end{pmatrix} \begin{pmatrix} x_D \\ x_S \end{pmatrix}$$

$$K^2 \propto V_z \sin^2 \phi_\kappa \cos \delta\phi$$

$$\phi_\kappa = \sin^{-1}(\kappa / \sqrt{\kappa^2 + \Delta_c^2})$$

$$\delta\phi = 2 \tan^{-1}(\lambda_S / \lambda_D) - \pi/2$$

Solutions

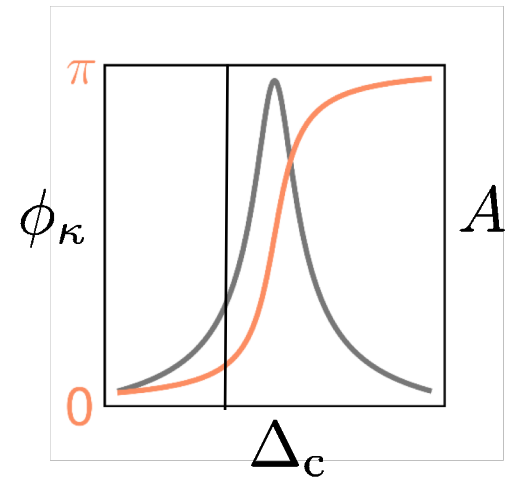
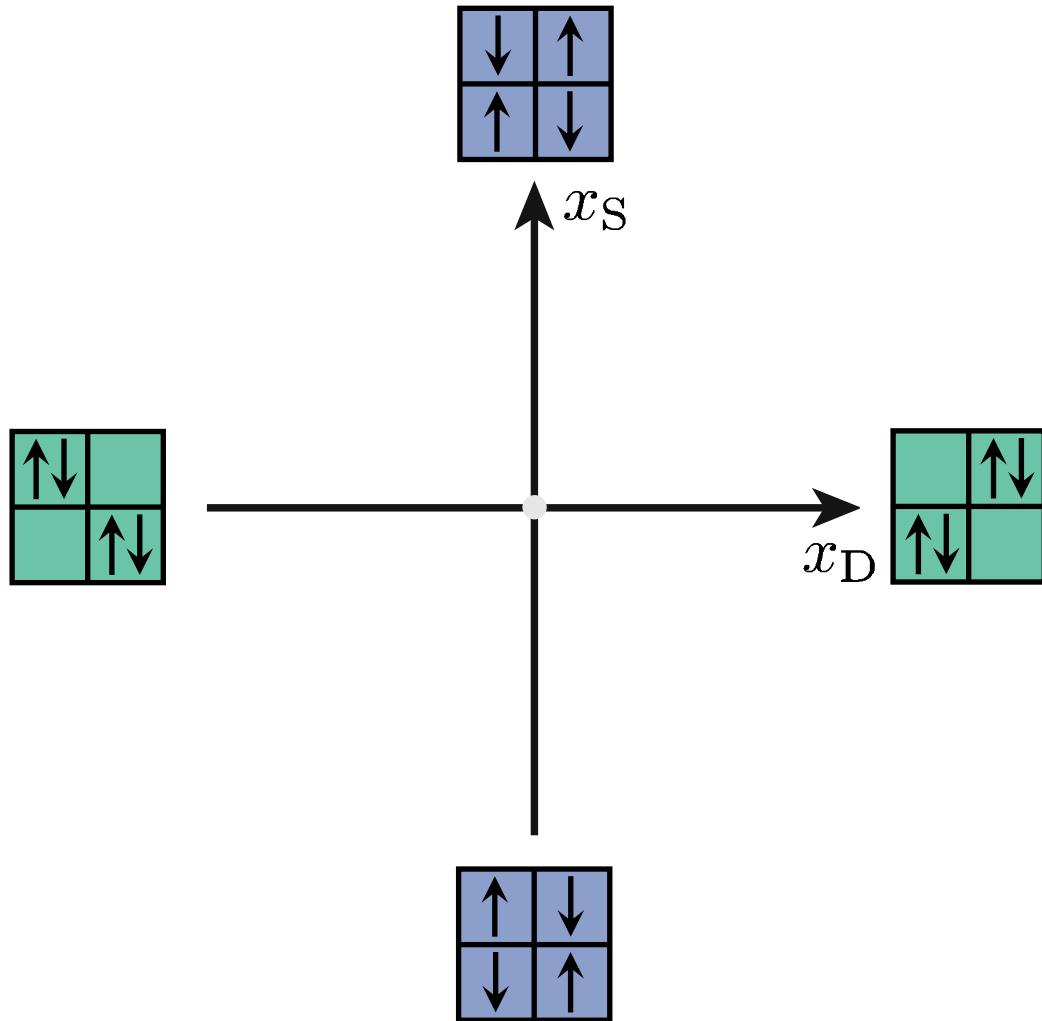
$$[x_D^c, x_S^c] = A \left[\cos \omega t, \sin \left(\omega t + \frac{\Delta_c}{\kappa} \delta \phi \right) \right] e^{gt}$$

$$\begin{aligned} \hat{a}^\dagger &\propto (x_D^c - i x_S^c) - \frac{\delta \phi}{2} (x_D^c + i x_S^c) \\ &\propto A \left[e^{-i\omega t} - \frac{\delta \phi}{2} \left(1 + i \frac{\Delta_c}{\kappa} \right) e^{i\omega t} \right] e^{gt} \end{aligned}$$

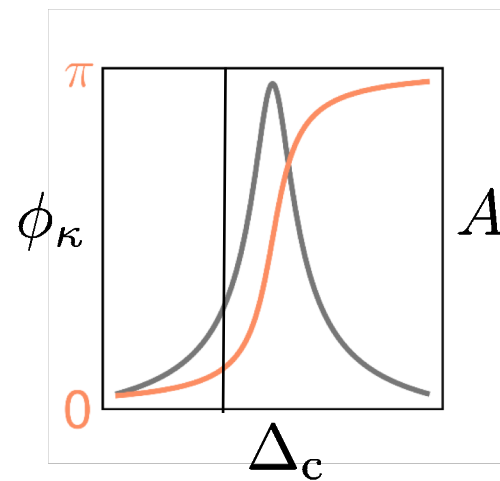
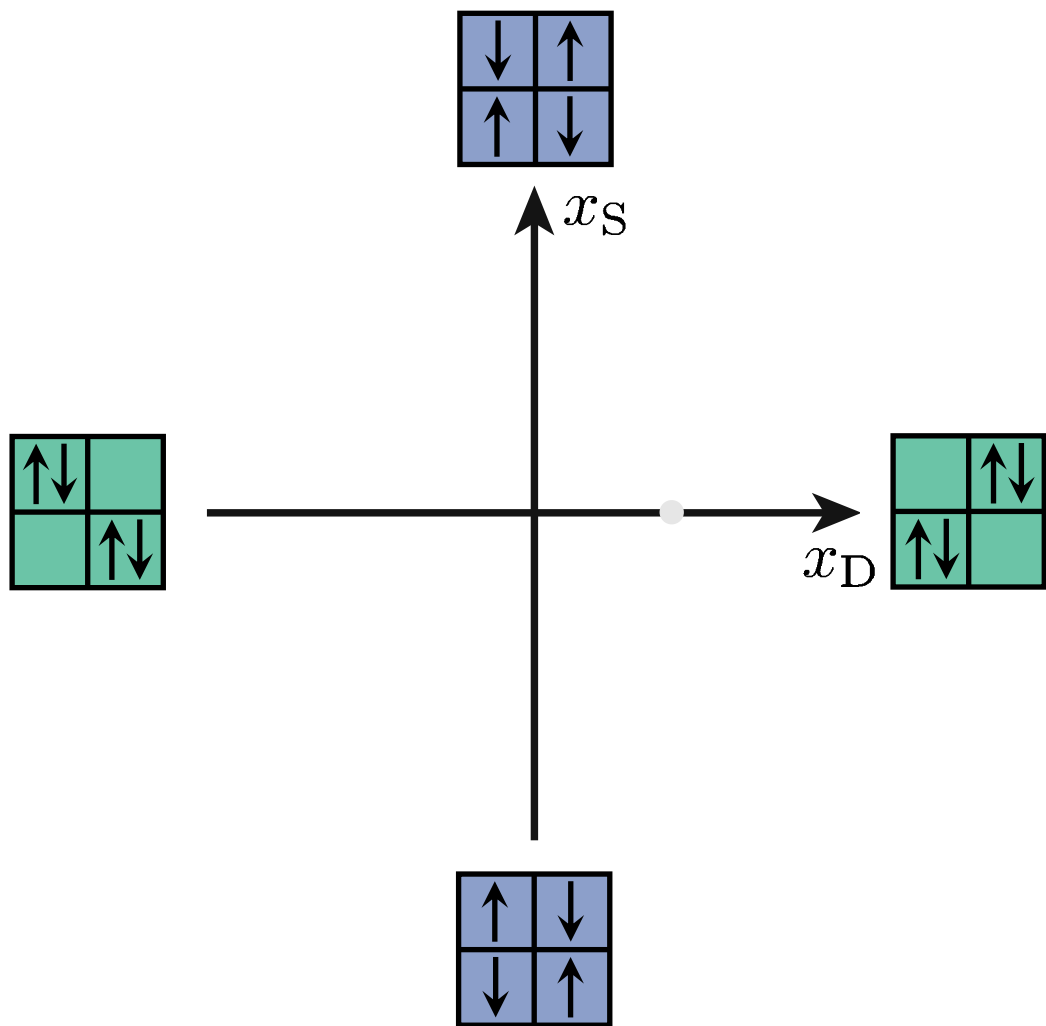
$$\omega \approx \sqrt{\frac{\omega_D^2 + \omega_S^2}{2}}$$

$$g \approx \frac{K^2}{\sqrt{2(\omega_D^2 + \omega_S^2)}}$$

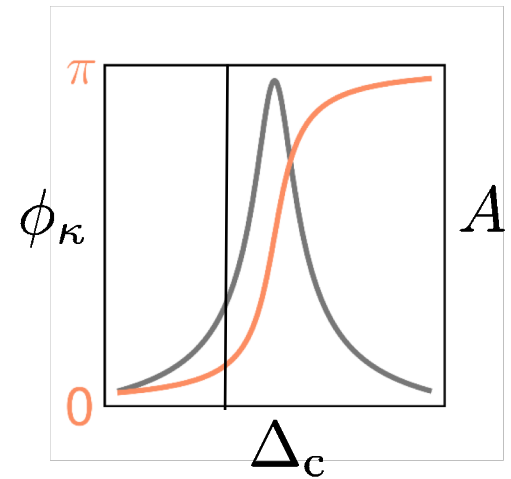
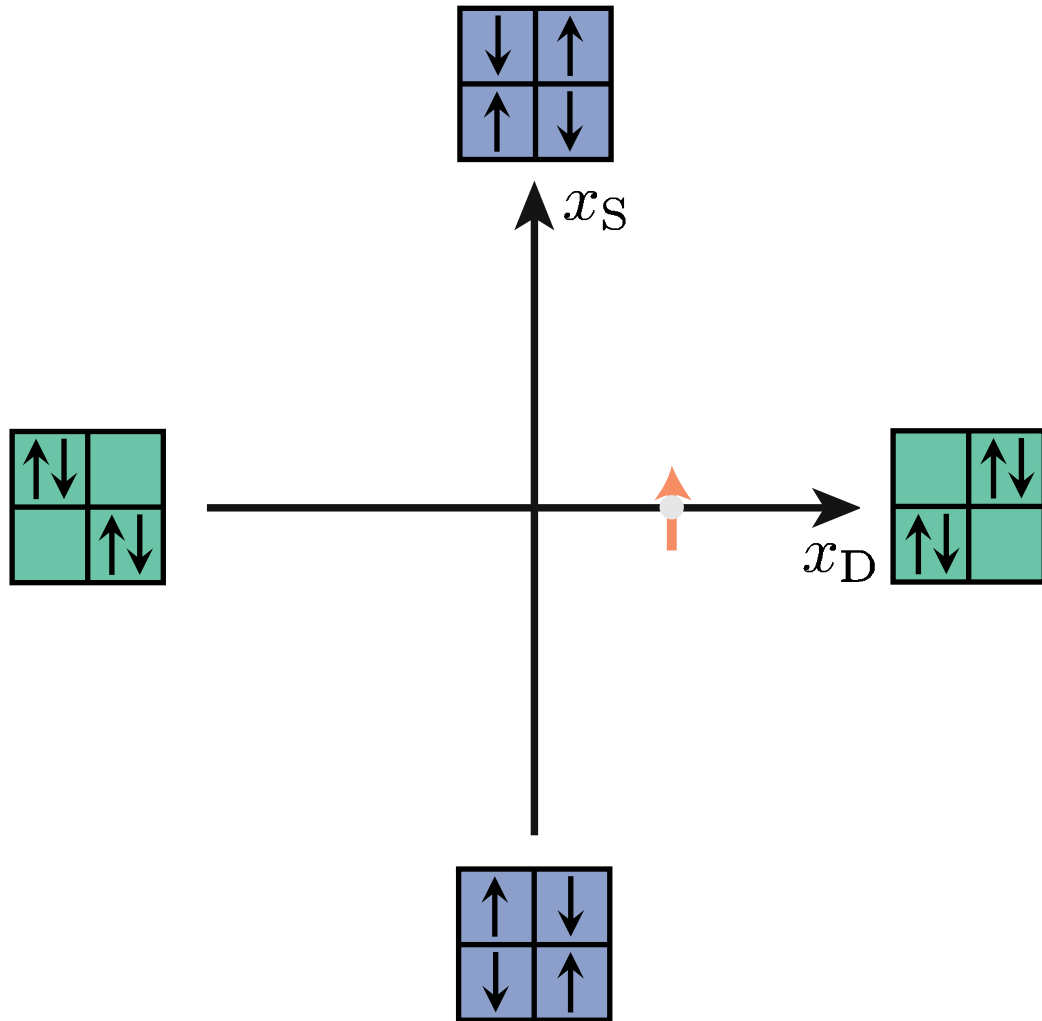
Dissipative coupling as a positional force



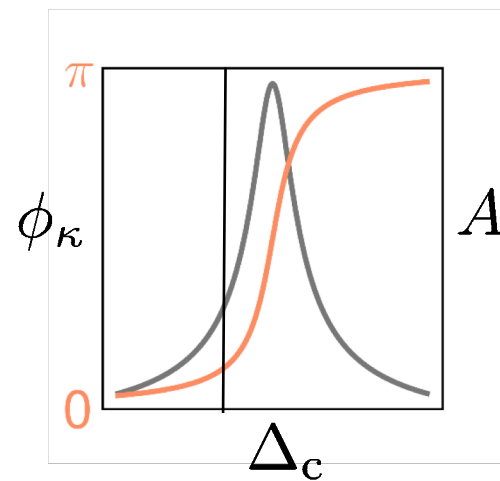
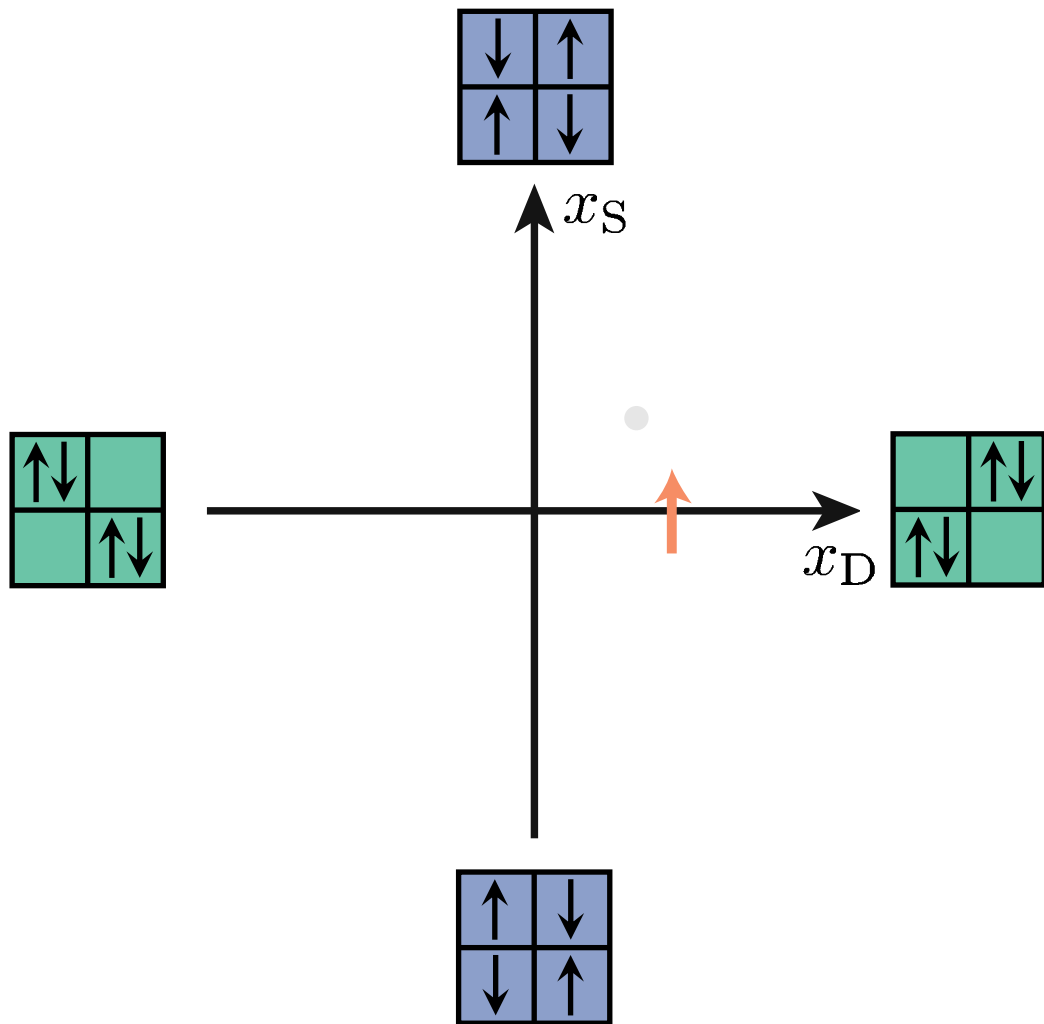
Dissipative coupling as a positional force



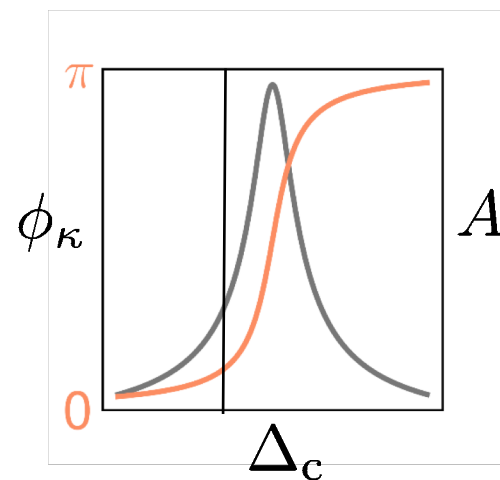
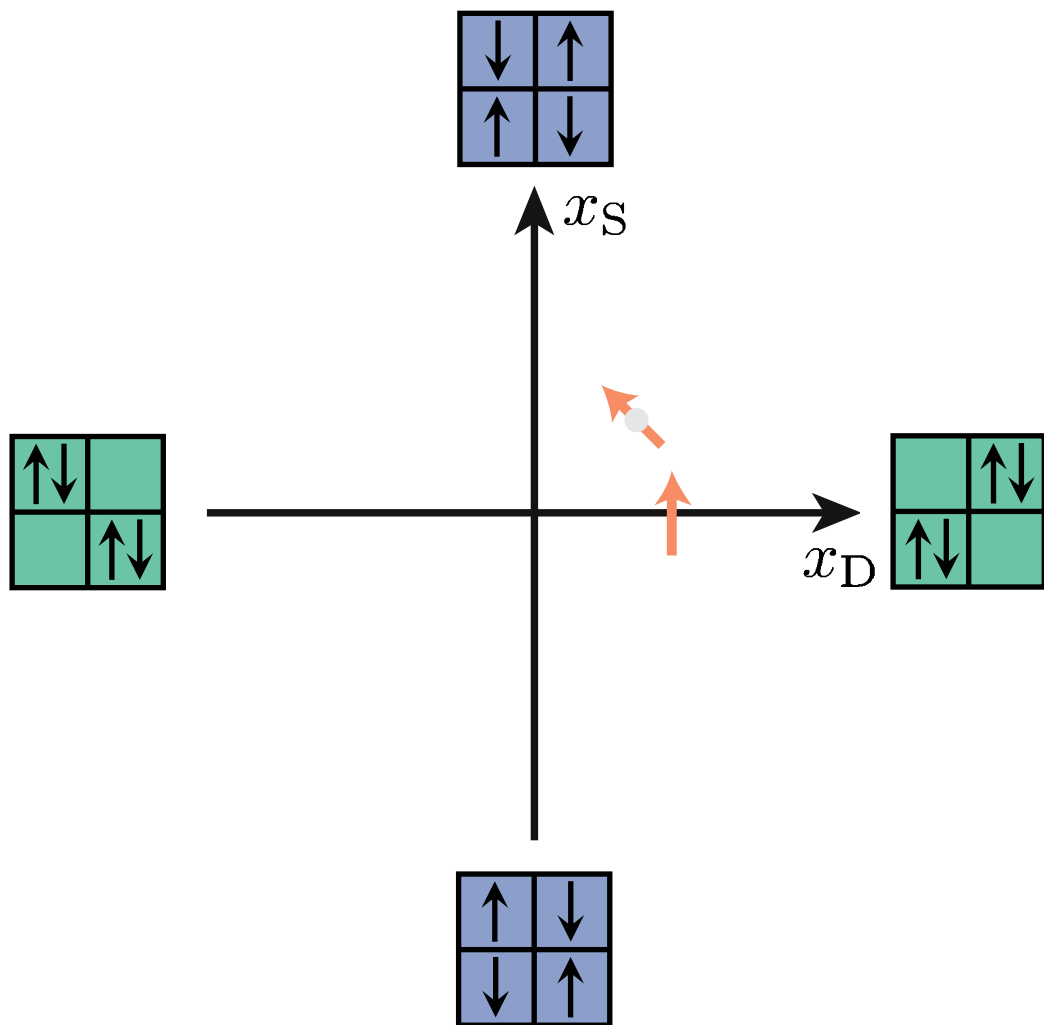
Dissipative coupling as a positional force



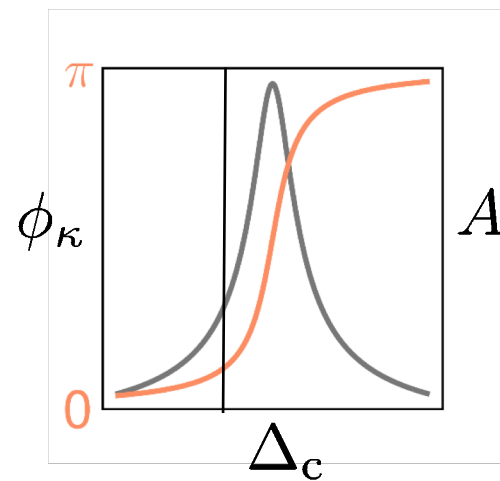
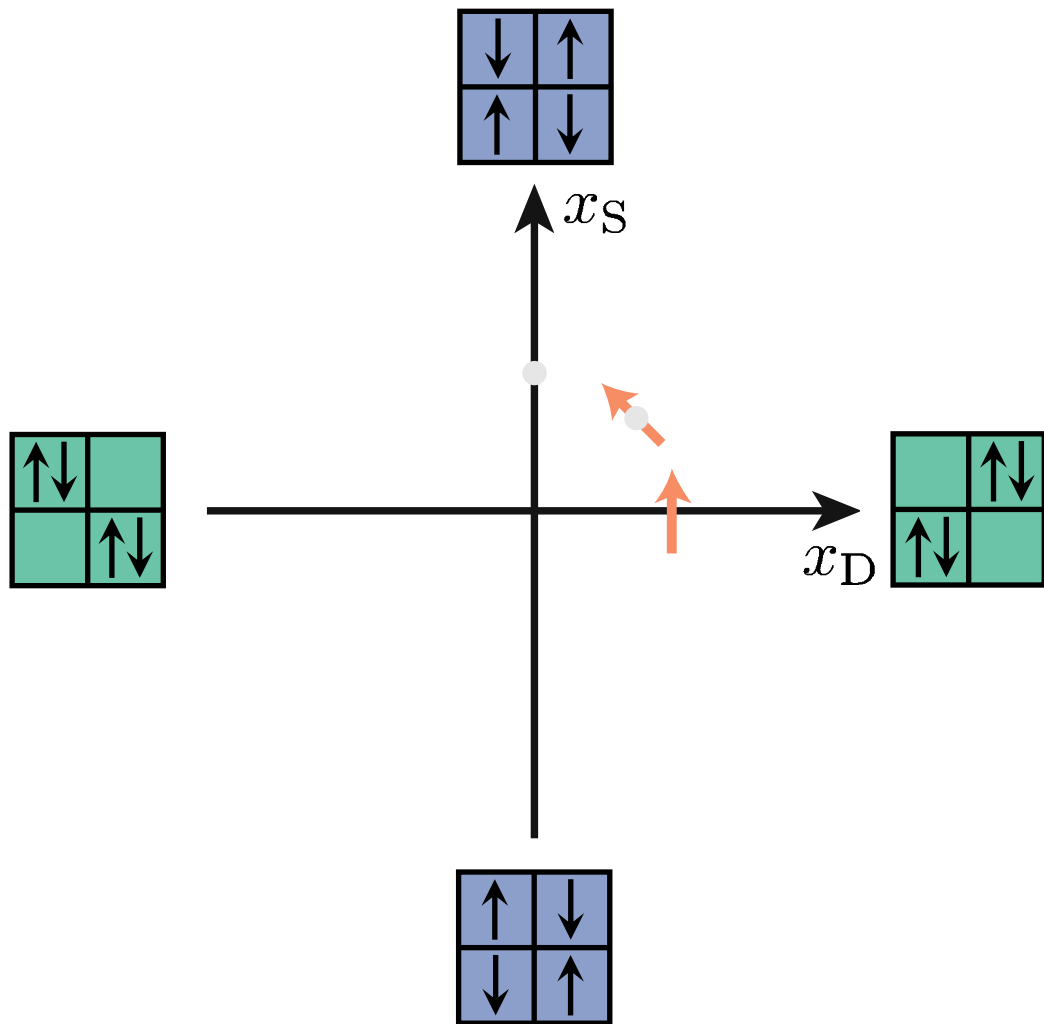
Dissipative coupling as a positional force



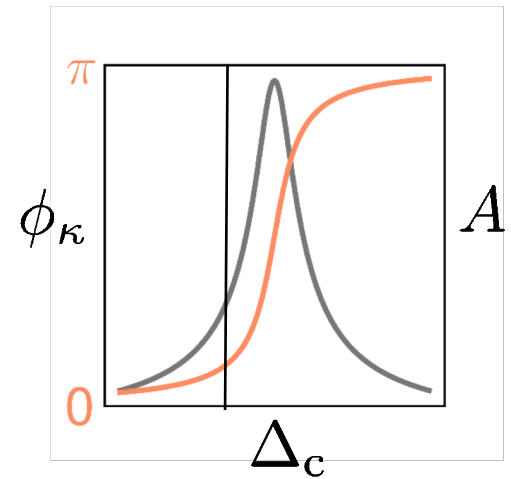
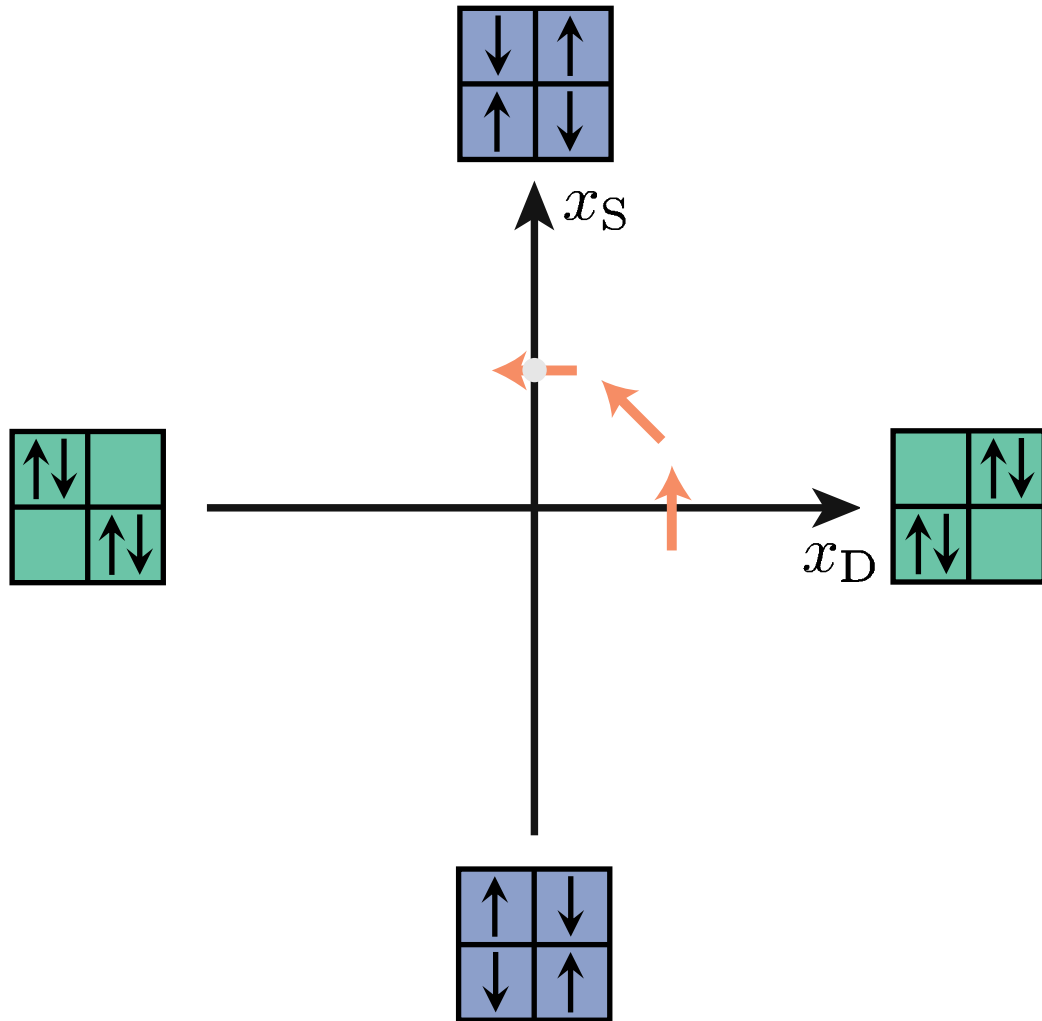
Dissipative coupling as a positional force



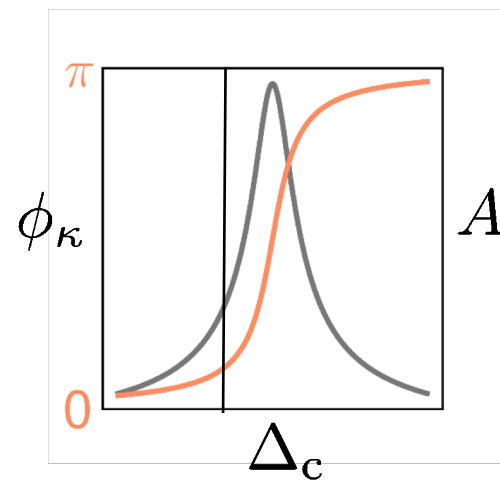
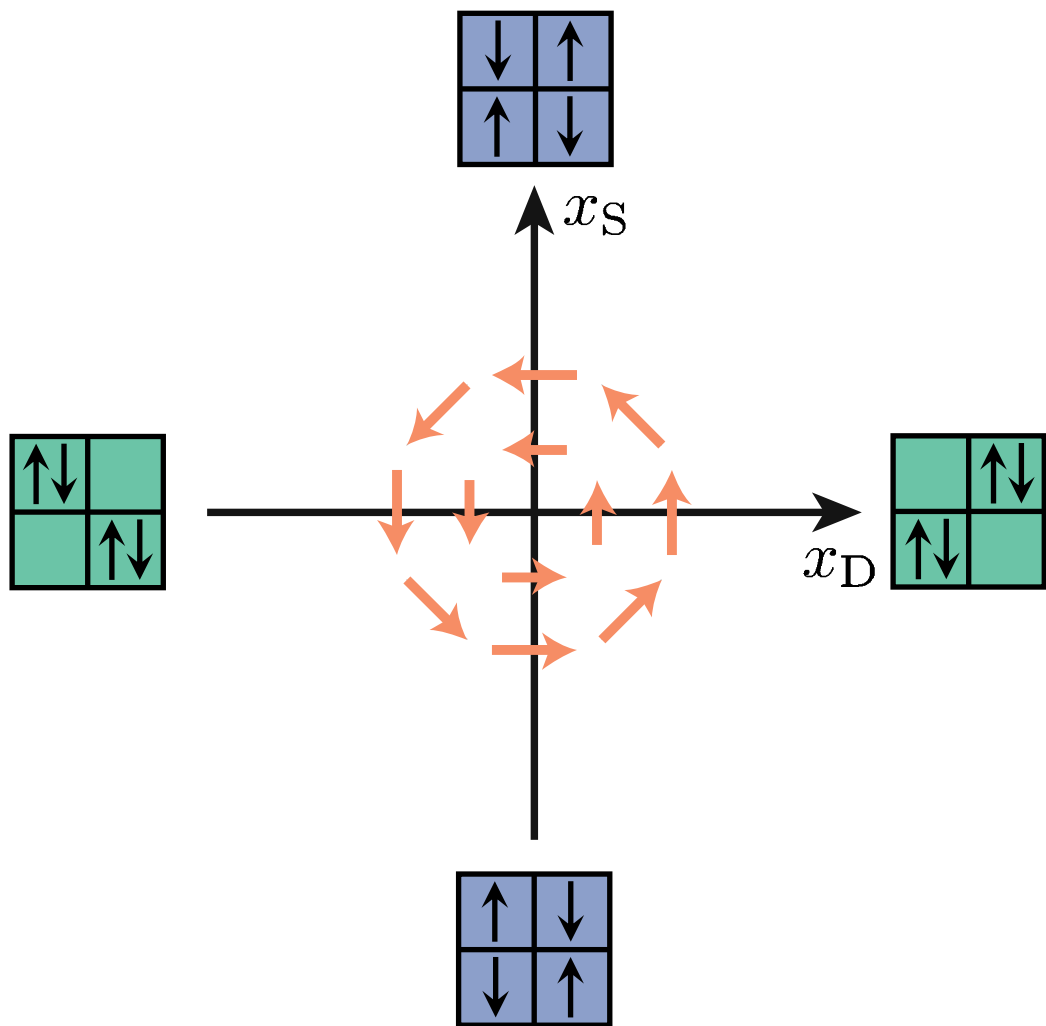
Dissipative coupling as a positional force



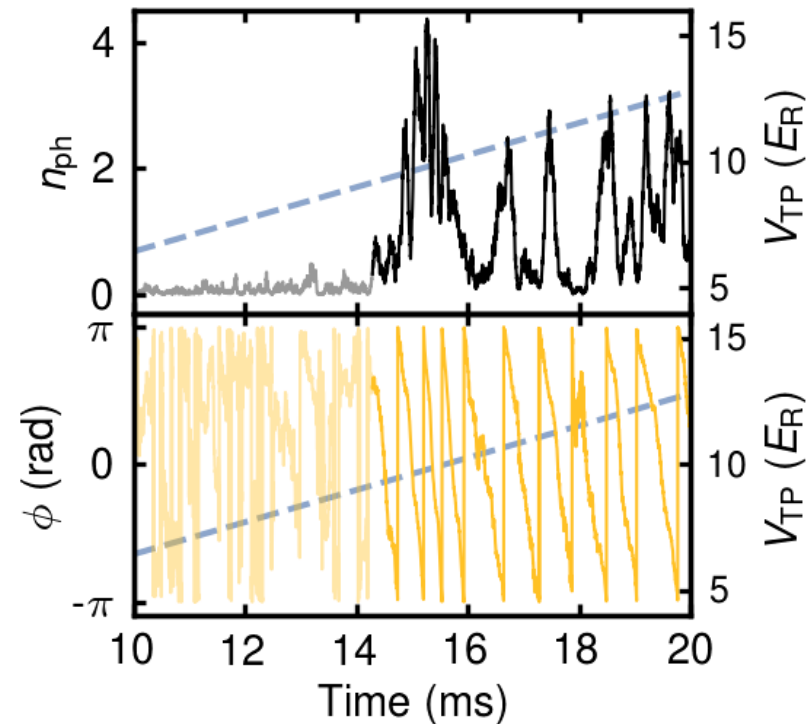
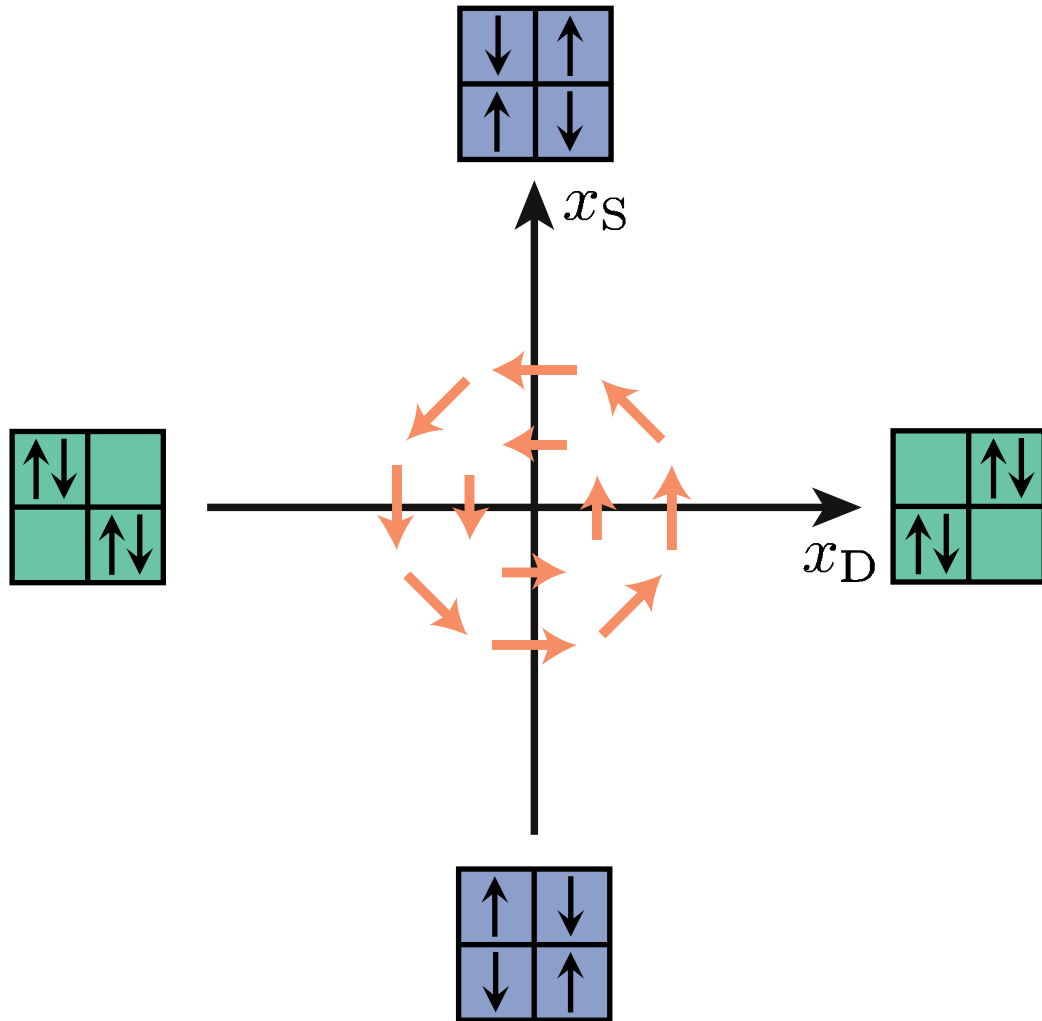
Dissipative coupling as a positional force



Dissipation induced instability

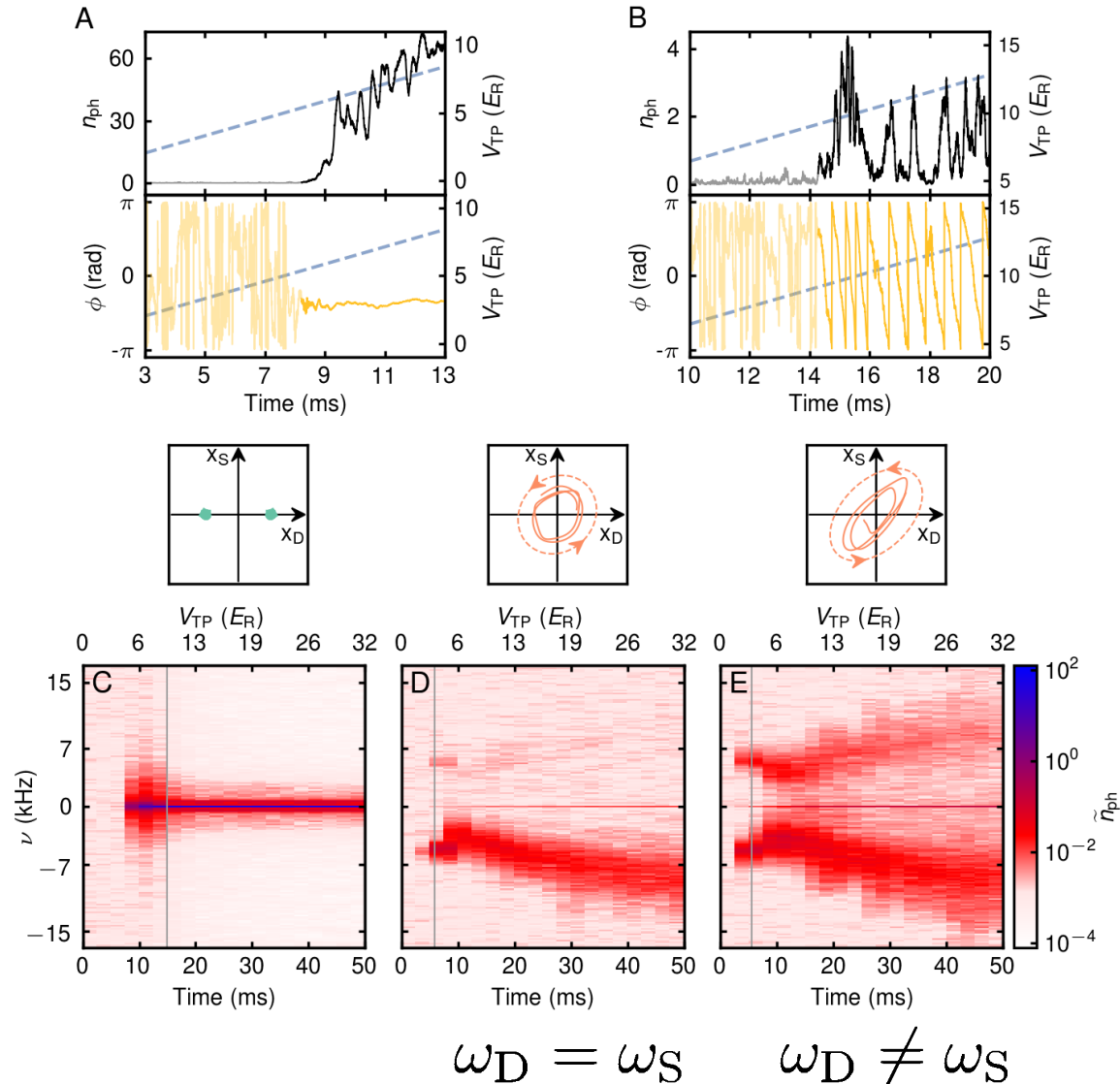


Experimental detection of the instability

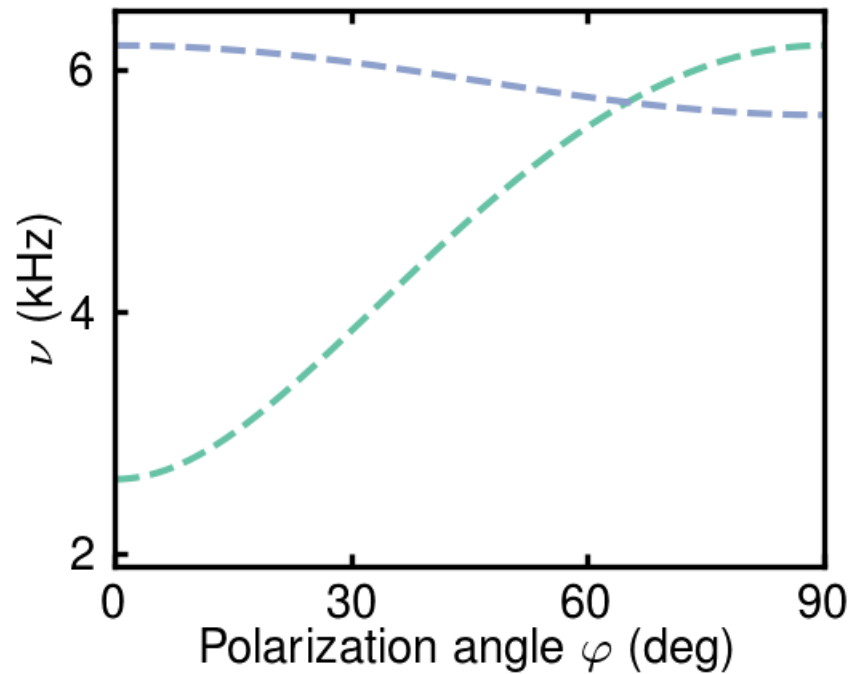
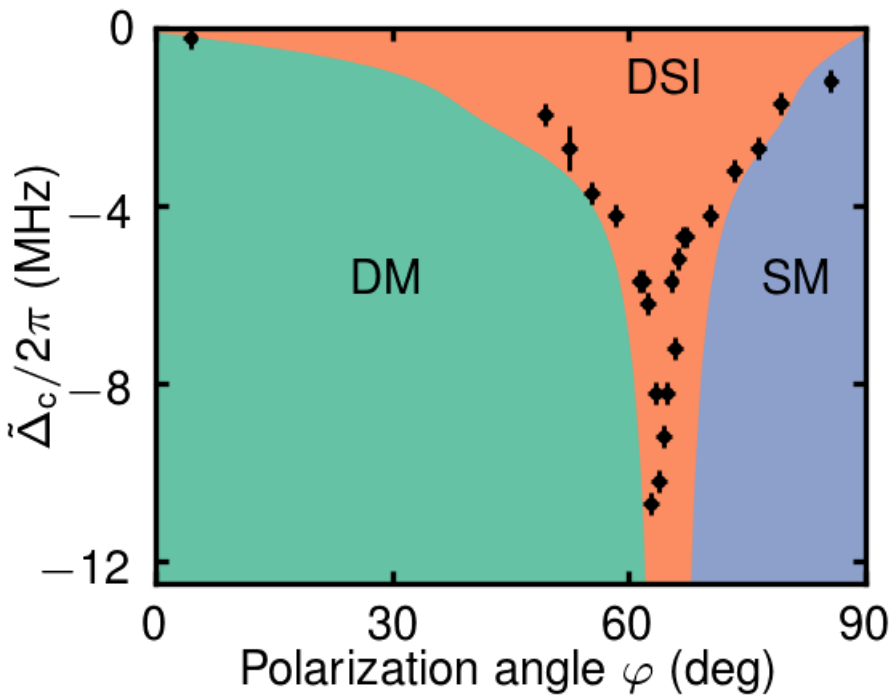


Running phase \rightarrow system evolving from one spatial configuration to another.

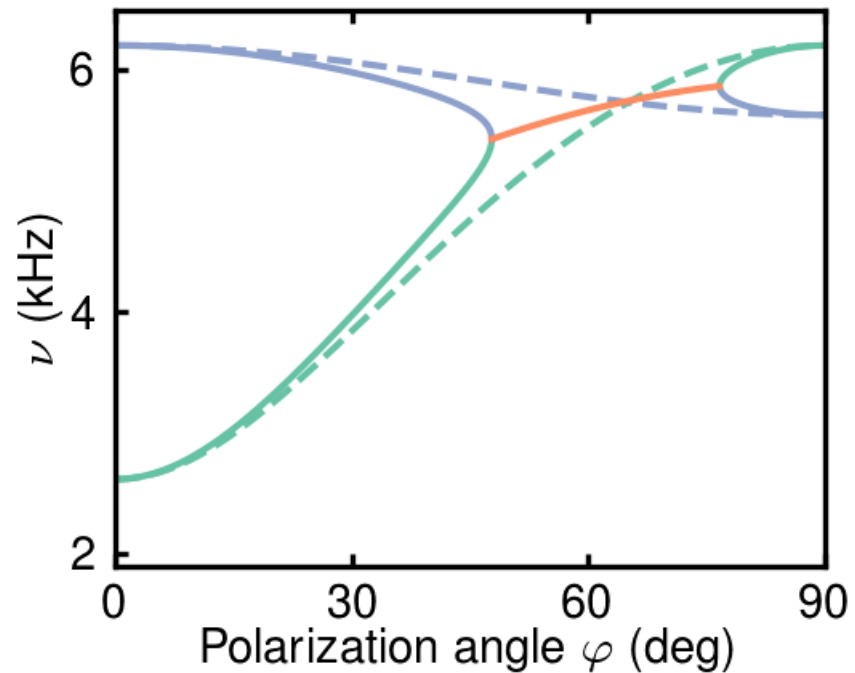
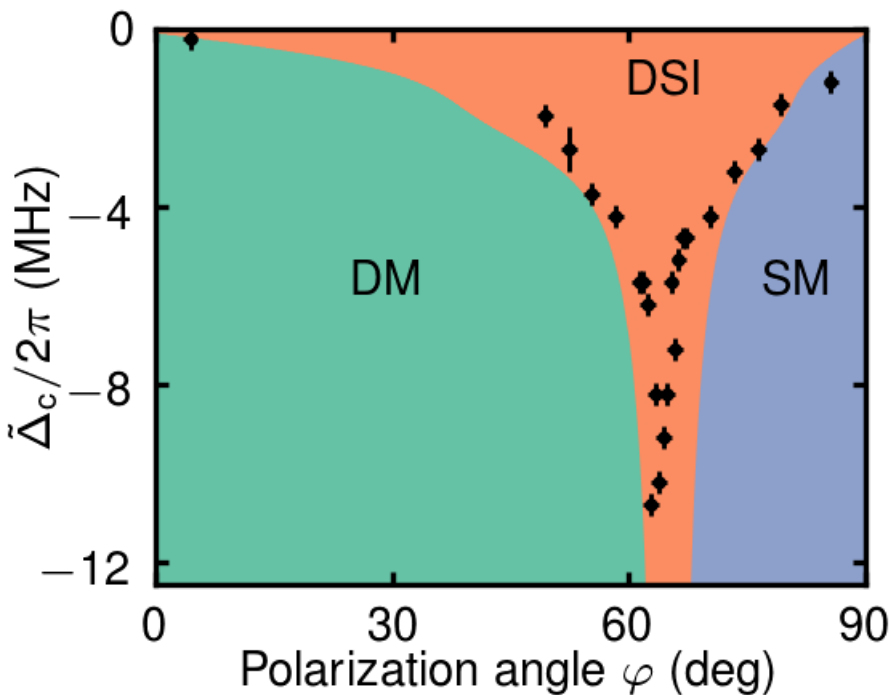
Information in the spectrum of light- Instability



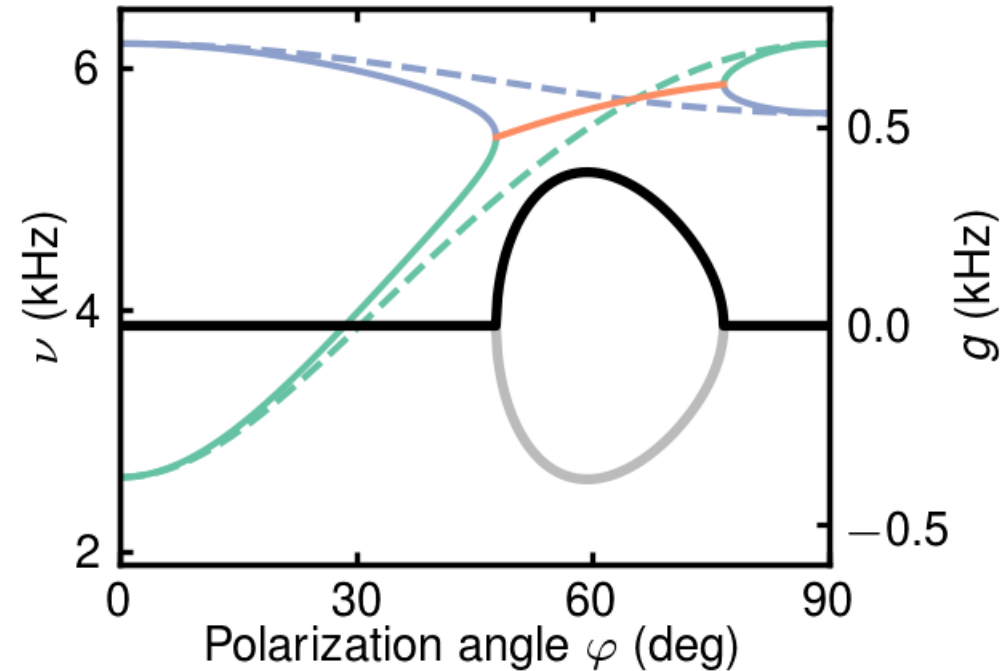
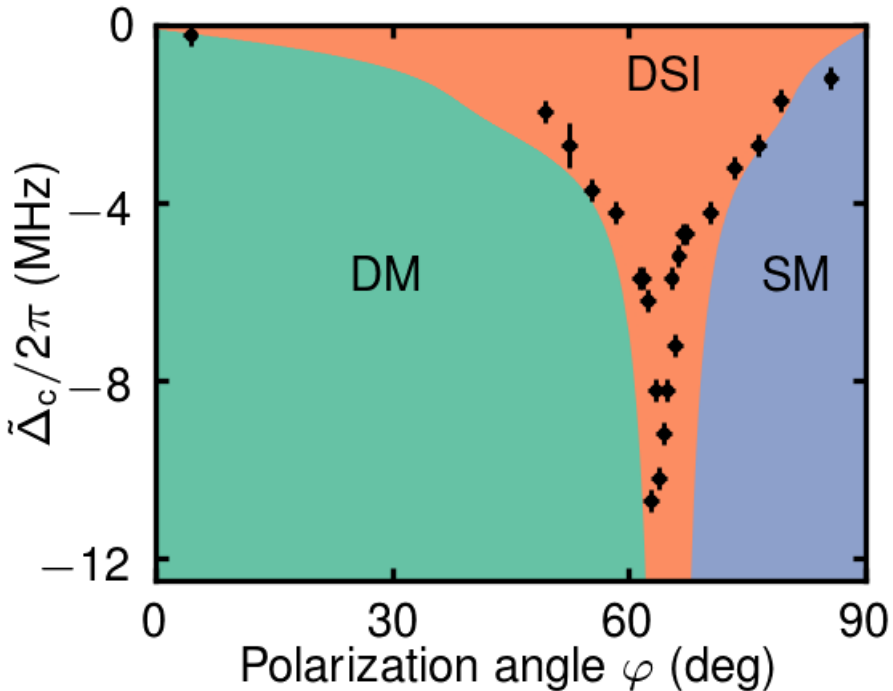
Competition between coherent and dissipative coupling



Competition between coherent and dissipative coupling



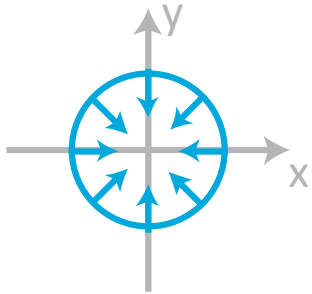
Competition between coherent and dissipative coupling



N. Dogra et al. arXiv:1901.05974

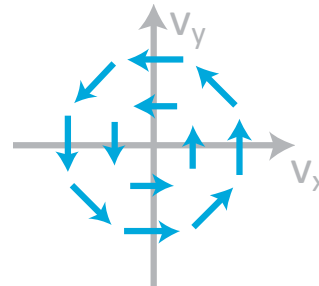
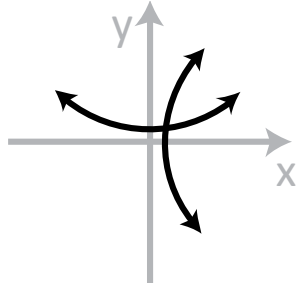
See also: E.R. Chiachio and A. Nunnenkamp, arXiv:1901.06996

Mechanical Forces



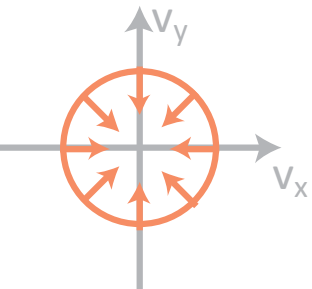
$$\begin{pmatrix} F_x \\ F_y \end{pmatrix} = \begin{pmatrix} -\omega_x^2 & 0 \\ 0 & -\omega_y^2 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

Conservative Force



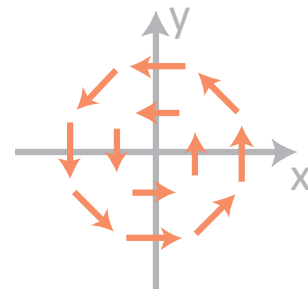
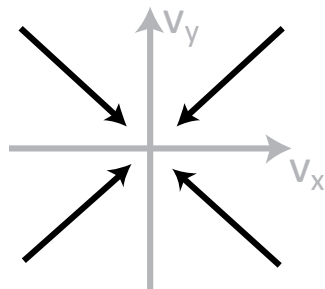
$$\begin{pmatrix} F_x \\ F_y \end{pmatrix} = \begin{pmatrix} 0 & qB_z \\ -qB_z & 0 \end{pmatrix} \begin{pmatrix} v_x \\ v_y \end{pmatrix}$$

Centripetal force or gauge fields



$$\begin{pmatrix} F_x \\ F_y \end{pmatrix} = \begin{pmatrix} -\alpha & 0 \\ 0 & -\beta \end{pmatrix} \begin{pmatrix} v_x \\ v_y \end{pmatrix}$$

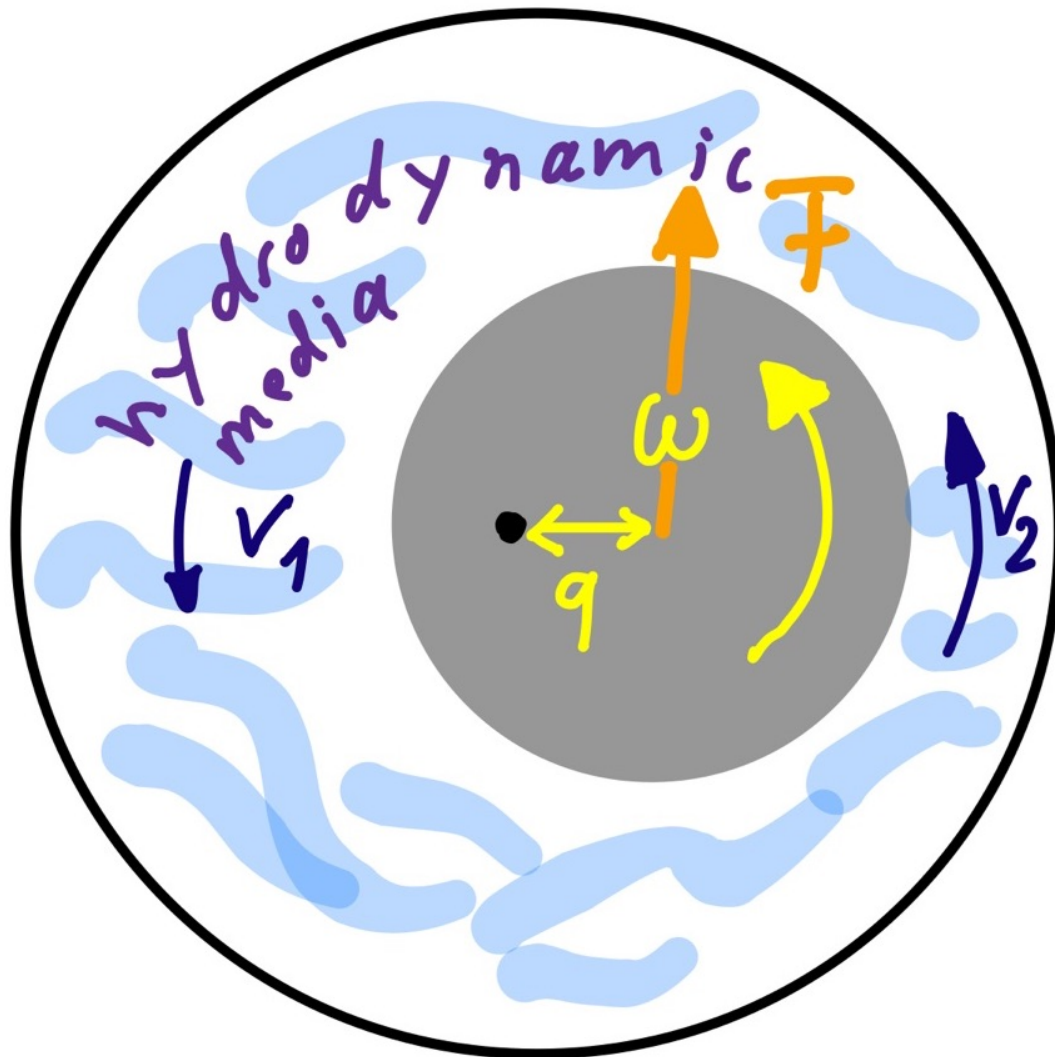
Frictional (Cooling) Force

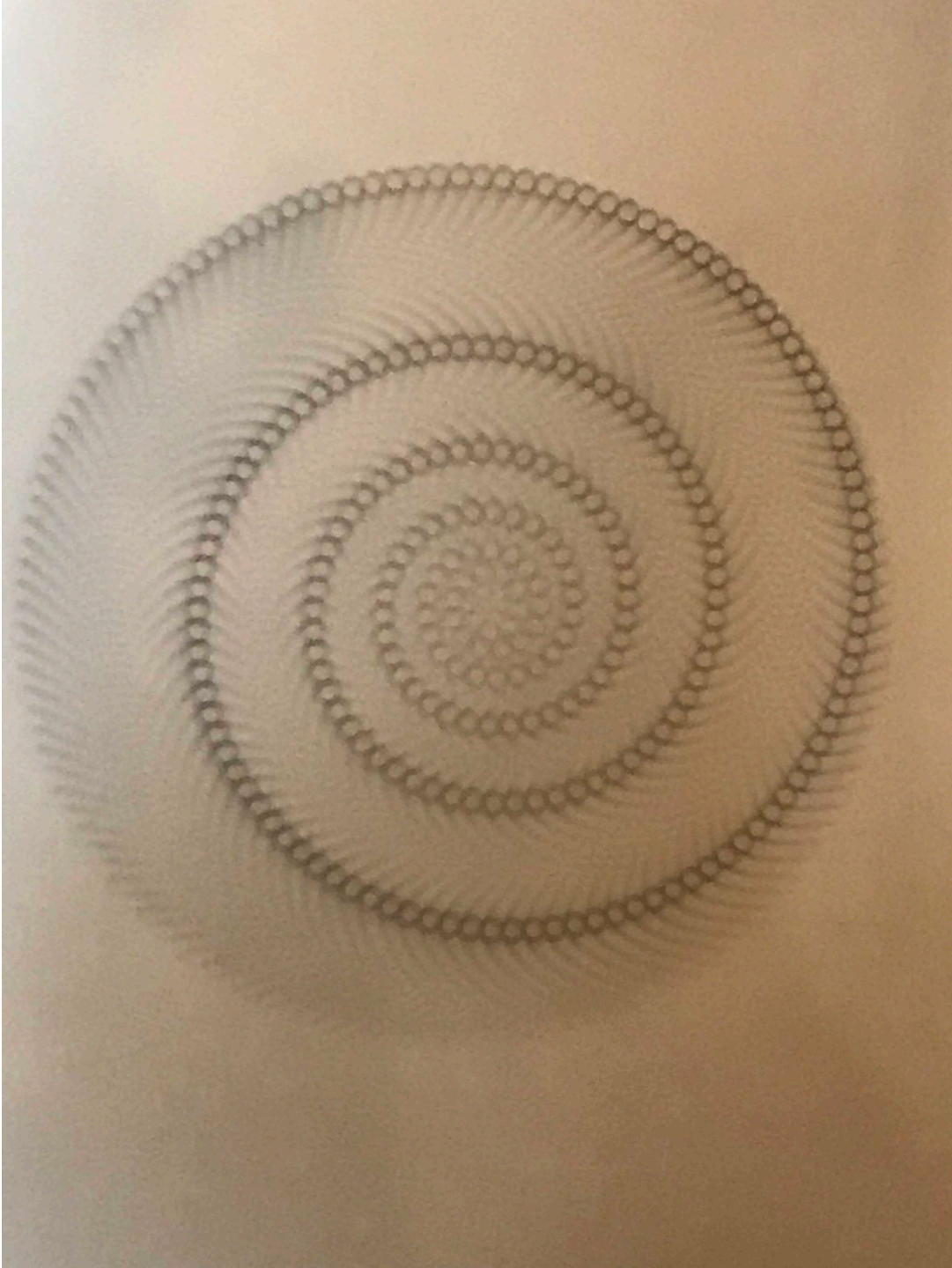


$$\begin{pmatrix} F_x \\ F_y \end{pmatrix} = \begin{pmatrix} 0 & -K^2 \\ K^2 & 0 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

Non-conservative positional Force

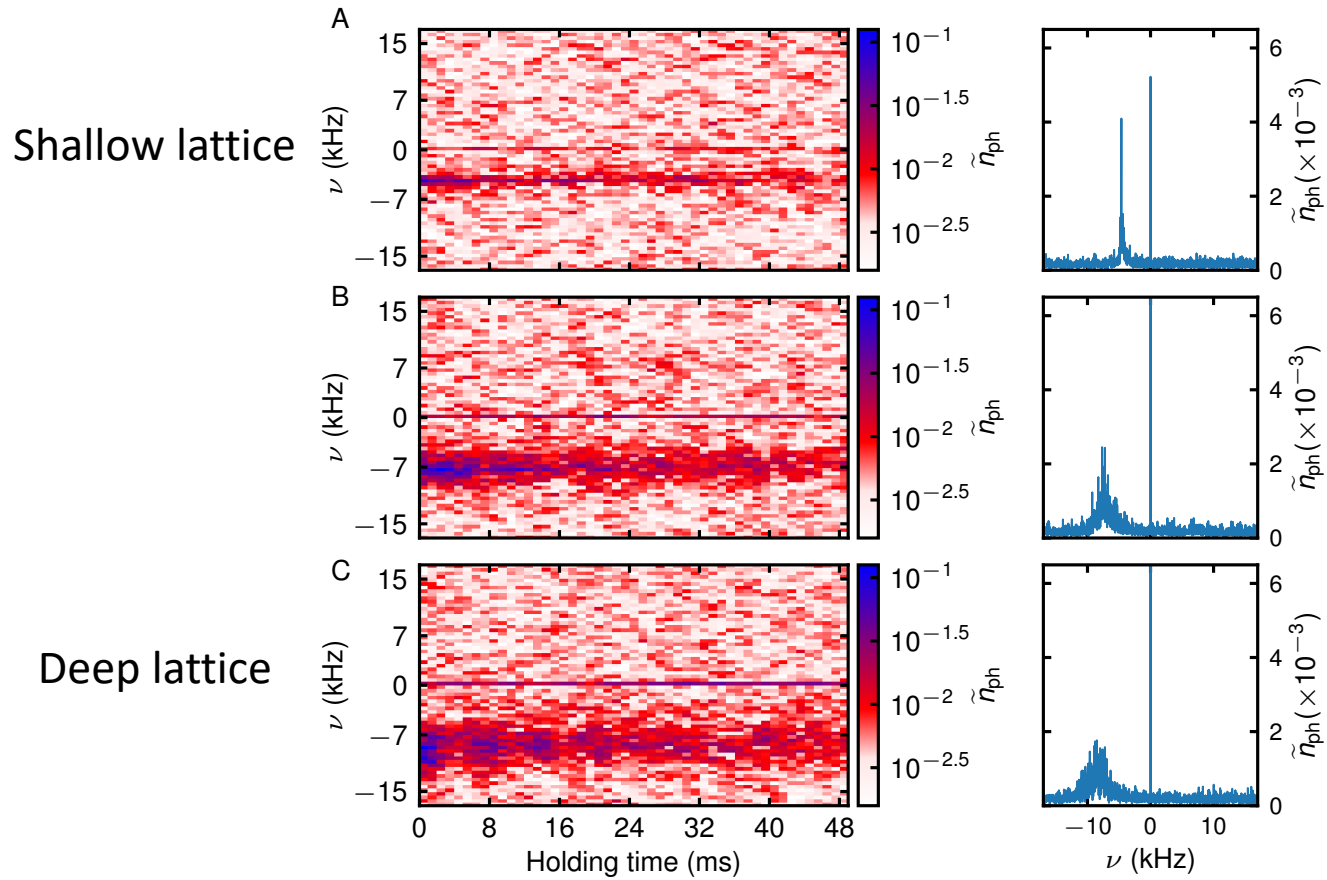
Position dependent friction force





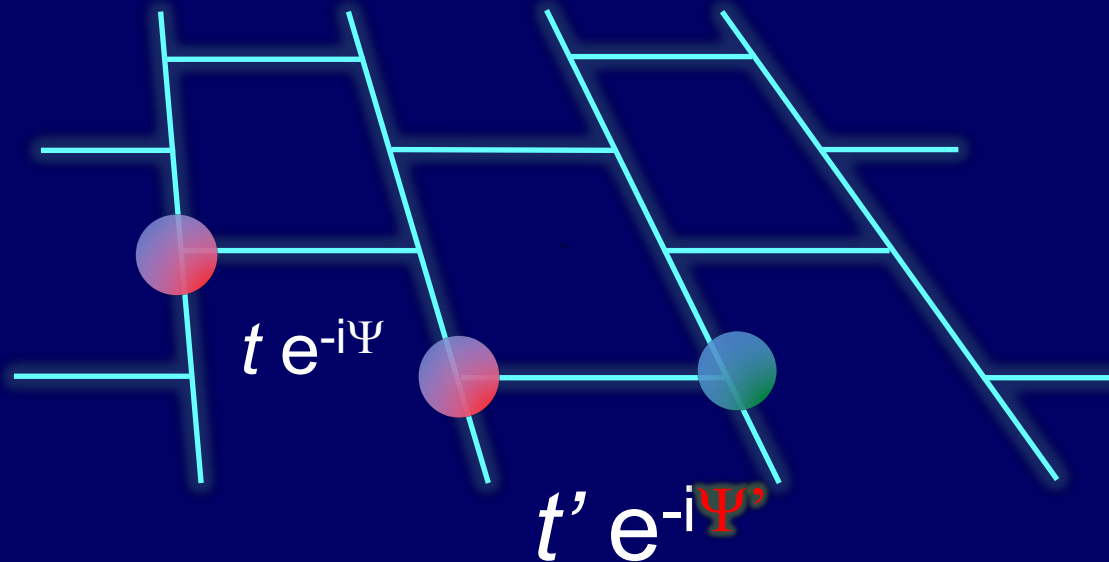
Limit cycles

Constant pump lattice



Density-dependent Peierls Phase to couple dynamical gauge fields to matter

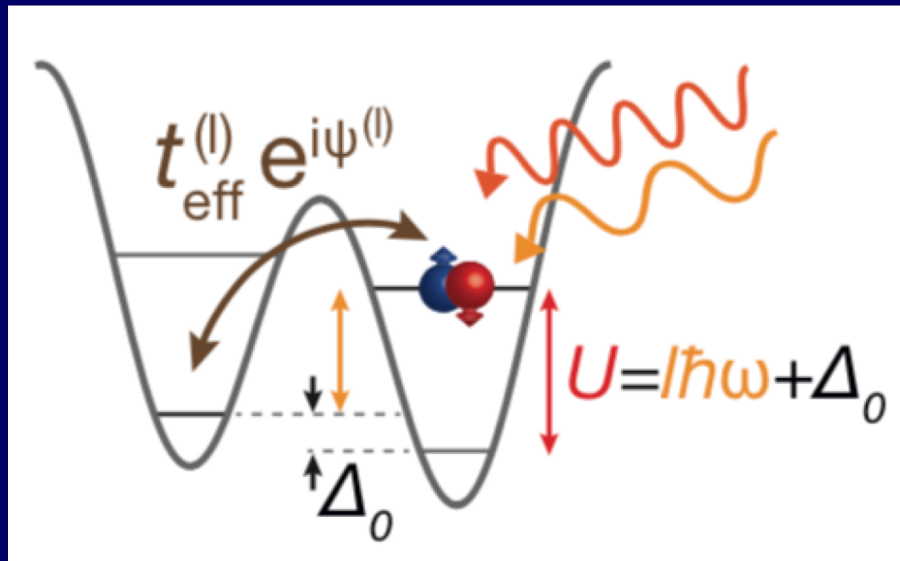
F. Görg, K. Sandholzer, J. Minguzzi, R. Desbuquois, M. Messer, and T. Esslinger, arXiv:1812.05895



See also: L. Barbiero, C. Schweizer, M. Aidelsburger, E. Demler, N. Goldman, and F. Grusdt,
Coupling ultracold matter to dynamical gauge fields in optical lattices: From flux-attachment to Z2 lattice gauge theories
arXiv:1810.02777

Two-frequency driven double well

Resonant Hamiltonian

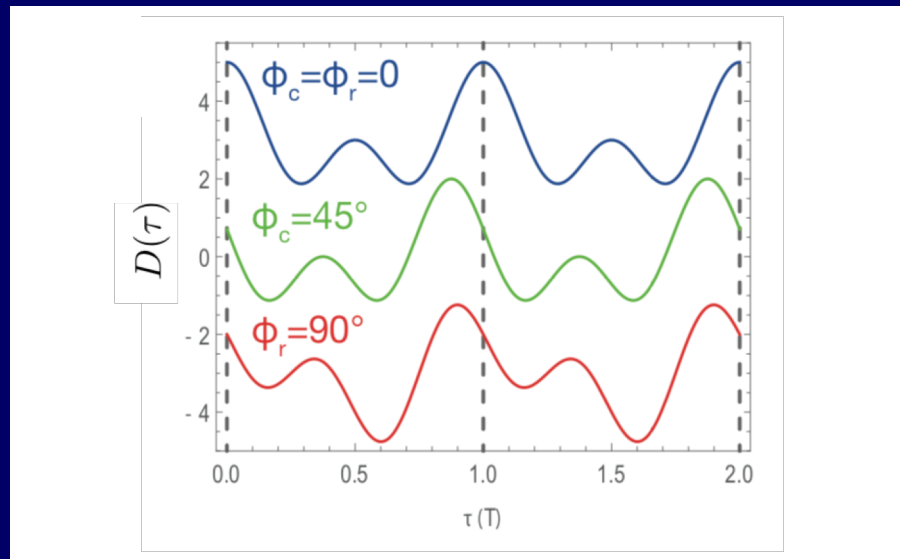


$$t_{\text{eff}}^{(2)} = t(\alpha^{(2)} + \beta^{(2)} e^{-i\phi_r})$$

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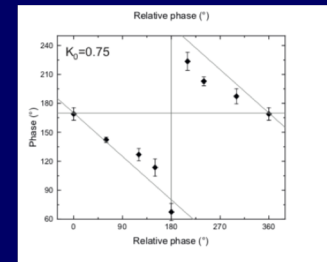
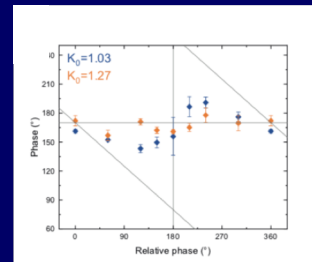
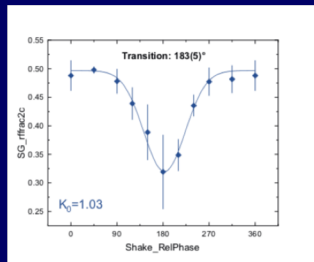
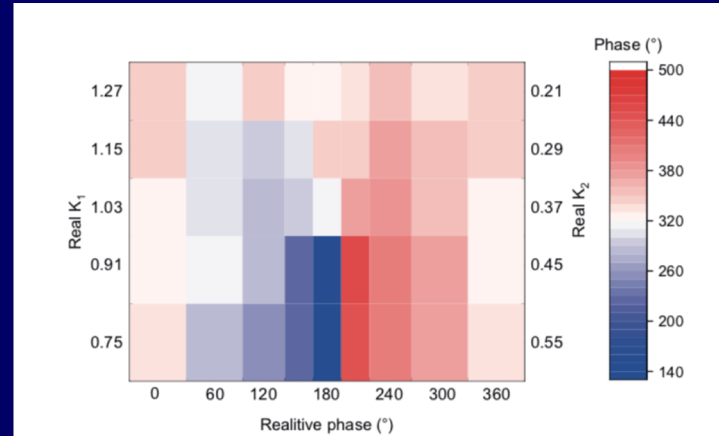
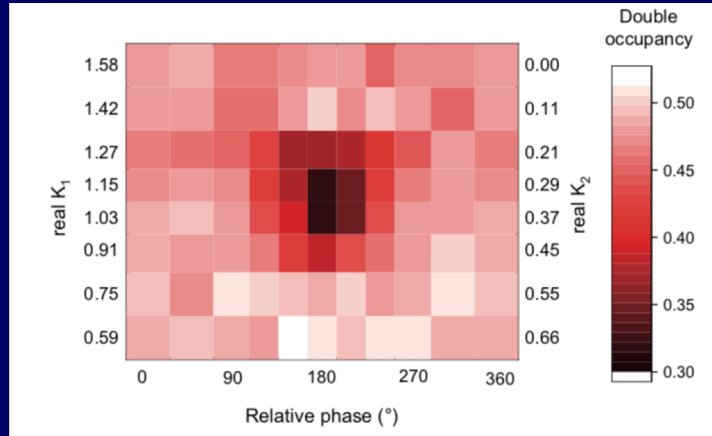
Two-frequency driven double well

Breaking time-reversal symmetry



$$D(\tau) = \hbar\omega K_1 \cos(\omega\tau + \phi_c) + 2\hbar\omega K_2 \cos(2\omega\tau + 2\phi_c + \phi_r)$$

Dirac point



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Quantum Gases in Optical Lattices

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Lithium Transport

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