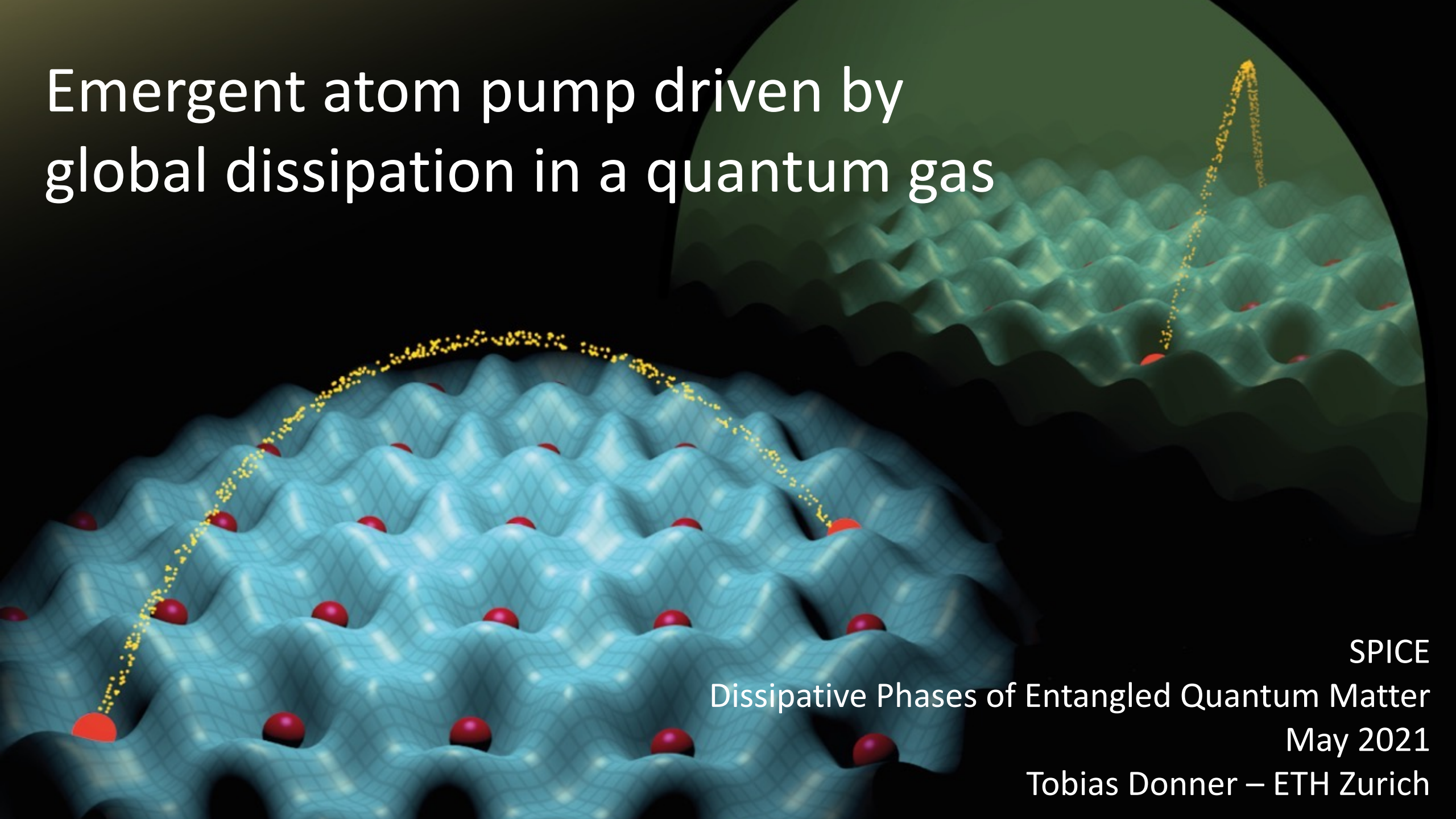
Emergent atom pump driven by global dissipation in a quantum gas



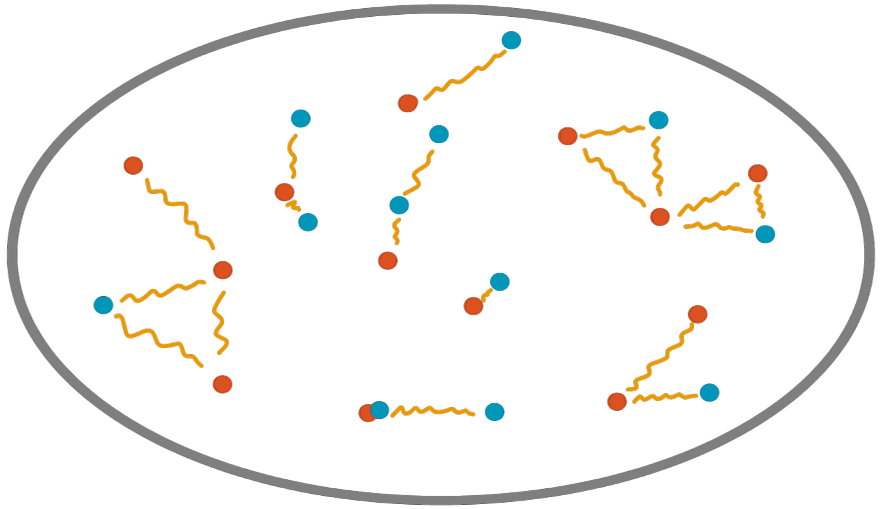
SPICE

Dissipative Phases of Entangled Quantum Matter

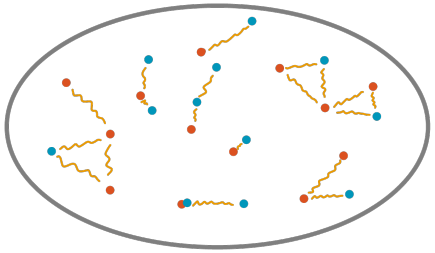
May 2021

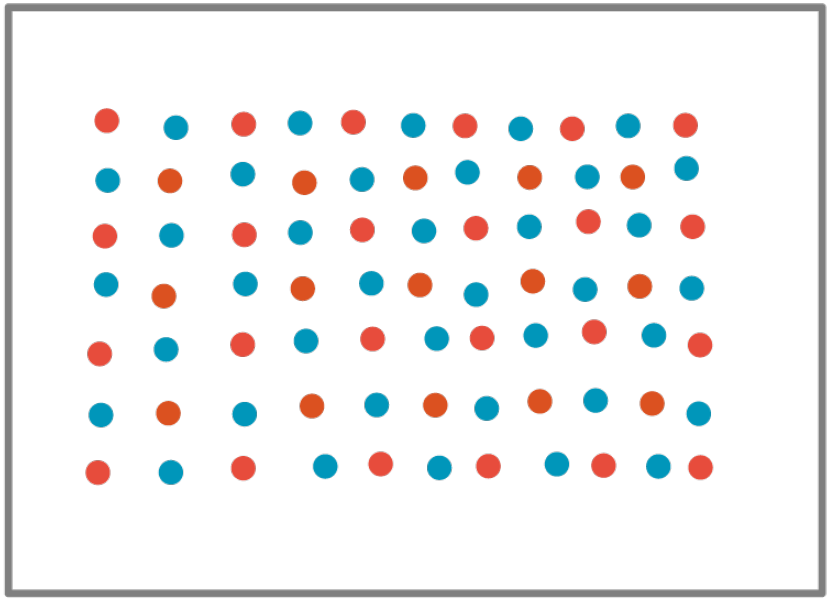
Tobias Donner – ETH Zurich

Quantum many-body systems

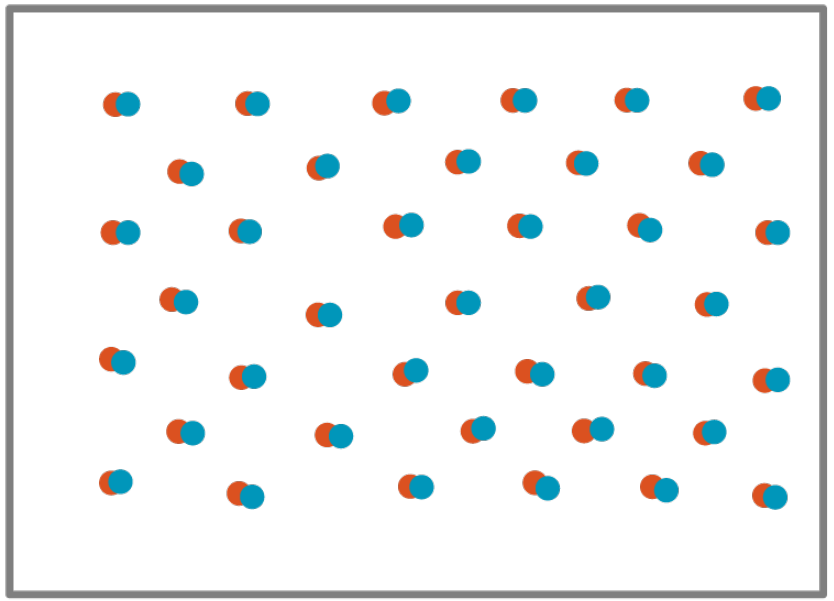


QMBS with interactions



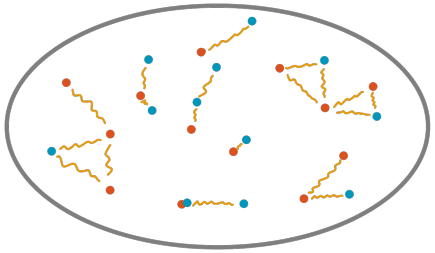


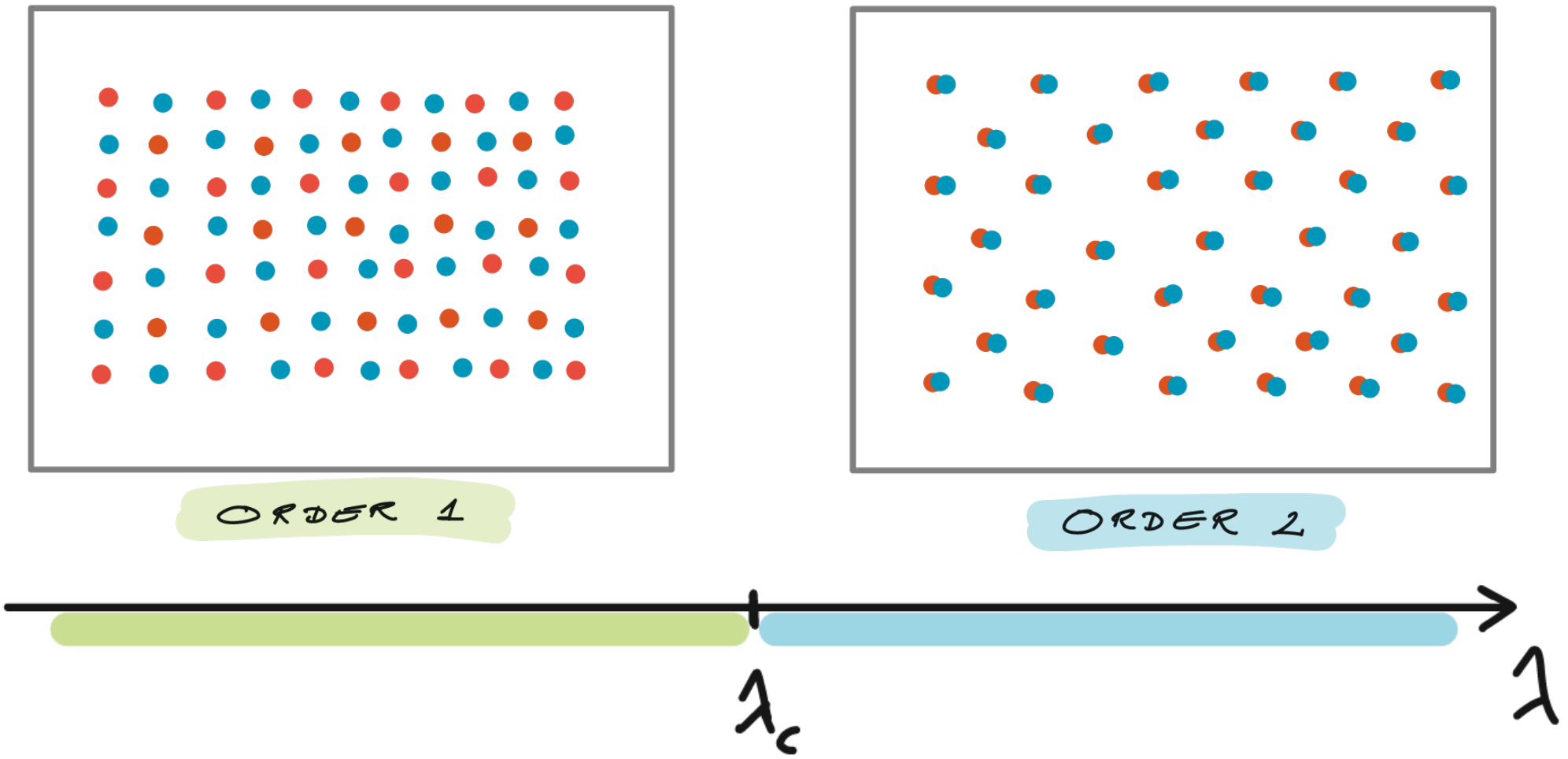
ORDER 1



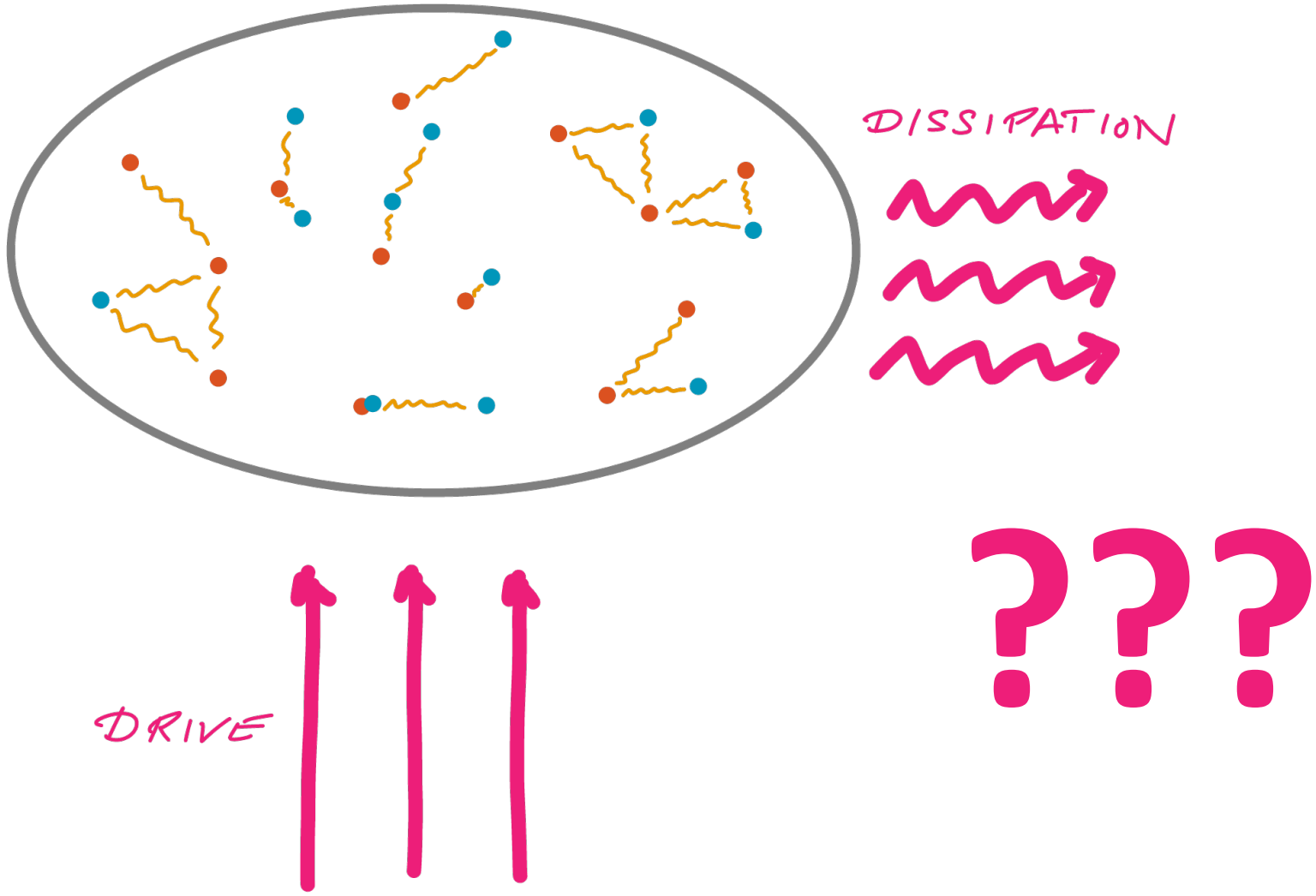
ORDER 2

QMBS with interactions

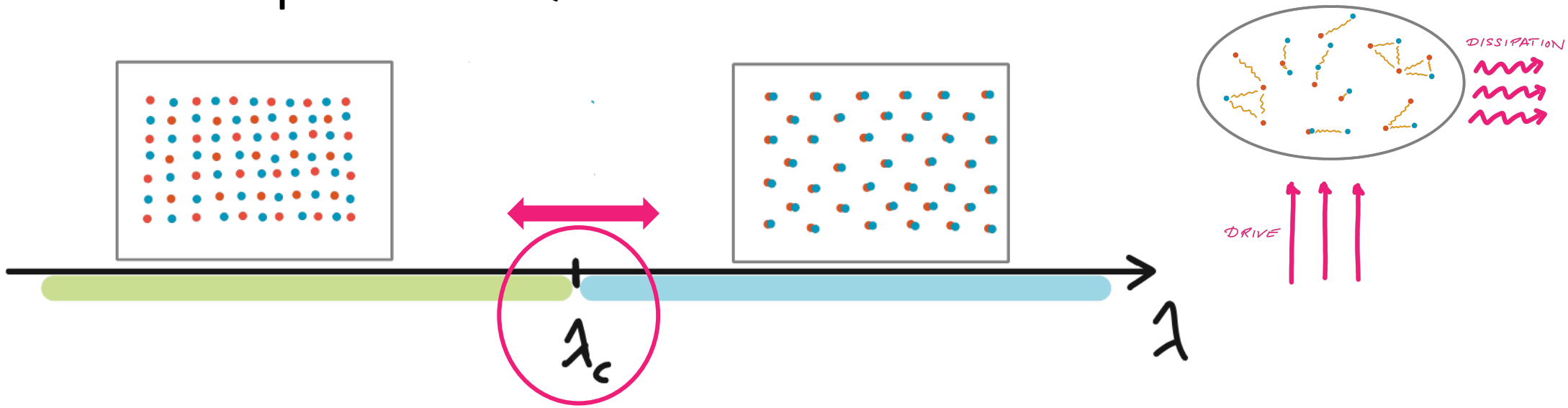




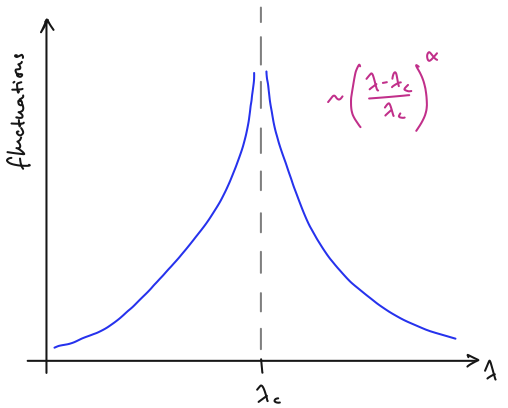
Driven-dissipative systems



Driven-dissipative QMBS

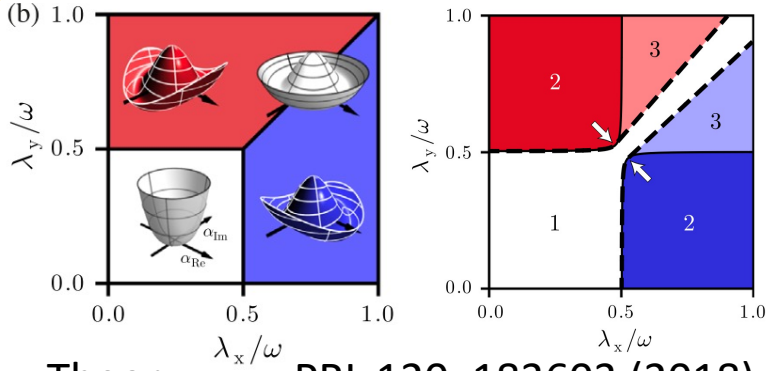


Criticality



PNAS 110, 11763 (2013)

New phases



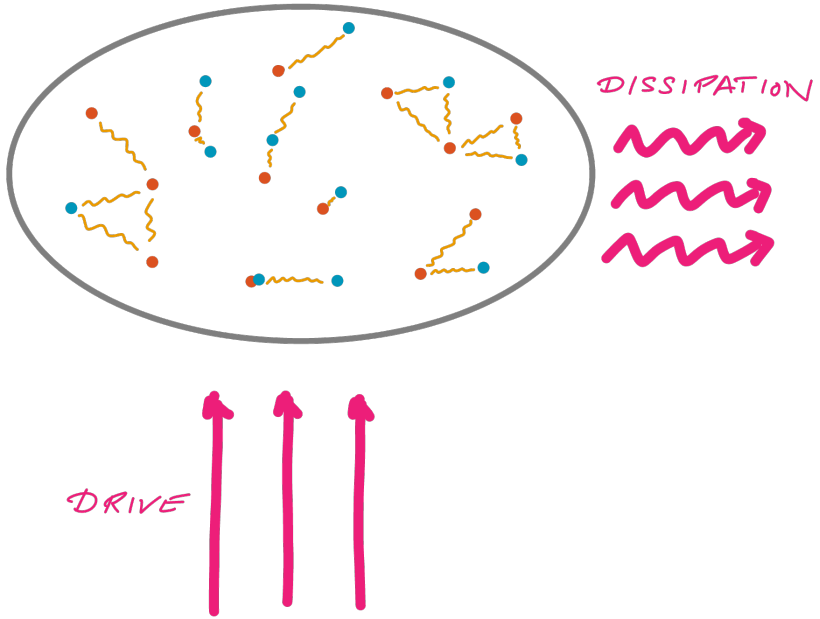
Theory: PRL 120, 183603 (2018)
PRA 101, 023823 (2020)

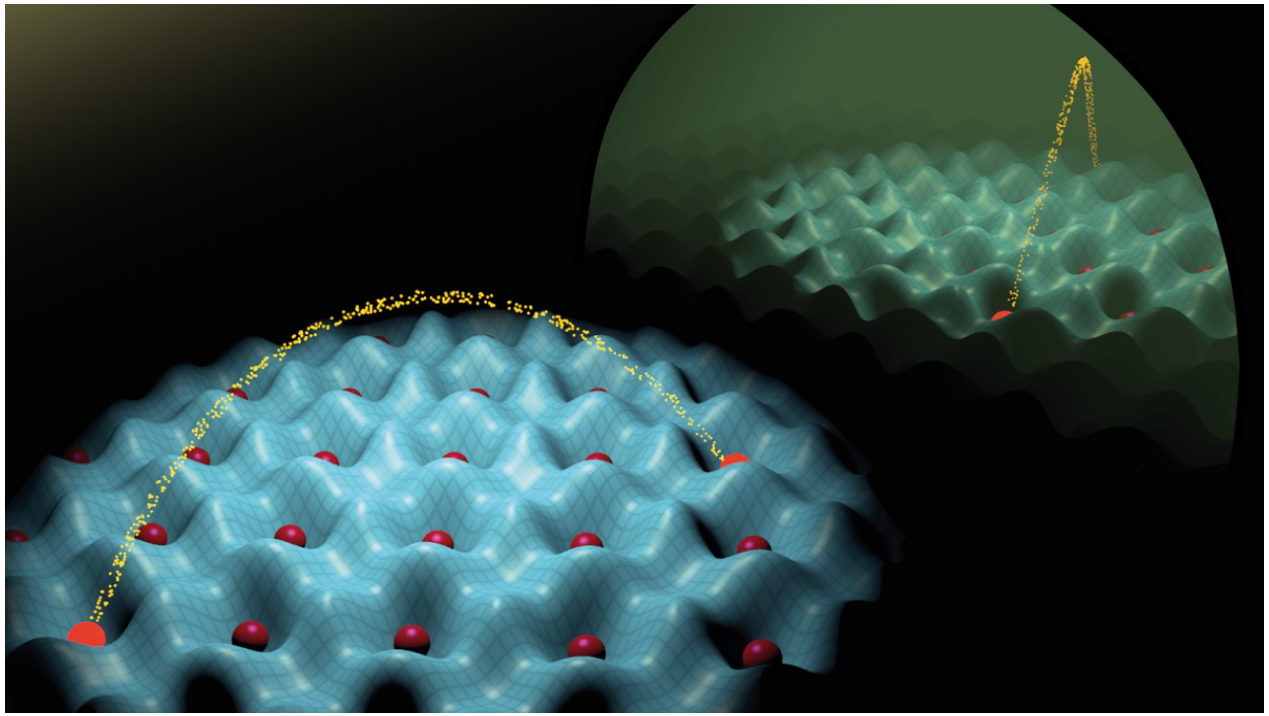
Experiment: arXiv:2104.12782 (2021)

Emergent dynamics

- Stationarity vs non-stationarity
- Synchronization
- Limit cycles
- Chaos
- *This talk: Emergent pumping*

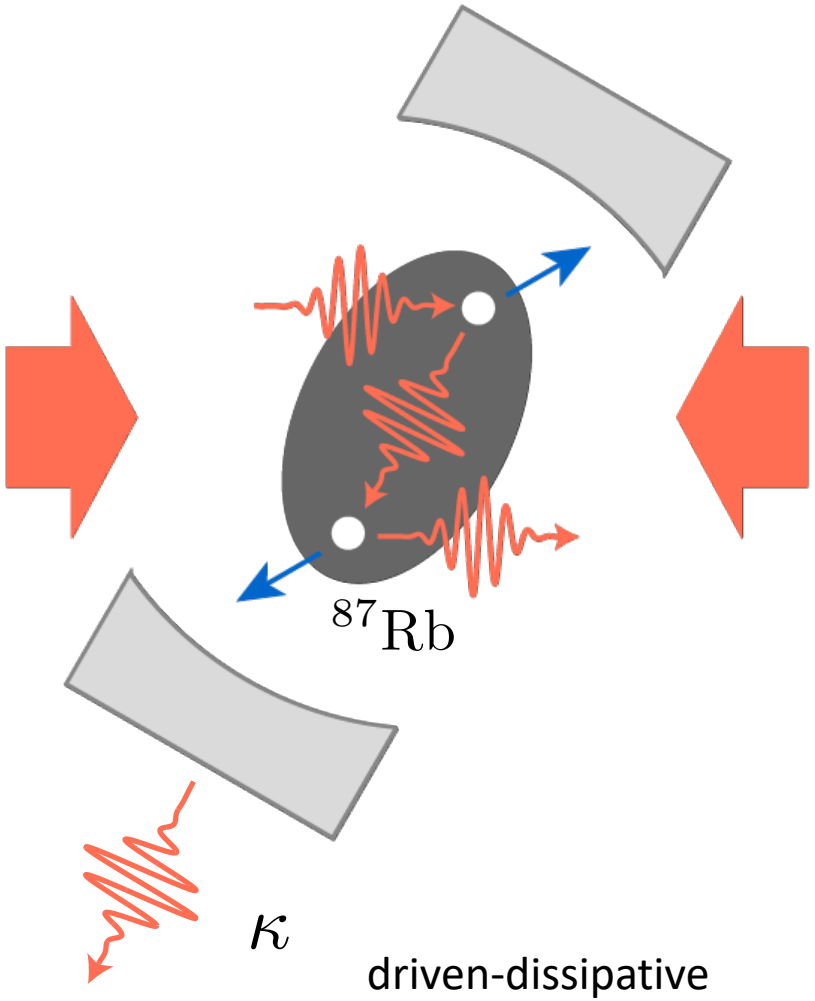
Many-body cavity QED:
A quantum gas coupled to an optical cavity





Other groups: Hemmerich (Hamburg), Lev group (Stanford), Zimmermann (Tübingen)

Cavity-mediated long-range interactions



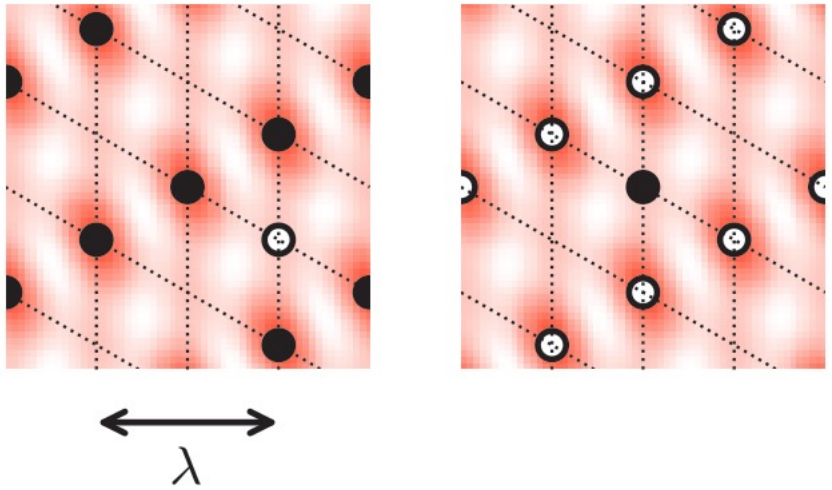
driven-dissipative system

Long-range interaction:

$$V(\mathbf{r},\mathbf{r}') = V\cos(\mathbf{k}_p\mathbf{r})\cos(\mathbf{k}_c\mathbf{r})\cos(\mathbf{k}_p\mathbf{r}')\cos(\mathbf{k}_c\mathbf{r}')$$

→ Interaction favors an atomic density modulation.

$$V \propto \frac{P}{\Delta_c}$$

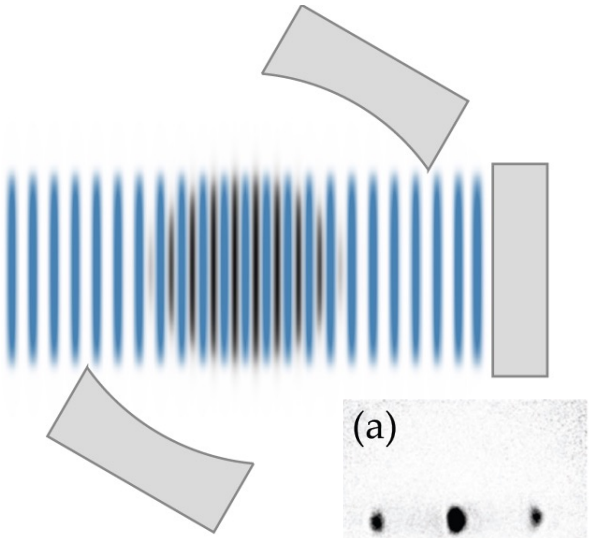


Superradiant phase transition: potential vs kinetic energy

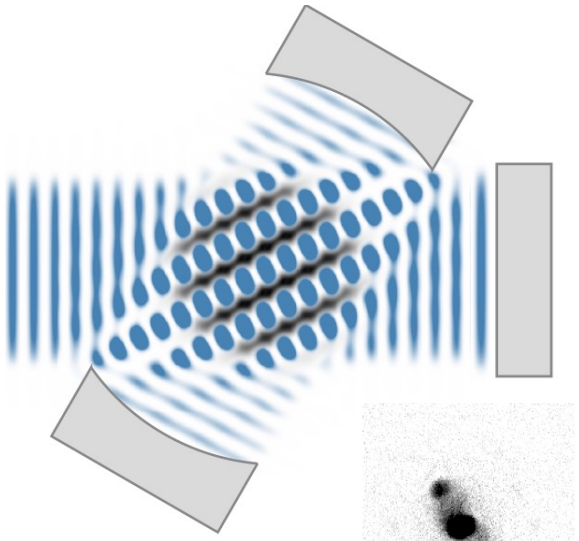
Single-particle Hamiltonian:

$$\hat{\mathcal{H}}_{\mathrm{SP}}/\hbar = -\Delta_c \hat{a}^\dagger \hat{a} + \frac{\hat{\mathbf{p}}^2}{2\hbar m} + \frac{\Omega^2}{\Delta_a}\cos^2(\mathbf{k}_p\hat{\mathbf{r}}) + \frac{g_0^2}{\Delta_a}\cos^2(\mathbf{k}_c\hat{\mathbf{r}})\hat{a}^\dagger\hat{a} + \frac{g_0\Omega}{\Delta_a}\cos(\mathbf{k}_p\hat{\mathbf{r}})\cos(\mathbf{k}_c\hat{\mathbf{r}})(\hat{a}+\hat{a}^\dagger)$$

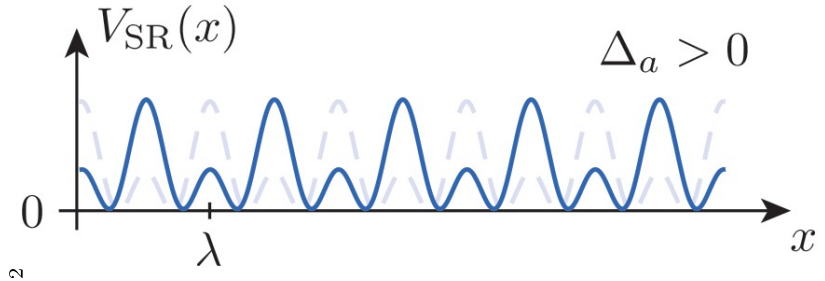
photon energy — kinetic energy — pump lattice potential — cavity lattice potential — interaction potential

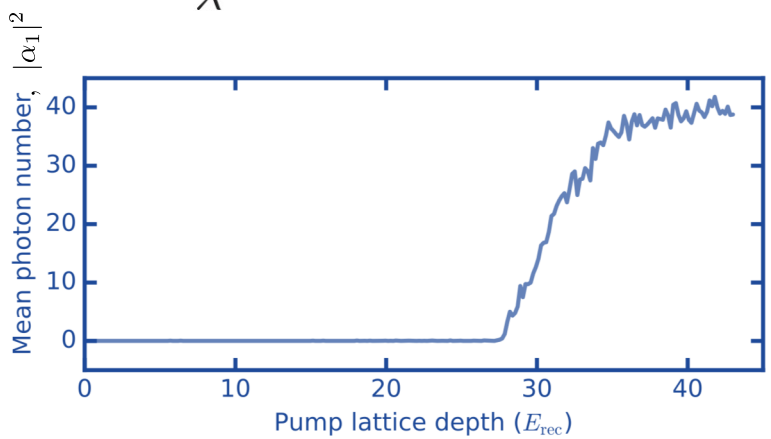


normal phase

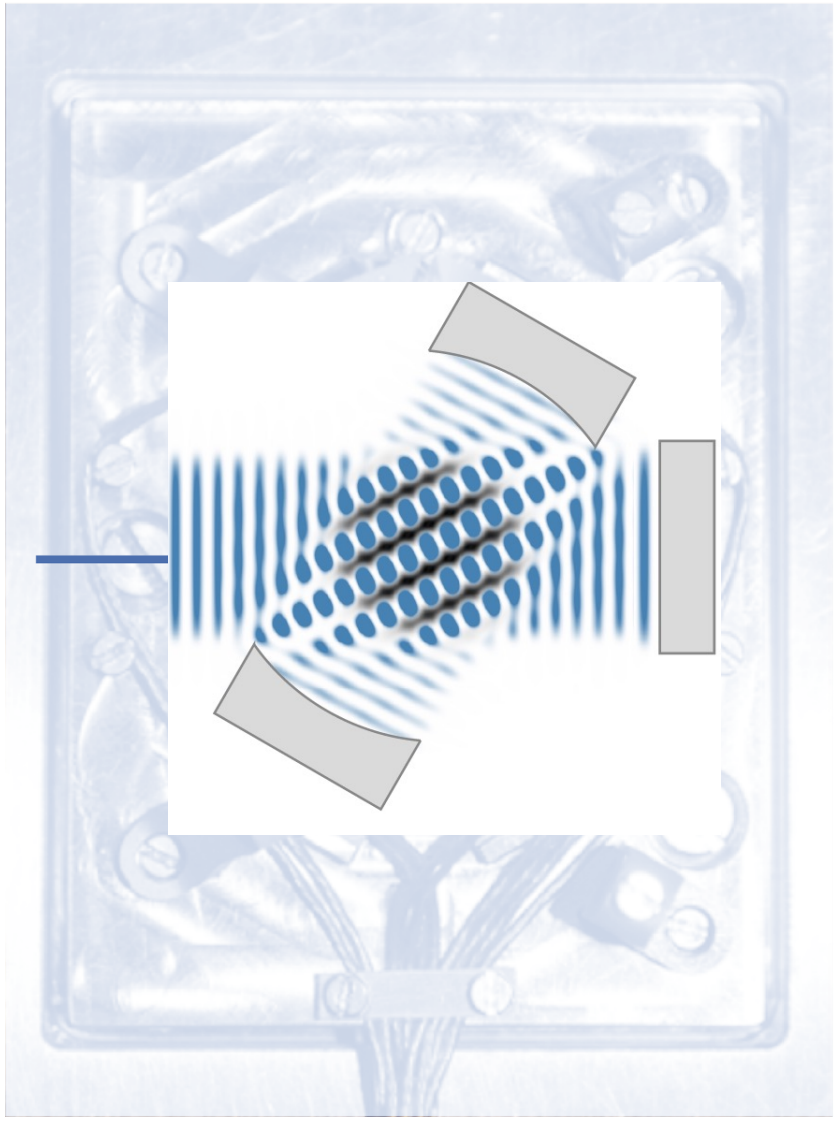


superradiant phase

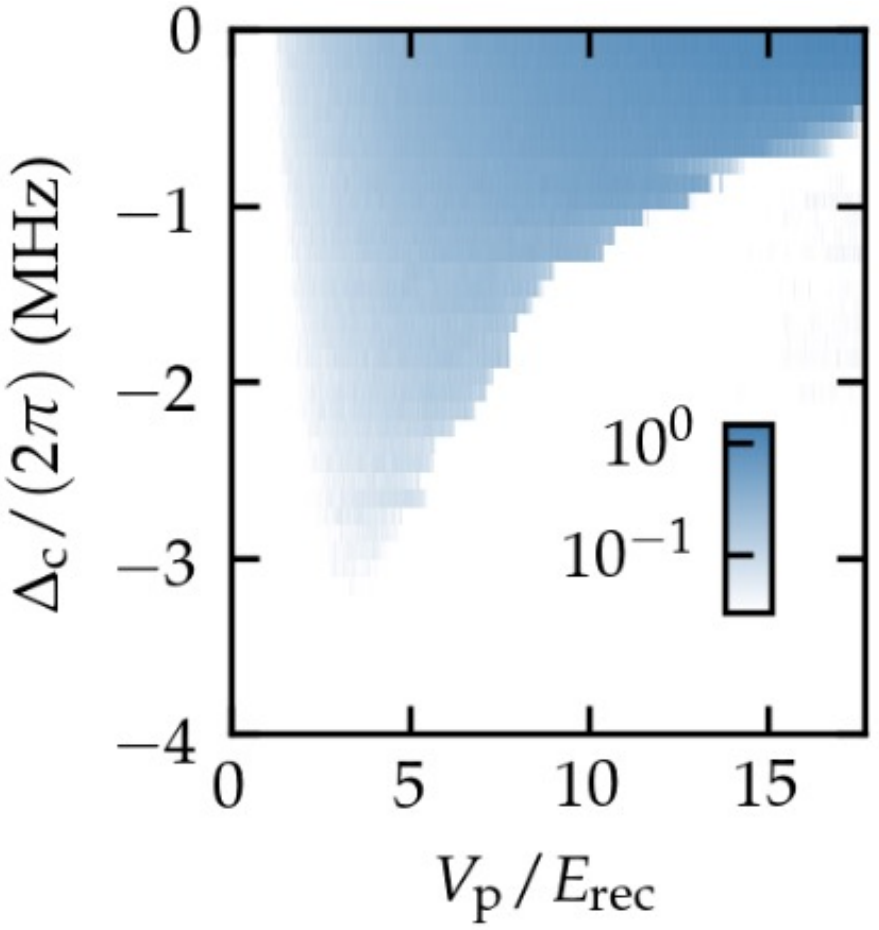




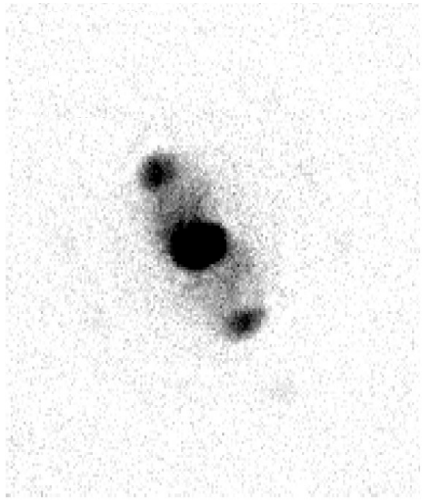
Measuring the phase diagram



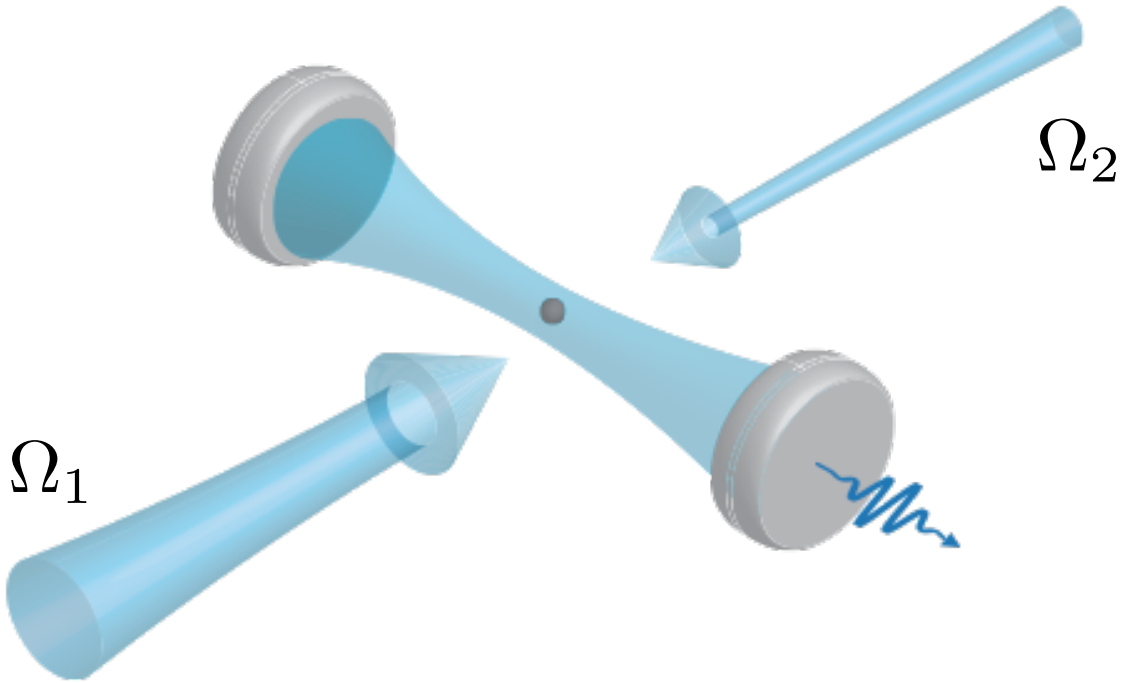
Phase diagram



Time-of-Flight Image



Running and Standing Wave Pump



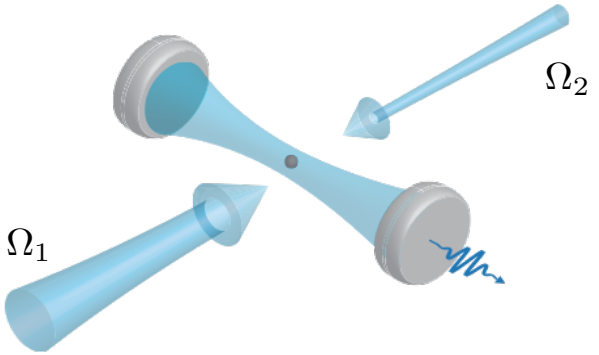
Li *et al.* , PRR 2021

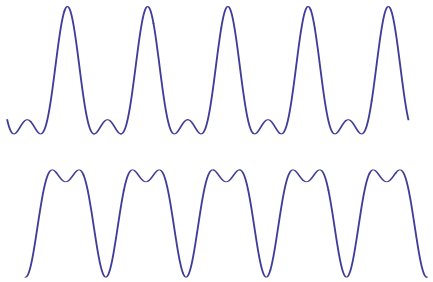
Running and Standing Wave Pump

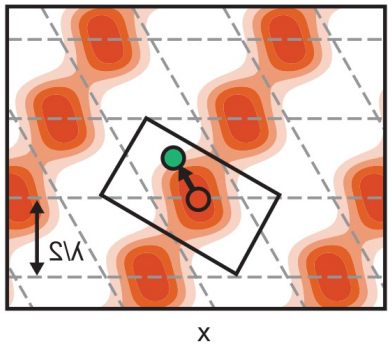
$$\hat{\mathcal{H}}/\hbar = -\Delta_c \hat{a}^\dagger \hat{a} + \frac{\hat{\mathbf{p}}^2}{2\hbar m} + \frac{\Omega_1 \Omega_2}{\Delta_a}\cos^2(\mathbf{k}_p\hat{\mathbf{r}}) + \frac{g_0^2}{\Delta_a}\cos^2(\mathbf{k}_c\hat{\mathbf{r}})$$

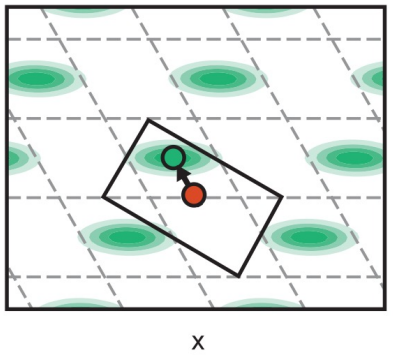
$$+ \frac{g_0(\Omega_1 + \Omega_2)}{\Delta_a}(\hat{a} + \hat{a}^\dagger)\cos(\mathbf{k}_p\hat{\mathbf{r}})\cos(\mathbf{k}_c\hat{\mathbf{r}})$$

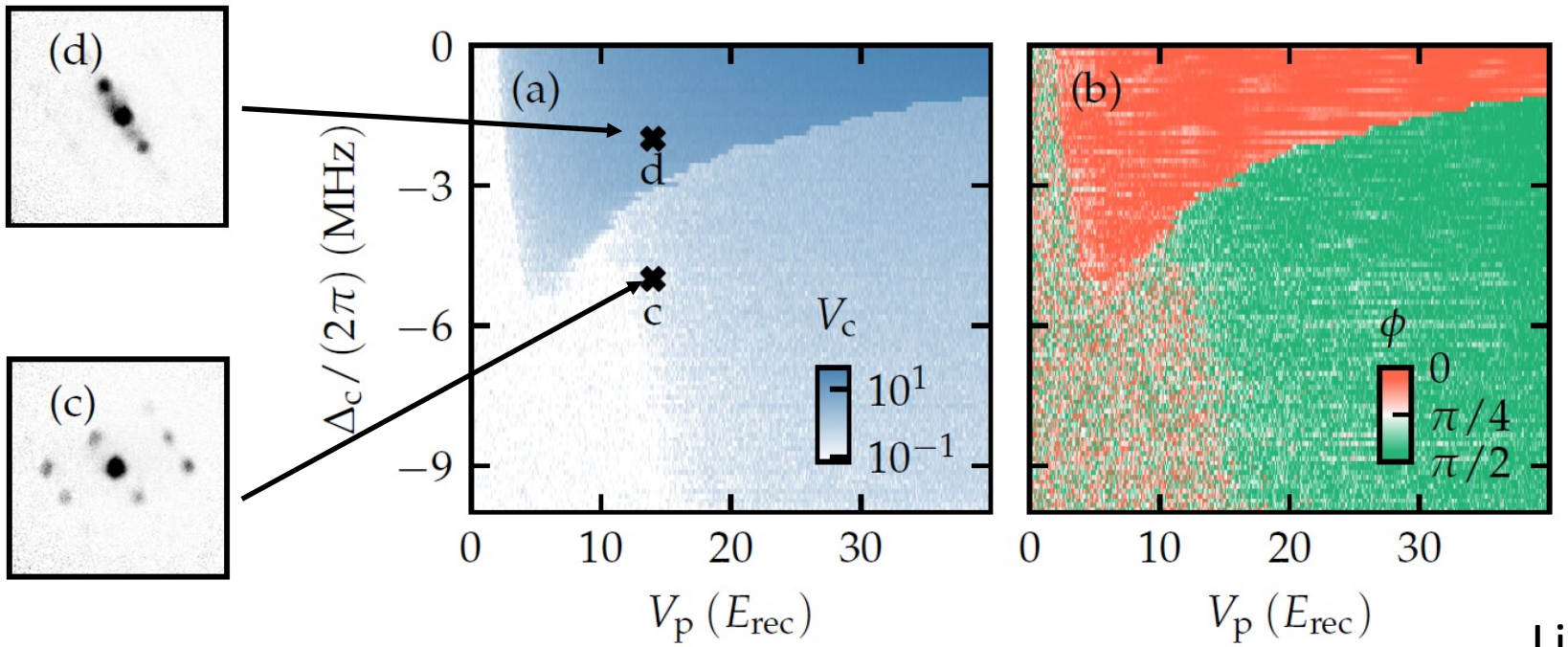
$$+ i\frac{g_0(\Omega_1 - \Omega_2)}{\Delta_a}(\hat{a} - \hat{a}^\dagger)\sin(\mathbf{k}_p\hat{\mathbf{r}})\cos(\mathbf{k}_c\hat{\mathbf{r}})$$









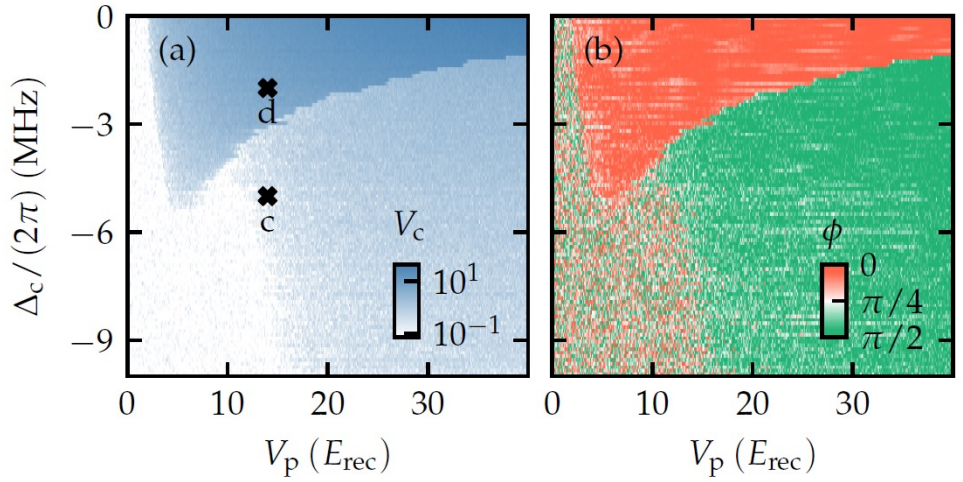


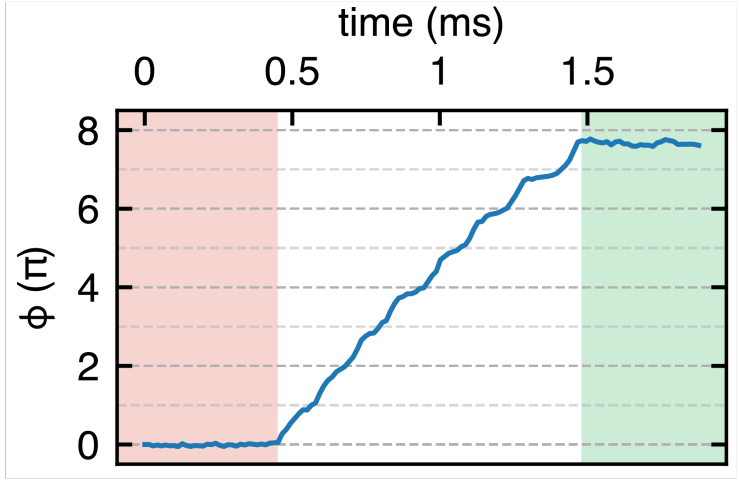
Li *et al.* , PRR 2021

Approaching the dissipative regime: $\Delta_c \simeq \kappa$

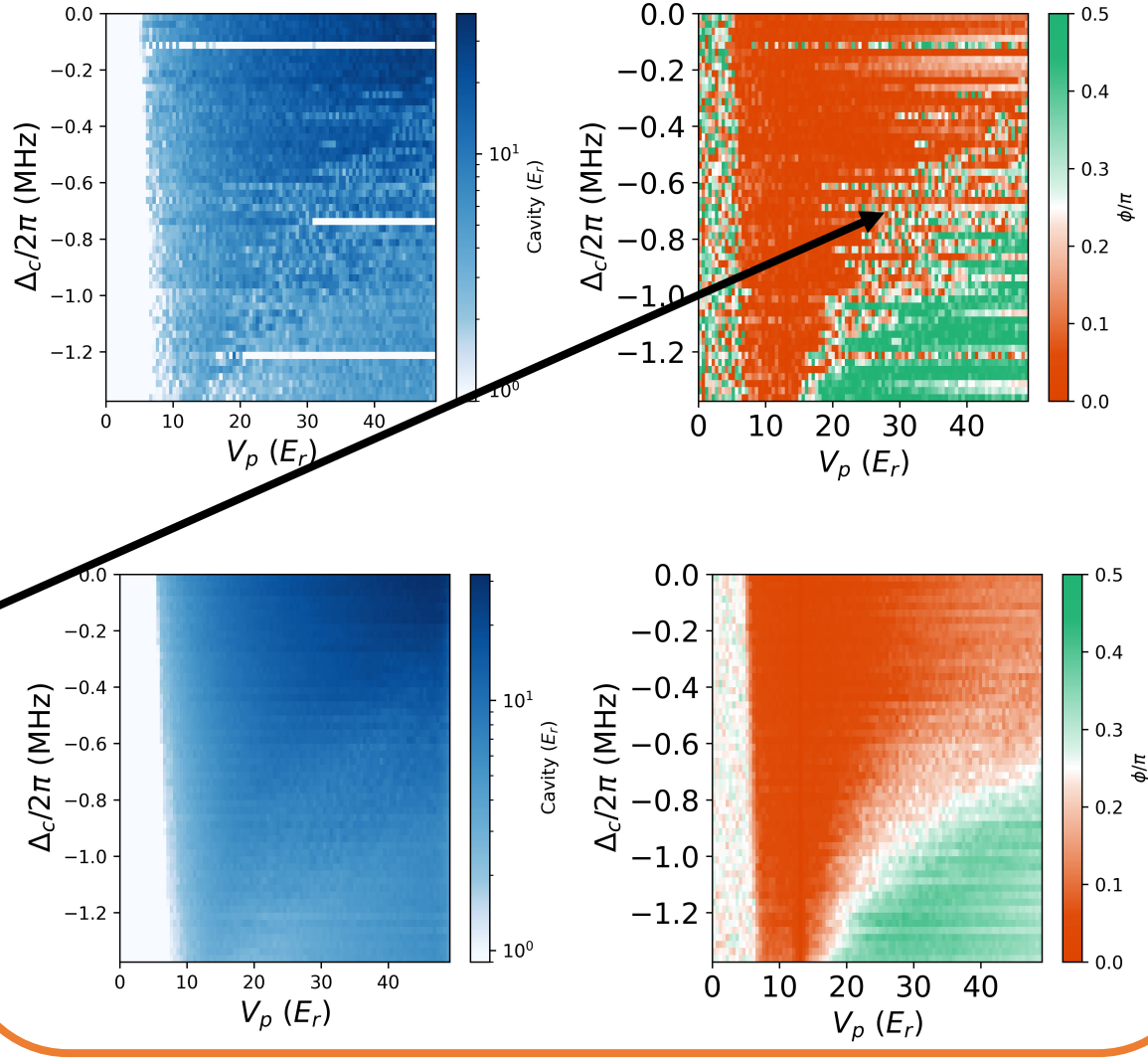
Work in progress

$\Delta_c \gg \kappa$



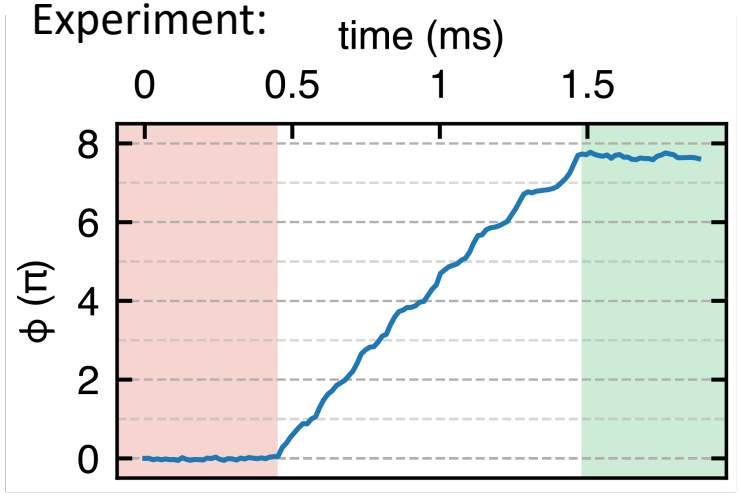


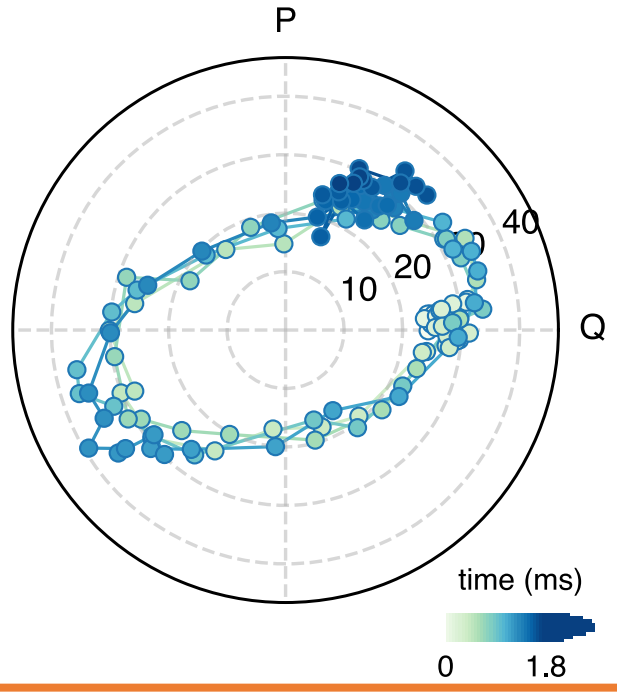
$\Delta_c \simeq \kappa$



Dissipation-induced instability: chiral dynamics

Experiment:





Equations of motion:

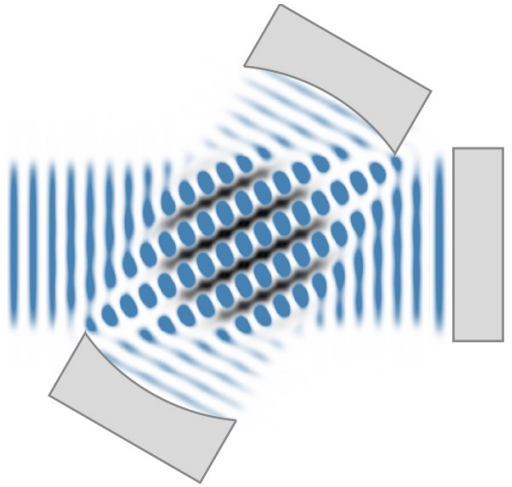
$$i\hbar\frac{\partial\psi}{\partial t} = \left(H_0 + V_{\text{lattice}}(\alpha)\right)\psi$$

$$\alpha = \frac{\eta\langle\psi|\Theta|\psi\rangle}{\Delta_c - i\kappa}$$

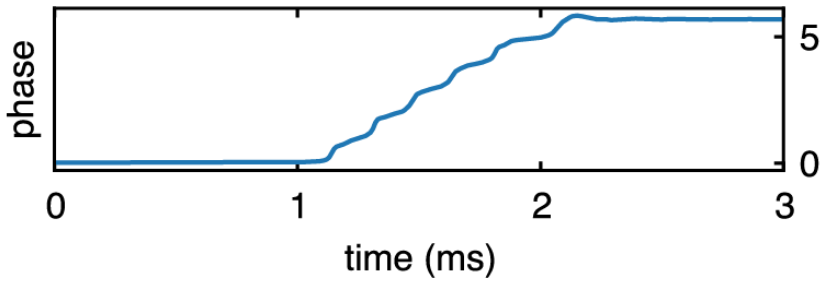
Mode integrals

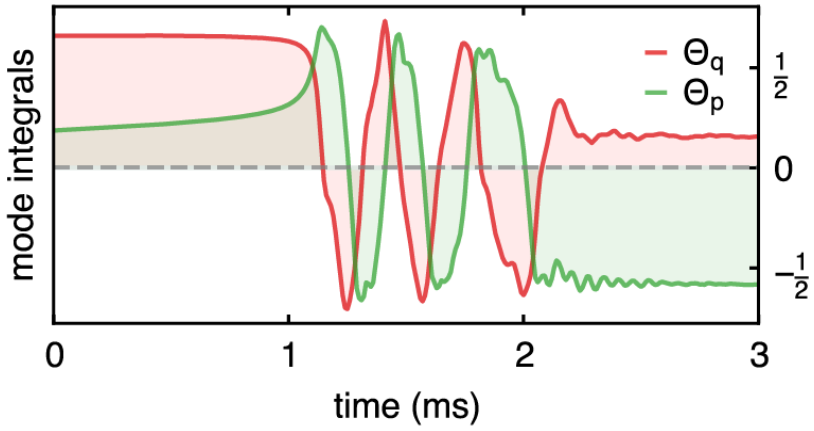
$$\langle\Theta_q\rangle = \langle\psi|\cos(\mathbf{k}_p\mathbf{r})\cos(\mathbf{k}_c\mathbf{r})|\psi\rangle$$

$$\langle\Theta_p\rangle = \langle\psi|\sin(\mathbf{k}_p\mathbf{r})\cos(\mathbf{k}_c\mathbf{r})|\psi\rangle$$

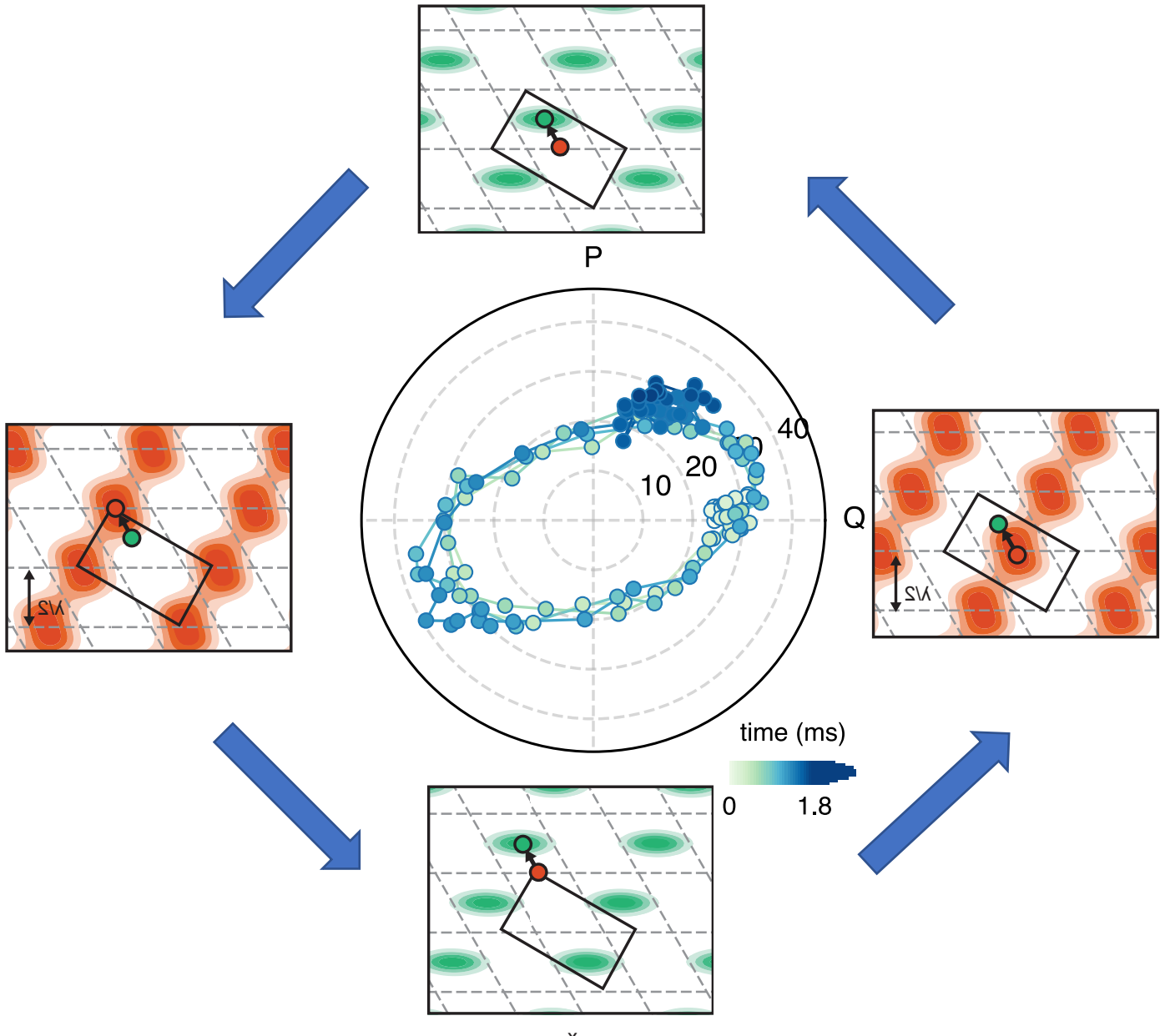


GPE simulation:

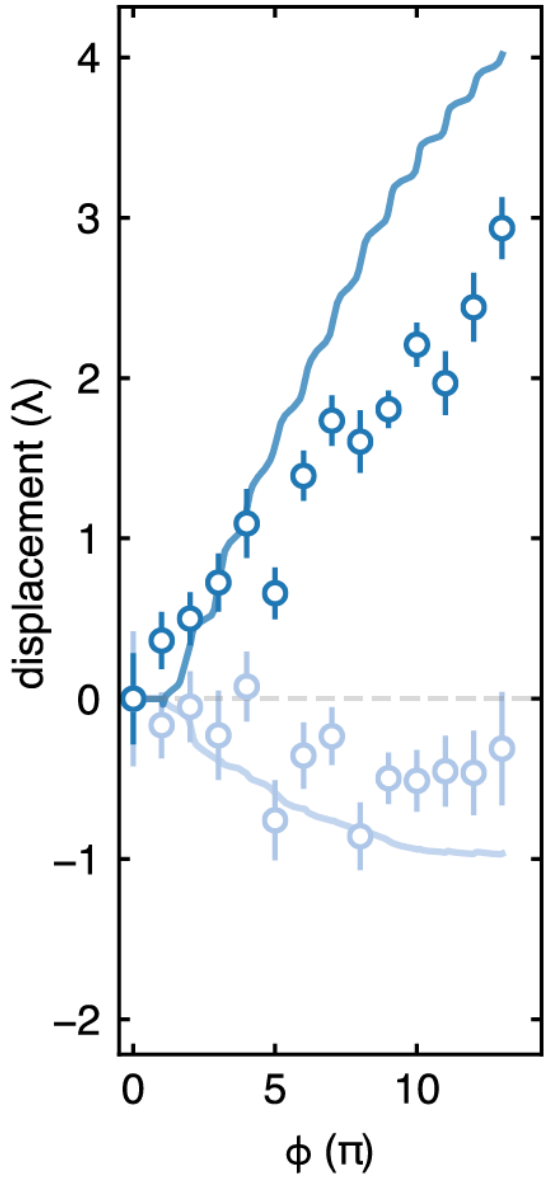




A dissipation-induced pump: transport of atoms

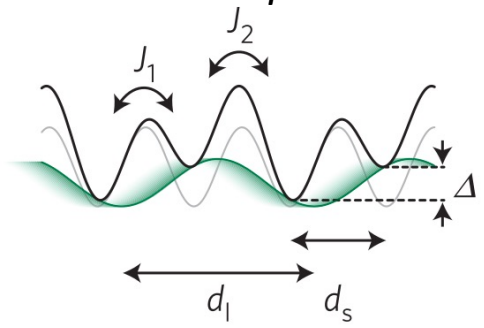


Cloud position *in situ*:

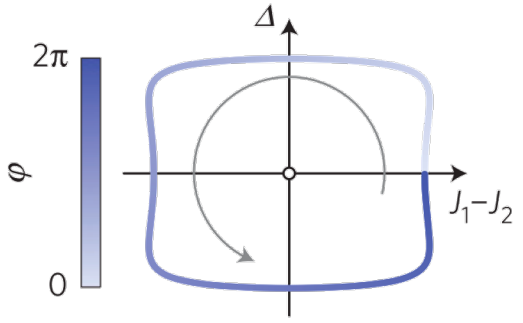


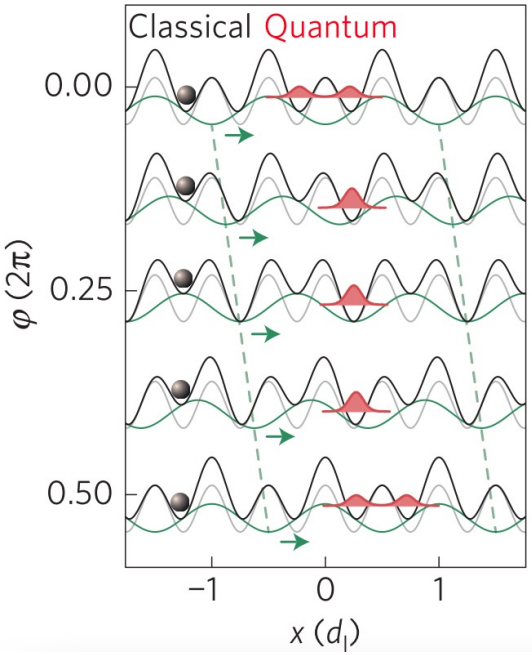
Quantum gas pumps

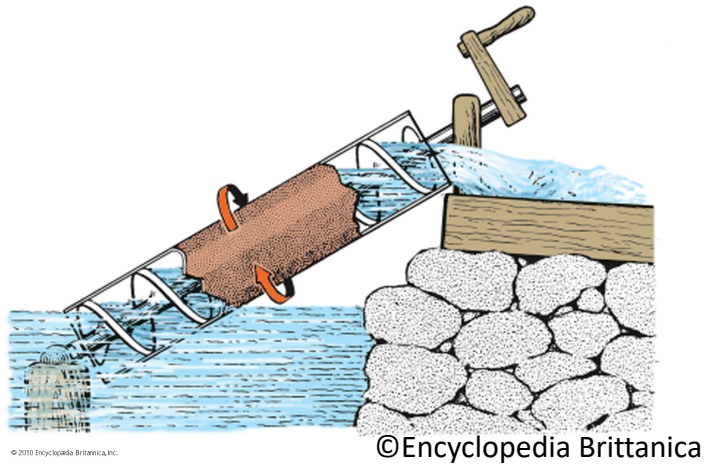
Geometrical pumps in cold atoms:
external time-dependent manipulation



$$V_{\mathrm{lattice}} = V_{\mathrm{short}} + V_{\mathrm{long}}(\phi)$$



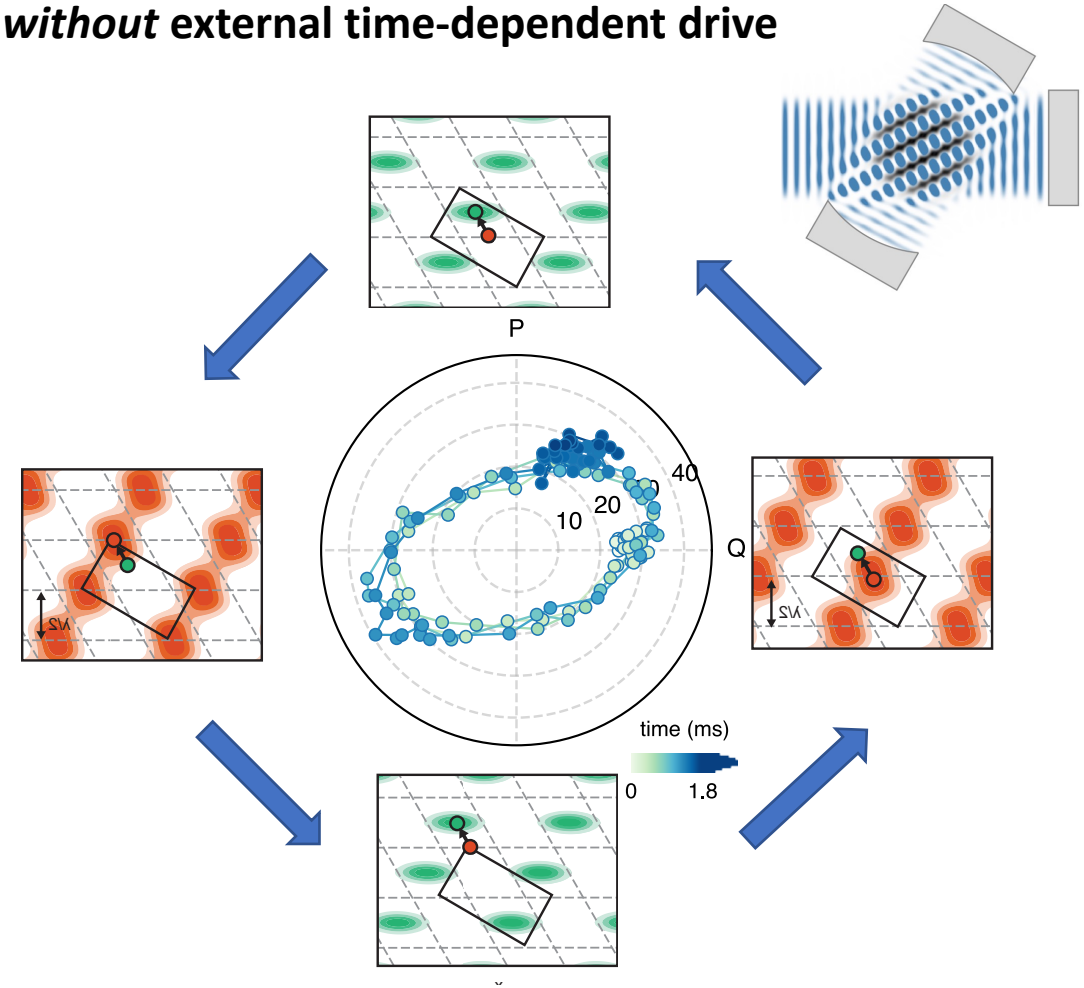




©Encyclopedia Brittanica

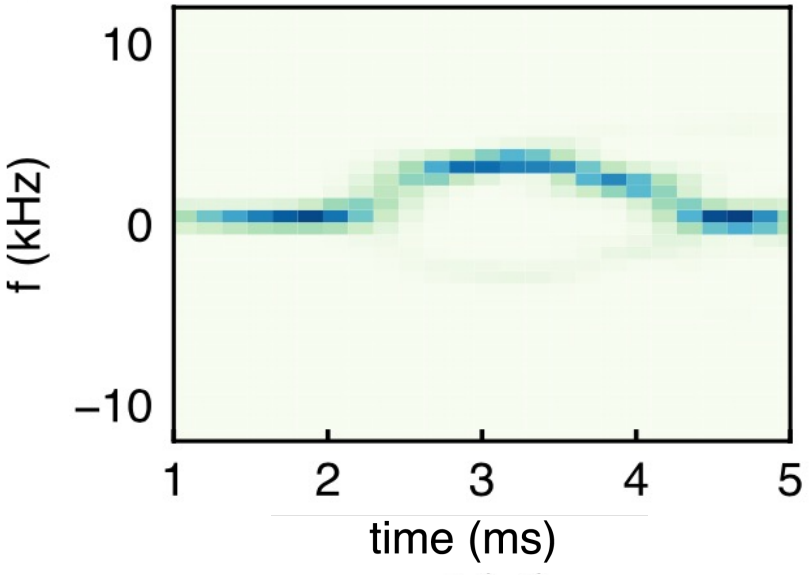
Nakjima et al., Nature Physics 12, 296 (2016)
Lohse et al., Nature Physics 12, 350 (2016)

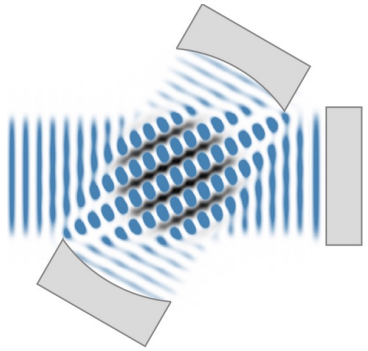
Here:
Self-consistent evolution
***without* external time-dependent drive**

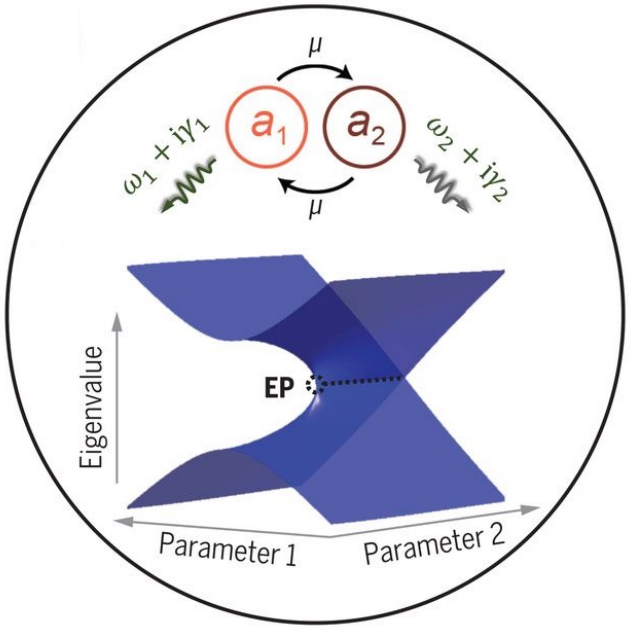


$$\phi = \tan^{-1}\left(\frac{\tilde{\Delta}_c(\Omega_1+\Omega_2)\Theta_q - \kappa(\Omega_1-\Omega_2)\Theta_p}{\tilde{\Delta}_c(\Omega_1-\Omega_2)\Theta_p + \kappa(\Omega_1+\Omega_2)\Theta_q}\right)$$

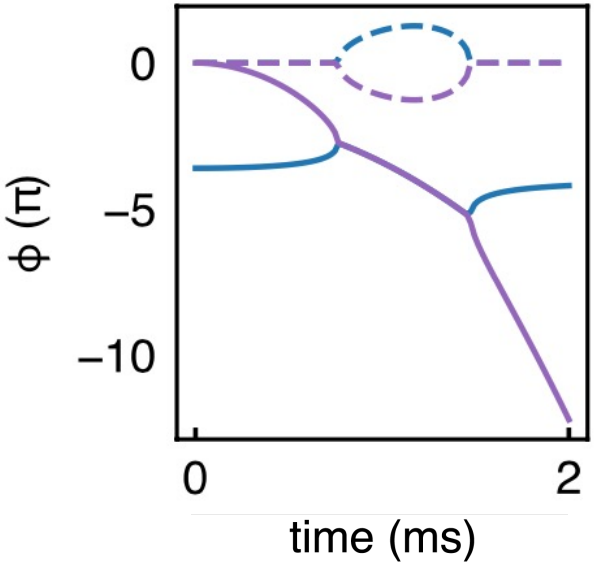
Frequency spectrum

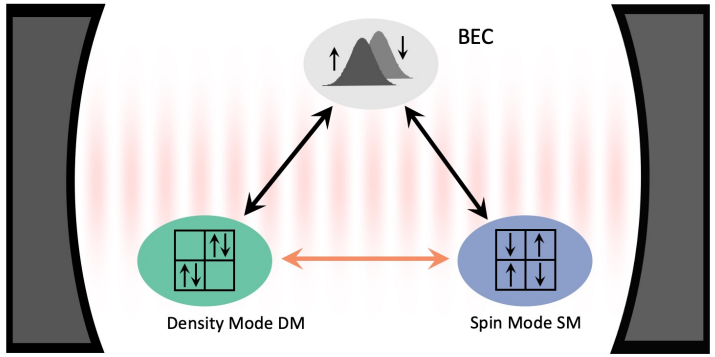






https://science.sciencemag.org/content/363/6422/eaar7709





- Dogra et al. Science, 366, 1496 (2019)
- Chiacchio & Nunnenkamp, PRL 122, 193605 (2019)
- Buca & Jaksch, PRL 123, 260401 (2019)

The Team

tner, Simon
ximo

:

Collective Effects and Non-Equilibrium Quantum Dynamics

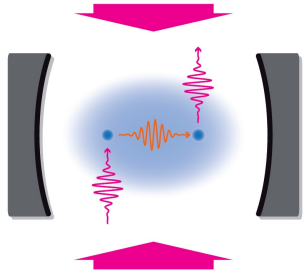
724. WE-Heraeus-Seminar Deadline this Friday!

27 Jun - 30 Jun 2021 online

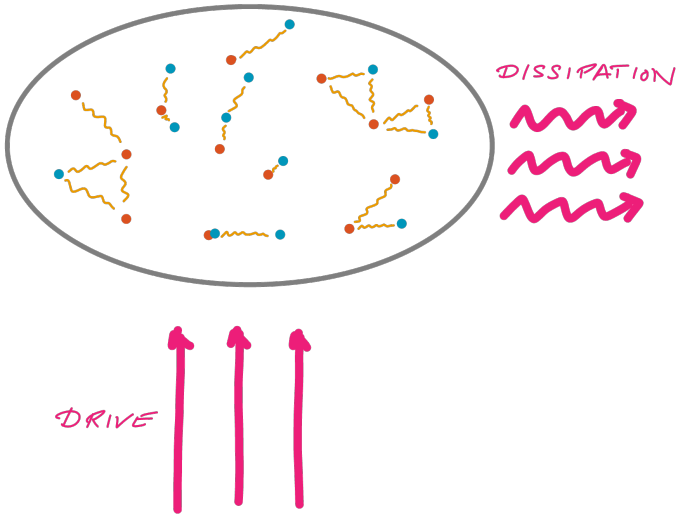
Where: Physikzentrum Bad Honnef

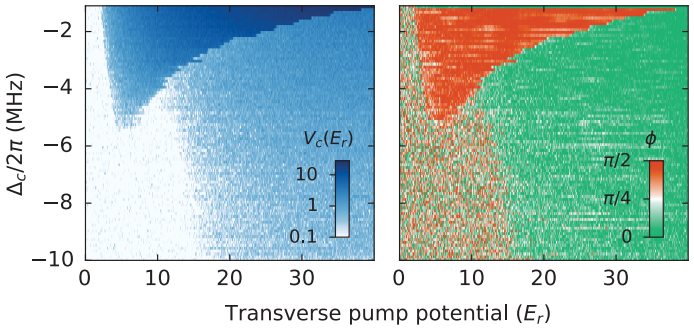
Scientific organizers: Dr. Tobias Donner, ETH Zürich, Switzerland • Prof. Dr. Thorsten Ackemann, U of Strathclyde, UK • Prof. Dr. Sebastian Slama, U Tübingen

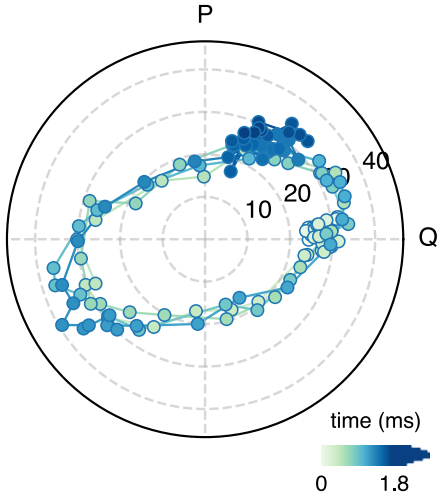
Summary

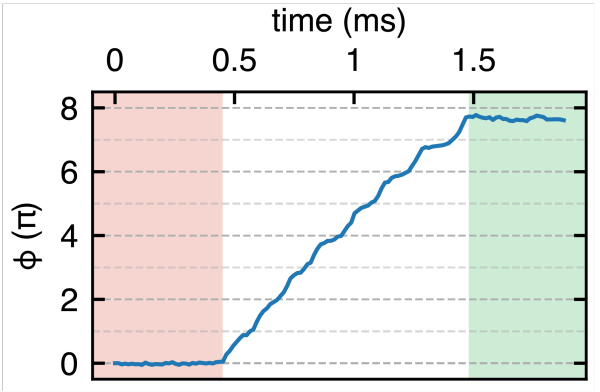


Review article:
arXiv:2102.04473









Zupancic, P. *et al. Phys. Rev. Lett.* **123**, 233601 (2019)
Li, X. *et al. Phys. Rev. Res.* **3**, L012024 (2021).

...manuscript in preparation...