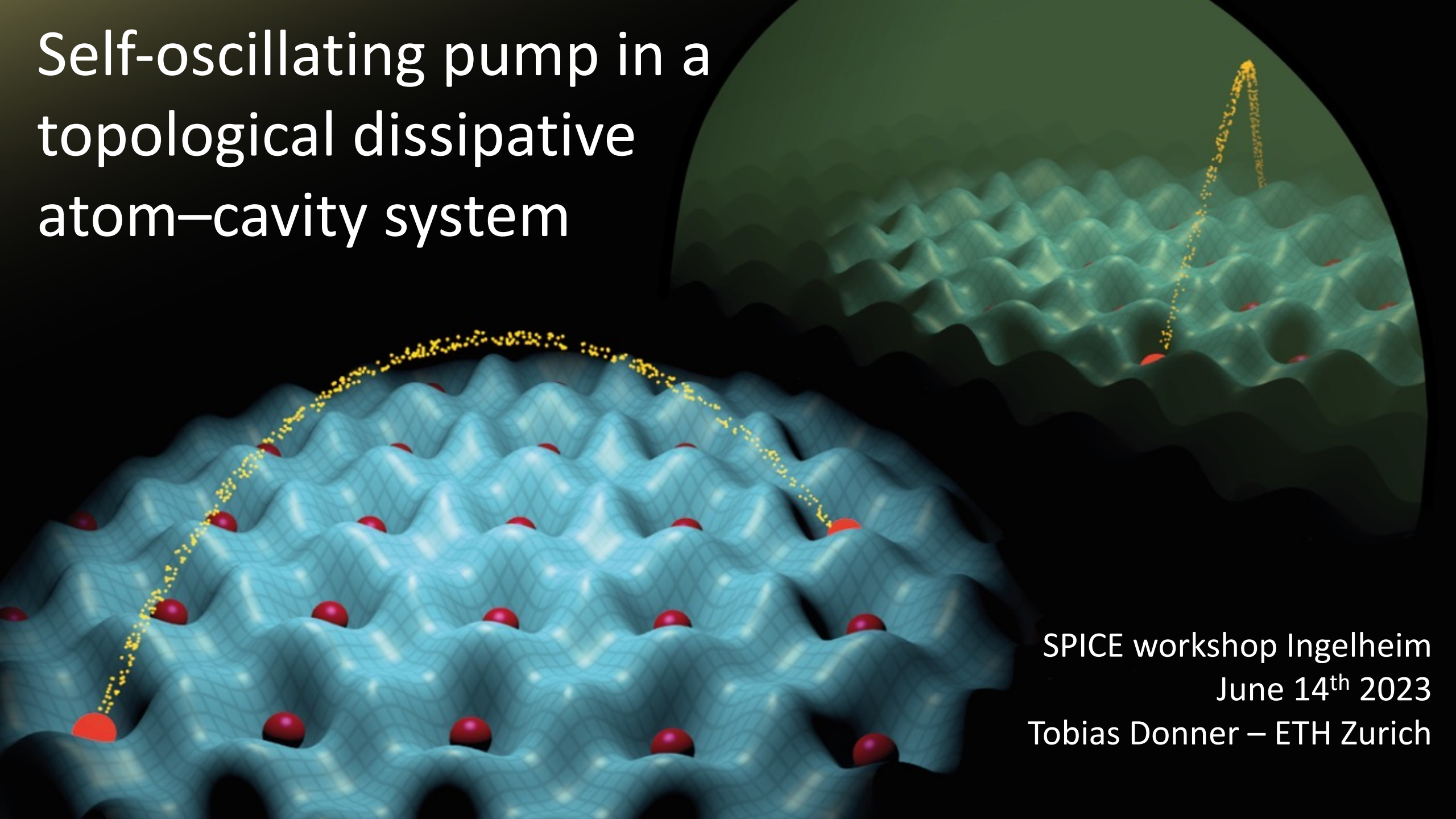
Self-oscillating pump in a topological dissipative atom–cavity system



SPICE workshop Ingelheim
June 14th 2023
Tobias Donner – ETH Zurich

Quantum Spinoptics

Workshop, June 13th - 15th 2023

The conference aims at the interdisciplinary experiment of **bringing together experts from solid state and quantum optics**, in order to foster dialogue at the interface of the two communities. The goal is to plant the seed of a novel hybrid research area, where solid state systems are treated on the same footing as AMO driven-dissipative platforms, and, viceversa, where quantum optics can be reshaped by using concepts from spintronics, magnetism and the physics of correlated materials.We invite and encourage the contribution of selected speakers advancing the frontiers of any of **the following fields**:

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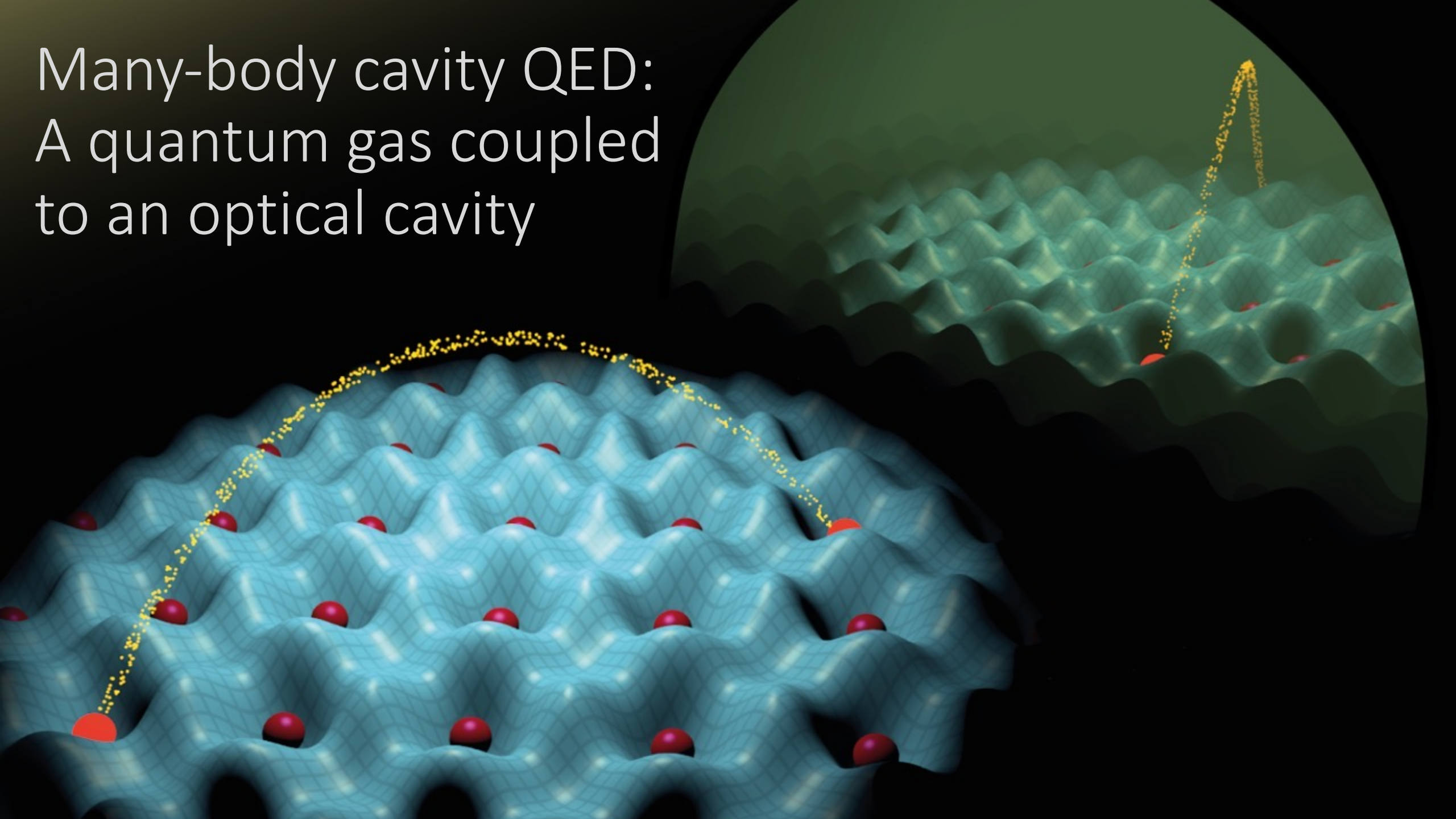
Many-body cavity QED: A quantum gas coupled to an optical cavity



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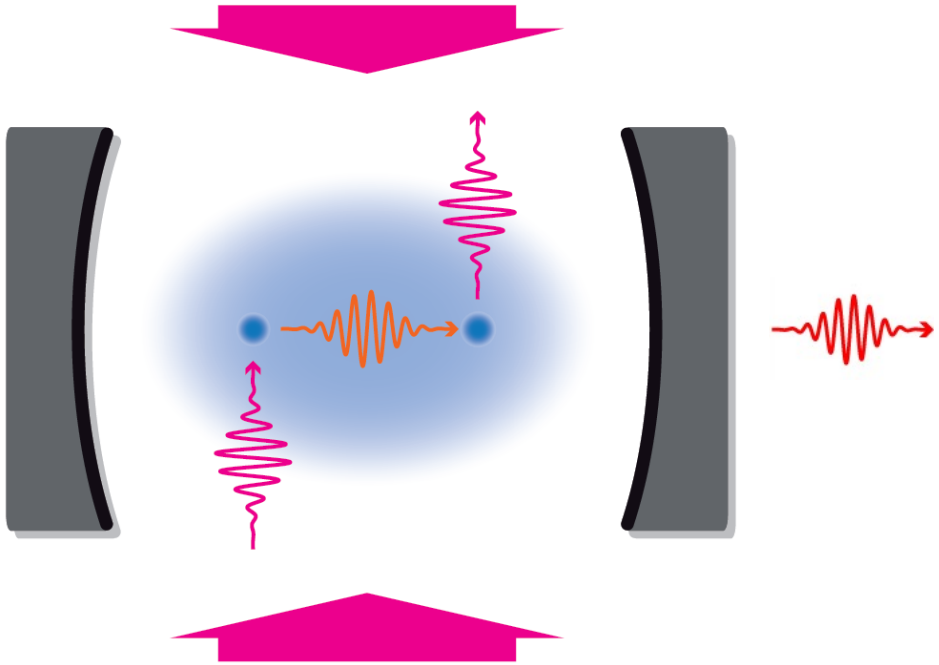
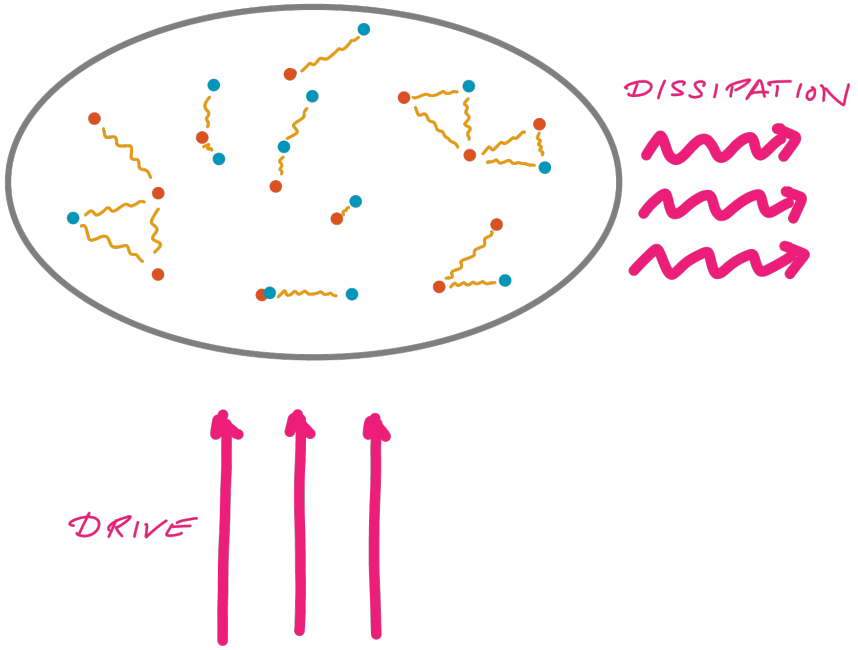


cavity-induced long-range interactions



Interacting driven-dissipative system

Review article: F. Mivehvar, F. Piazza, T. Donner, H. Ritsch, Advances in Physics 70 (2021)

Superradiant quantum phase transition: potential vs kinetic energy

Single-particle Hamiltonian:

$$\hat{\mathcal{H}}_{\mathrm{SP}} = -\Delta_c \hat{a}^\dagger \hat{a} + \frac{\hat{\mathbf{p}}^2}{2m} + V_p \cos^2(\mathbf{k}_p \hat{\mathbf{r}}) + U_0 \cos^2(\mathbf{k}_c \hat{\mathbf{r}}) \hat{a}^\dagger \hat{a} + \sqrt{V_p U_0} \cos(\mathbf{k}_p \hat{\mathbf{r}}) \cos(\mathbf{k}_c \hat{\mathbf{r}})(\hat{a} + \hat{a}^\dagger)$$

photon energy

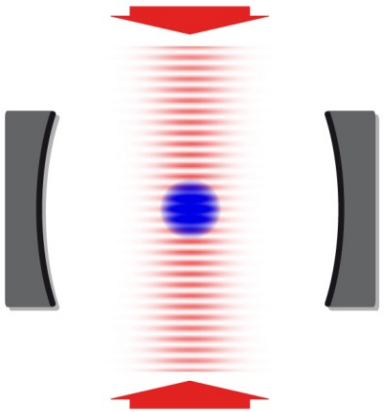
kinetic energy

pump lattice potential

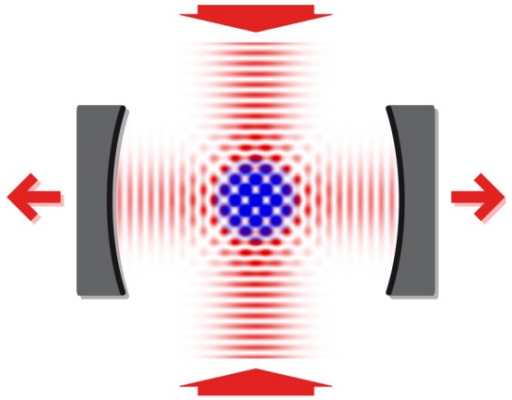
cavity lattice potential

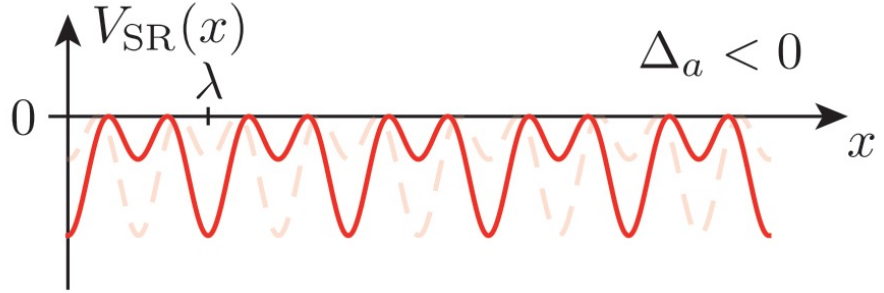
interaction potential

normal phase

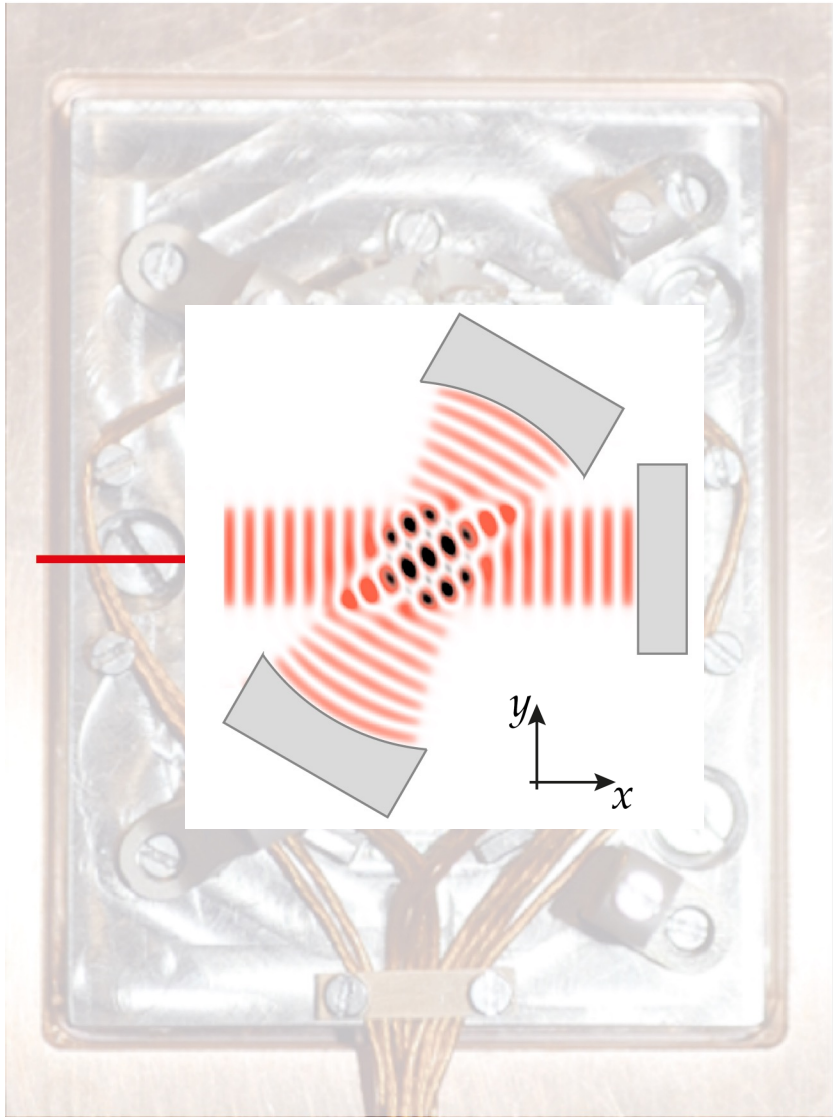


superradiant phase

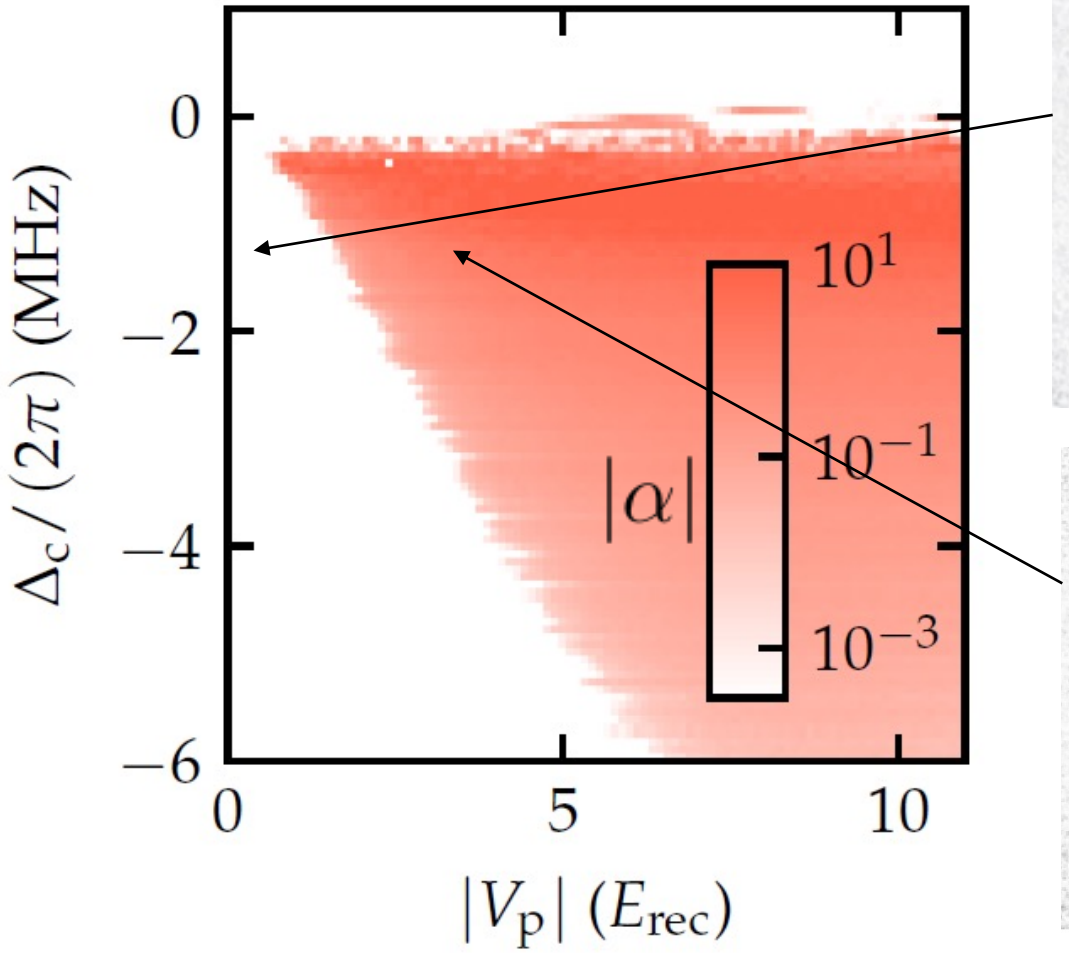




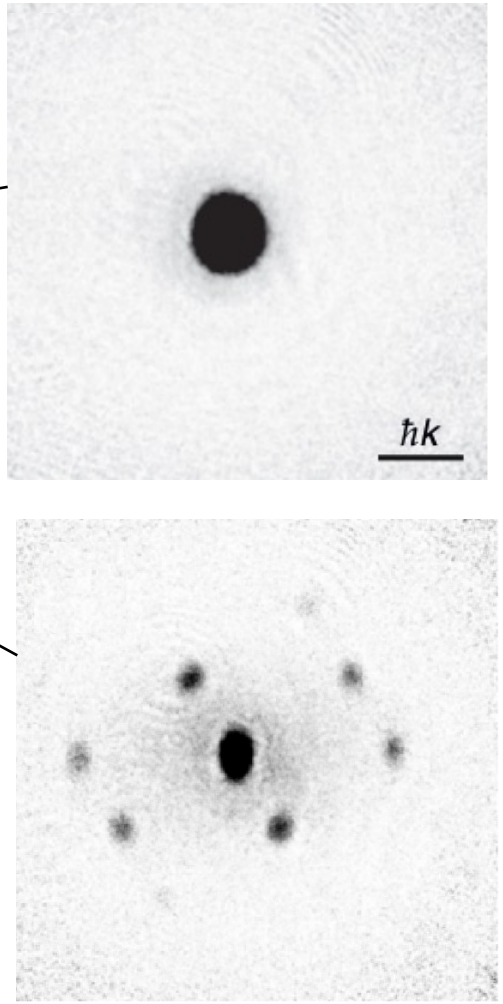
Phase diagram



Phase Diagram



Time-of-Flight Image



First observation in a BEC: K. Baumann, C. Guerlin, F. Brennecke, and T. Esslinger. Nature 464, 1301 (2010)

Two new ingredients:

1. Self-Organization with Repulsive Potentials

2. Imbalanced Drive Field

1) Repulsive Potentials

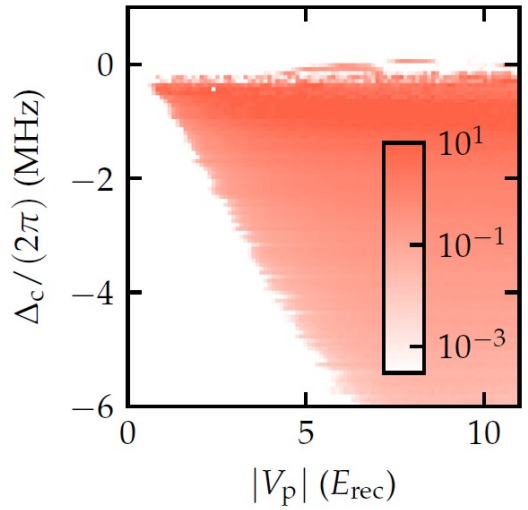
Attractive vs Repulsive Potentials

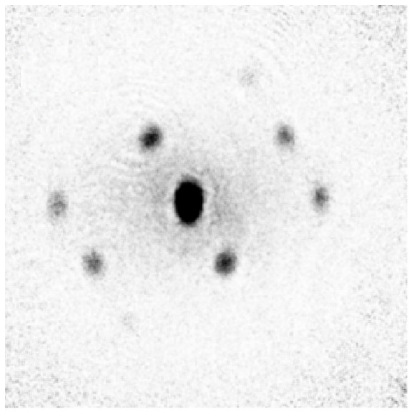
Phase Diagram

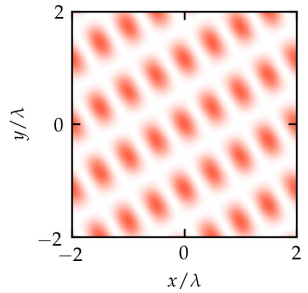
Time of Flight Image

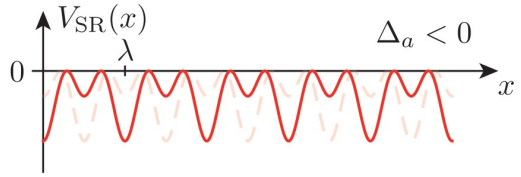
Real Space Structure

$\Delta_a < 0$

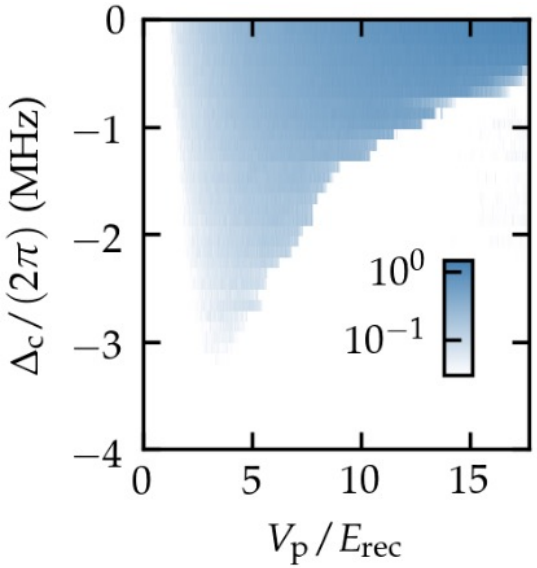


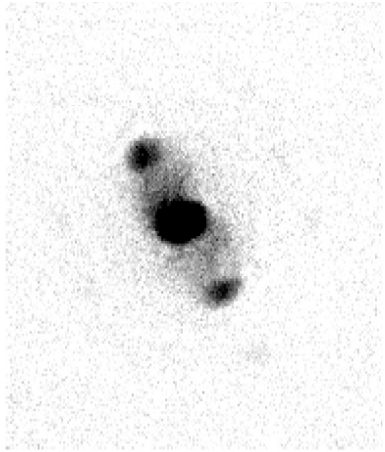


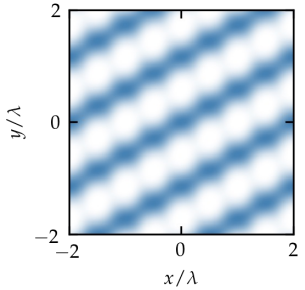


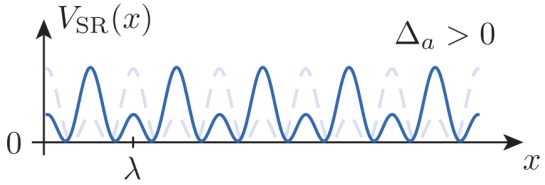


$\Delta_a > 0$



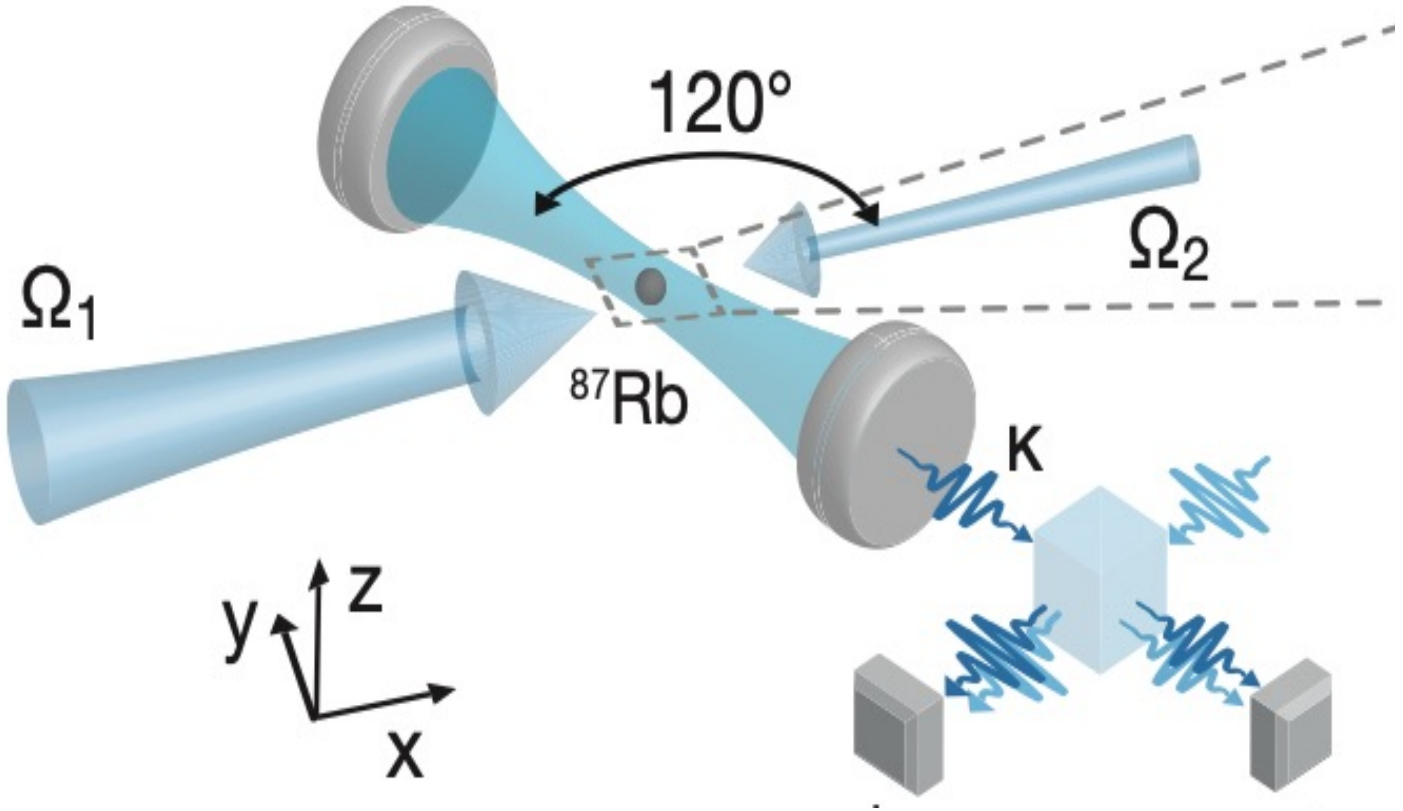






Zupancic *et al.*, PRL 2019

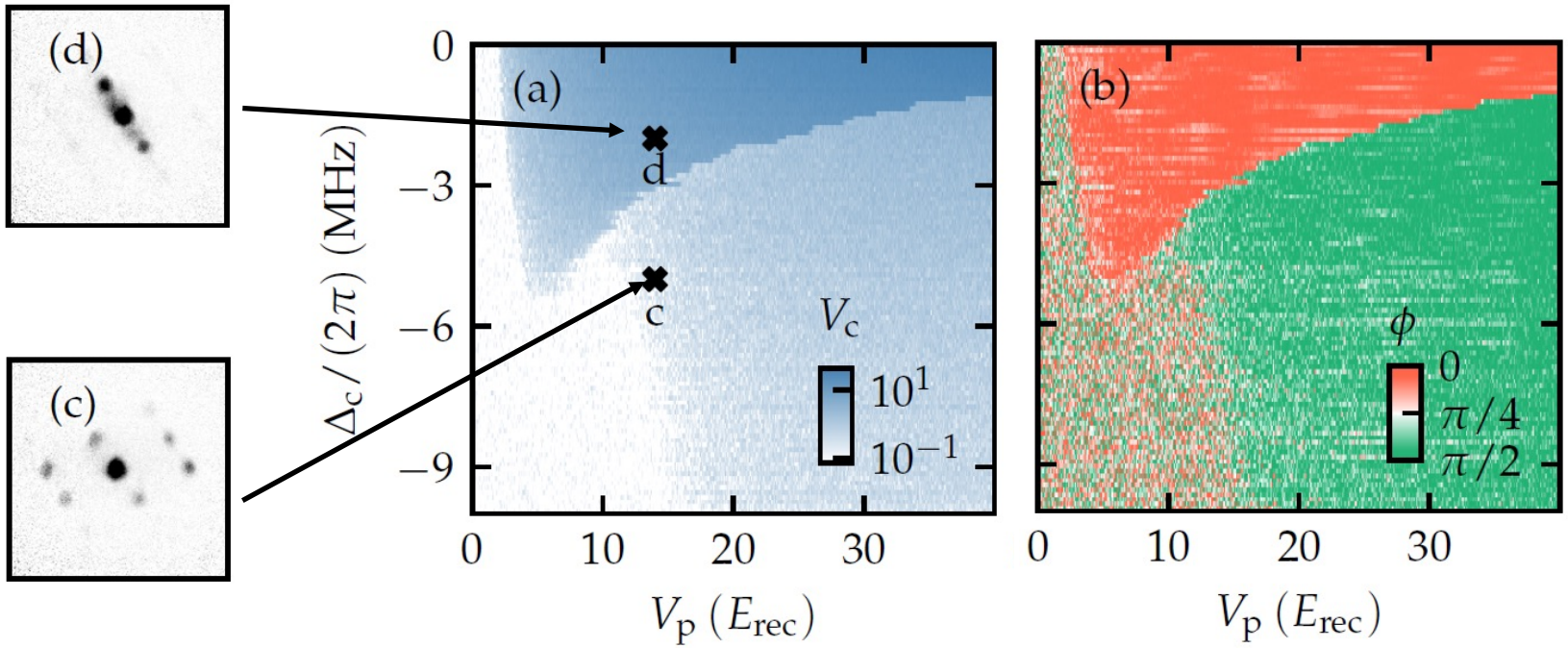
2) Imbalanced Drive: Running and Standing Wave Pump



$$\hat{E}_{\mathrm{p}}(\hat{\boldsymbol{r}}) = \frac{E_{\mathrm{p}}}{2}\exp(i\boldsymbol{k}_{\mathrm{p}}\hat{\boldsymbol{r}}) + (1-\epsilon)\frac{E_{\mathrm{p}}}{2}\exp(-i\boldsymbol{k}_{\mathrm{p}}\hat{\boldsymbol{r}})$$

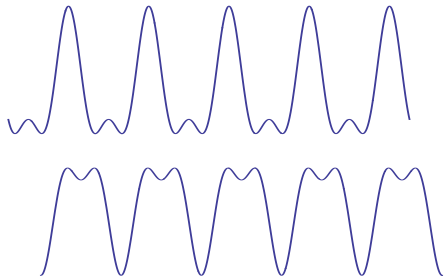
Li *et al.* , PRR 2021

Imbalanced Drive: Running and Standing Wave Pump



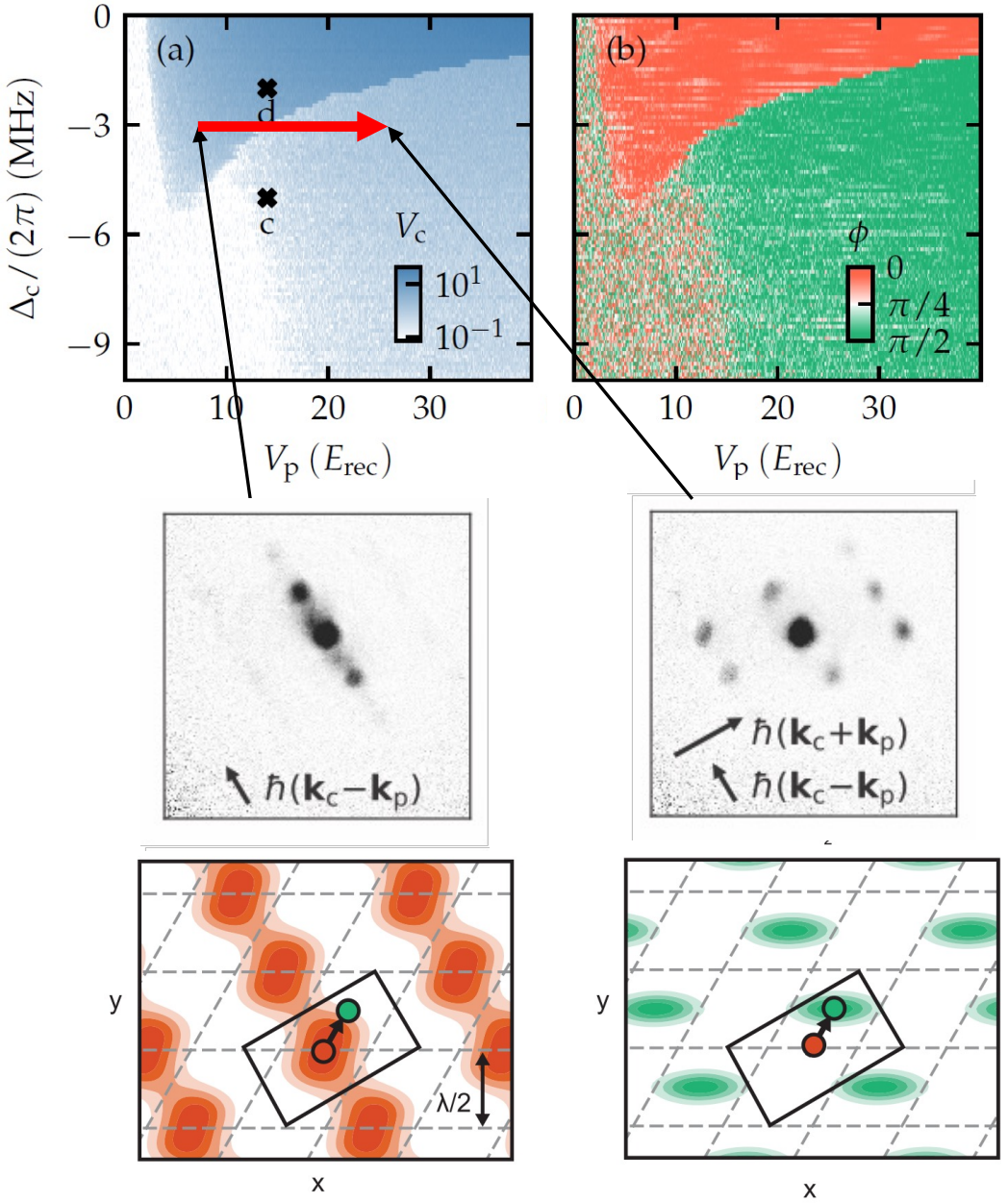
$$\hat{\mathcal{H}} = V_p \cos^2(\boldsymbol{k}_p\hat{\boldsymbol{r}}) + U_0 \cos^2(\boldsymbol{k}_c\hat{\boldsymbol{r}})\hat{a}^\dagger\hat{a} - \Delta_c\hat{a}^\dagger\hat{a} + \frac{\hat{\boldsymbol{p}}^2}{2m}$$

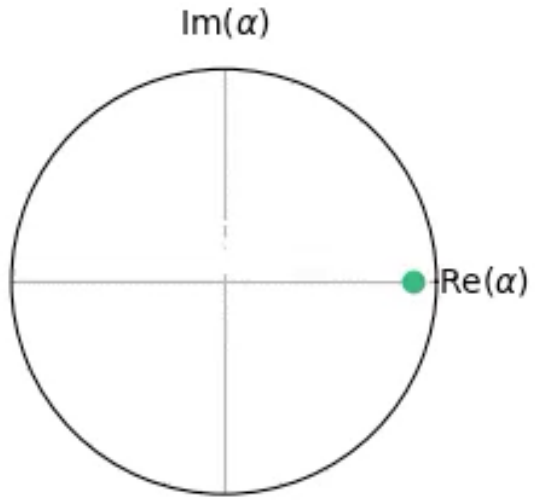
$$+ \frac{1-\epsilon/2}{\sqrt{1-\epsilon}}\sqrt{V_p U_0}\cos(\boldsymbol{k}_p\hat{\boldsymbol{r}})\cos(\boldsymbol{k}_c\hat{\boldsymbol{r}})(\hat{a}+\hat{a}^\dagger)$$

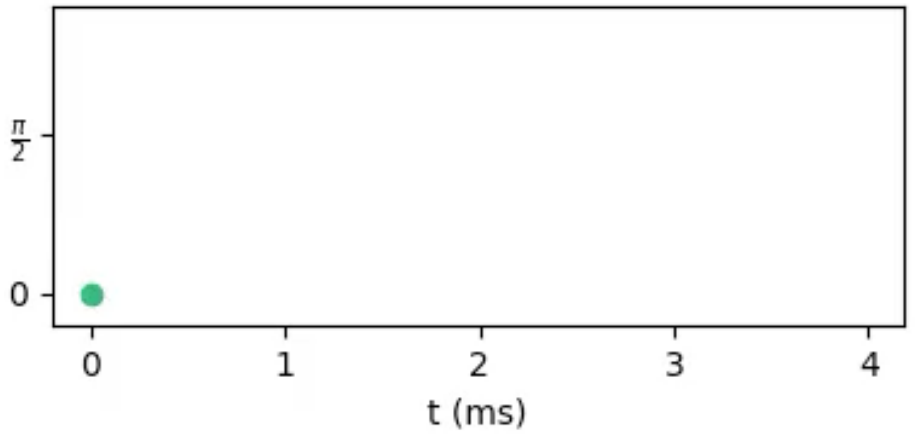


Li *et al.* , PRR 2021

Dynamics at 1st order structural phase transition

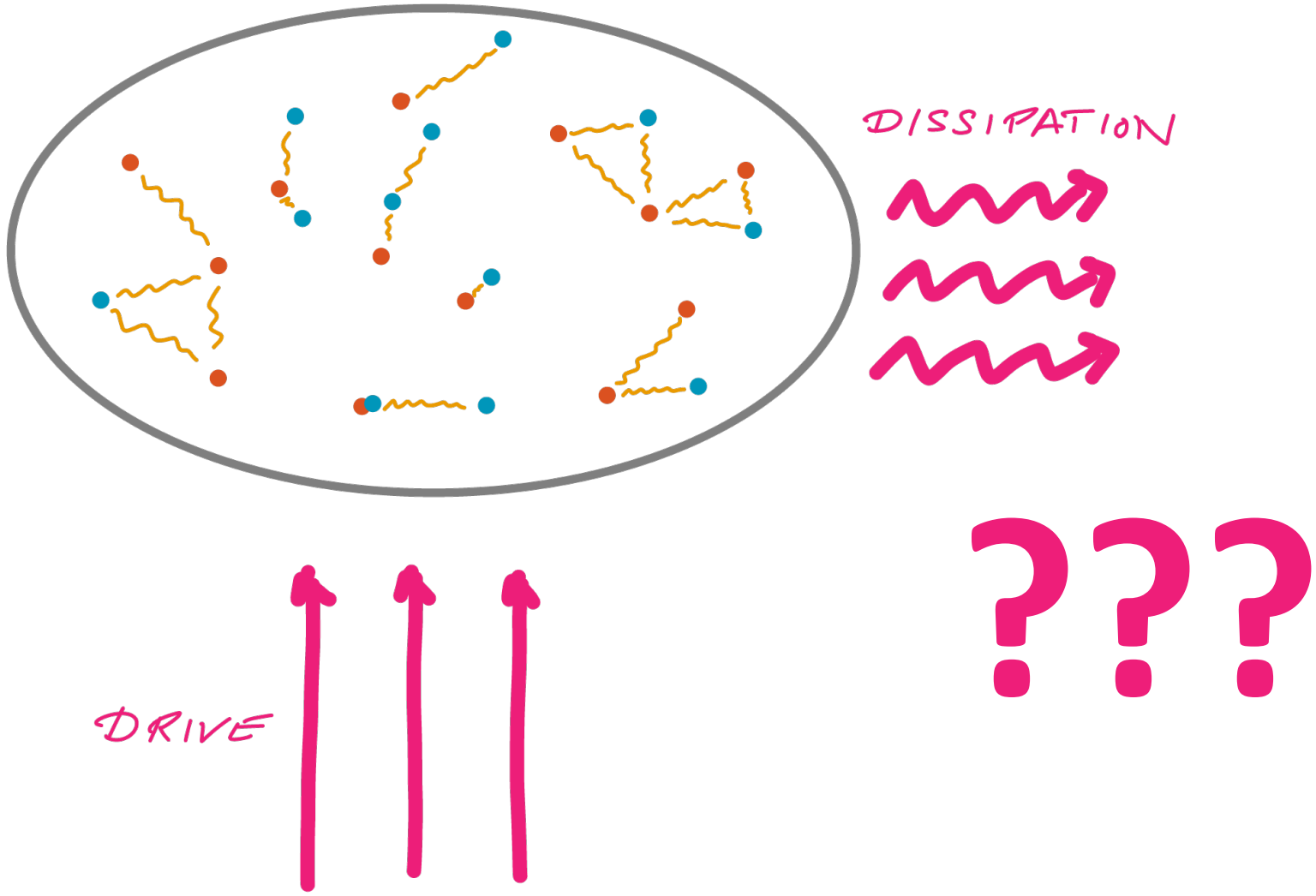






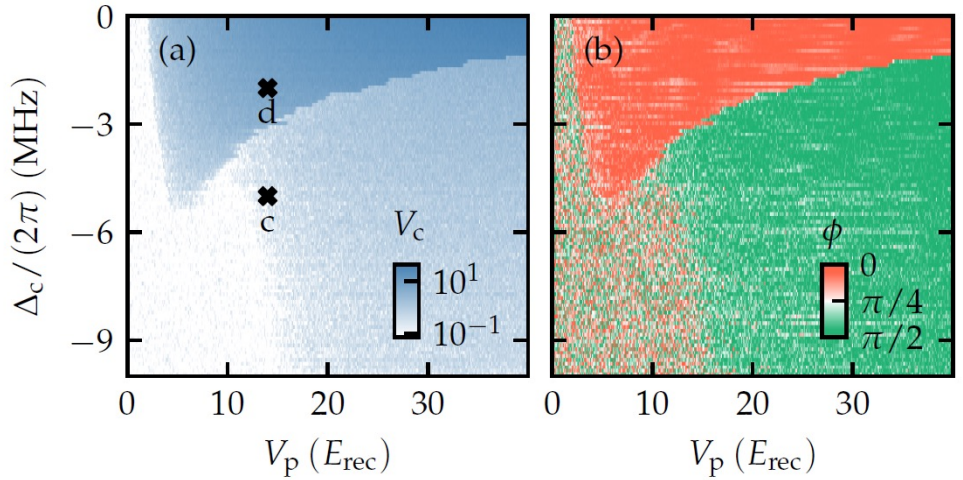
Li *et al.* , PRR 2021

Driven-dissipative systems

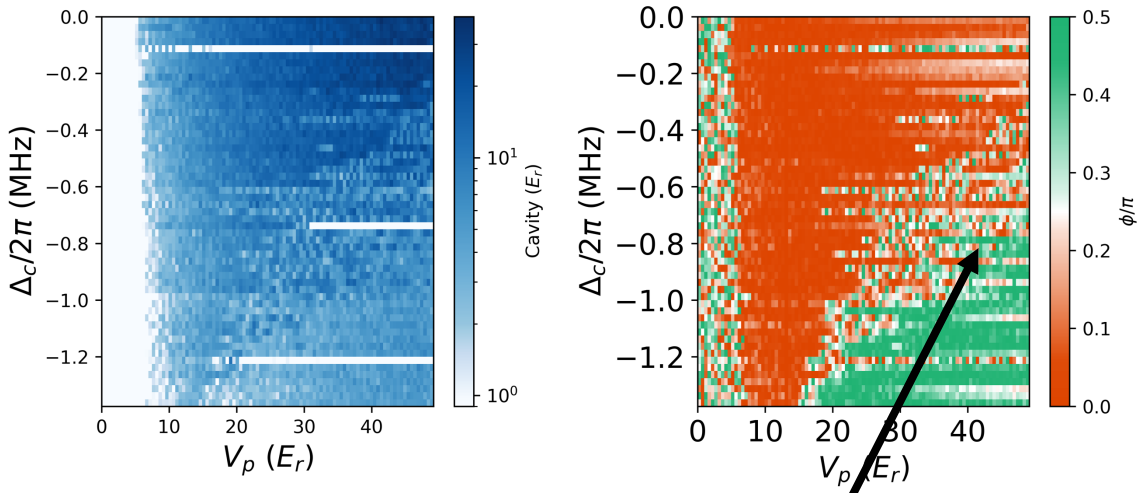


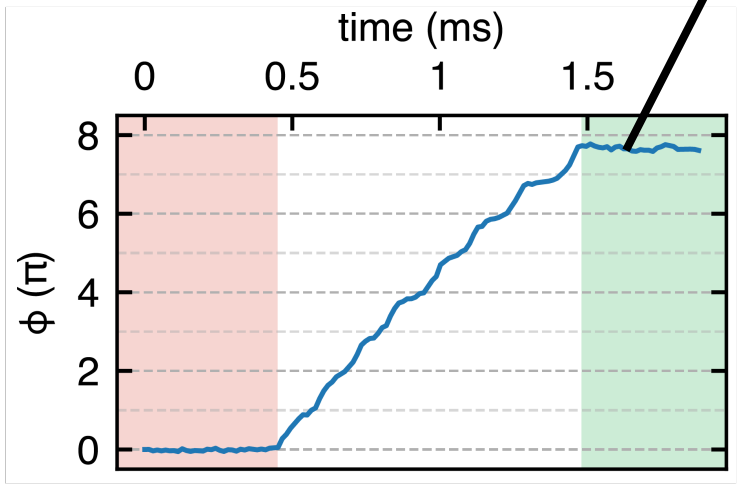
Approaching the dissipative regime: $\Delta_c \simeq \kappa$

$\Delta_c \gg \kappa$



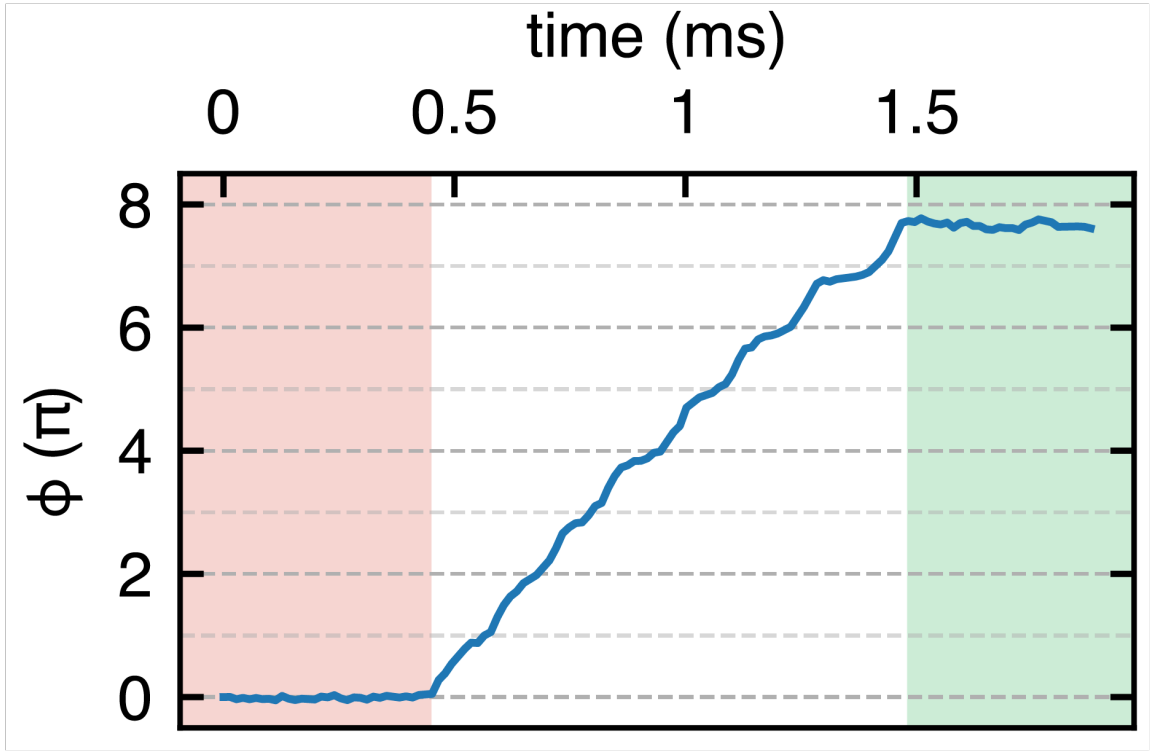
$\Delta_c \simeq \kappa$



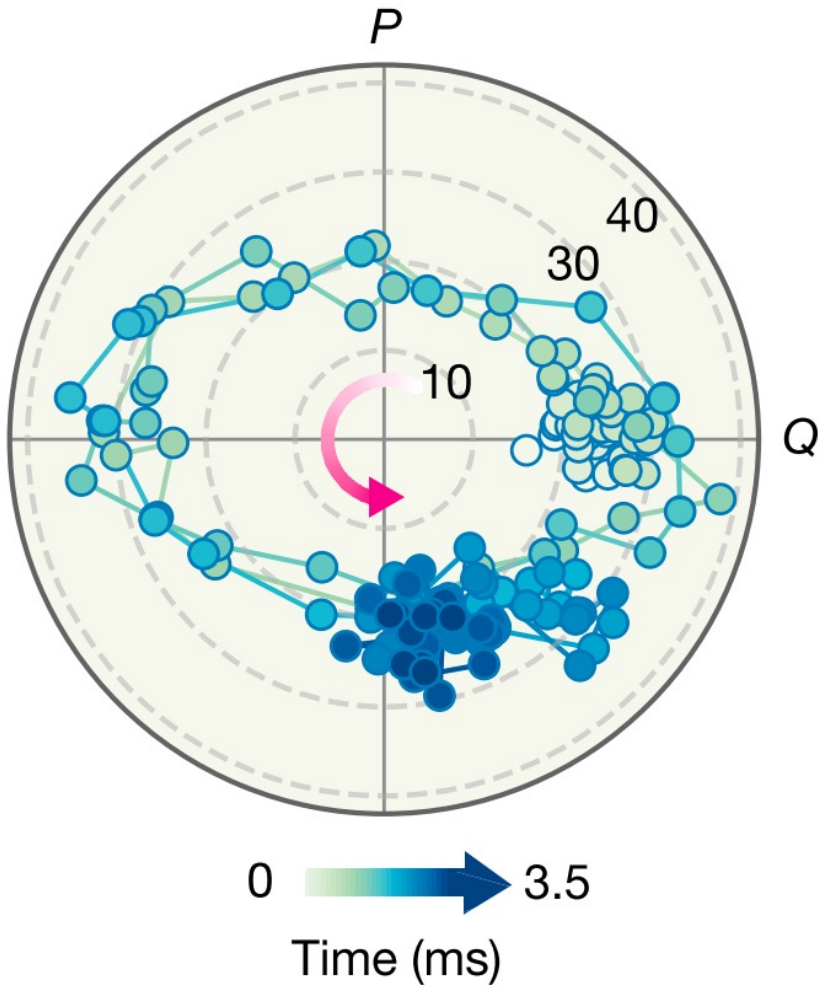


Dissipation-induced instability: chiral dynamics

Phase of cavity field

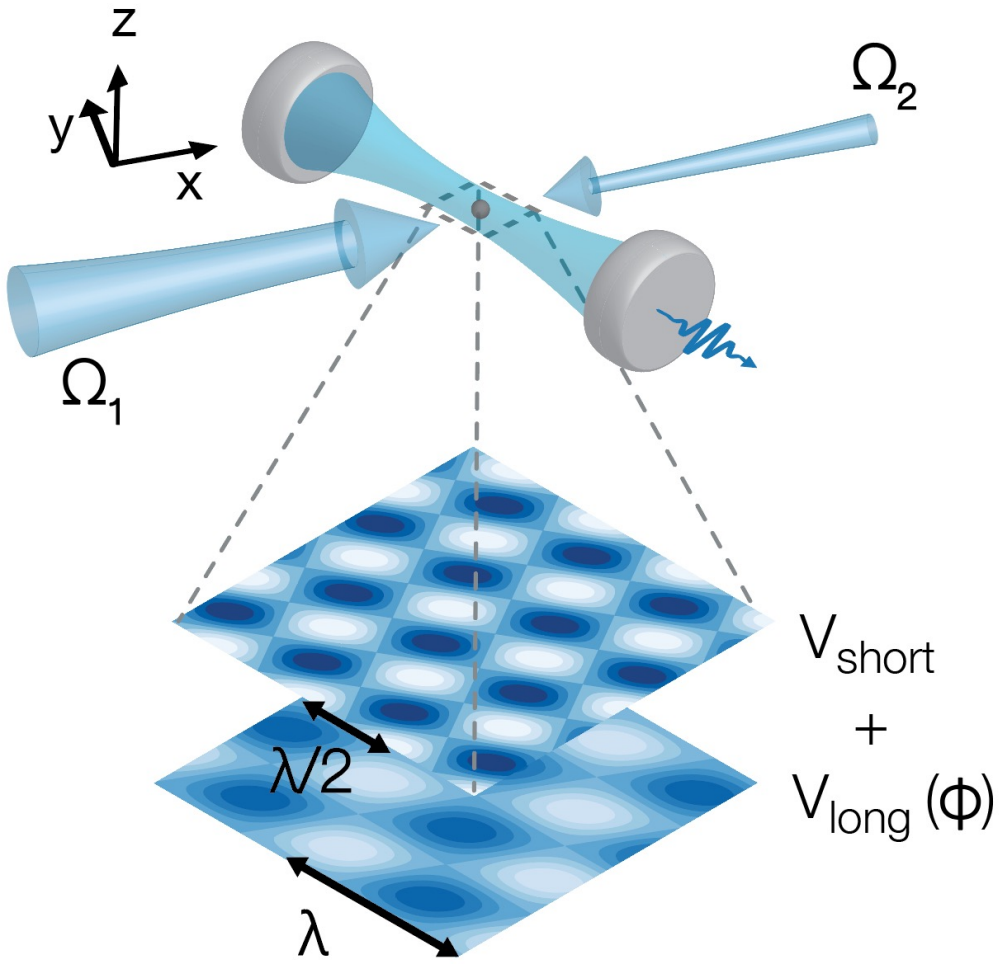


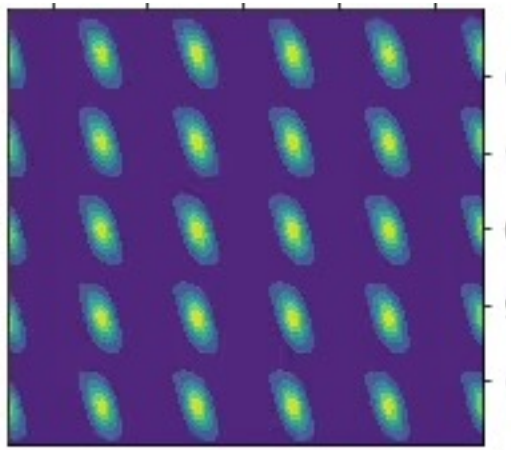
cavity field quadratures



D. Dreon, P. Zupancic, A. Baumgärtner, X. Li, S. Hertlein, T. Esslinger, T. Donner, Nature, 608, 494 (2022)

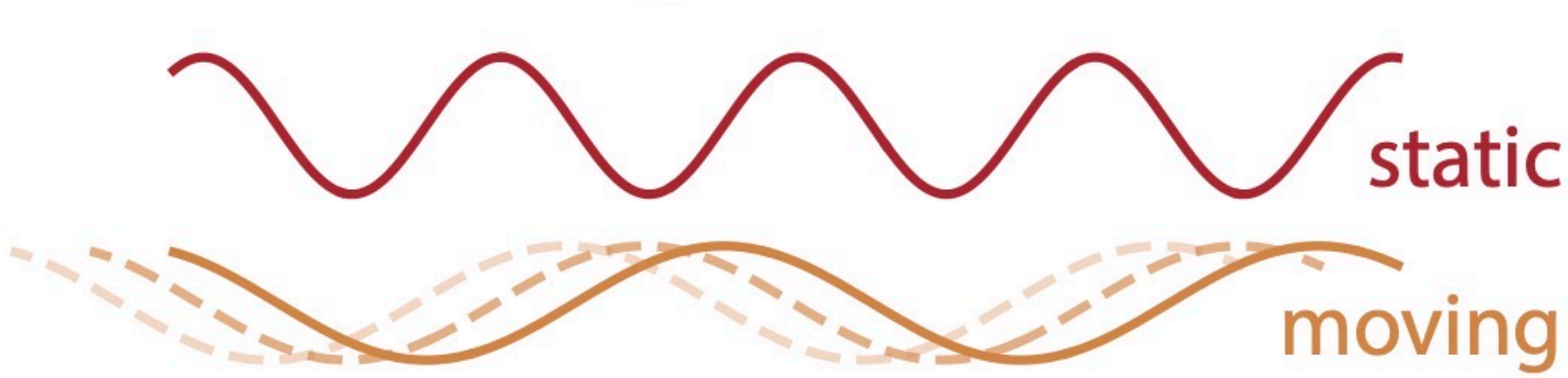
Dissipation-induced dynamics





Gives two interference lattices coupled to the orthogonal light quadratures

Topological pumping

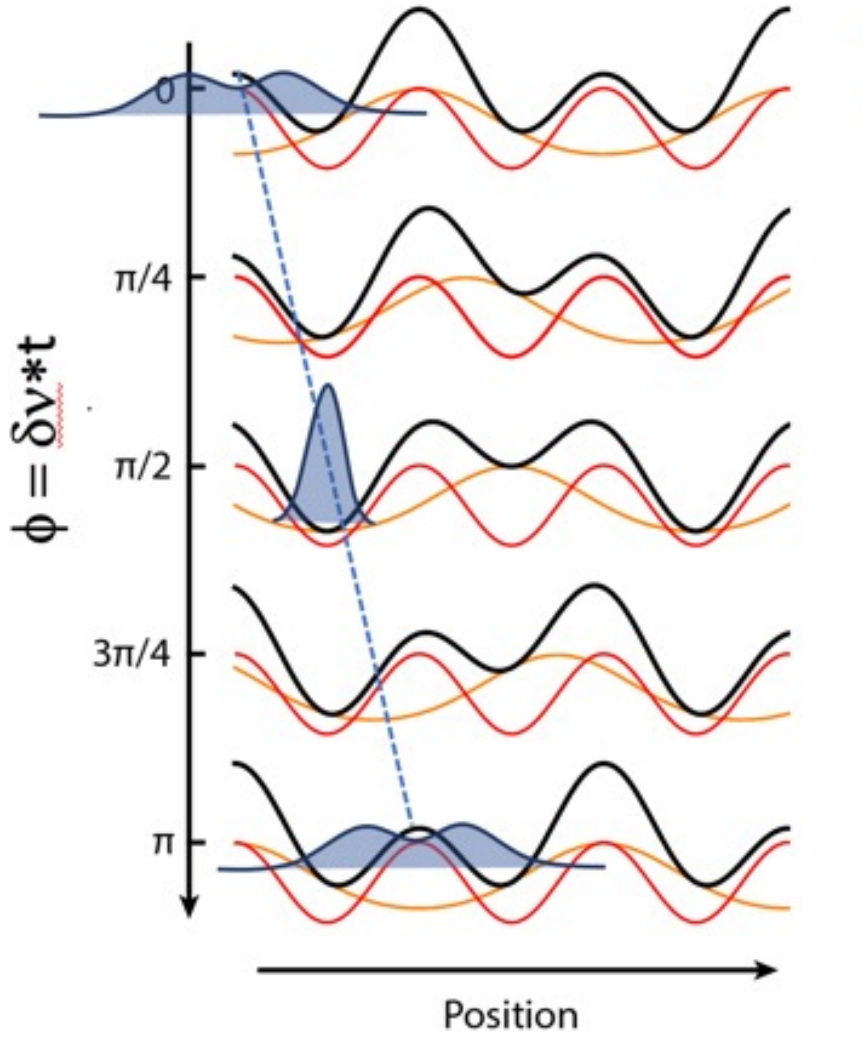


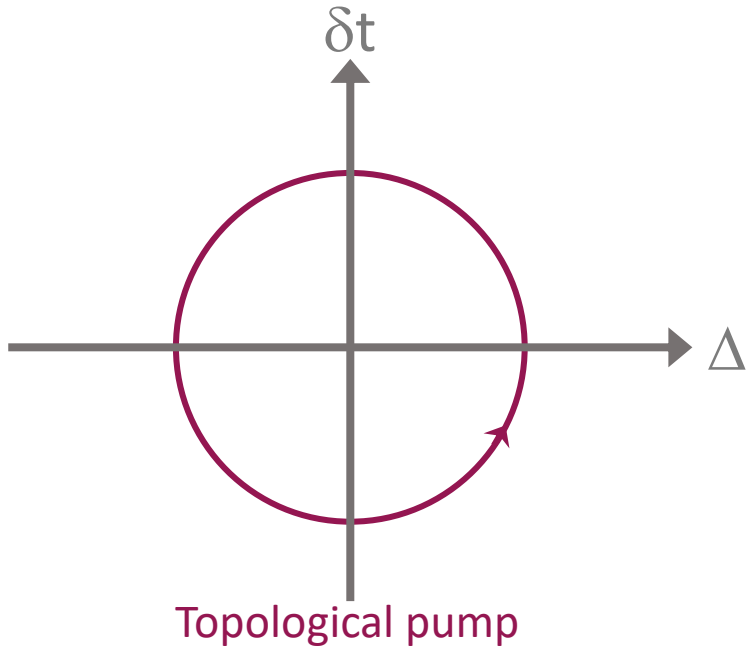
Transport in an insulating state

Lei Wang, Matthias Troyer, and Xi Dai, PRL 111, 026802 (2013)
Q Niu and D J Thouless 1984 *J. Phys. A: Math. Gen.* **17** 2453

Review: Collège de France, chair Atoms and Radiation Lecture series 2018

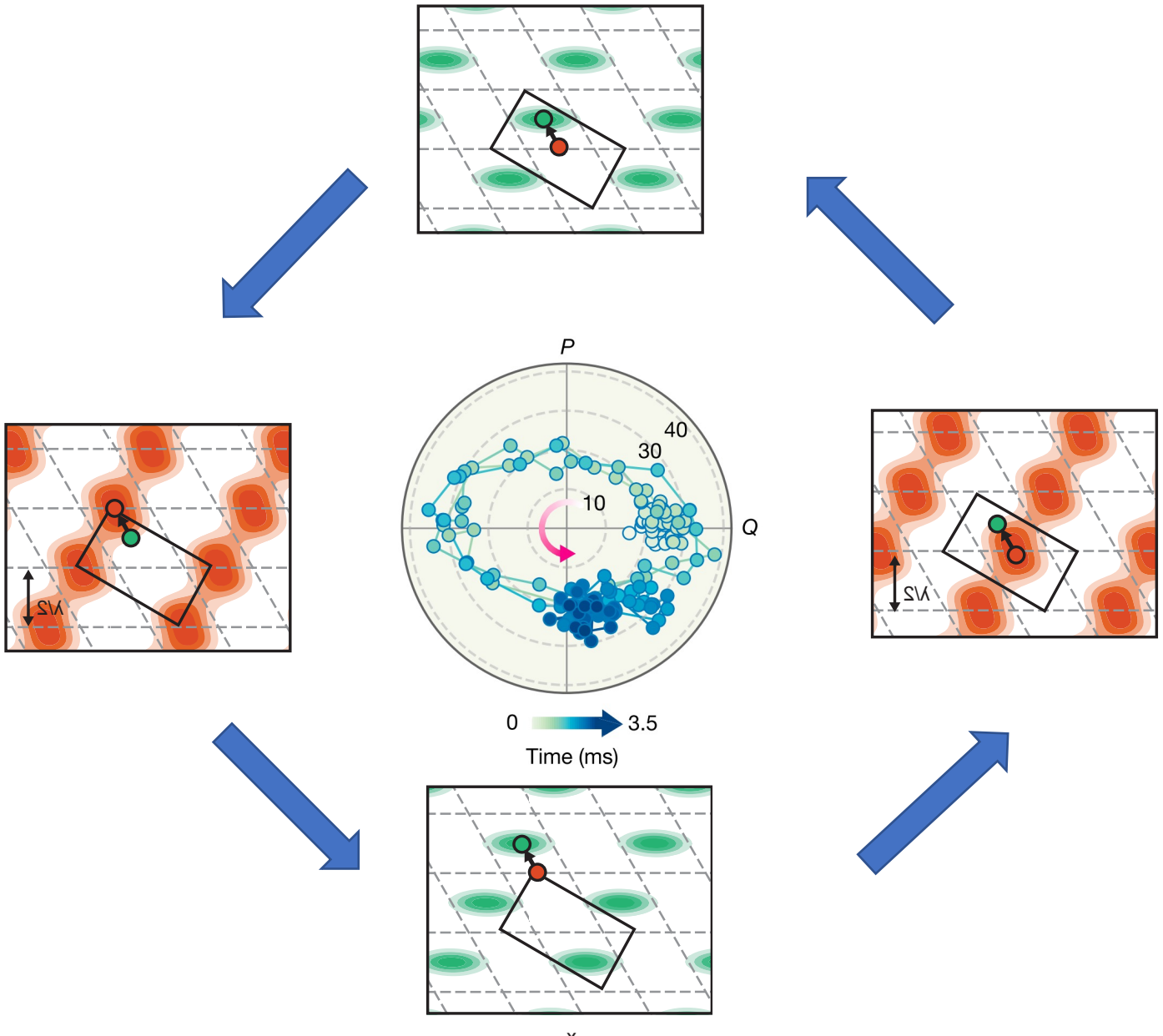
Topological pumping



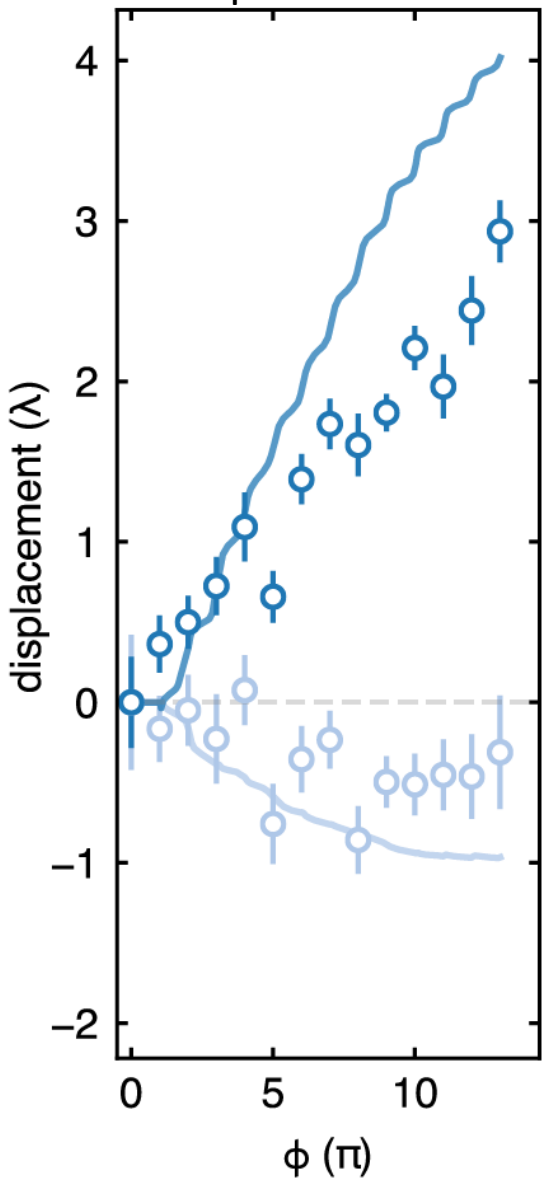


Experiments: Lohse et al. Nat. Phys. 12, 296 (2016) , Aidelsburger/Bloch
Nakajima et al. Nat. Phys. 12, 350 (2016), Takahashi

Dissipation-induced geometrical atom pump



Cloud position *in situ*:

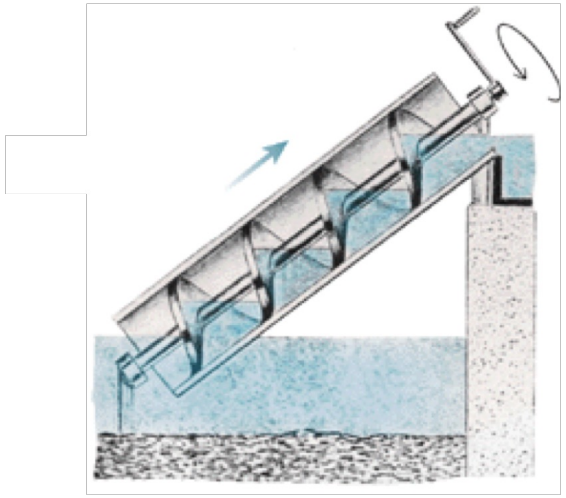


Adiabatic pumps

In general: a DC current follows a AC perturbation

Classical example

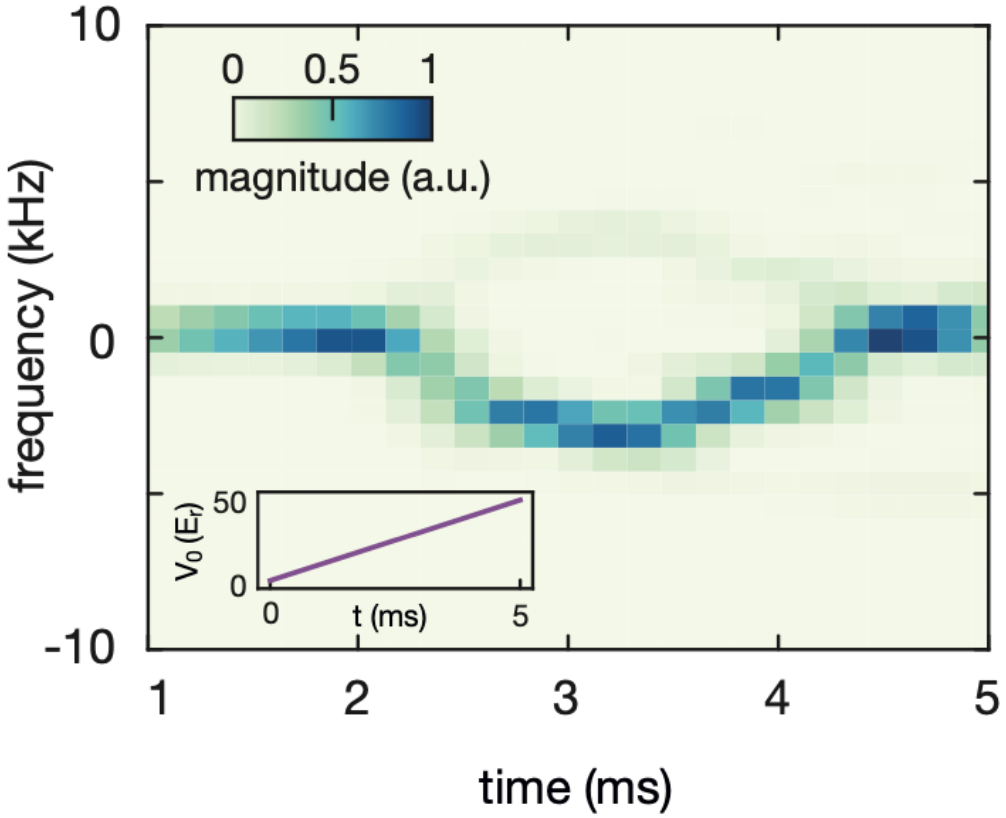
Archimedes' screw

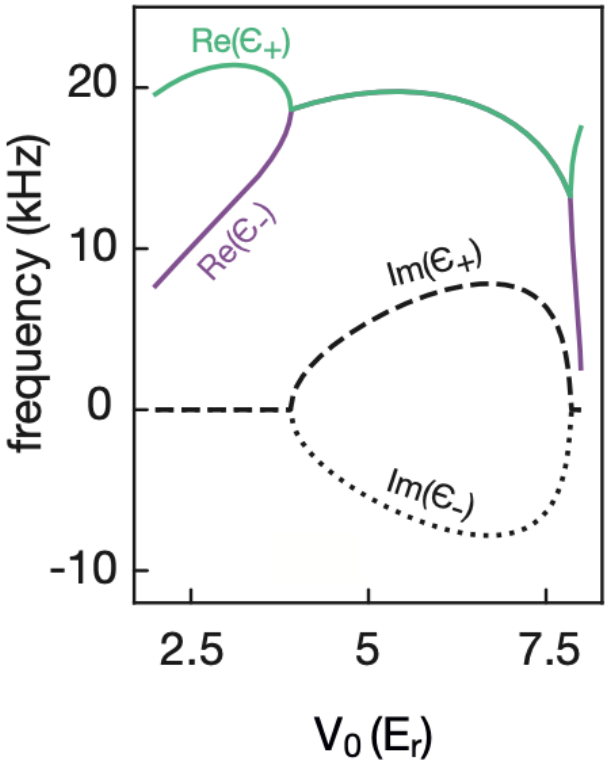


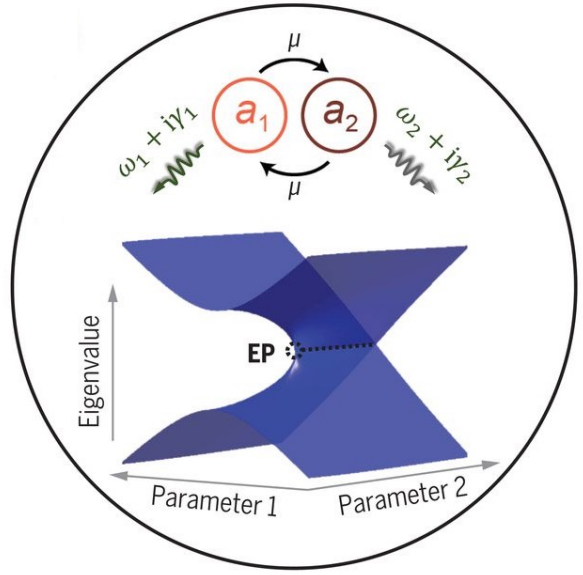
from Science, 283, 1864-1865 (1999)

x

Frequency spectrum







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

D. Dreon, P. Zupancic, A. Baumgärtner, X. Li, S. Hertlein, T. Esslinger, T. Donner, Nature, 608, 494 (2022)

See also:

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

Quantum Spinoptics

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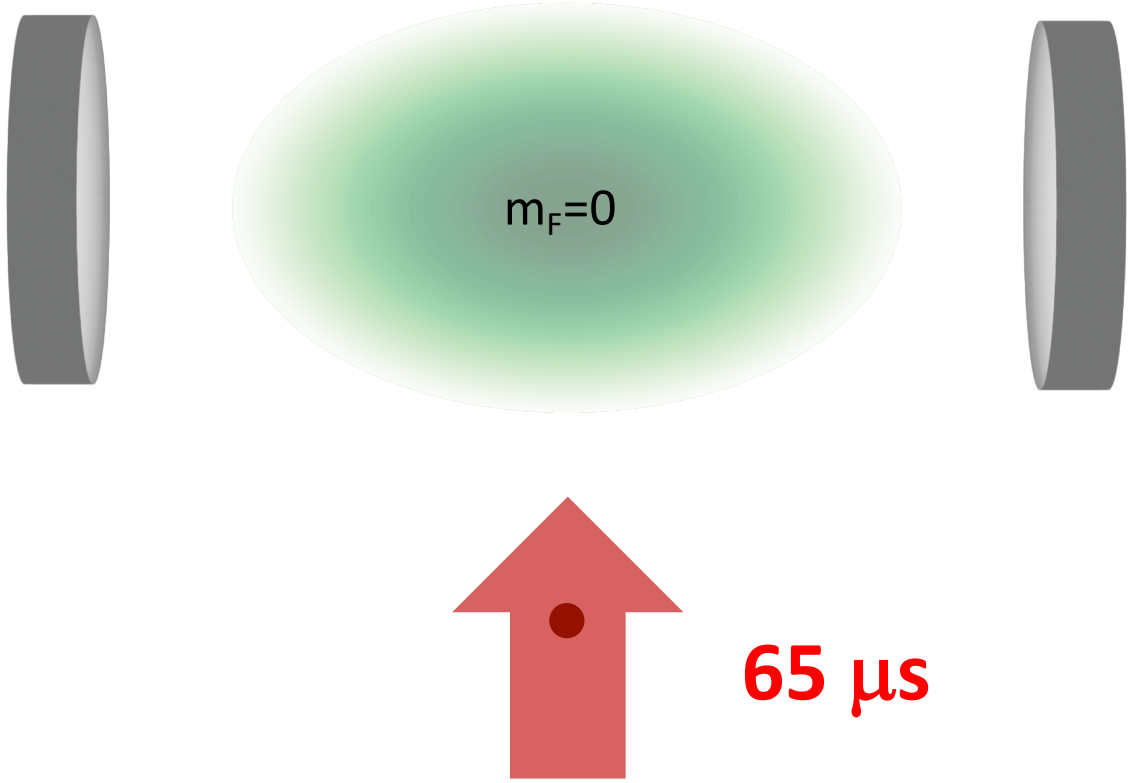
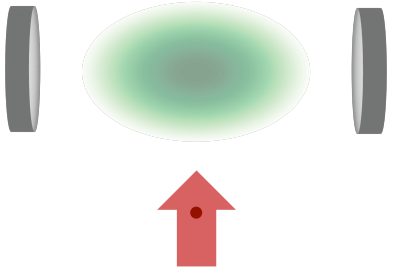
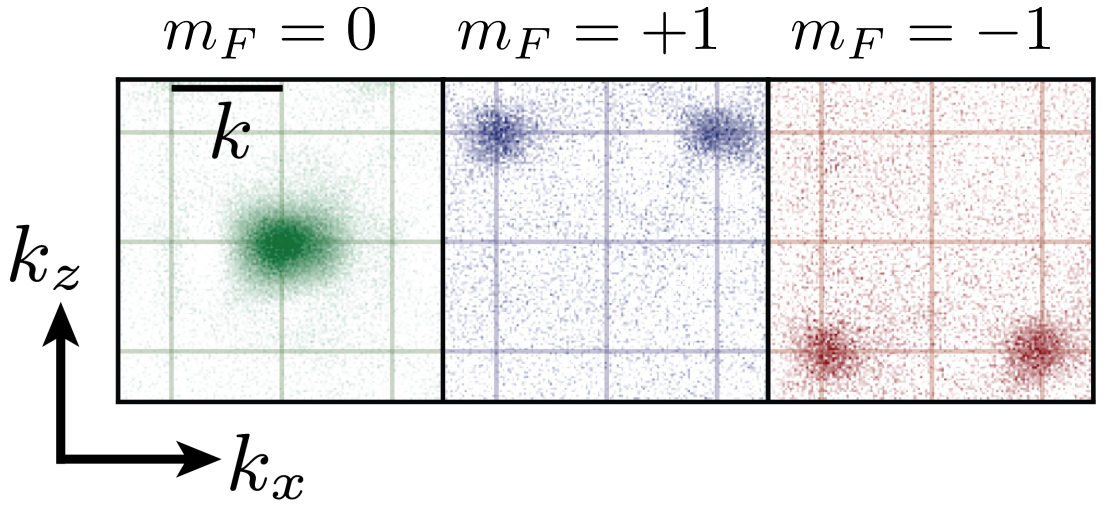
Creation of atom pairs correlated in spin and momentum



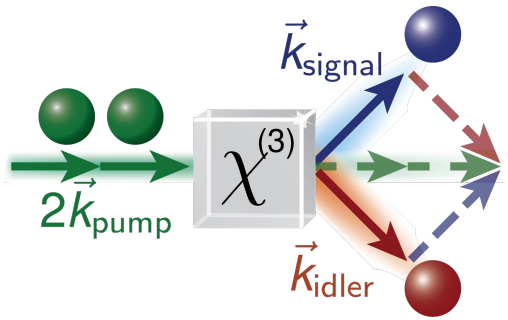
F. Finger*, R. Rosa-Medina*, N. Reiter, P. Christodoulou, T. Donner, T. Esslinger, arXiv:2303.11326

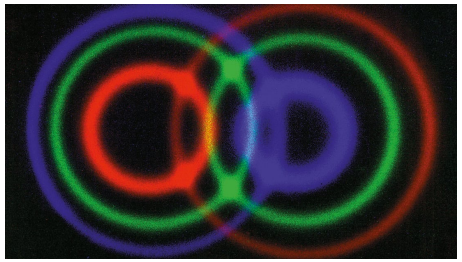
Creation of atom pairs correlated in spin and momentum

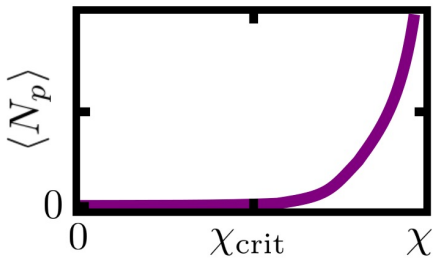




Non-linear photonics

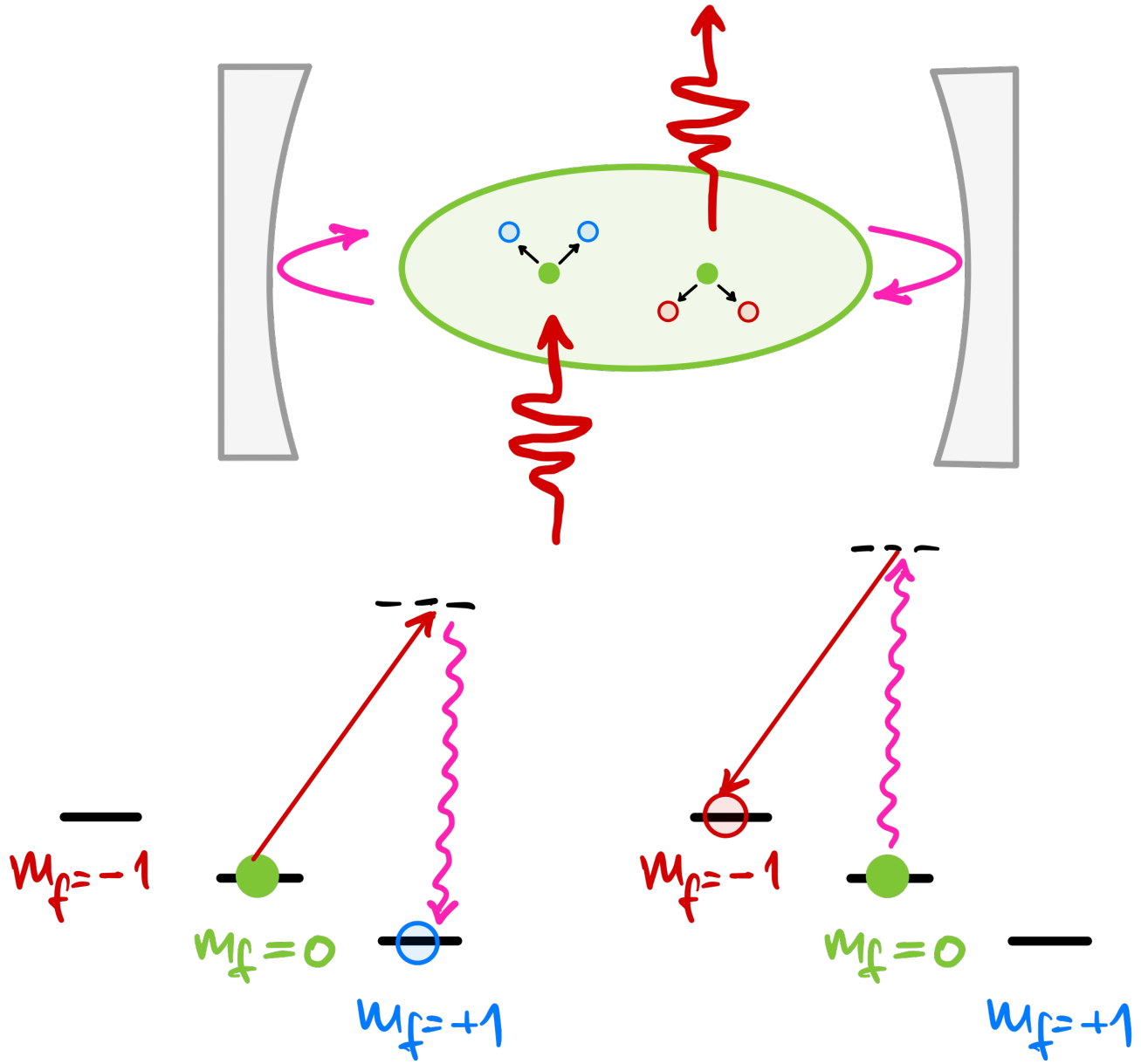


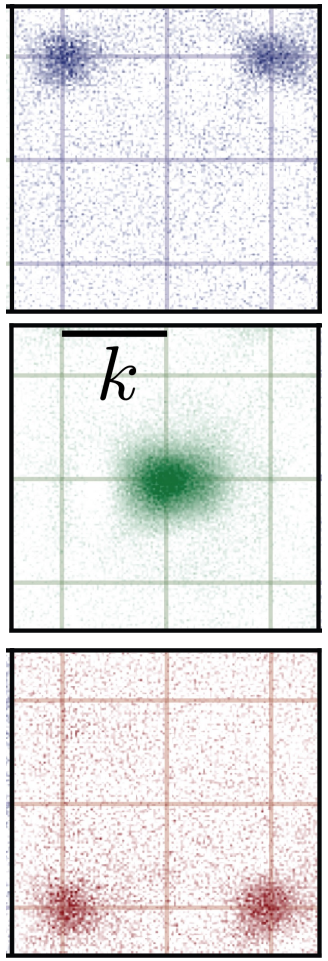




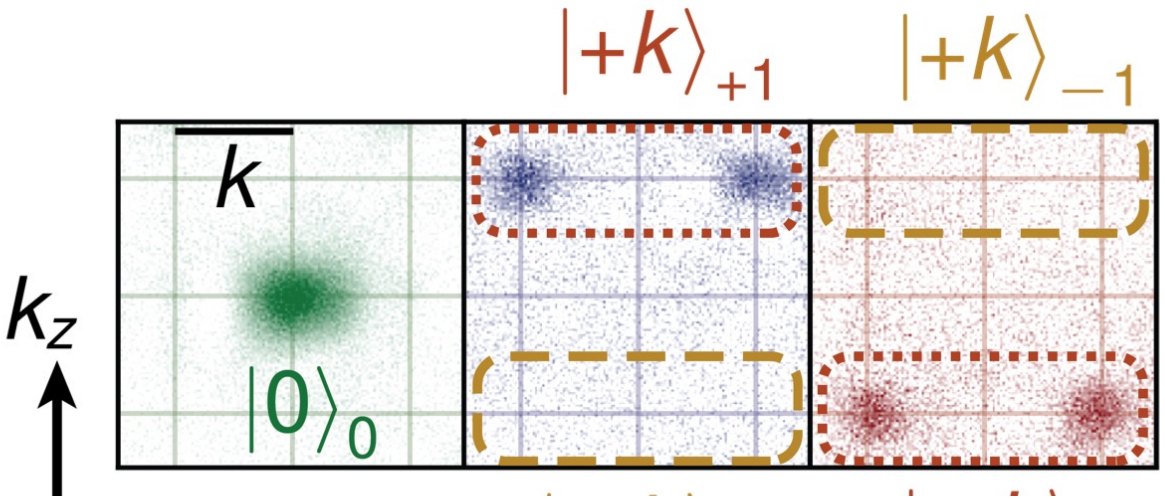
F. Finger*, R. Rosa-Medina*, N. Reiter, P. Christodoulou, T. Donner, T. Esslinger, arXiv:2303.11326

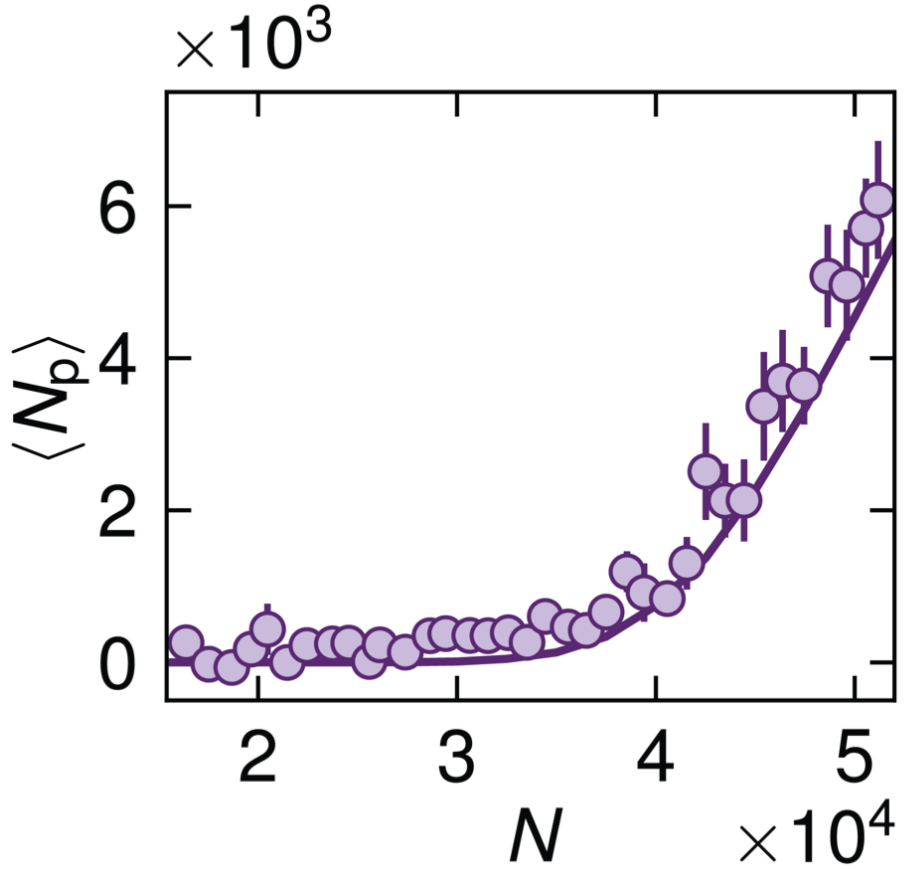
Spin and momentum changing mediated by virtual photons





Vary atom number @ pulse duration: 65 us



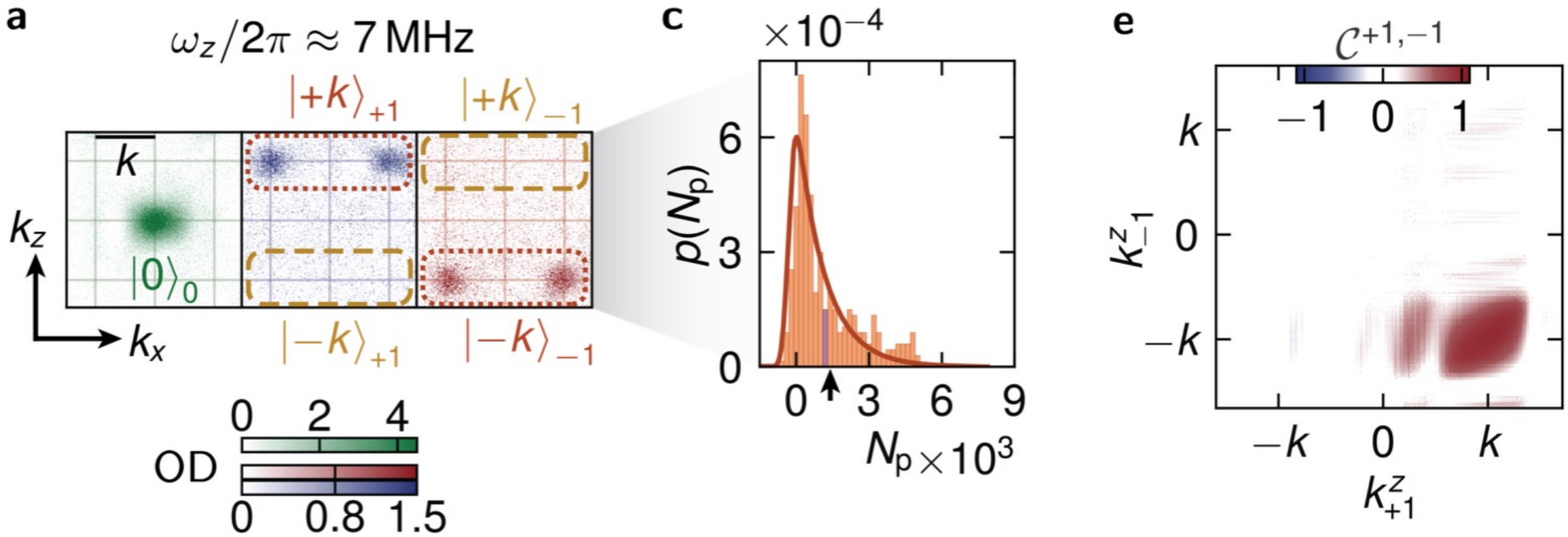


F. Finger*, R. Rosa-Medina*, N. Reiter, P. Christodoulou, T. Donner, T. Esslinger, arXiv:2303.11326

Similar process with thermal atoms:
Periwal, *et al.*, Nature 600, 630 (2021)
Luo *et al.* arXiv:2304.01411

Theoretical estimate:
10 pairs per lost photon

Statistics and Correlations



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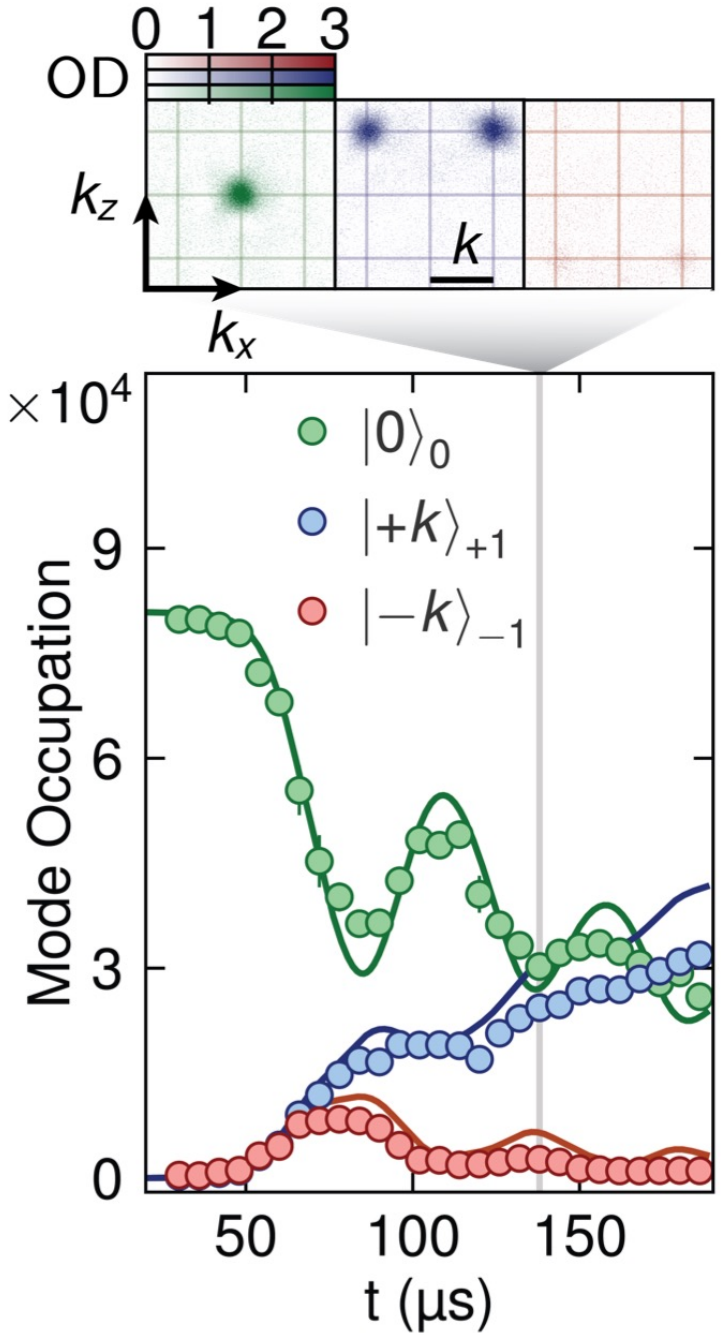
Time evolution



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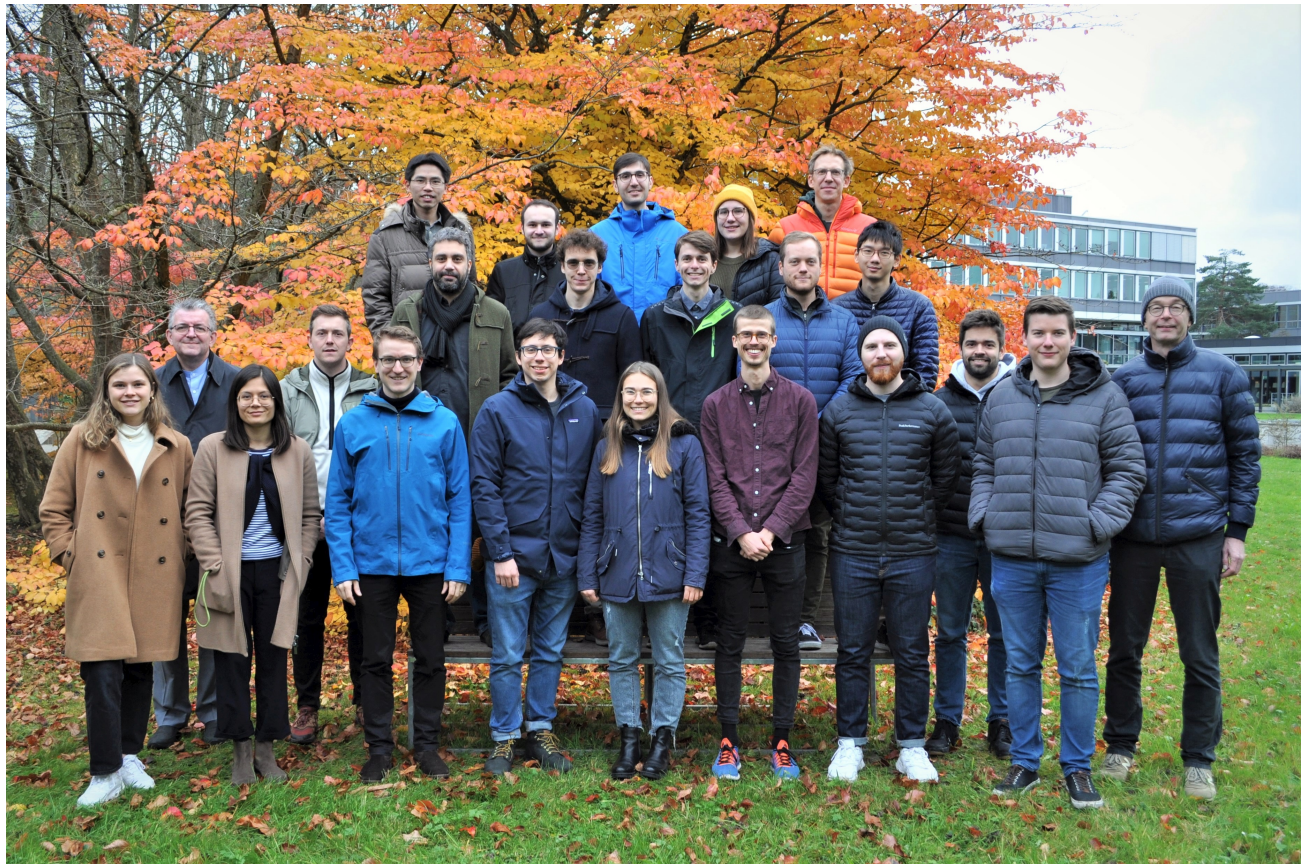
The Teams



The current teams:

Pumping scheme:

Alexander Baumgärtner, Simon Hertlein, Justyna Stefaniak, Dalila Rivero, Gabriele Natale

Correlated pairs:

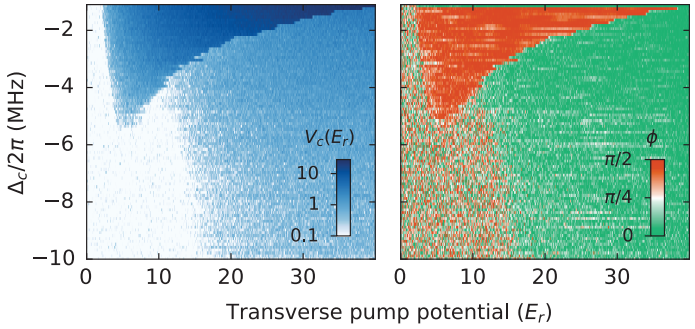
Rodrigo Rosa-Medina, Fabian Finger, Nicola Reiter, Jacob Fricke, Panagiotis Christodoulou

Tobias Donner, Tilman Esslinger

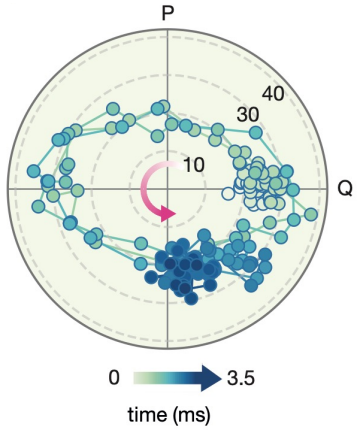
Collaborators:

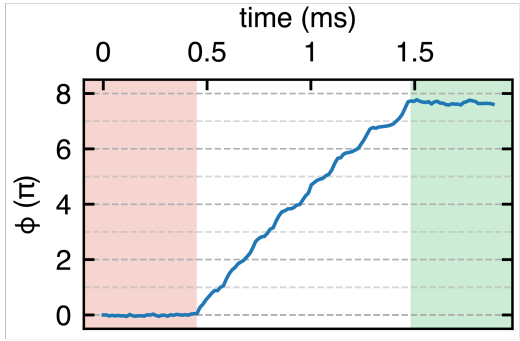
Wei Zhang, Nigel Cooper, Matteo Soriente, R. Chitra, Oded Zilberberg, Jamir Marino, Oksana Chelpanova, Tom Schmit, Giovanna Morigi

Summary

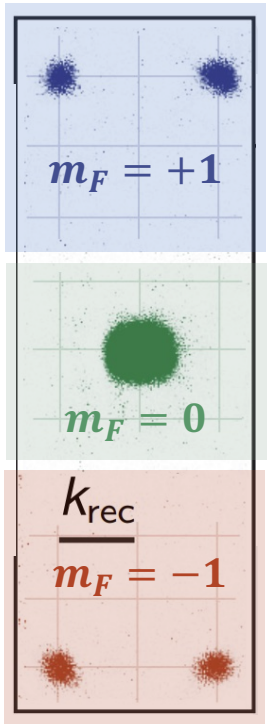


PRL **123**, 233601 (2019)
PRR **3**, L012024 (2021)





Nature ***608****, 494 (2022)*



arXiv:2303.11326