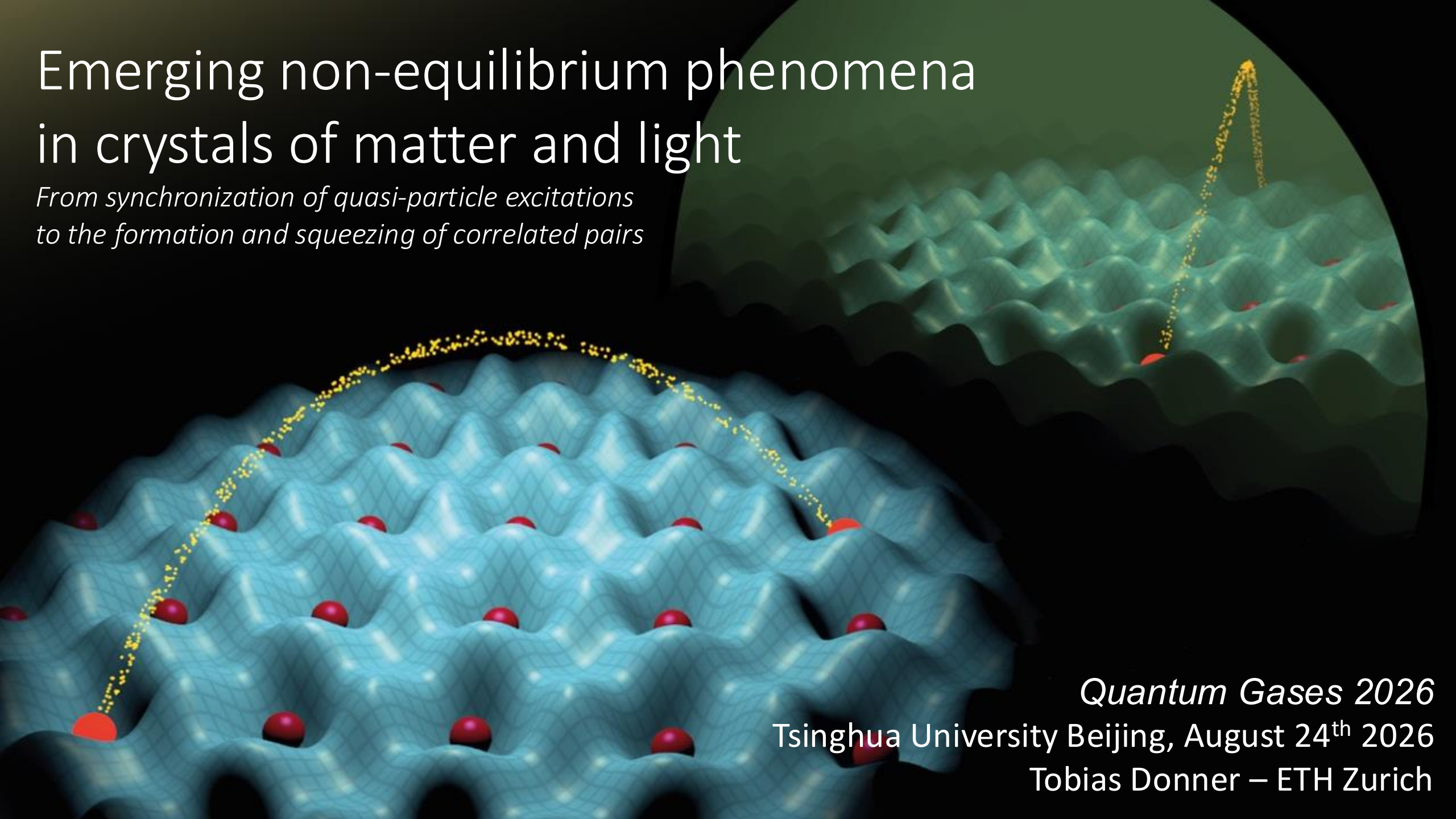


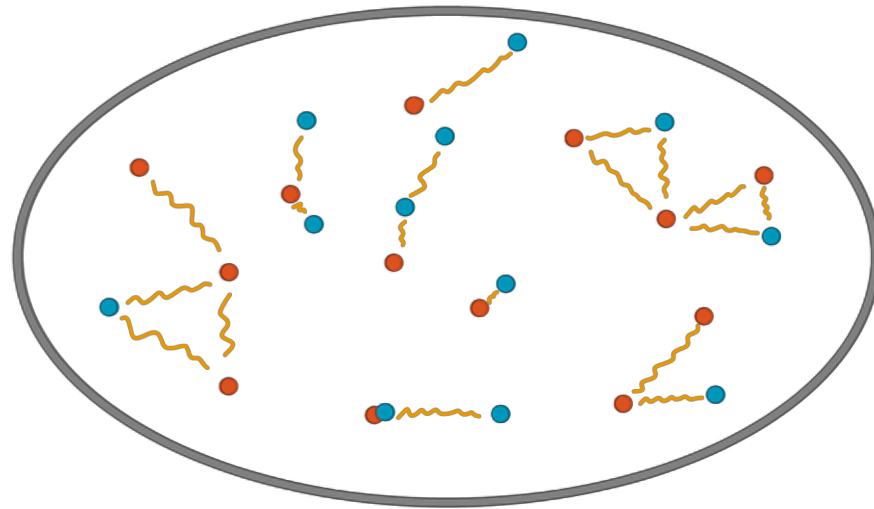
Emerging non-equilibrium phenomena in crystals of matter and light

*From synchronization of quasi-particle excitations
to the formation and squeezing of correlated pairs*



Quantum Gases 2026
Tsinghua University Beijing, August 24th 2026
Tobias Donner – ETH Zurich

Quantum many-body systems

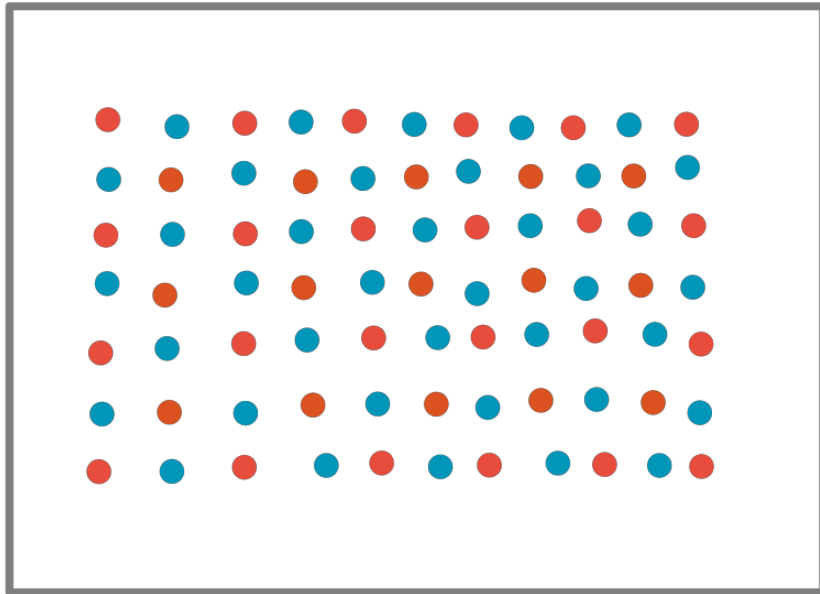
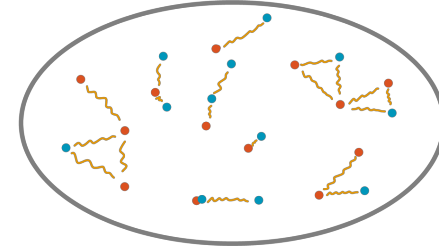


Interactions

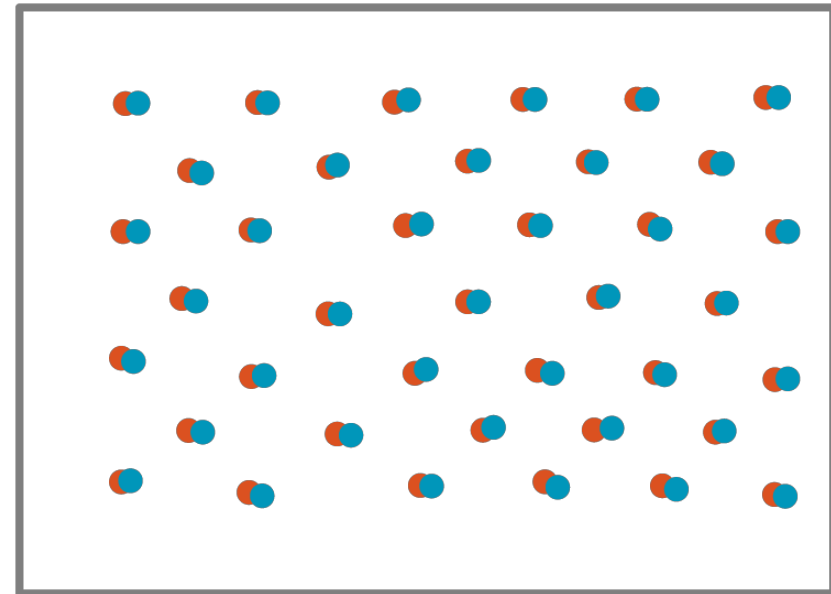
Correlated Fluctuations

$$\langle \delta\psi(\mathbf{r})\delta\psi(\mathbf{r}') \rangle \neq 0$$

QMBS with interactions

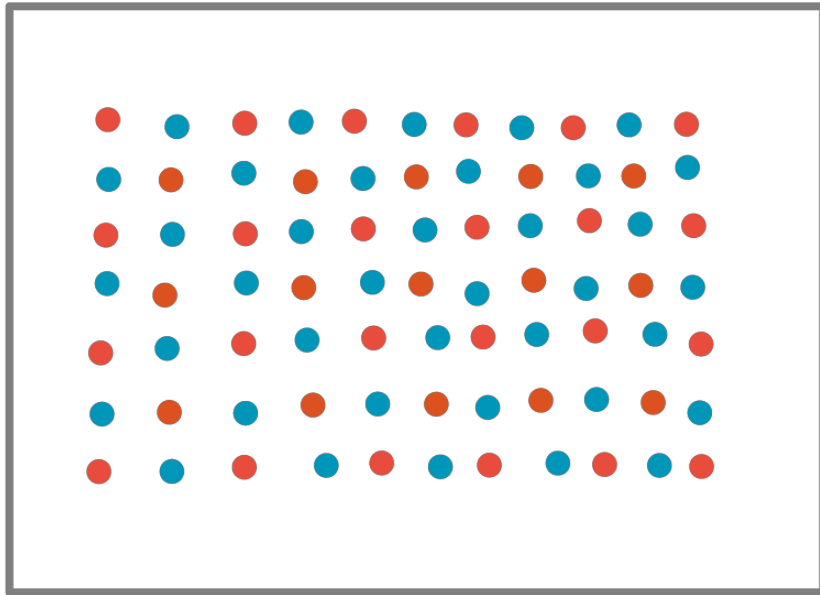
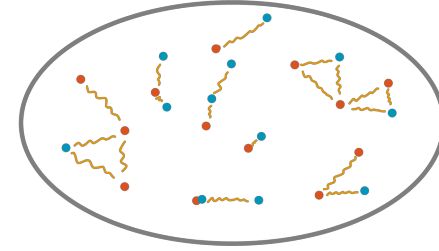


ORDER 1

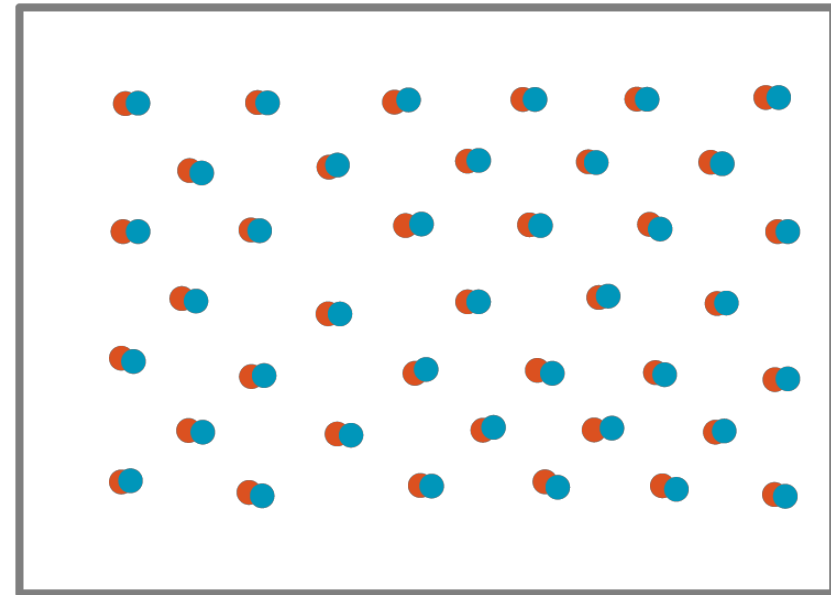


ORDER 2

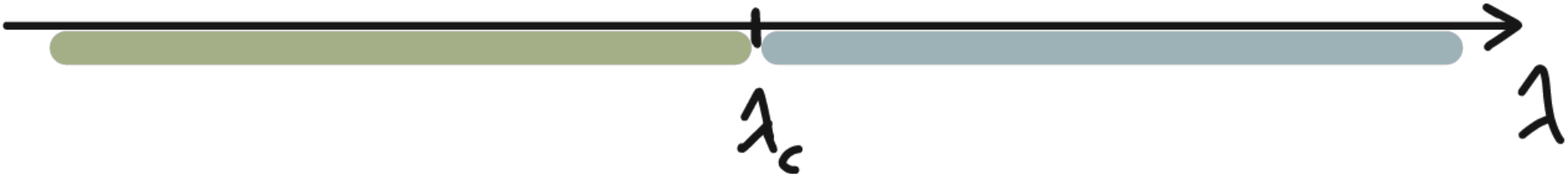
QMBS with interactions



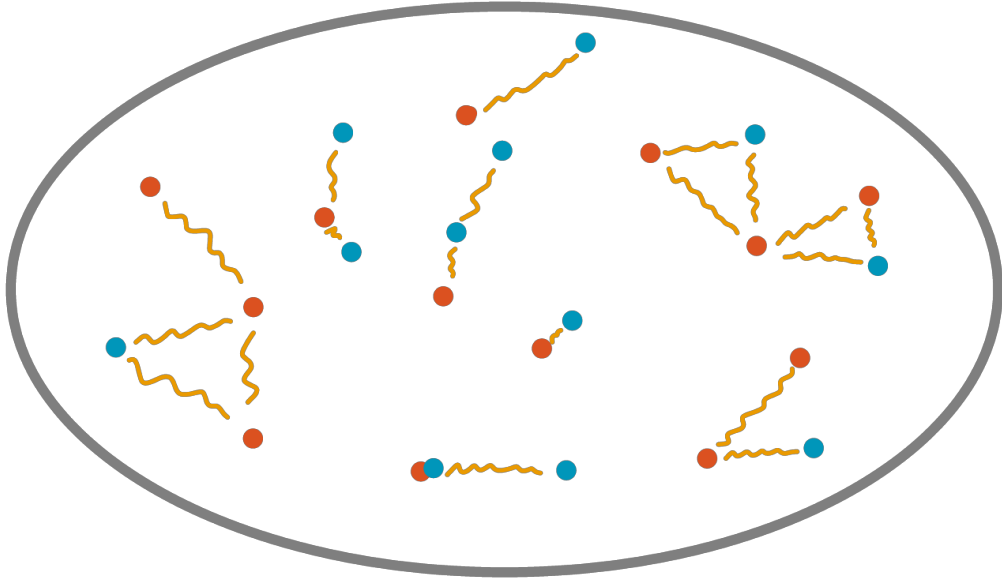
ORDER 1



ORDER 2

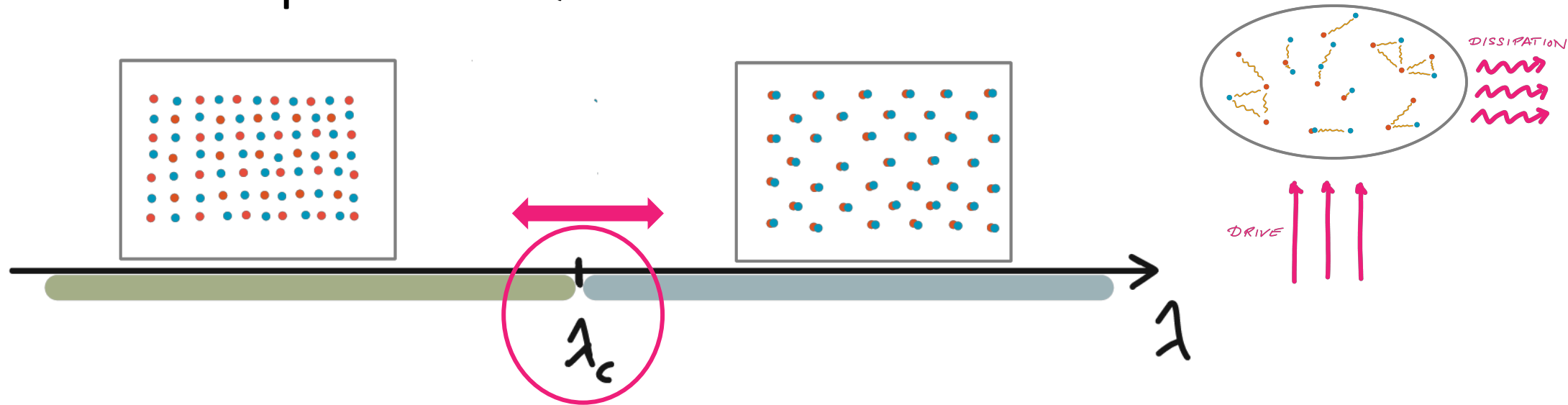


Driven-dissipative systems



???

Driven-dissipative QMBS



- **Modified Criticality**

PNAS 110, 11763-11767 (2013)

Nature Comm 6, 7046 (2015)

- **Irreversible Entropy Production**

PRL 121, 160604 (2018)

- **Dissipation stabilized phases**

PRL120, 183603 (2018)

PRX 11, 041046 (2021)

- **Emergent dynamics**

- Stationarity vs non-stationarity

- Synchronization

- Limit cycles / Emergent pumping

Nature 608, 494 (2022)

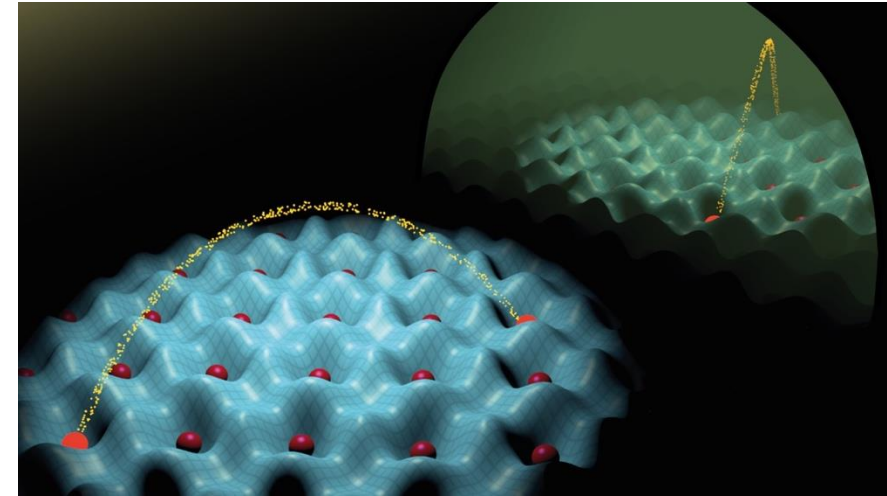
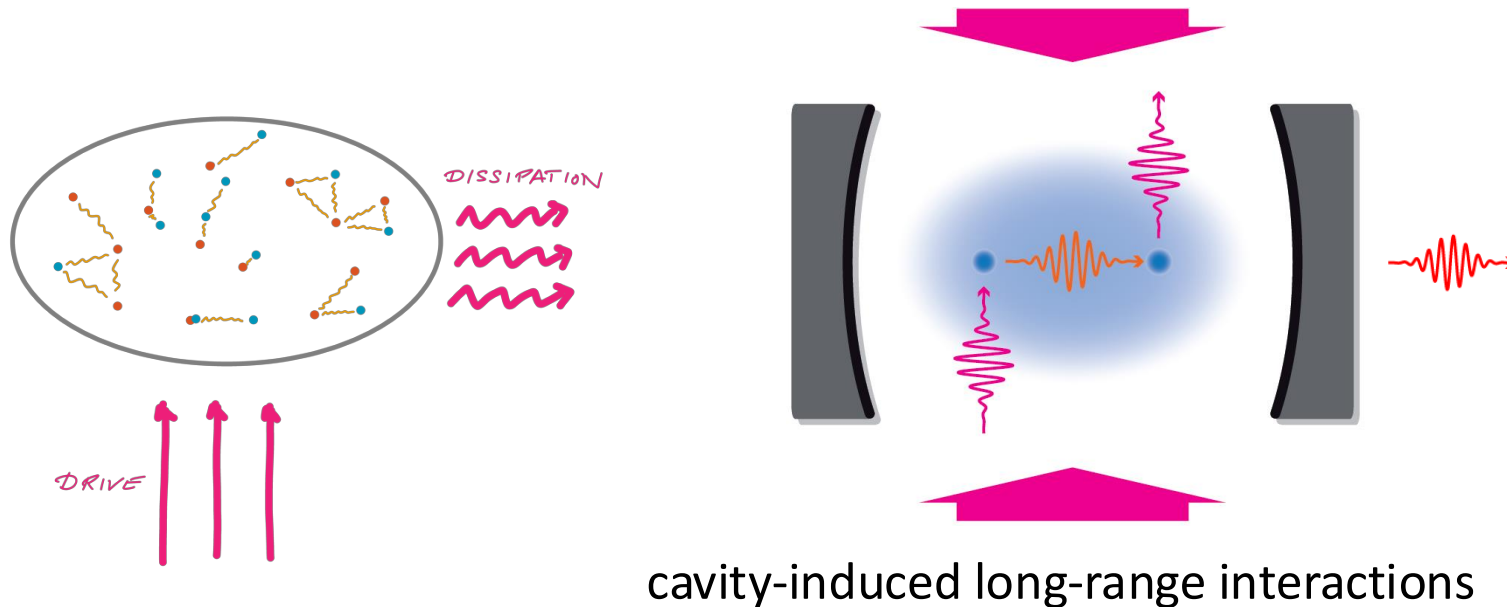
PRA 113, 043307 (2026) / PRL 136, 140401 (2026)

- **Fate of Pair Correlations**

PRL 132, 093402 (2024)

...plus preliminary data...

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



Experiments:

QG Bosons: Stamper-Kurn, Reichel, Lev, Hemmerich, Zimmermann

QG Fermions: Brantut, Wu

Thermal atoms: Schleier-Smith, Thompson, Vuletic, Barrett, ...

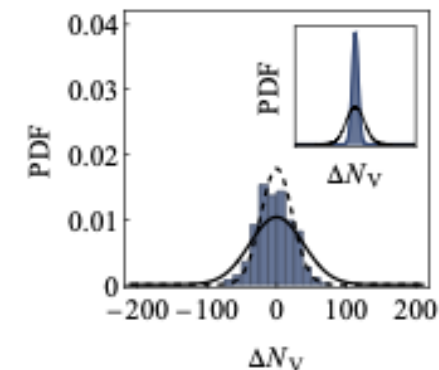
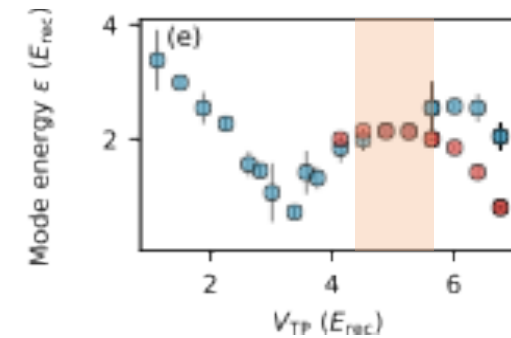
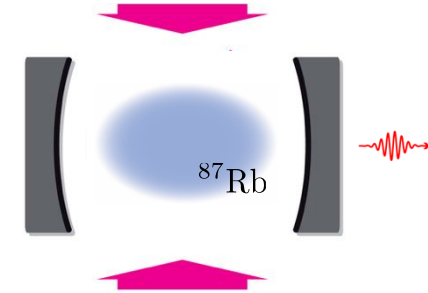
Theory: Morigi, Ritsch, Mathey, Piazza, Keeling, Domokos, Carmichael, Gopalakrishnan, Strack, Mekhov, Lin, Kollath, Zilberberg, Zhang, Chitra, ...

Review article:

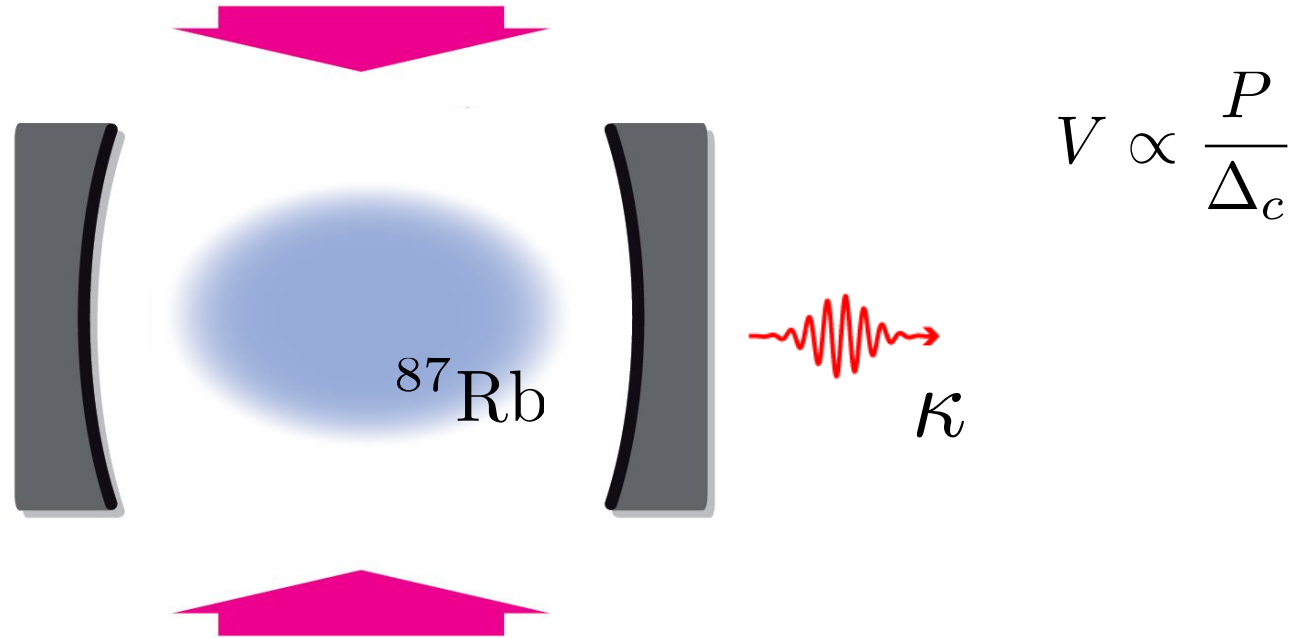
Advances in Physics 70 (2021)

Outline

- Intro to many-body cavity QED
- Synchronisation of fluctuations in an open many-body system
- Squeezing of atomic pairs correlated in momentum space



Cavity-mediated long-range interactions

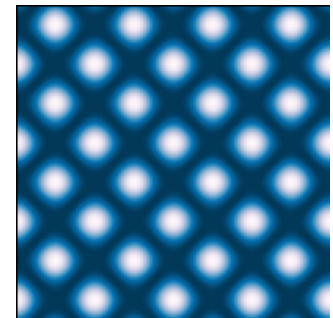


Long-range interaction:

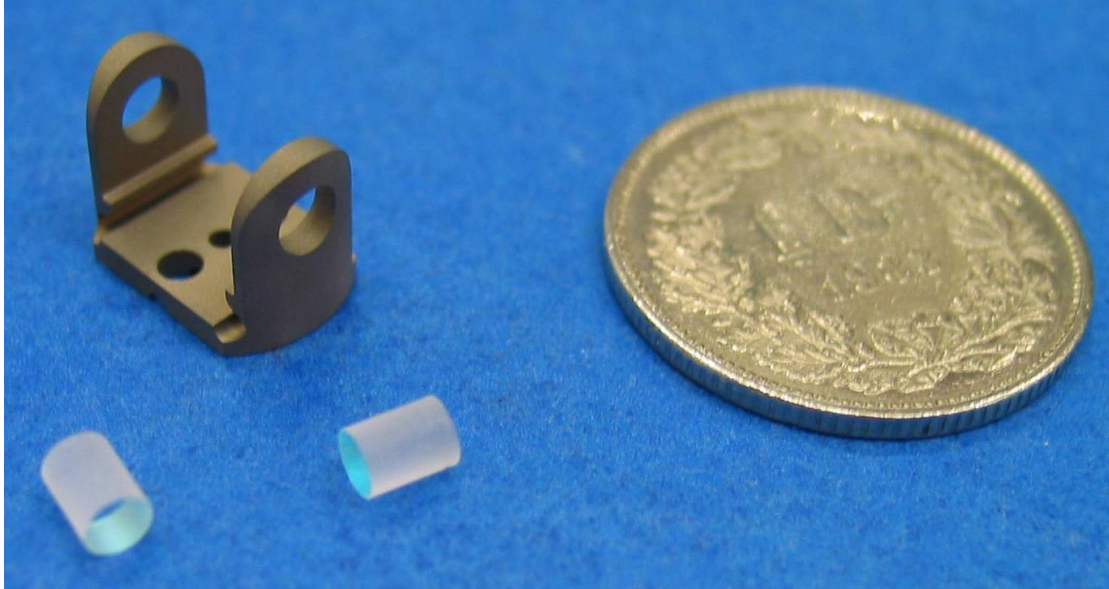
$$\hat{c}_k^\dagger \hat{c}_{k'}^\dagger \hat{c}_0 \hat{c}_0 + h.c. \quad \text{Creation of correlated pairs!}$$

$$V(\mathbf{r}, \mathbf{r}') = V \cos(kx) \cos(kz) \cos(kx') \cos(kz')$$

→ Interaction favors checkerboard density modulation.

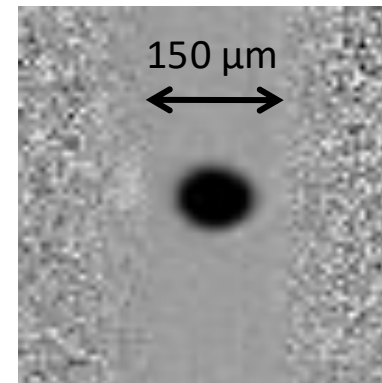


High-finesse cavity



Optical Fabry-Perot cavity

- $L = 178 \mu\text{m}$
- $F = 340.000$
- $(g_0, \kappa, \gamma) = 2\pi \times (10, 1, 3)\text{MHz}$



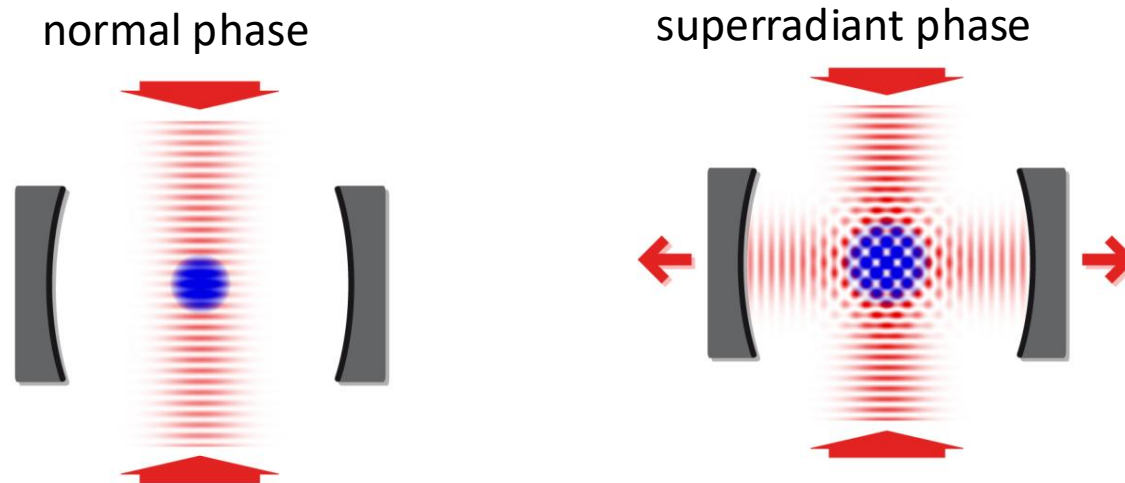
Bose-Einstein condensate

- 10^5 atoms (^{87}Rb)
- $T < 100 \text{ nK}$

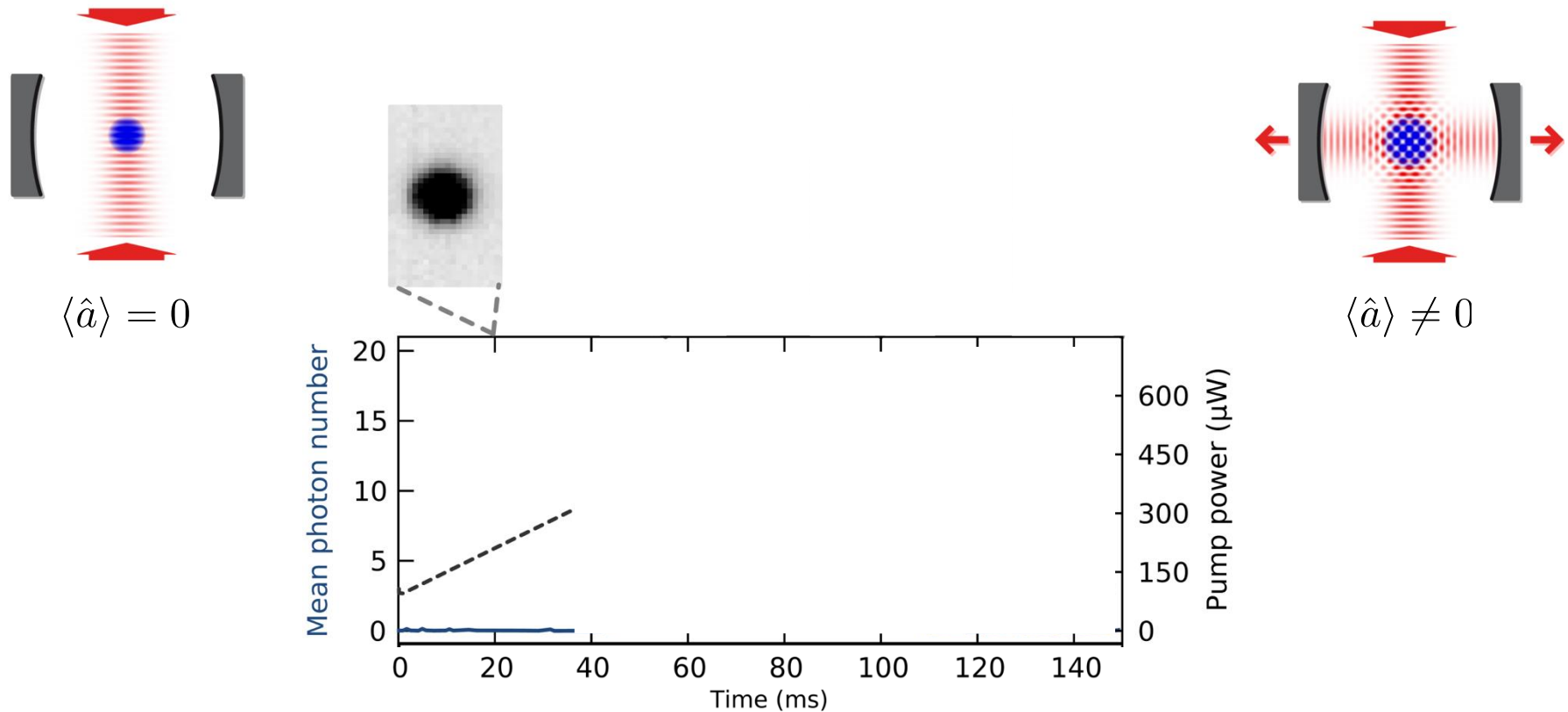
Superradiant phase transition: potential vs kinetic energy

Single-particle Hamiltonian:

$$\hat{\mathcal{H}}_{\text{SP}} = \underbrace{-\Delta_c \hat{a}^\dagger \hat{a}}_{\text{photon energy}} + \underbrace{\frac{\hat{\mathbf{p}}^2}{2m}}_{\text{kinetic energy}} + \underbrace{V_p \cos^2(\mathbf{k}_p \hat{\mathbf{r}})}_{\text{pump lattice potential}} + \underbrace{U_0 \cos^2(\mathbf{k}_c \hat{\mathbf{r}})}_{\text{cavity lattice potential}} \hat{a}^\dagger \hat{a} + \underbrace{\sqrt{V_p U_0} \cos(\mathbf{k}_p \hat{\mathbf{r}}) \cos(\mathbf{k}_c \hat{\mathbf{r}}) (\hat{a} + \hat{a}^\dagger)}_{\text{interaction potential}}$$



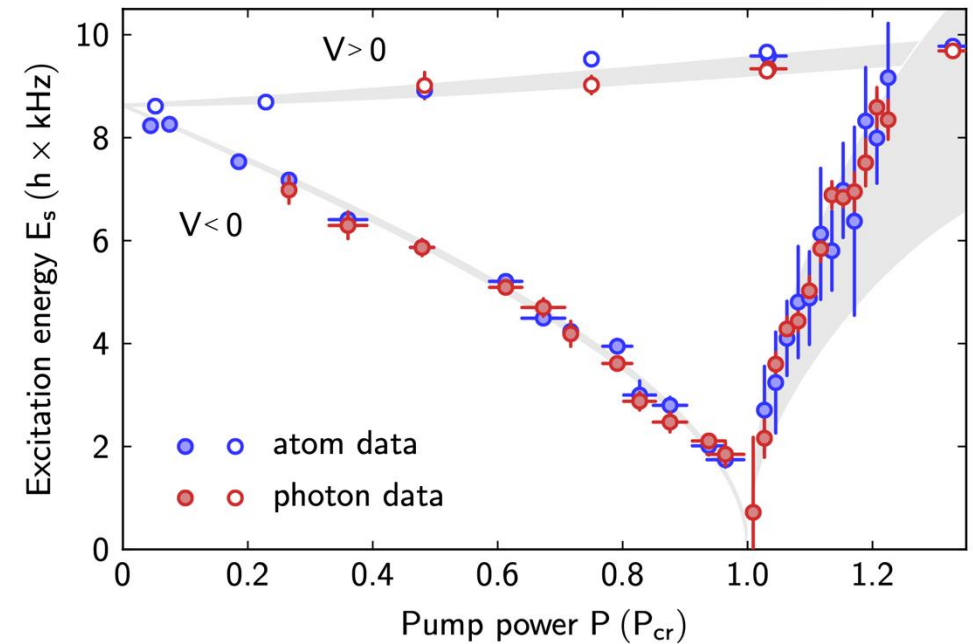
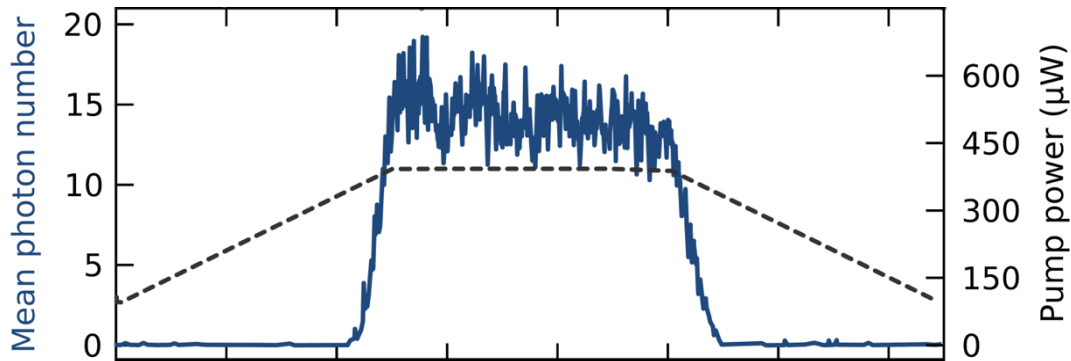
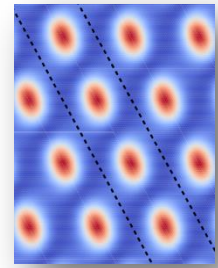
Structural Phase Transition kinetic vs potential energy



Light field measures order parameter (density modulation):

$$\langle \alpha \rangle \propto \langle \Theta \rangle \propto \langle \Psi | V_i | \Psi \rangle$$

Roton softening at phase transition



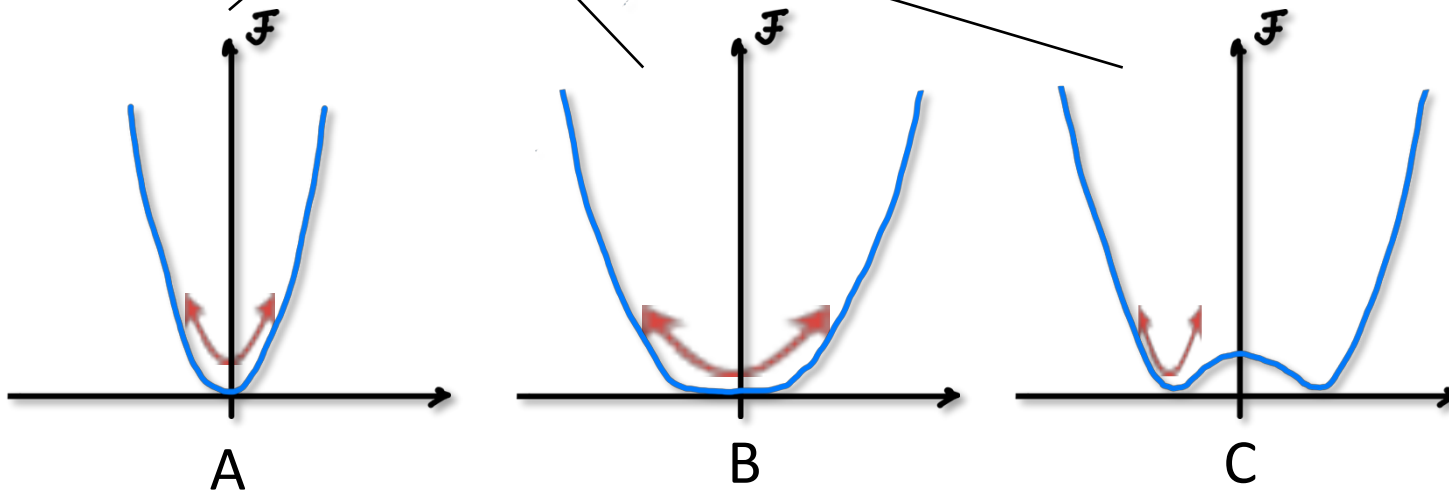
Measured mode softening:

Mottl et al. Science 336, 1570 (2012)

Measured fluctuations:

Brennecke et al. PNAS 110, 11763 (2013)

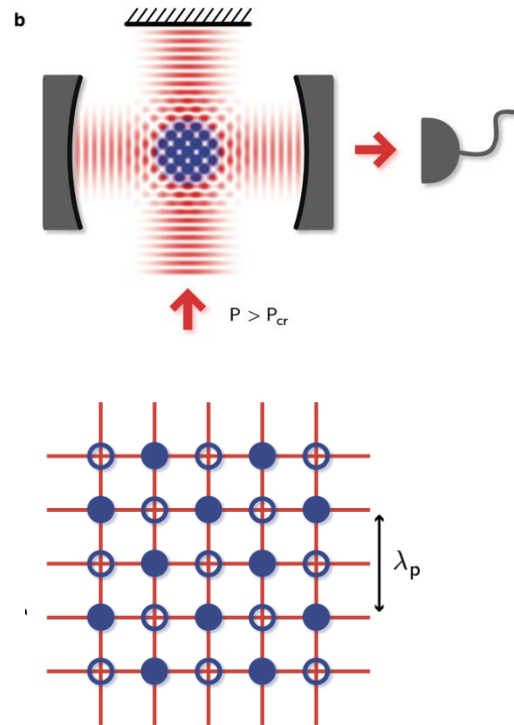
Landig et al. Nature Communications 6, 7046 (2015).



Landau theory

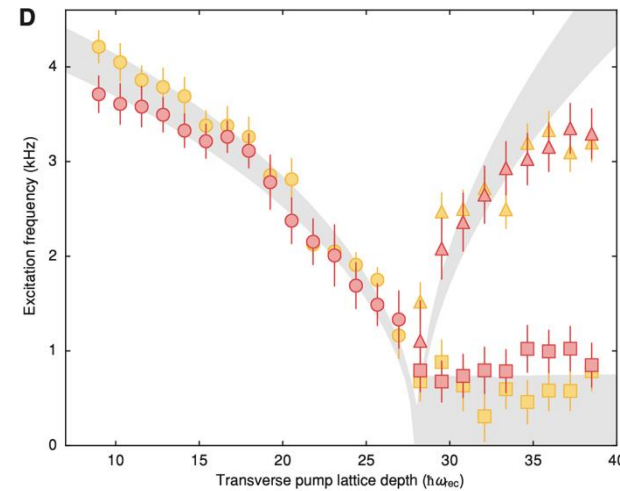
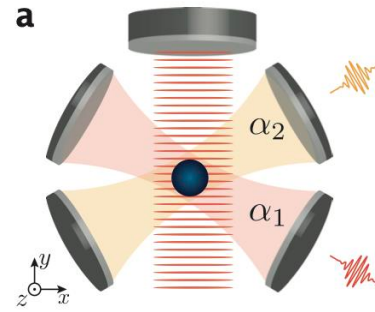
Light-induced many-body phases

Lattice supersolid
Breaking $Z(2)$ symmetry



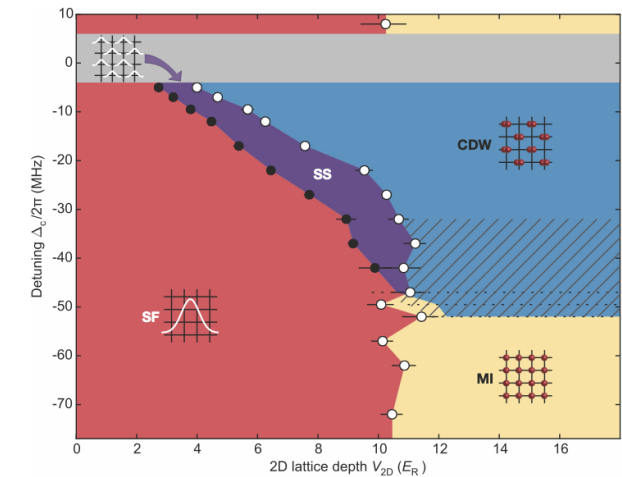
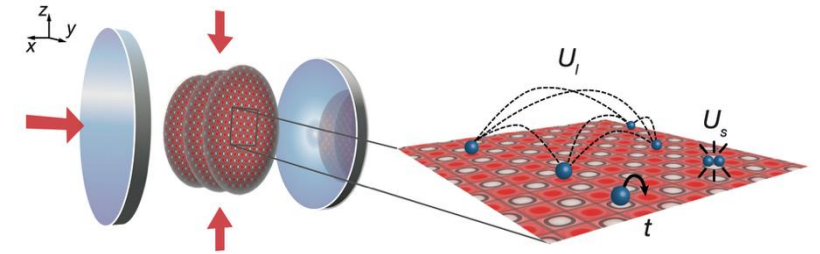
Baumann et al.
Nature 464, 1301 (2010)

Supersolid
breaking $U(1)$ symmetry



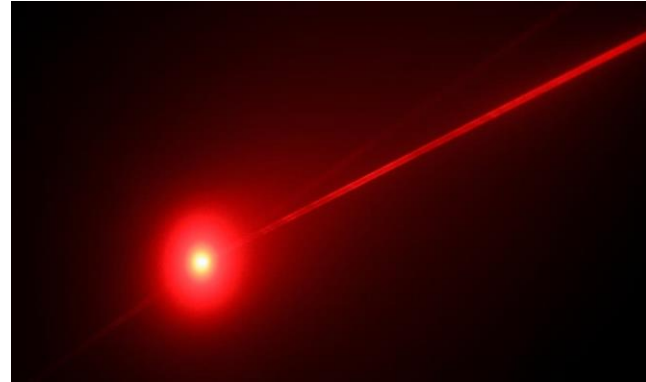
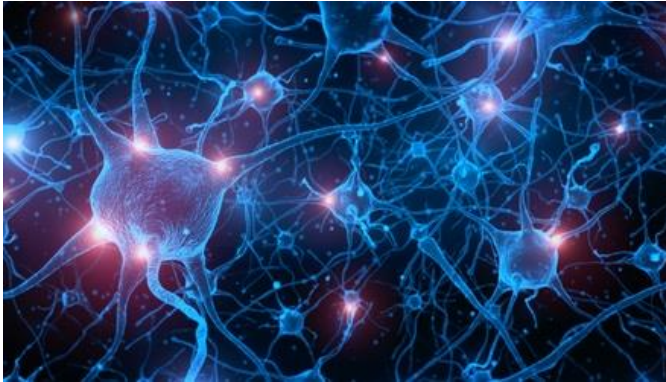
Léonard et al.
Nature 543, 87 (2017)
Science 358, 1415 (2017)

Extended Bose-Hubbard model



Landig et al.
Nature 532, 476-479 (2016)

Synchronization – an emergent phenomenon in open many-body systems

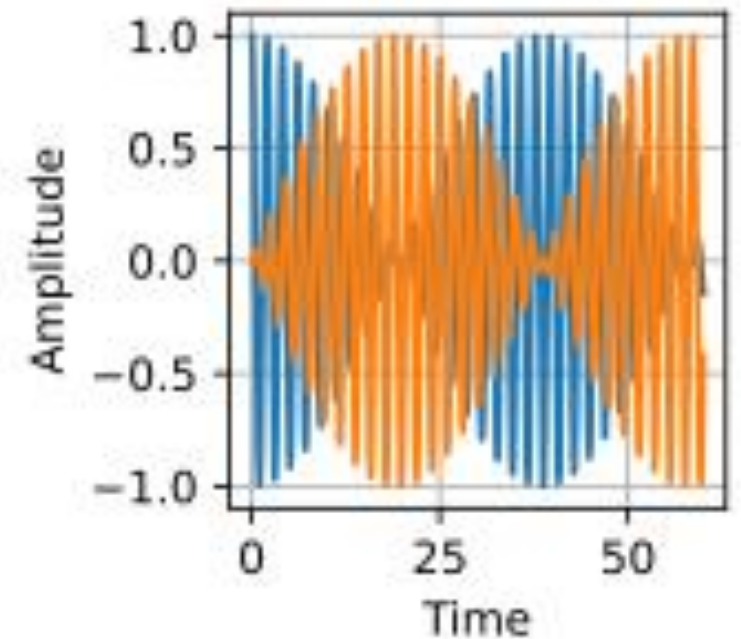
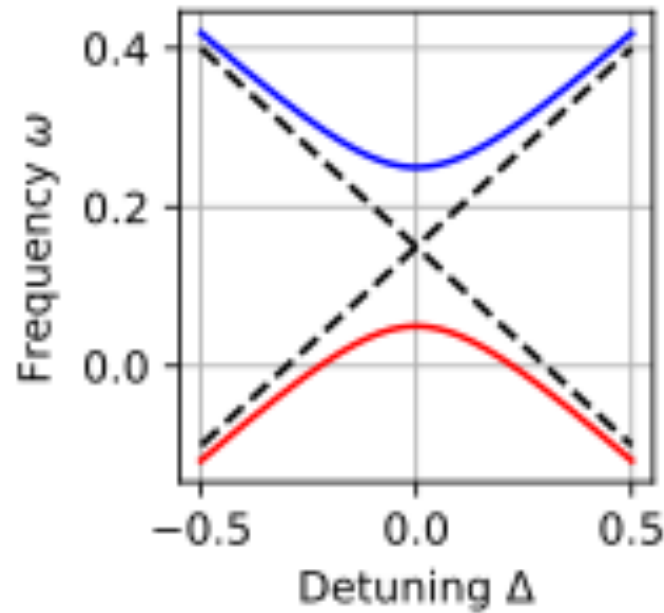
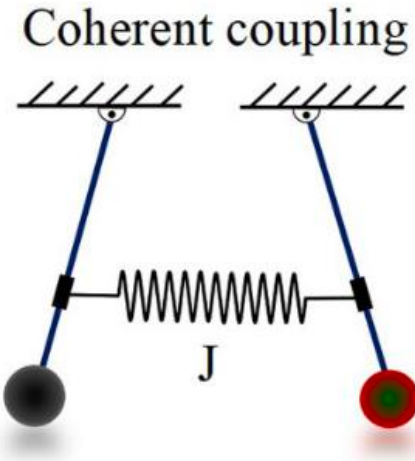


ω_1



ω_2

Coherent coupling



$$\hat{H} = \begin{pmatrix} \omega_0 + \frac{\Delta}{2} & J \\ J & \omega_0 - \frac{\Delta}{2} \end{pmatrix}$$

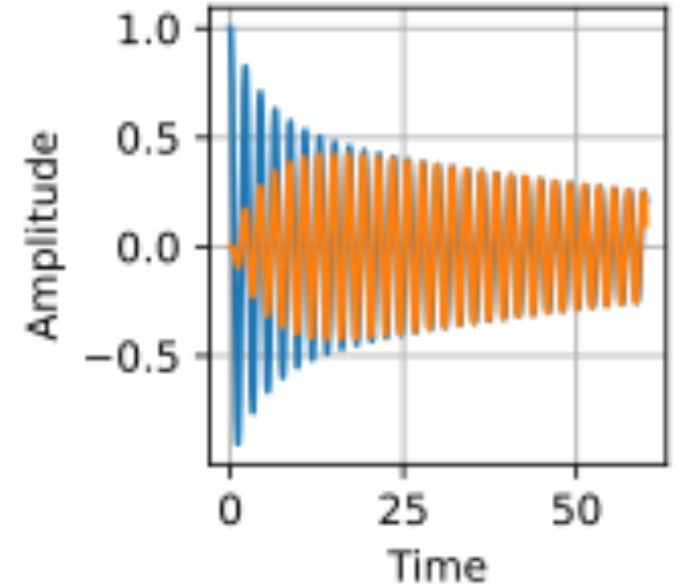
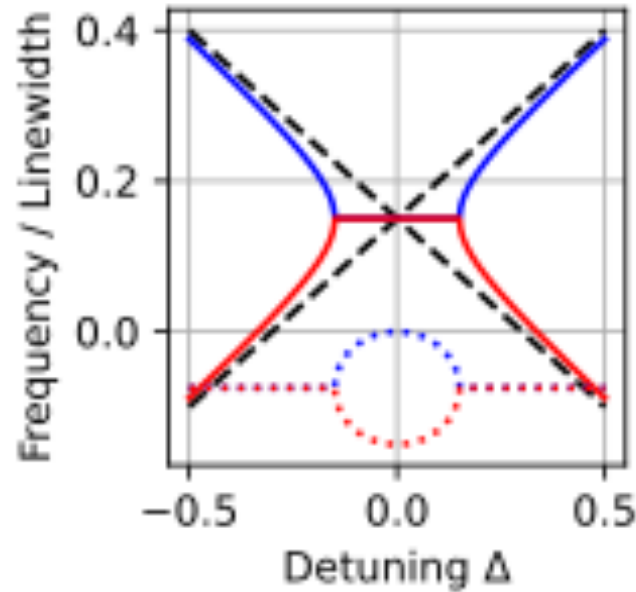
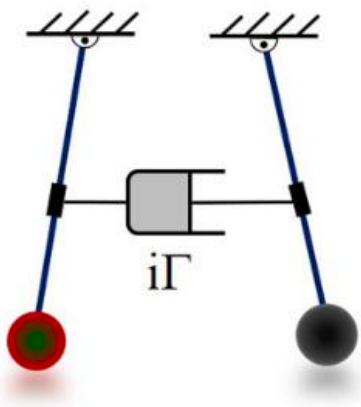
$$\omega_{\pm} = \omega_0 \pm \sqrt{\left(\frac{\Delta}{2}\right)^2 + J^2}$$

$$\hat{H} = \hat{H}^\dagger$$

- Real eigenvalues
- Orthogonal states

Dissipative synchronization

Dissipative coupling



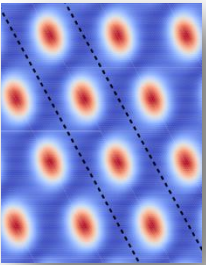
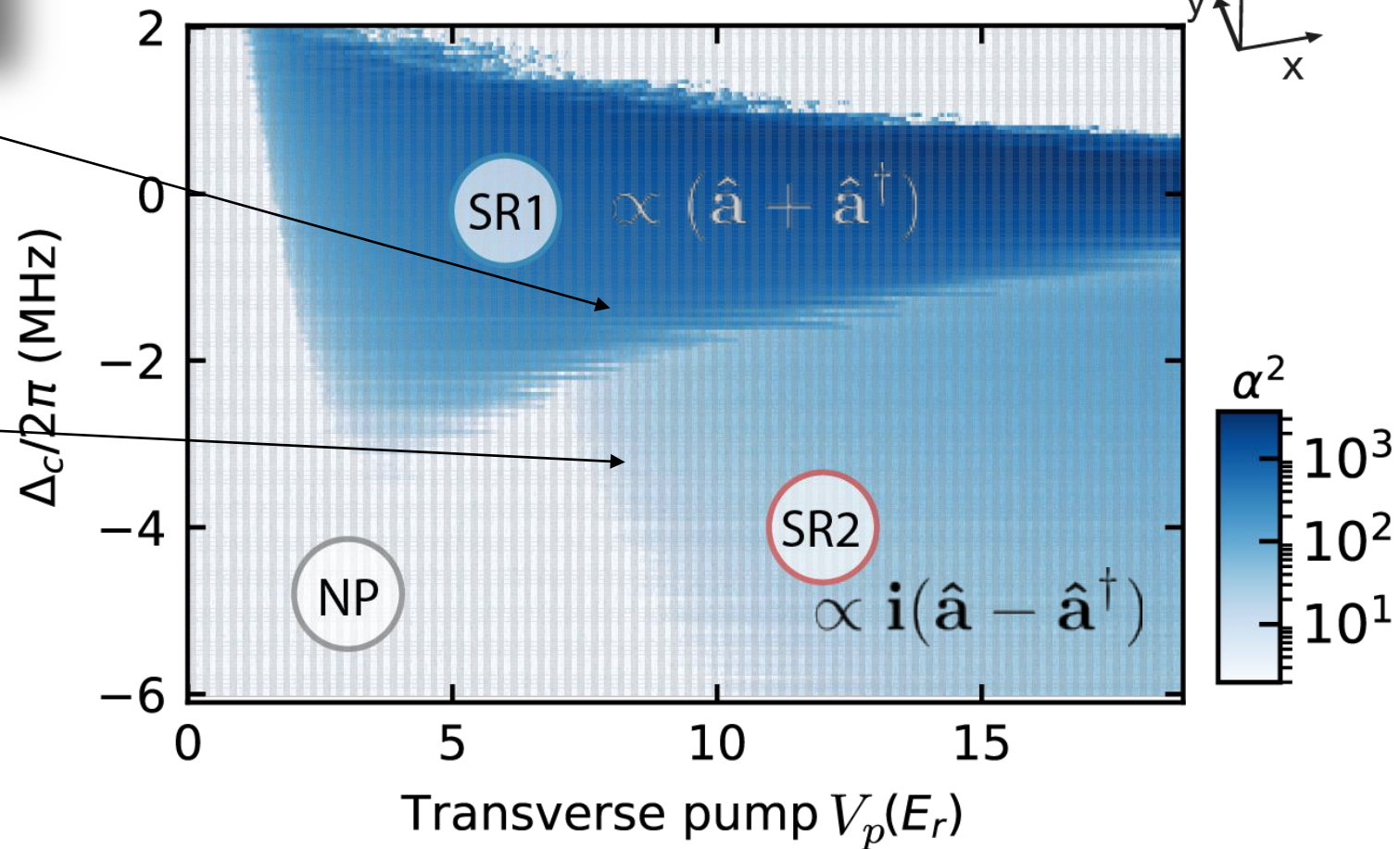
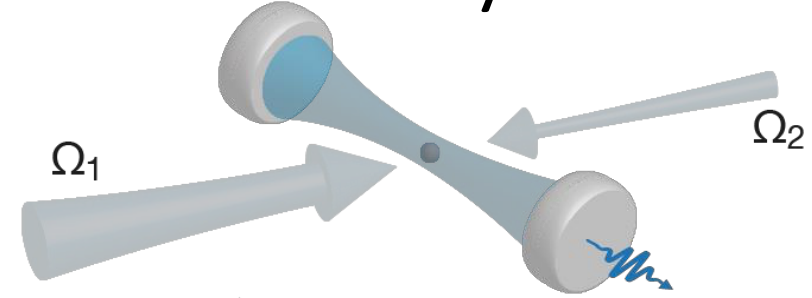
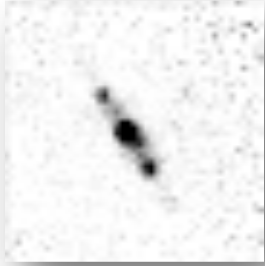
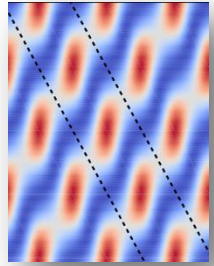
$$\hat{H} = \begin{pmatrix} \omega_1^2 - i\Gamma\omega & i\Gamma\omega \\ i\Gamma\omega & \omega_2^2 - i\Gamma\omega \end{pmatrix}$$

$$\hat{H} \neq \hat{H}^\dagger$$

- Complex eigenvalues
- Non-orthogonal states
- Exceptional points
- Gain and loss (instability)
- Chirality

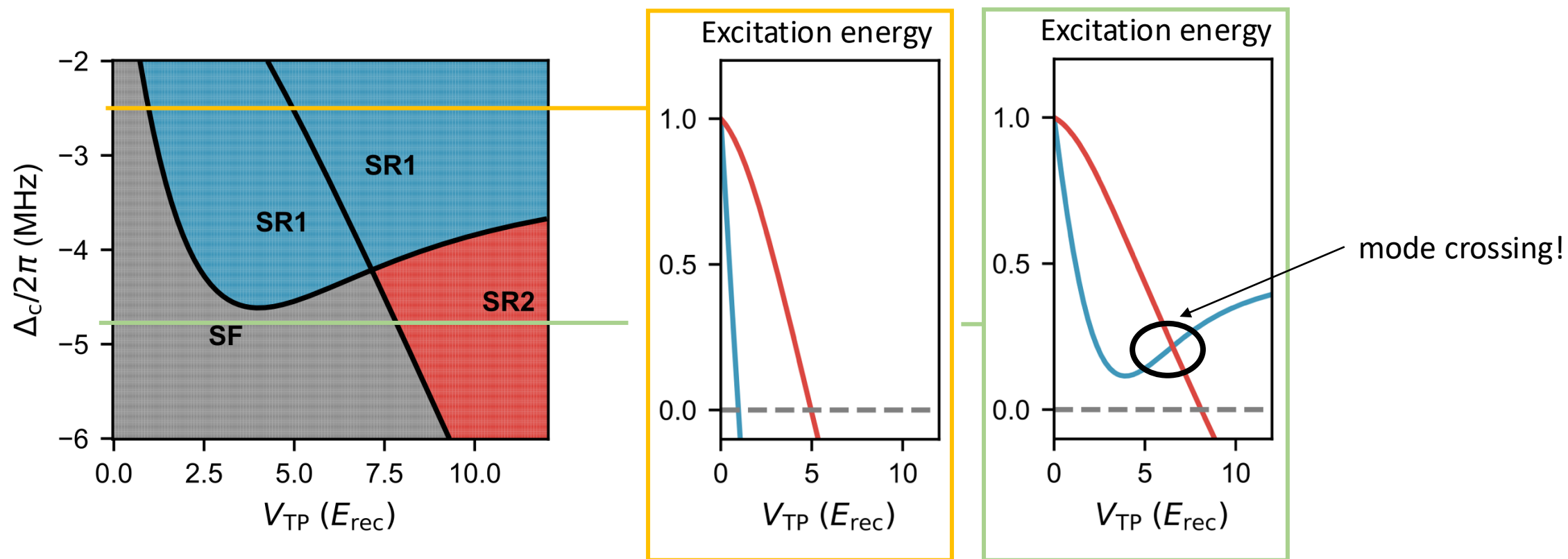
$$\omega_{\pm} \approx \omega_0 \pm \sqrt{\left(\frac{\Delta}{2}\right)^2 - \left(\frac{\Gamma}{2}\right)^2} - i\frac{\Gamma}{2}$$

Unbalanced blue driving – two self-ordered crystals

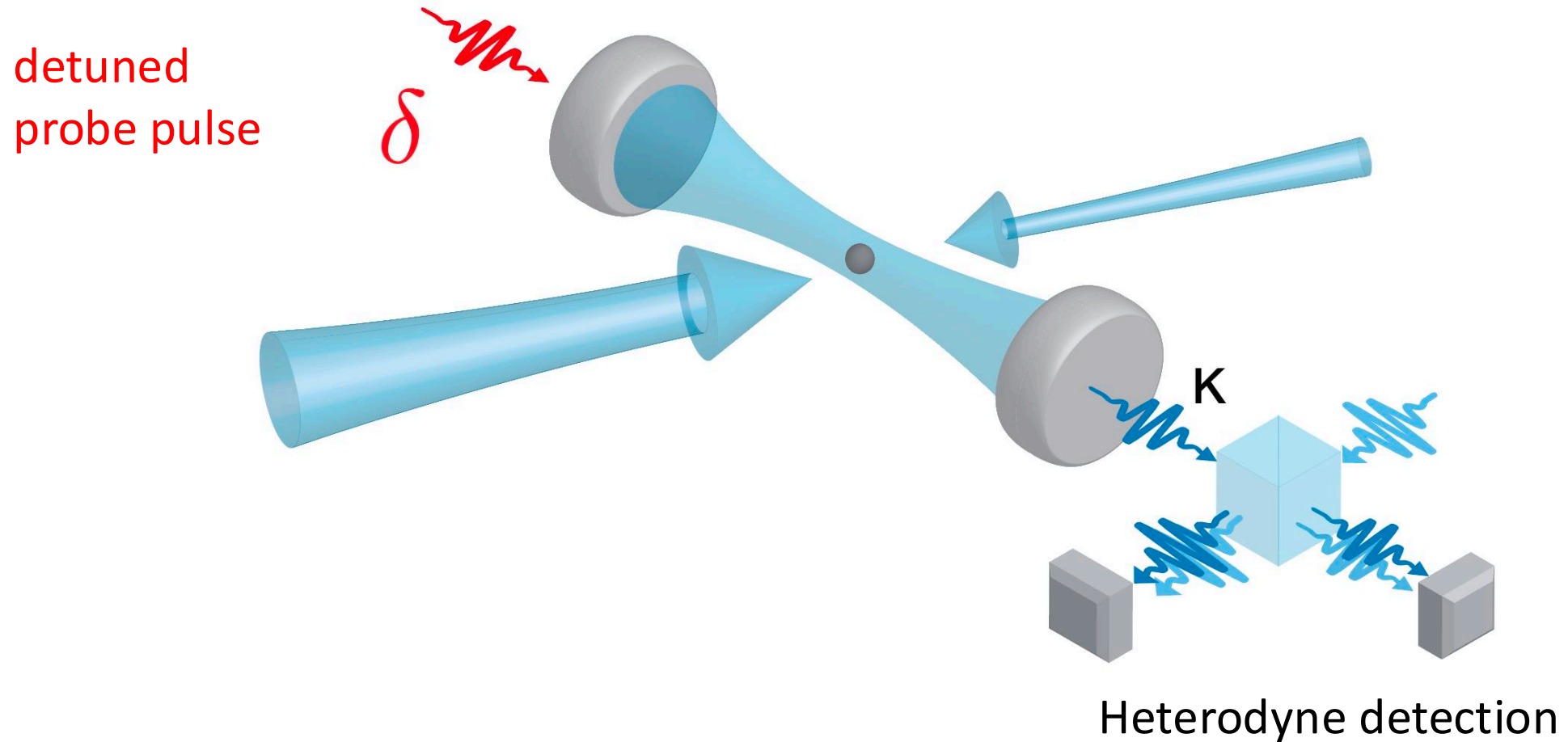


Mean-field phase diagram

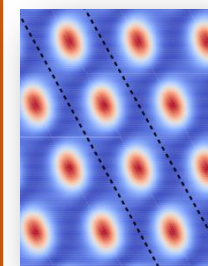
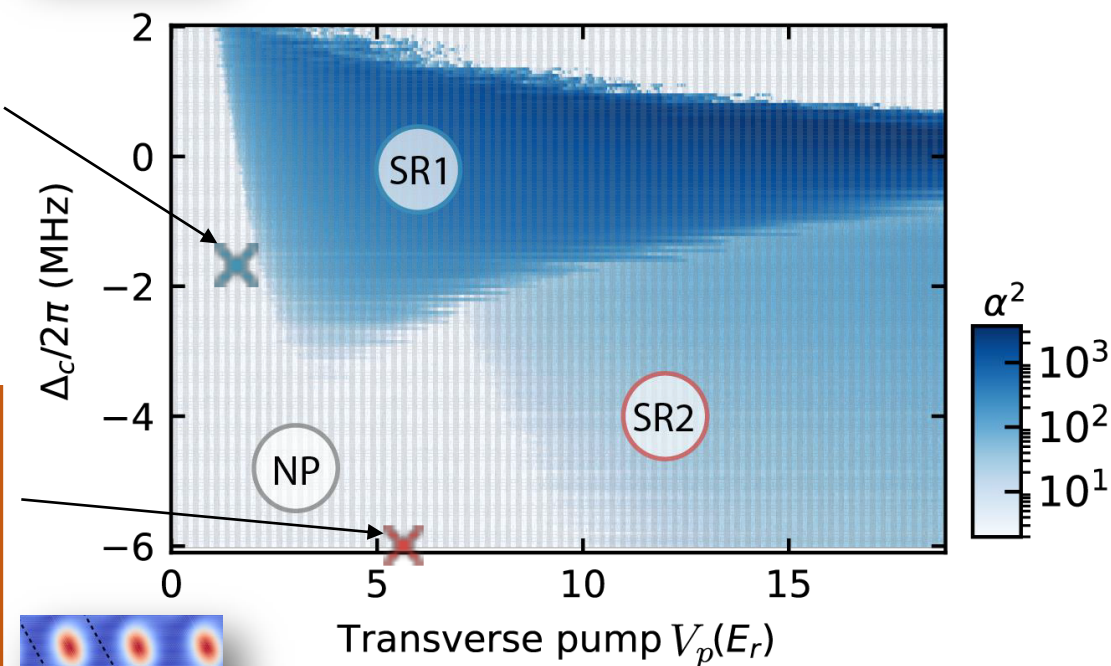
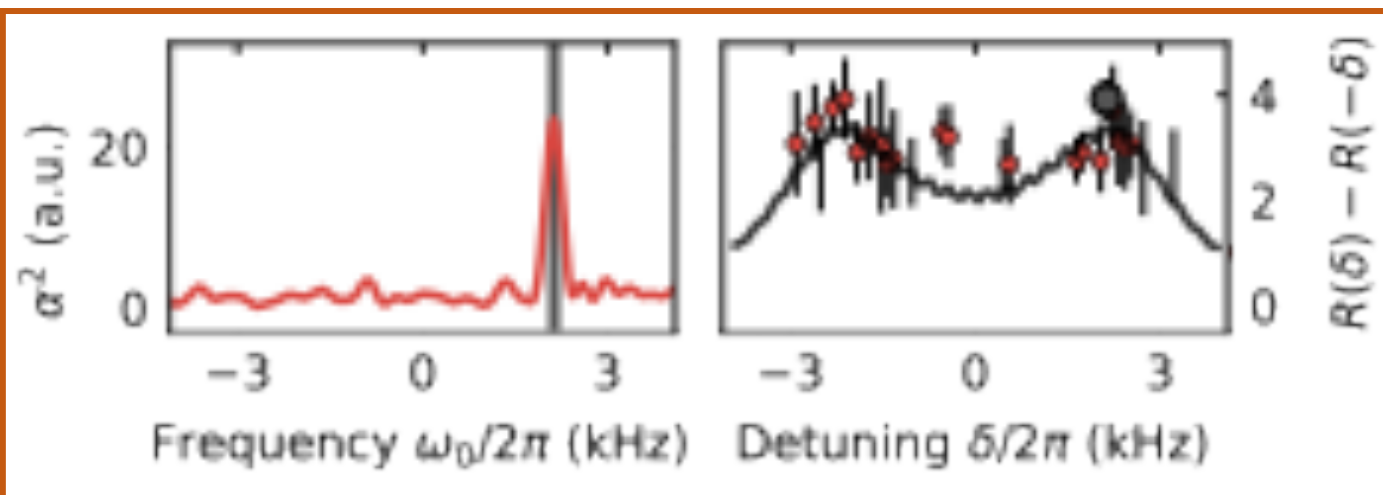
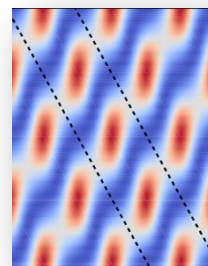
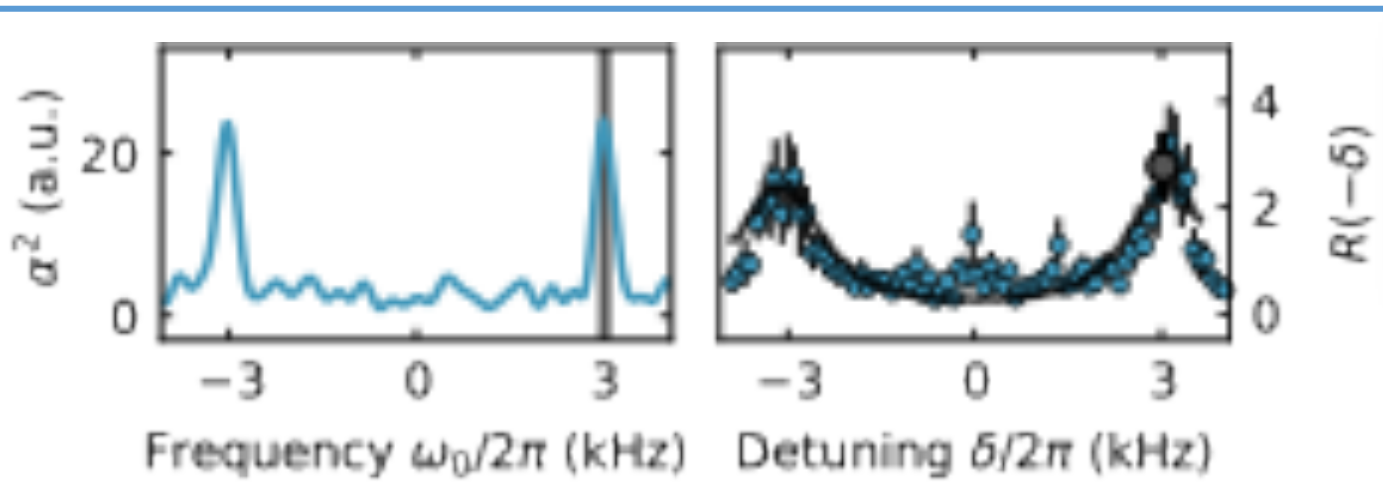
(from band structure analysis – without dissipation)



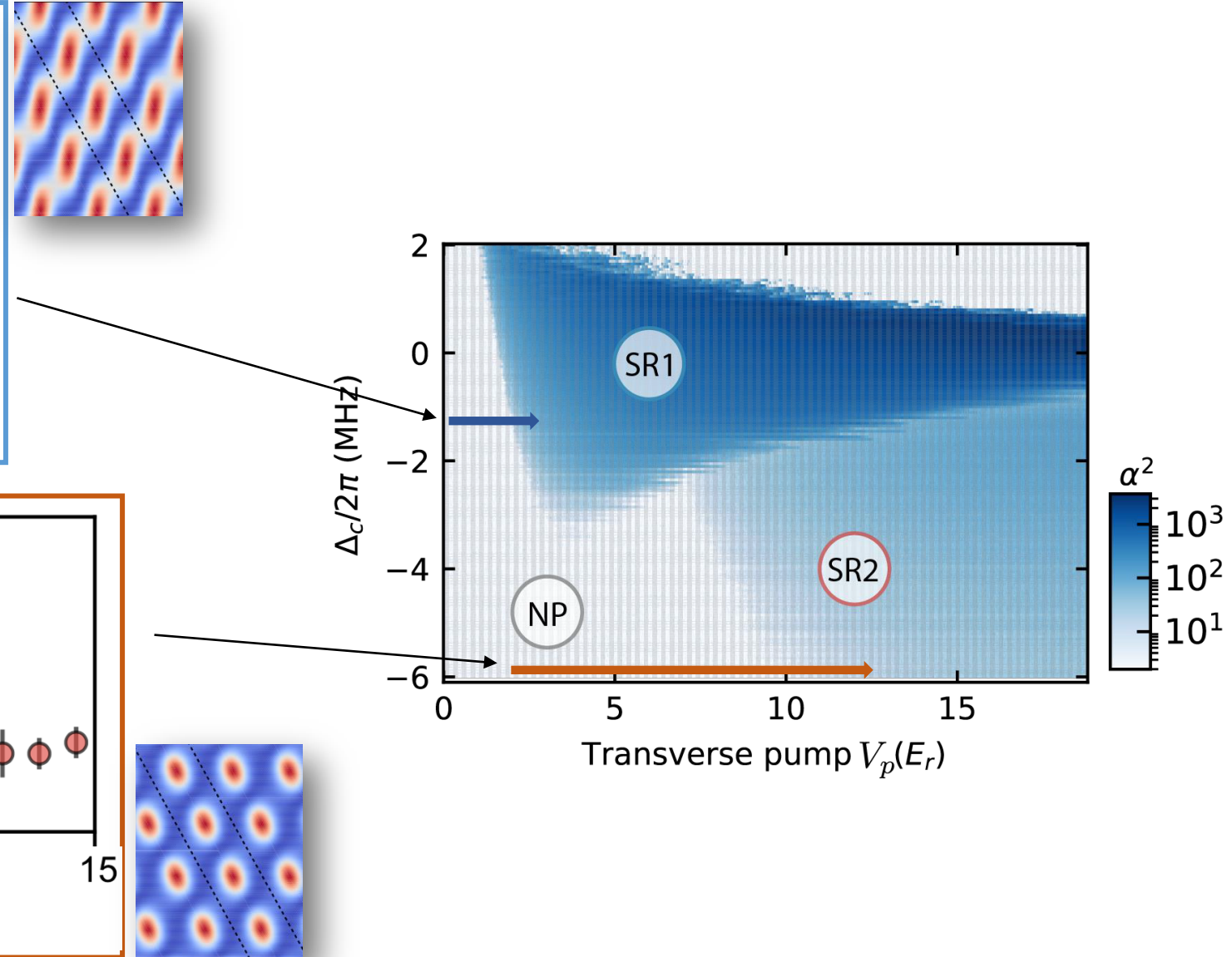
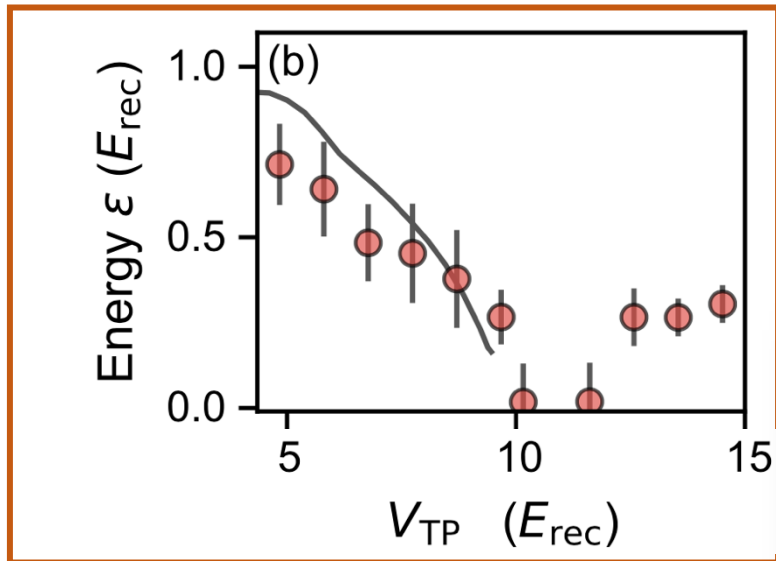
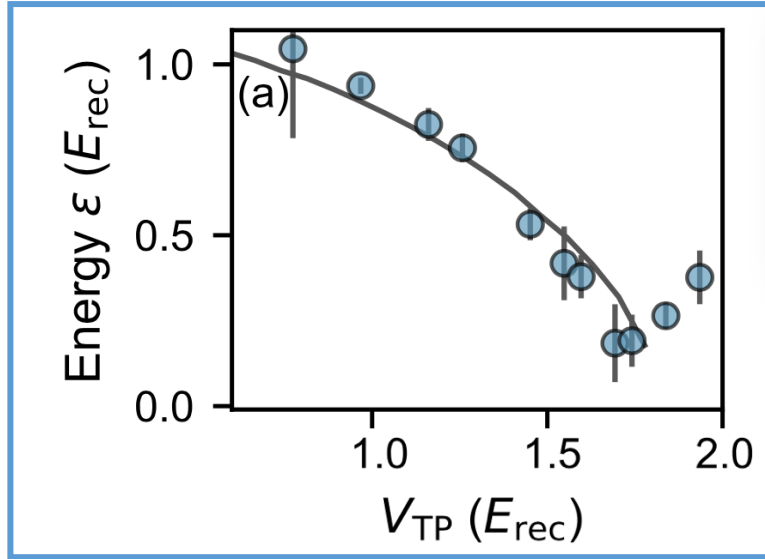
Cavity-enhanced Bragg spectroscopy



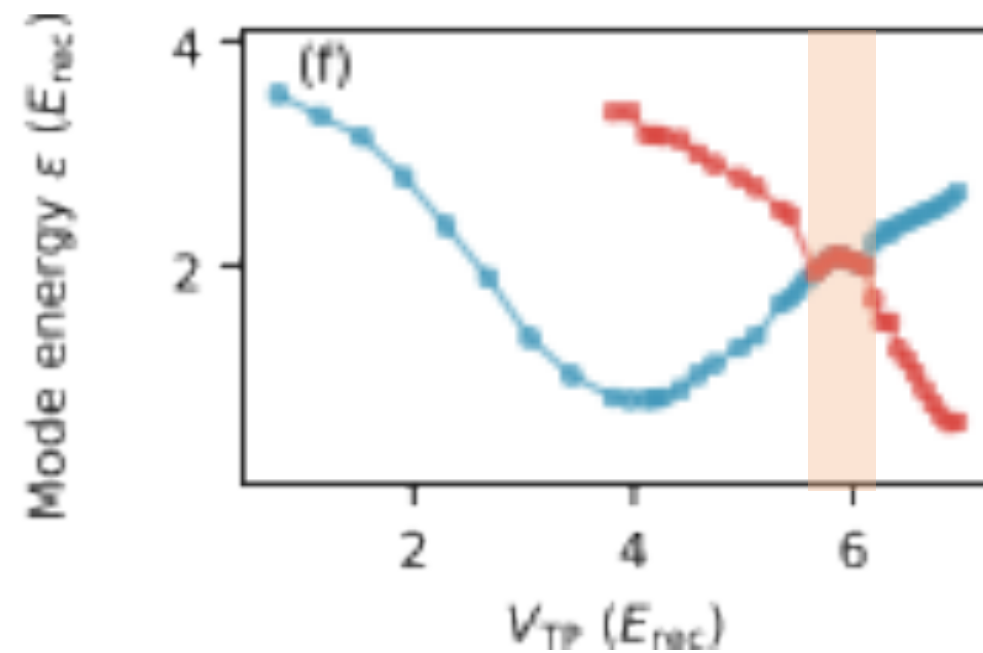
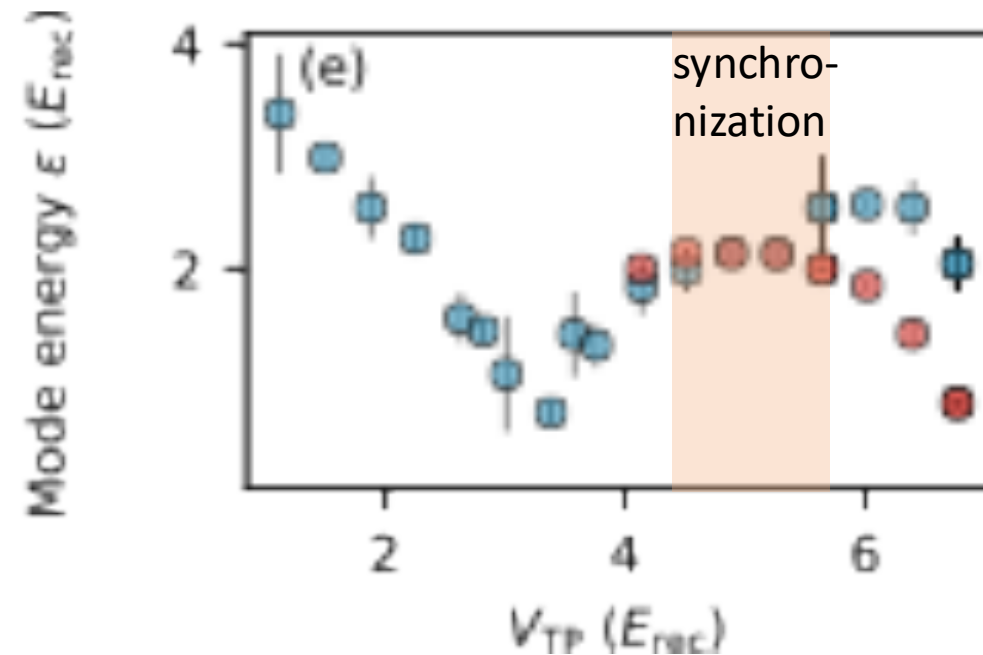
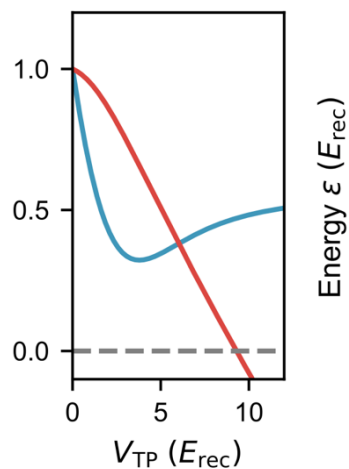
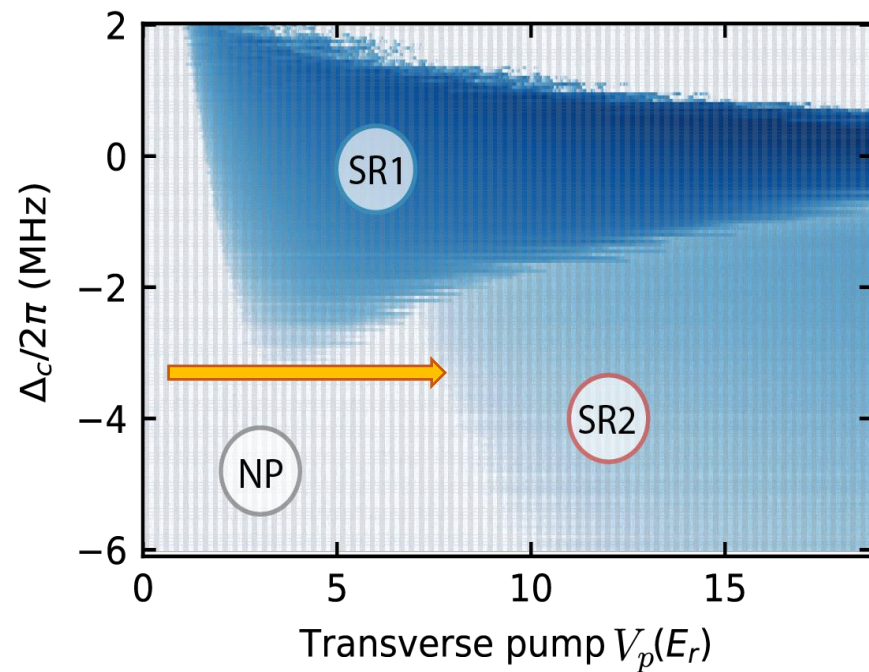
Probing and distinguishing the excitations



Measuring the mode softening

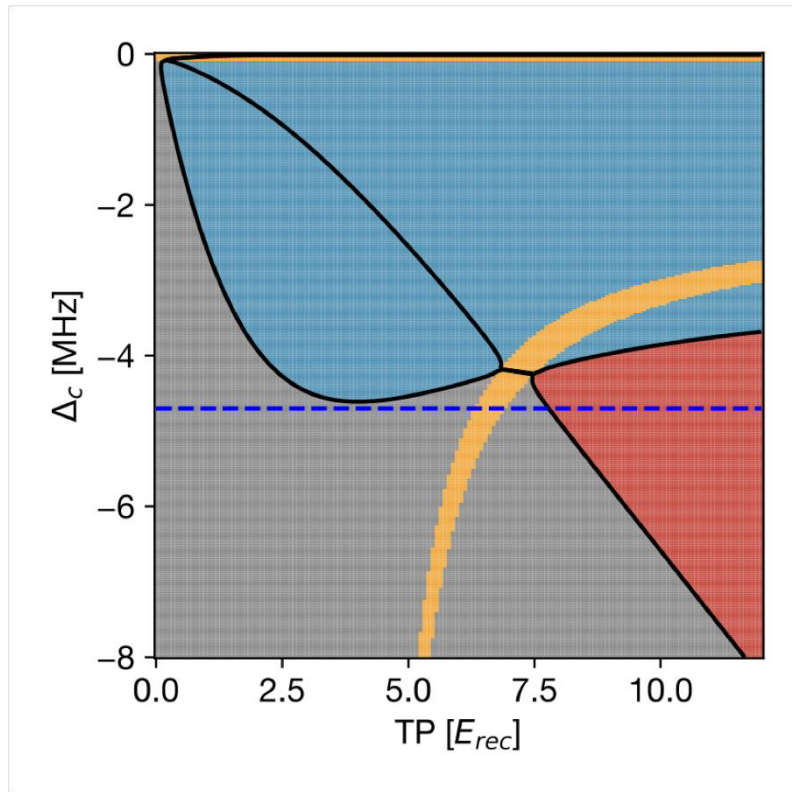


Mode synchronization



Mean-field phase diagram

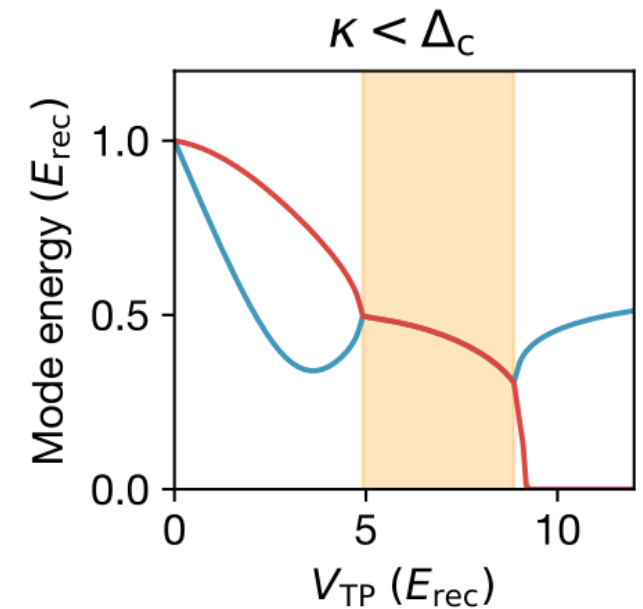
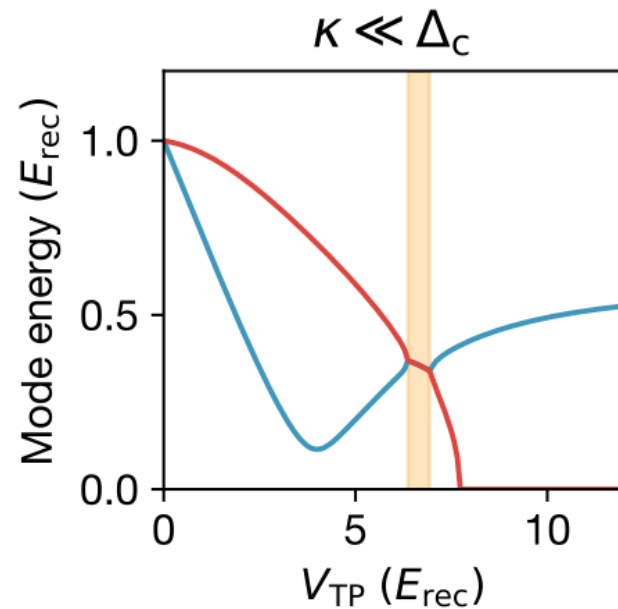
(from band structure analysis – **with** dissipation)



$$SR_1 \propto (\hat{a} + \hat{a}^\dagger)$$

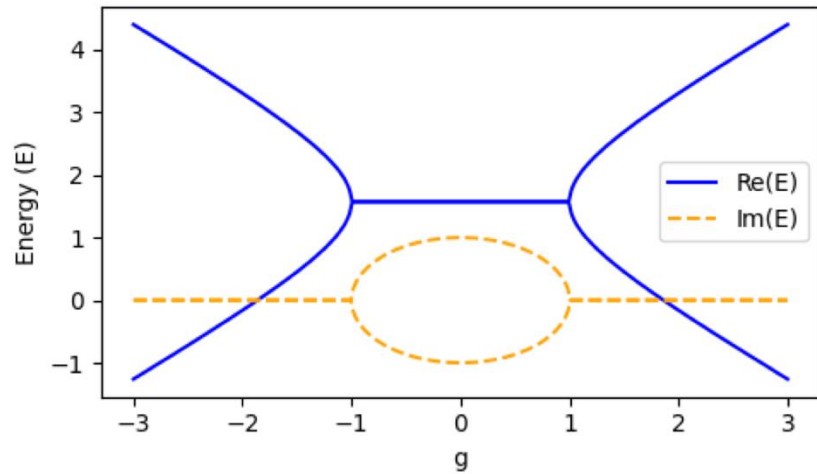
$$SR_2 \propto i(\hat{a} - \hat{a}^\dagger)$$

$$\dot{a} \propto -\kappa a$$

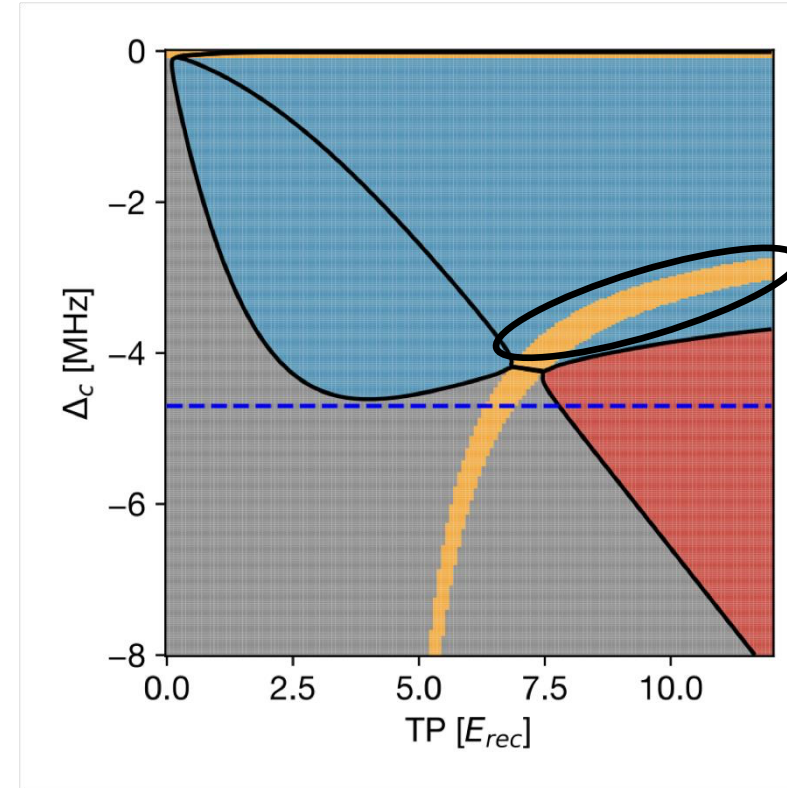


Synchronization of (critical) fluctuations

Instability to a limit cycle



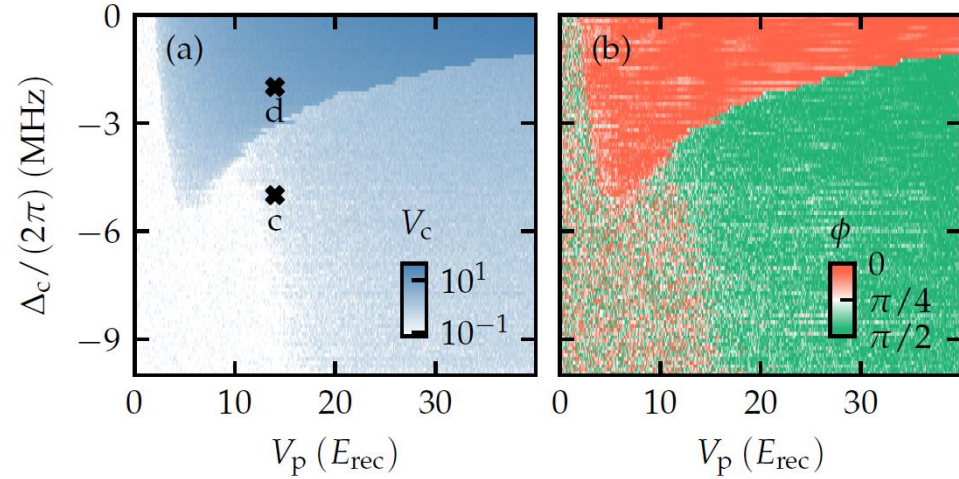
Imaginary part signals gain which can trigger an instability



Mode synchronization within the self-organized phase?!

Dissipation induced instability: $\Delta_c \simeq \kappa$

$$\Delta_c \gg \kappa$$

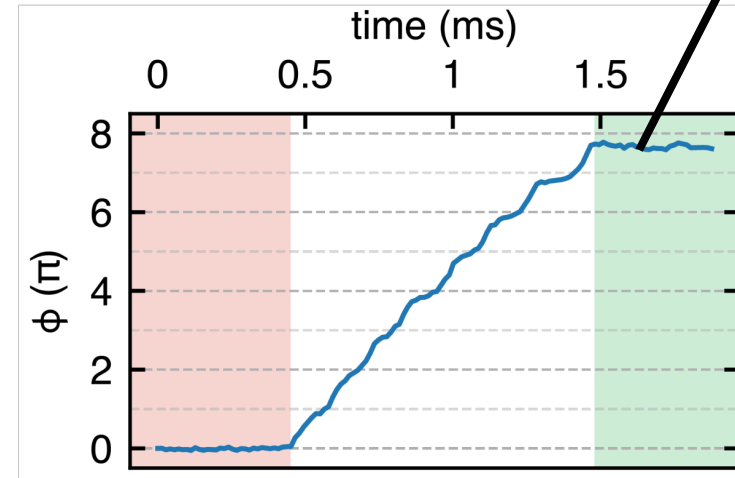
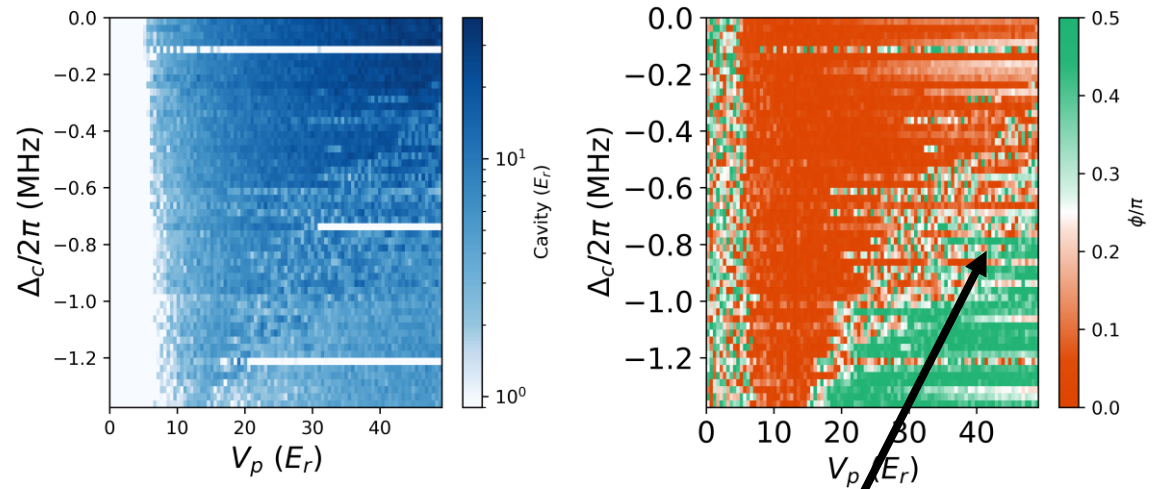


$$SR_1 \propto (\hat{a} + \hat{a}^\dagger)$$

$$SR_2 \propto i(\hat{a} - \hat{a}^\dagger)$$

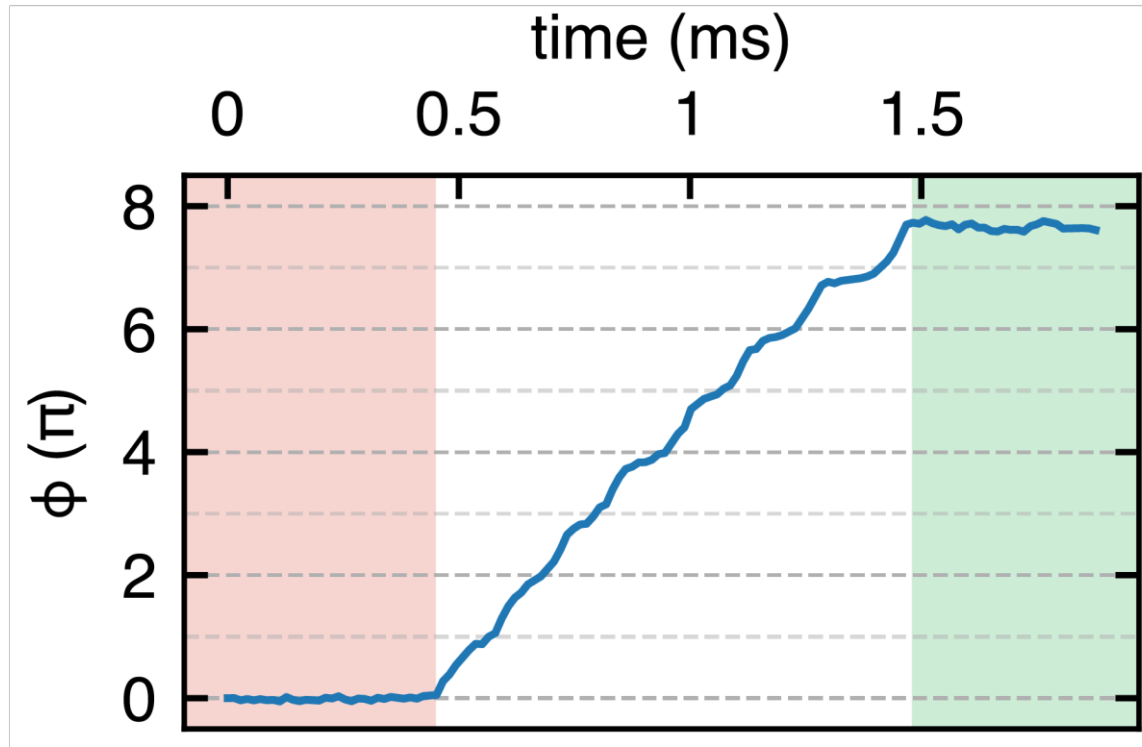
$$\dot{a} \propto -\kappa a$$

$$\Delta_c \simeq \kappa$$

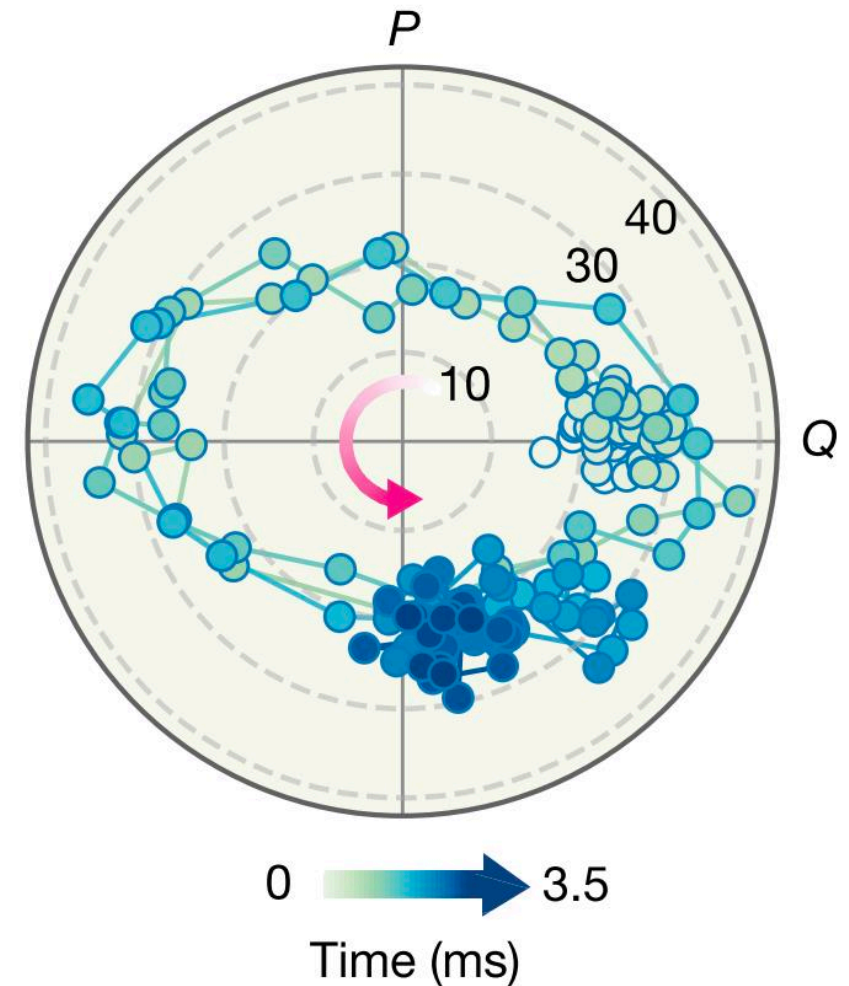


Dissipation-induced instability: chiral dynamics, limit cycle, time crystal, ...?

Phase of cavity field

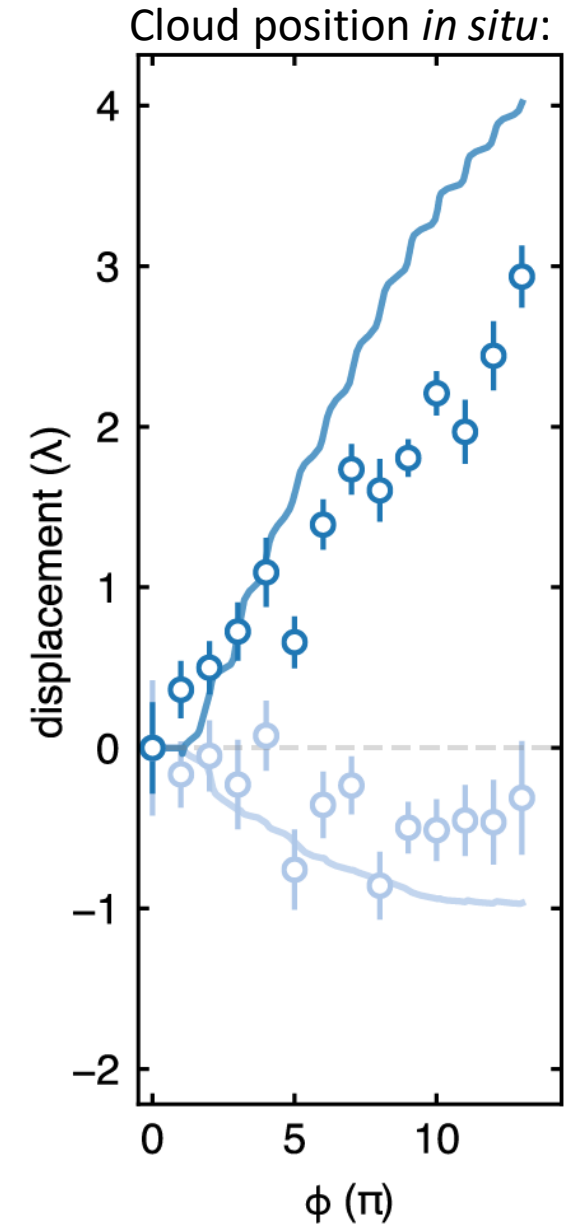
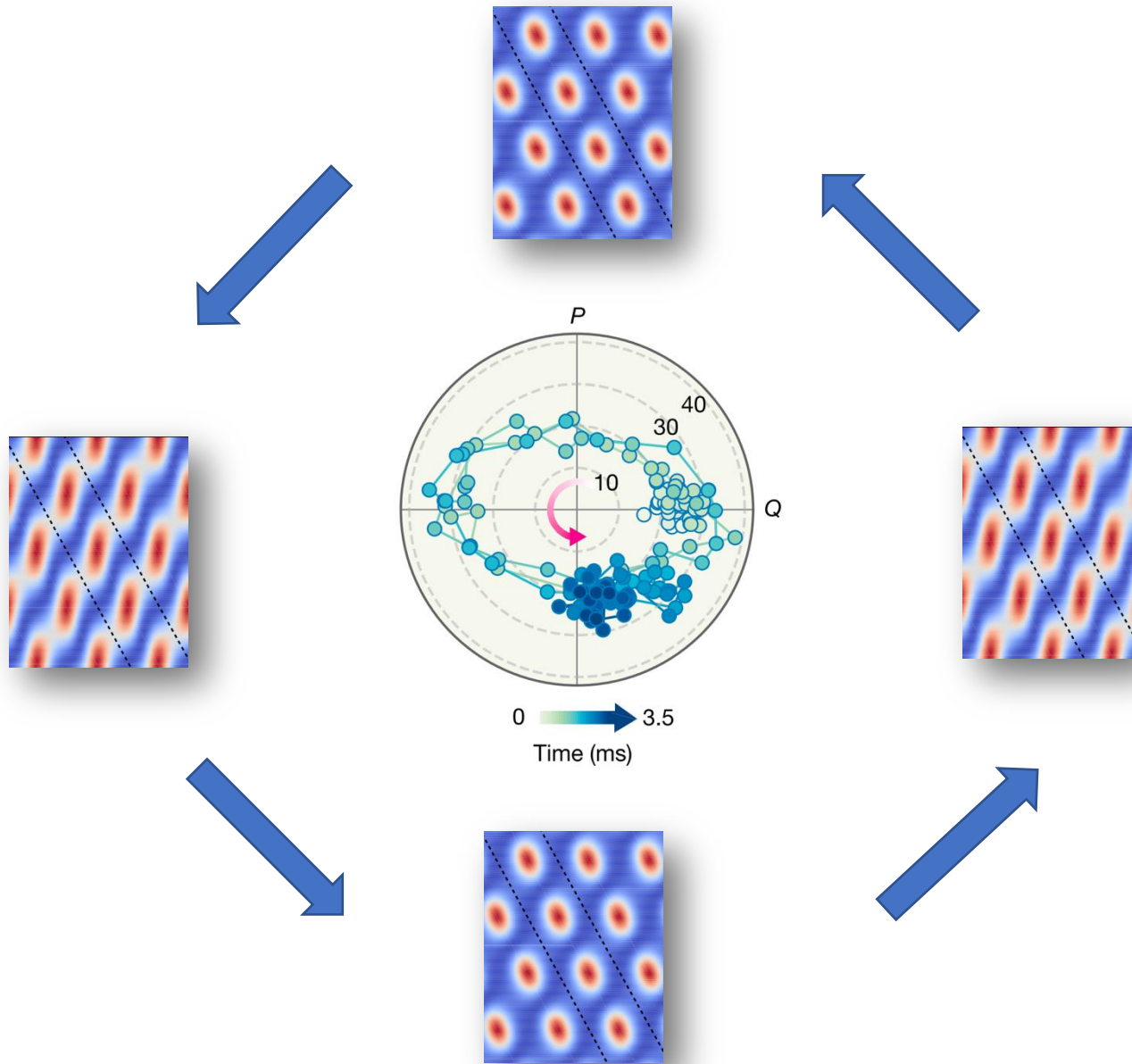


cavity field quadratures



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

Dissipation-induced geometrical atom pump

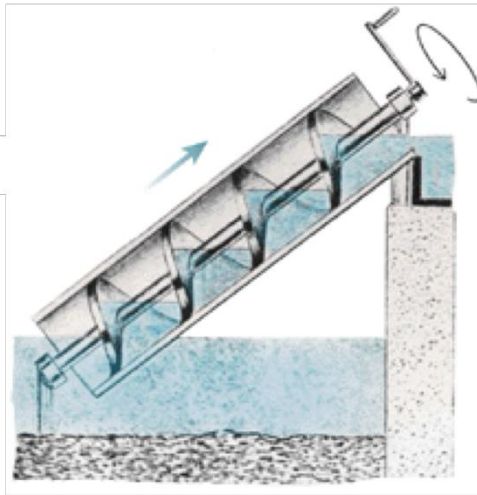


Adiabatic pumps

In general: a DC current follows a AC perturbation

Classical example

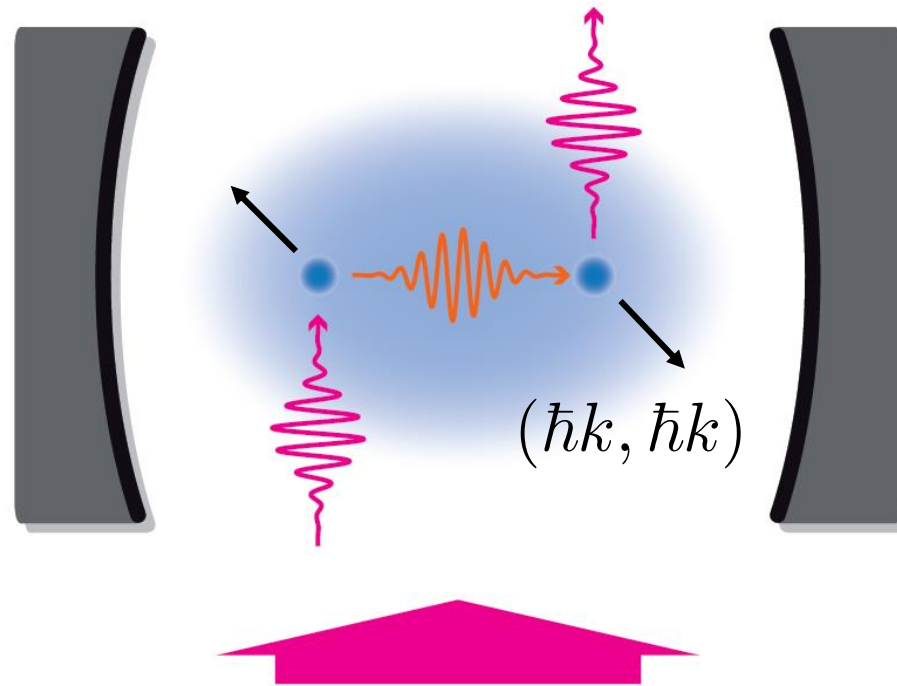
Archimedes' screw



from Science, 283, 1864-1865 (1999)

preliminary

Observation of correlated momentum pairs



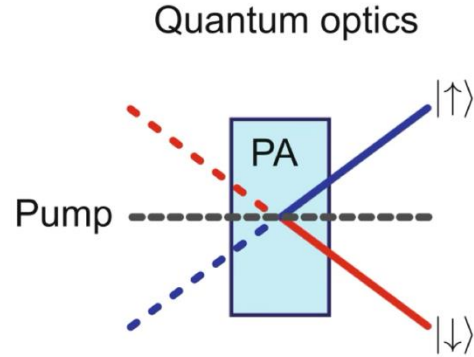
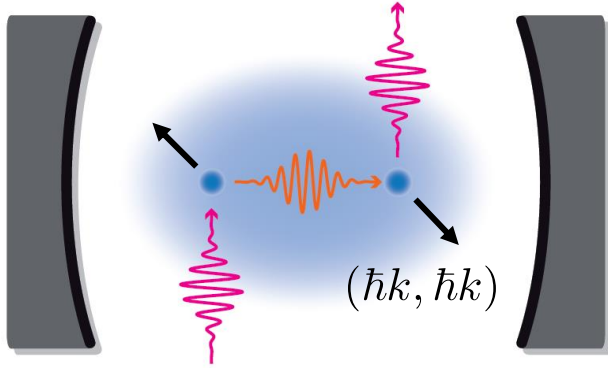
New regime

- Running wave pump
- Short pulses (μs)
- Far detuned from cavity

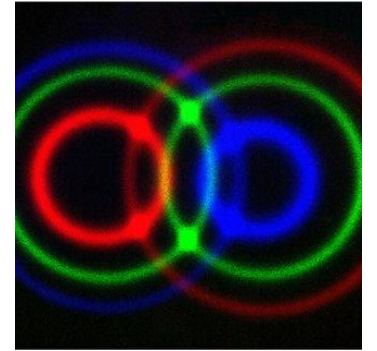
Forward scattered atoms $N_{\uparrow}$

Backward scattered atoms $N_{\downarrow}$

Analogy: spontaneous parametric down conversion

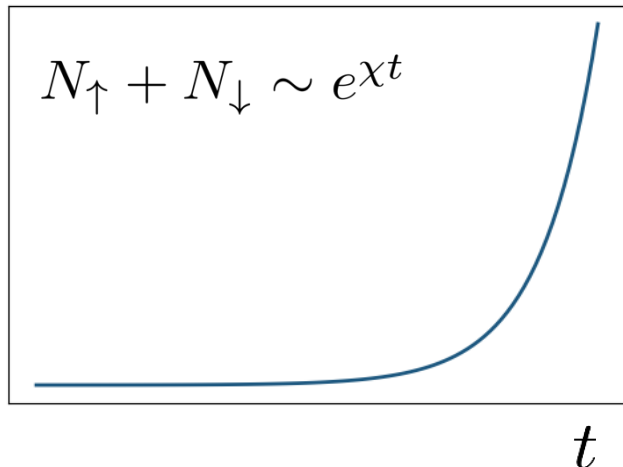


$$\hat{H} = \chi \left(\hat{c}_{\uparrow}^{\dagger} \hat{c}_{\downarrow}^{\dagger} + \hat{c}_{\uparrow} \hat{c}_{\downarrow} \right)$$

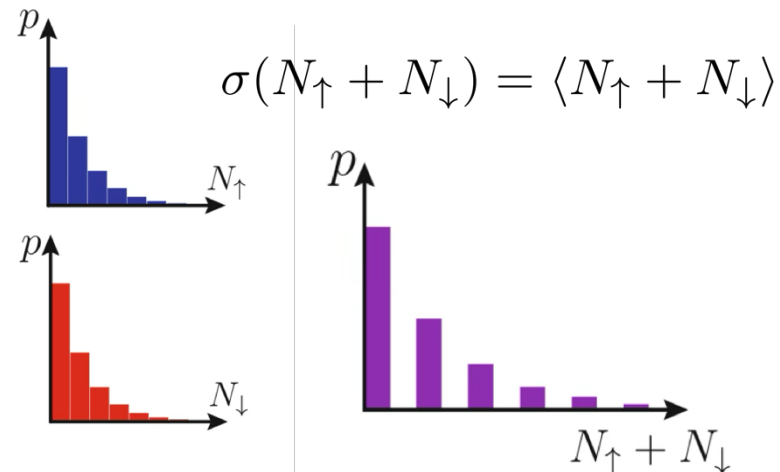


Process seeded by vacuum fluctuations:

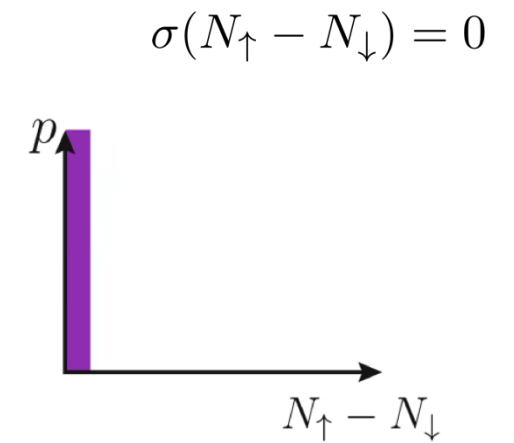
Exponential dynamics



Bose-Einstein statistics

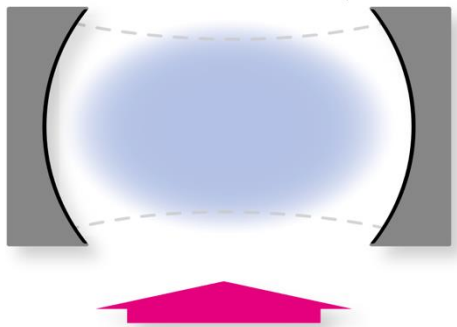


Squeezing

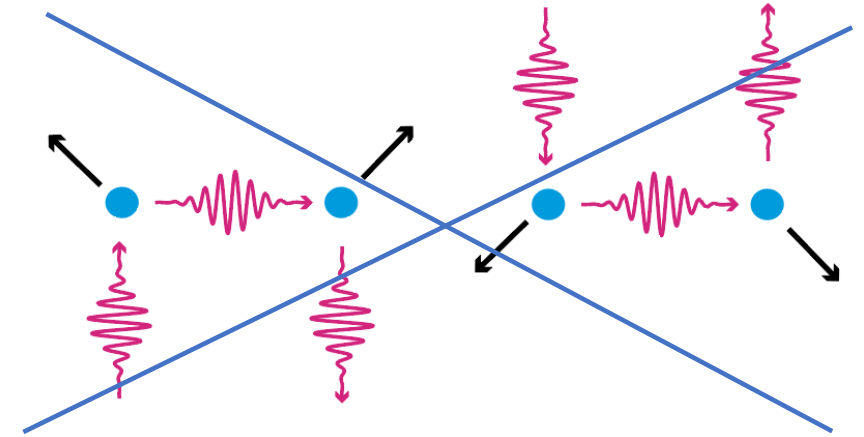
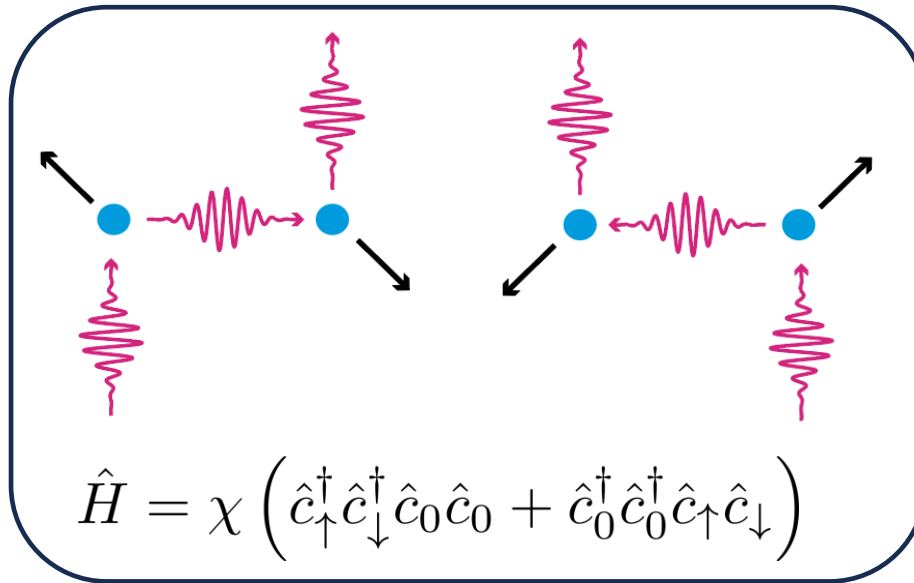


preliminary

Microscopic processes



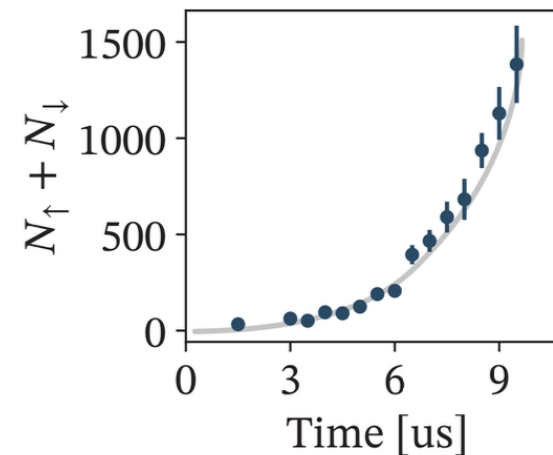
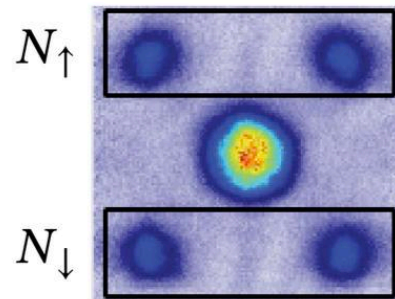
Running wave



(Standing wave processes)

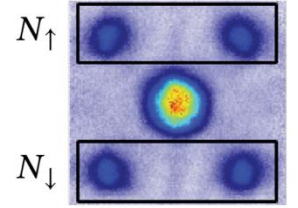
Forward scattered atoms

Backward scattered atoms

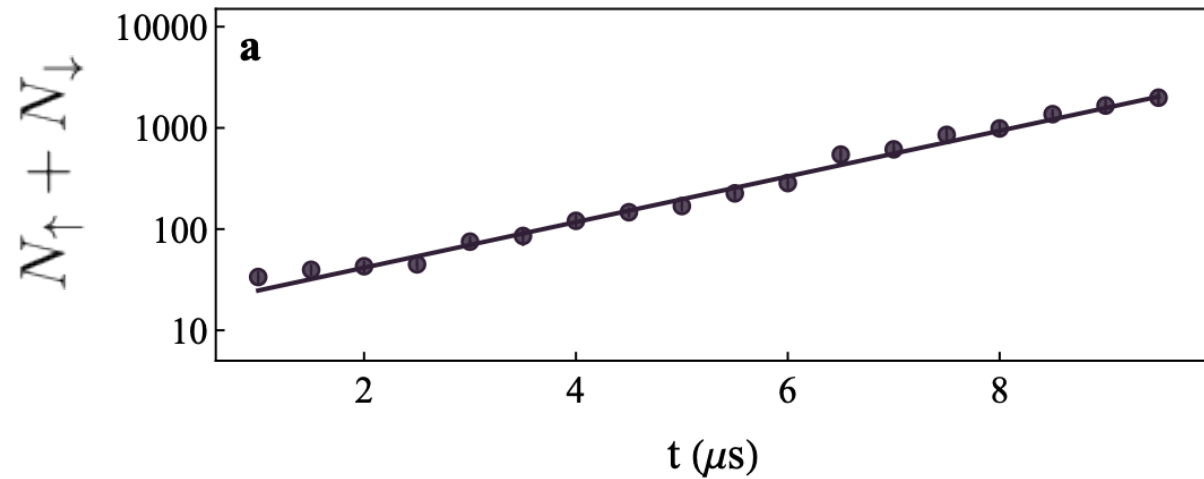


preliminary

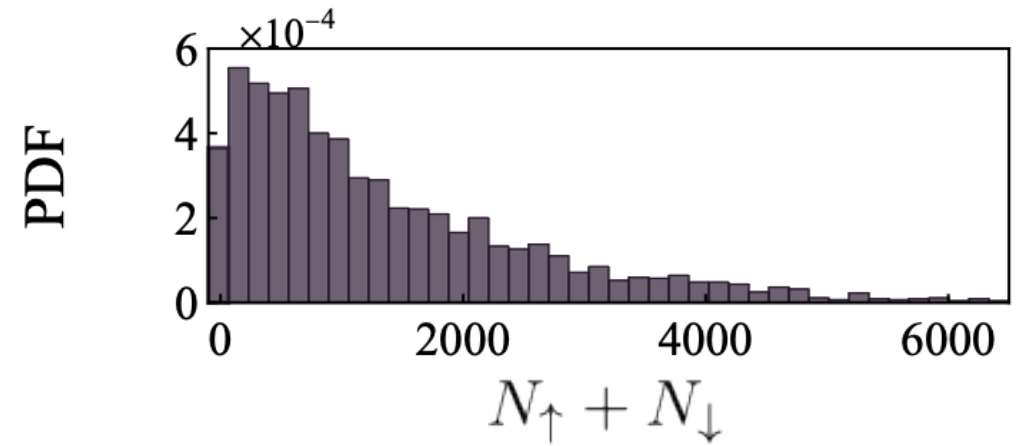
Pair creation characteristics



Exponential growth of atom pair number



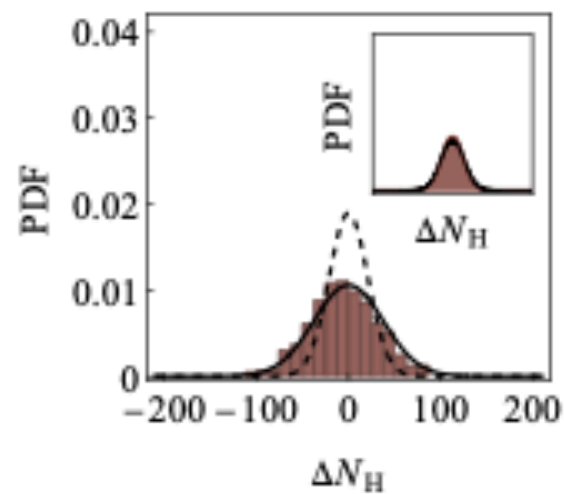
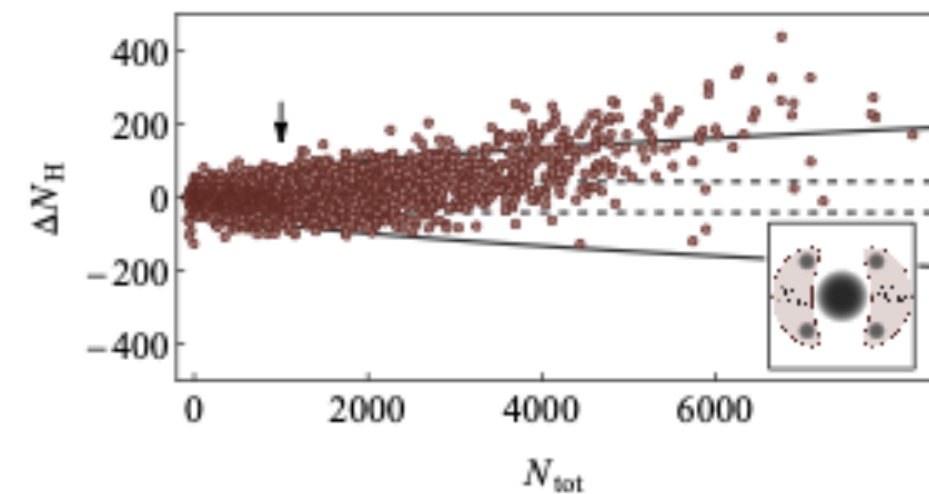
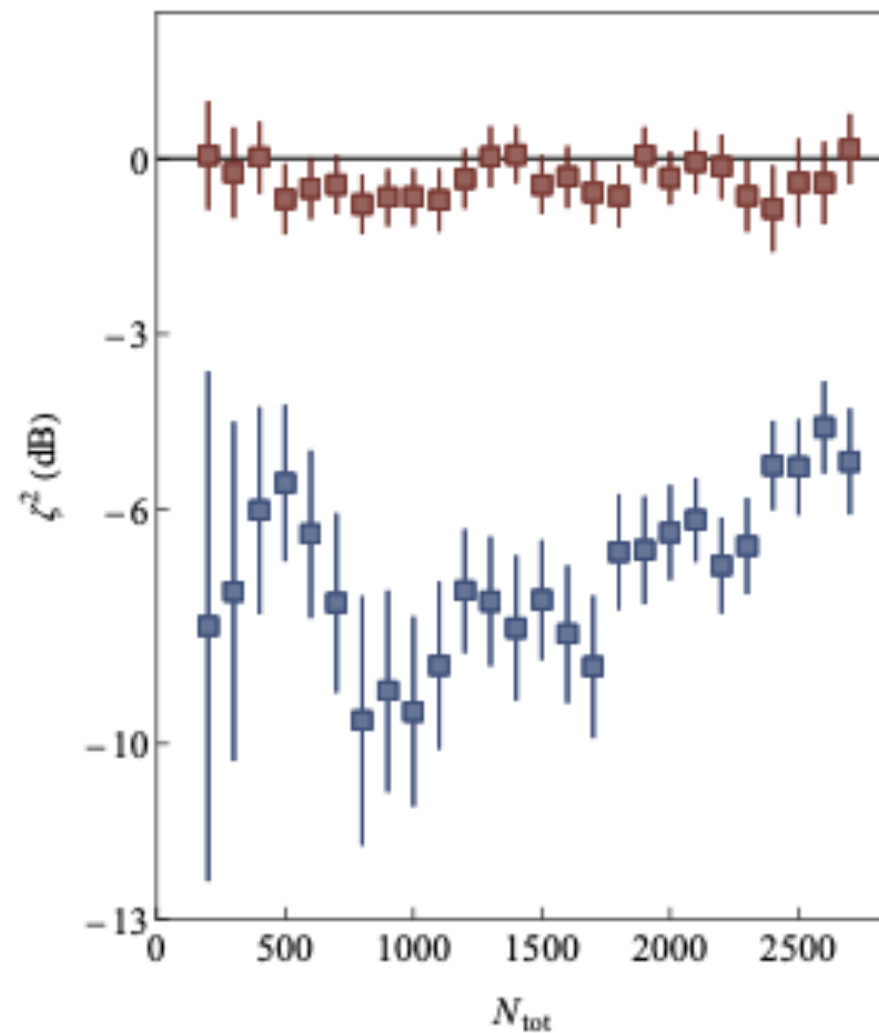
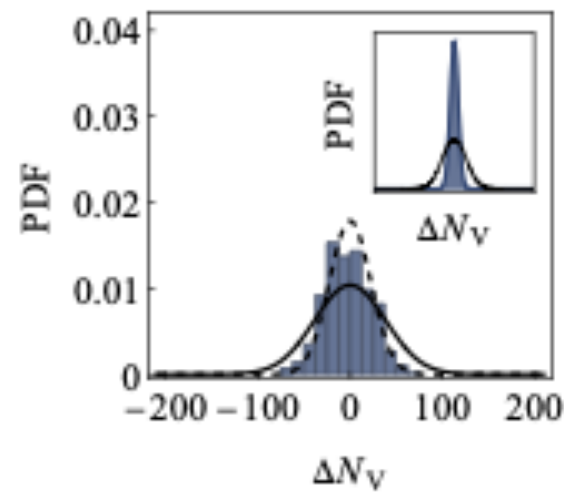
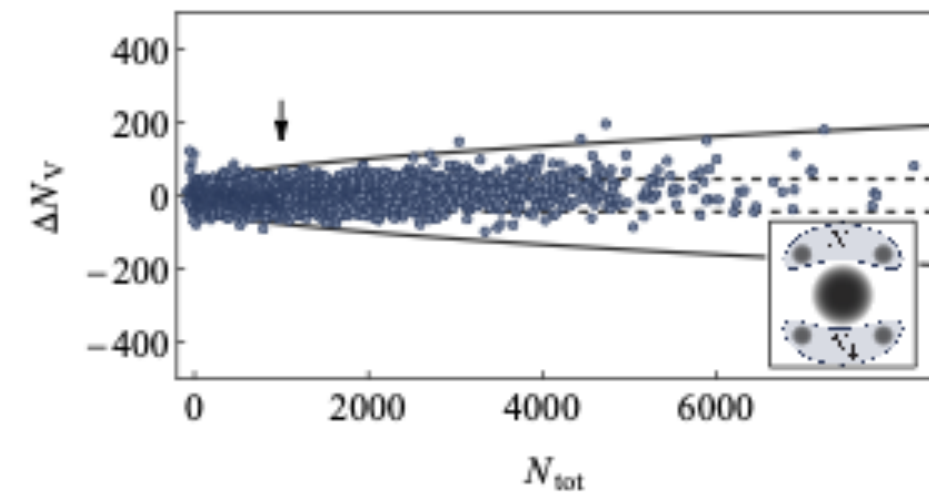
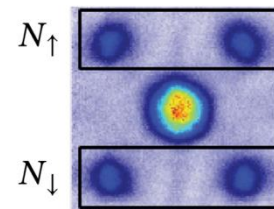
Bose-Einstein statistics



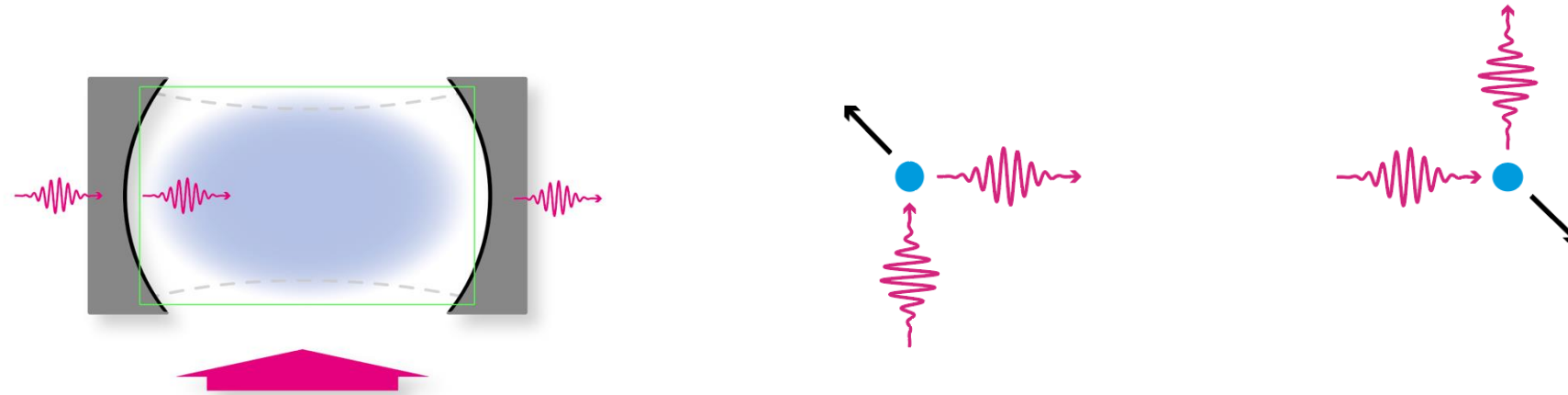
$$\sigma(N_{\uparrow} + N_{\downarrow}) \approx \langle N_{\uparrow} + N_{\downarrow} \rangle$$

preliminary

Squeezing of number difference



Role of cavity occupation / cavity dissipation



Cavity dissipation / finite cavity population destroy correlations in momentum modes

$$\hat{H} = \hbar (\omega + \chi) \left[\hat{c}_{\uparrow}^{\dagger} \hat{c}_{\uparrow} + \hat{c}_{\downarrow}^{\dagger} \hat{c}_{\downarrow} \right] + \hbar \chi \left[\hat{c}_{\uparrow}^{\dagger} \hat{c}_{\downarrow}^{\dagger} + \hat{c}_{\uparrow} \hat{c}_{\downarrow} \right]$$

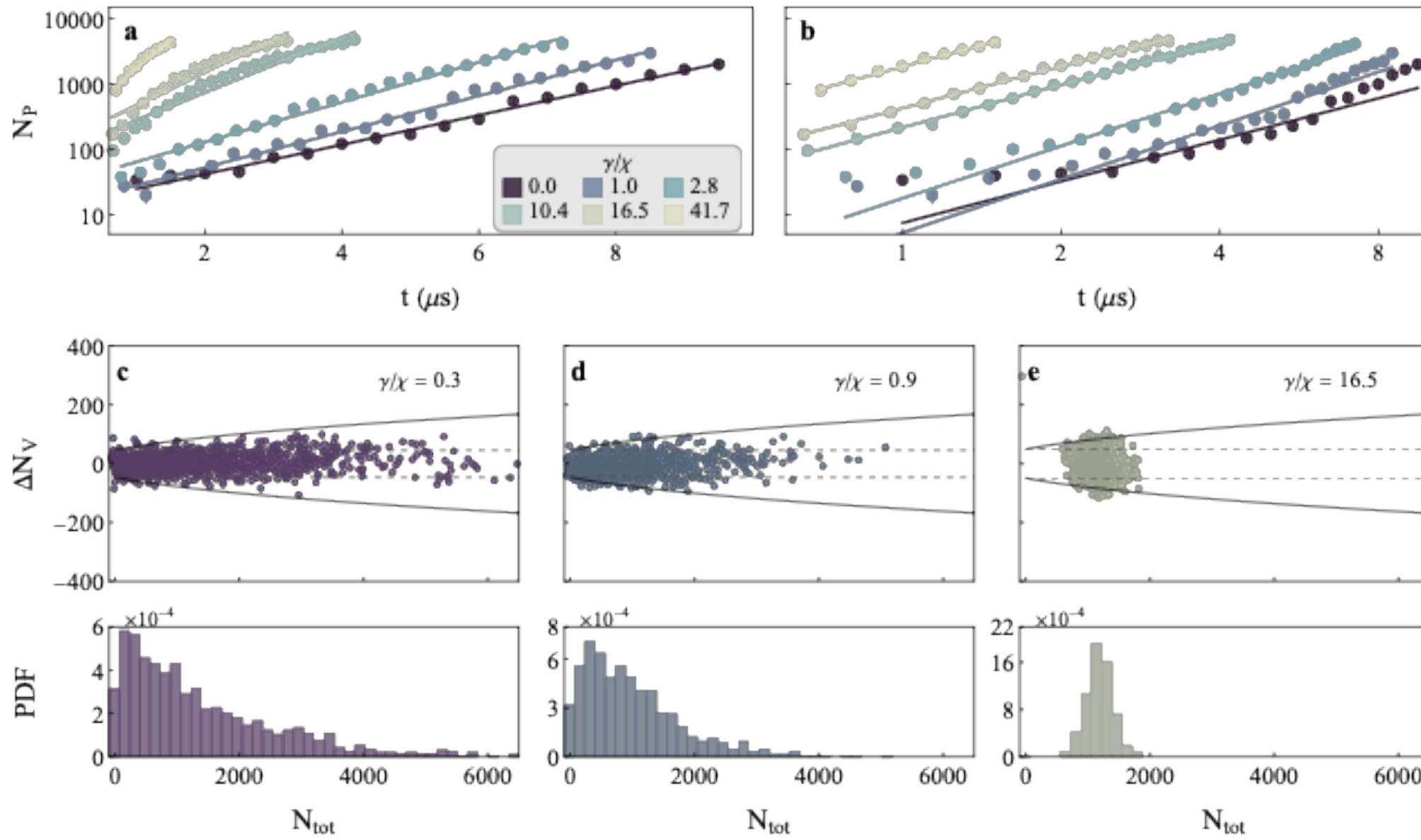
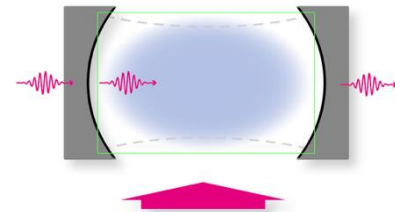
vacuum only

$$+ \hbar \chi \left[\frac{\gamma}{\eta \sqrt{N}} \left(\hat{c}_{\uparrow} + \hat{c}_{\downarrow}^{\dagger} \right) + \frac{\gamma^*}{\eta \sqrt{N}} \left(\hat{c}_{\uparrow}^{\dagger} + \hat{c}_{\downarrow} \right) \right]$$

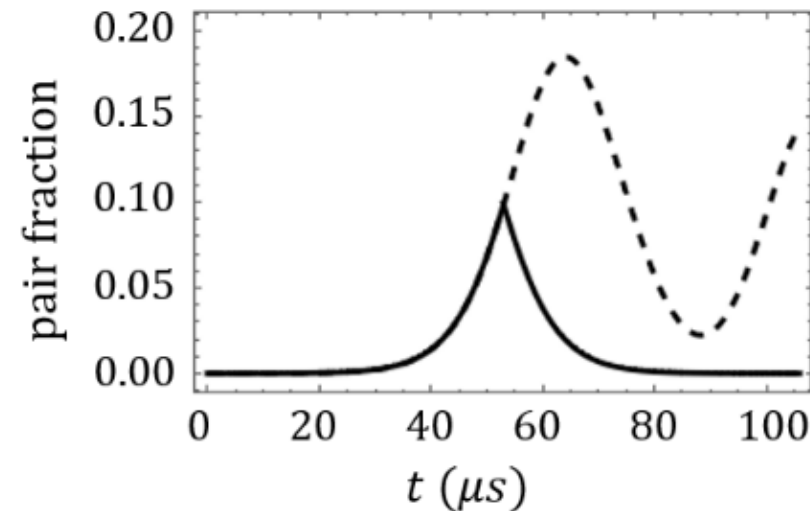
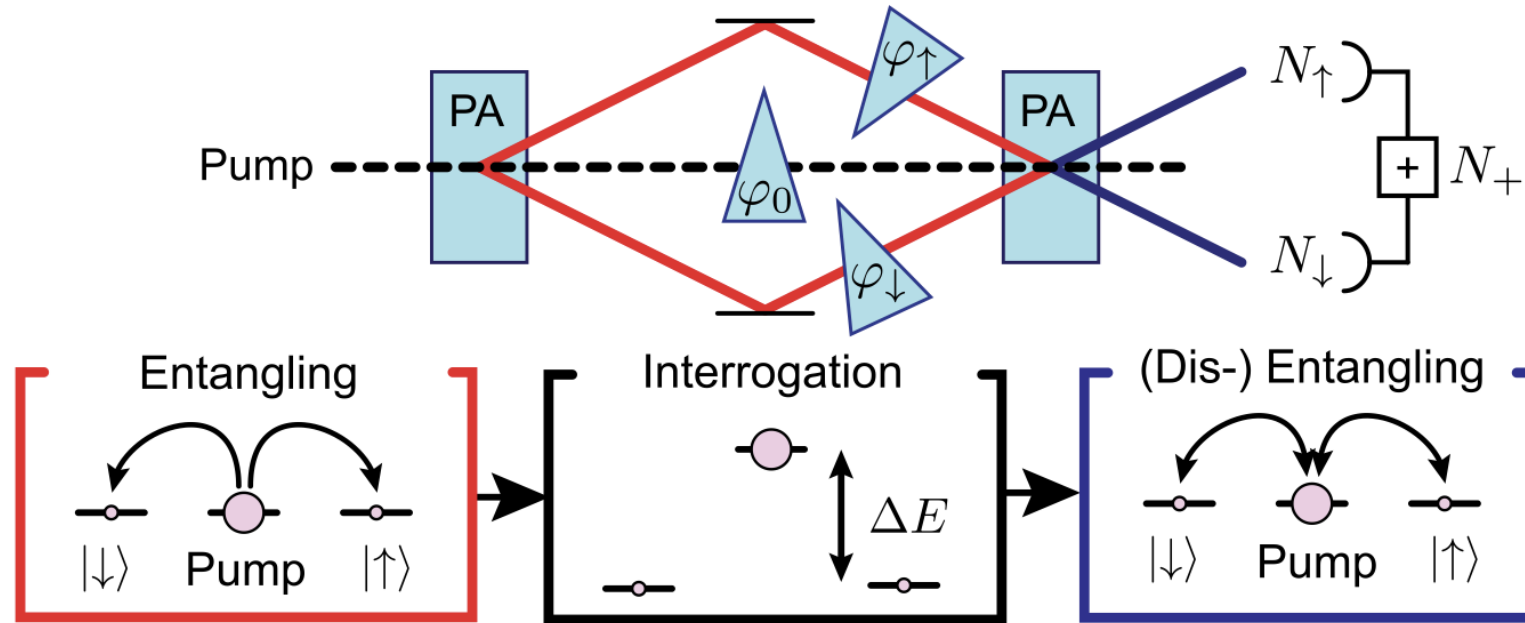
including seed

preliminary

Seeded cavity

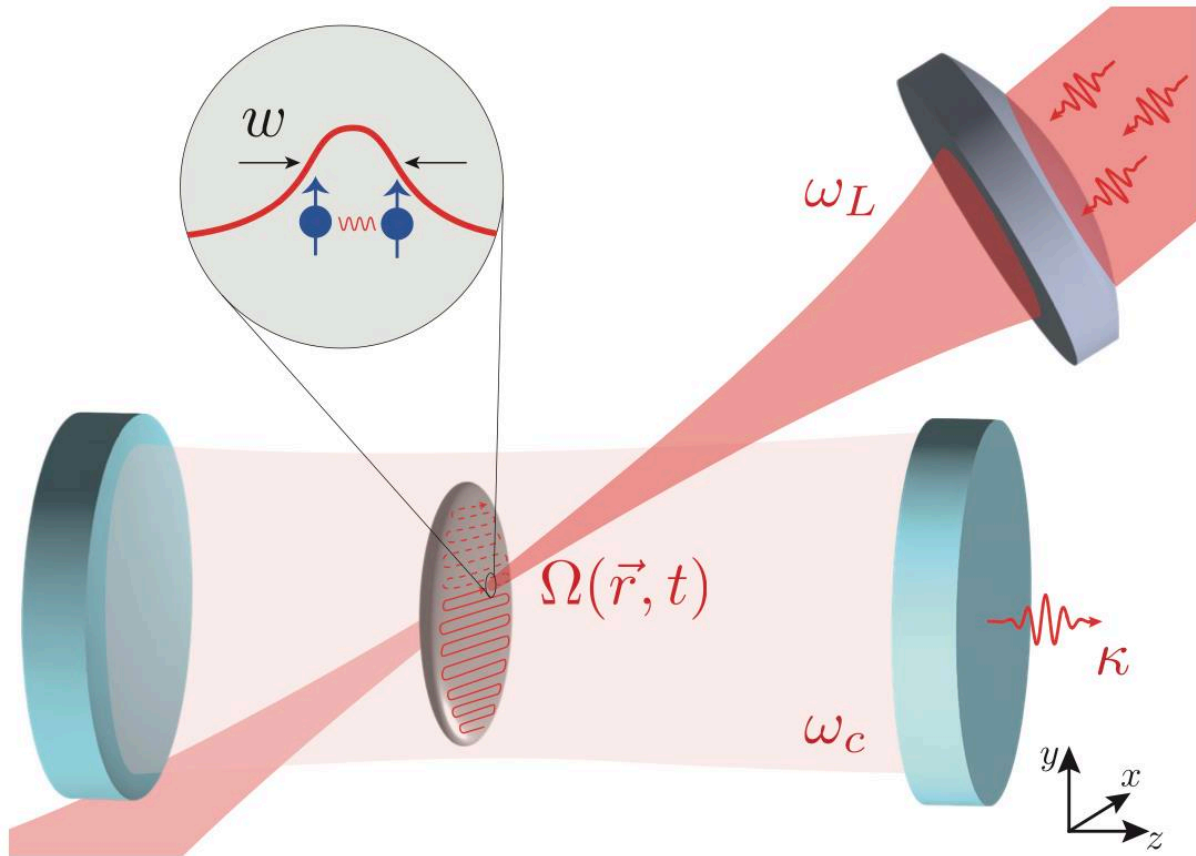


Active atom interferometer SU(1,1)



Yurke, B., McCall, S., Klauder, J.
Phys. Rev. A **33**, 4033 (1986)
 Linnemann, D, et al.,
Phys. Rev. Lett. 117, 013001 (2016)

Painted interactions in cavity QED

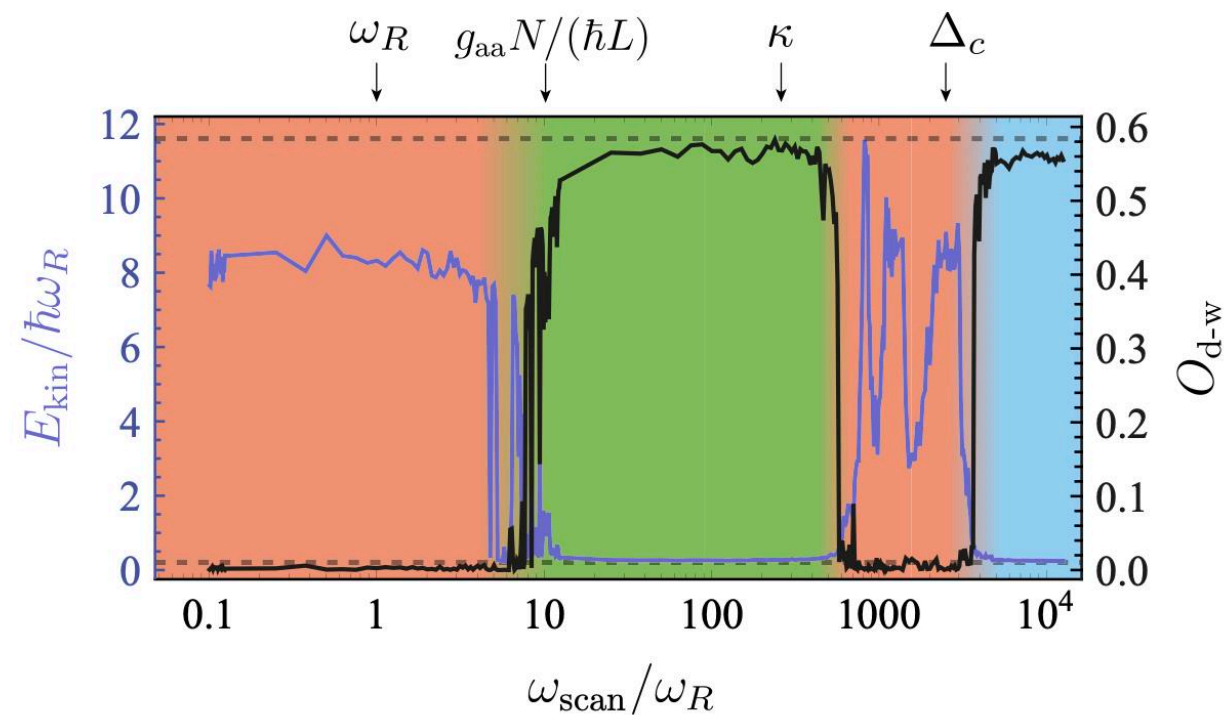
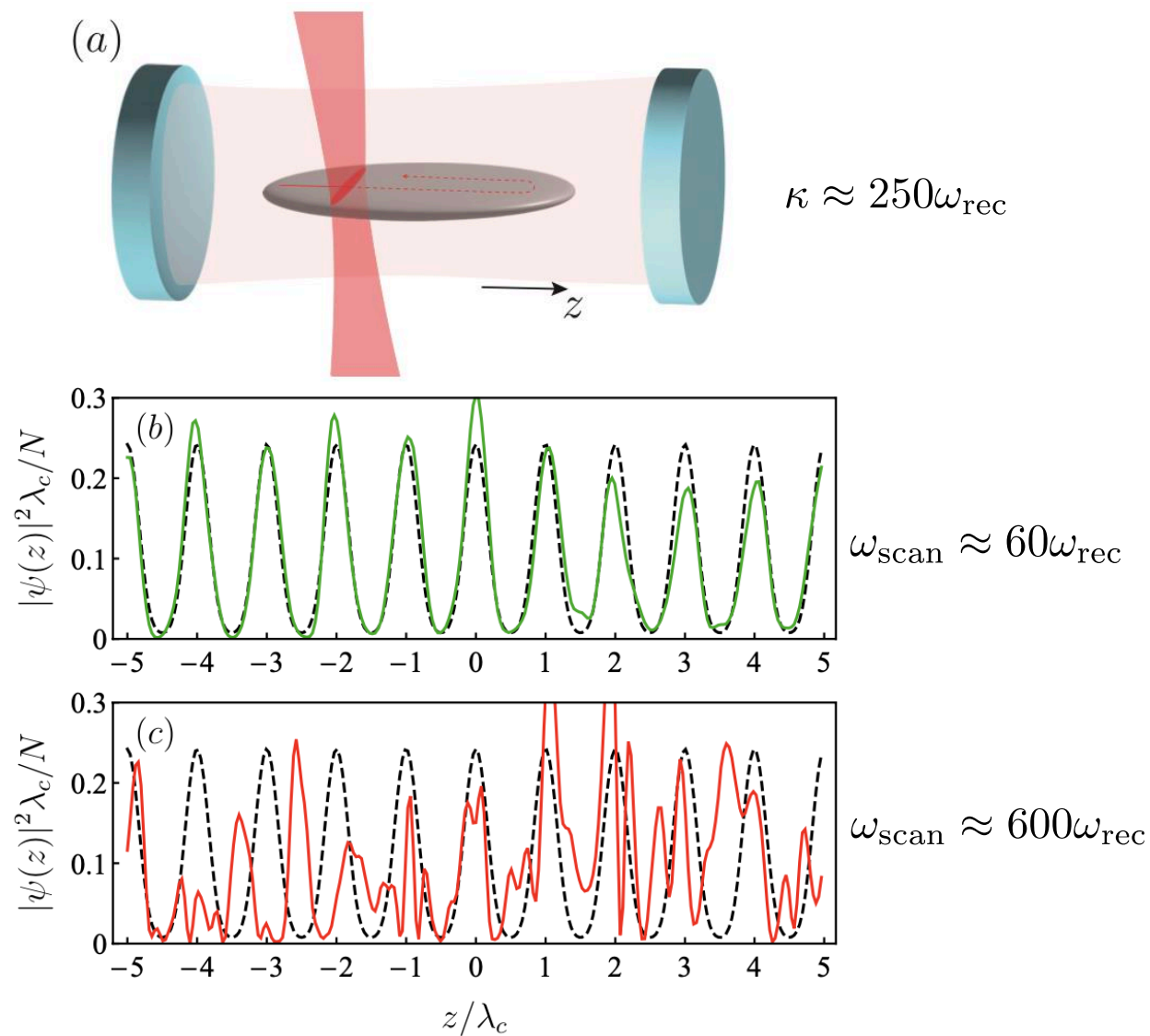


$$V(\vec{r}, \vec{r}') = \frac{2\Delta_c g_0^2}{\Delta_a^2(\kappa^2 + \Delta_c^2)} \overline{\Omega(\vec{r}, t)\Omega(\vec{r}', t)}$$

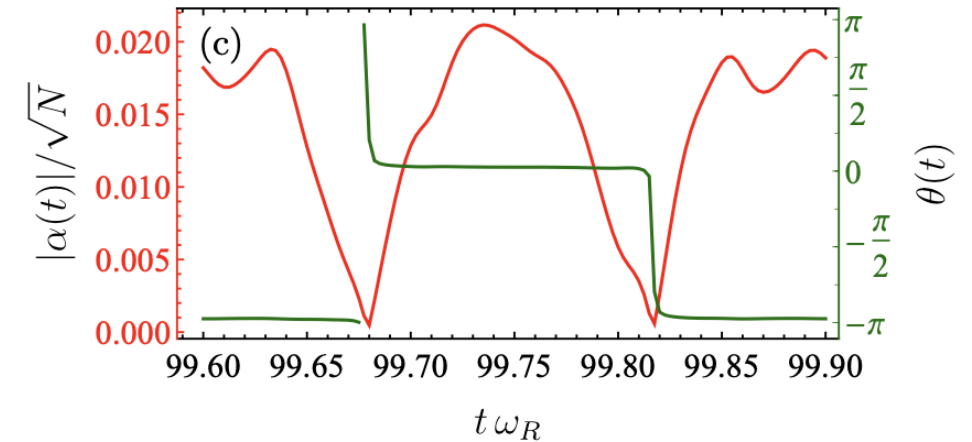
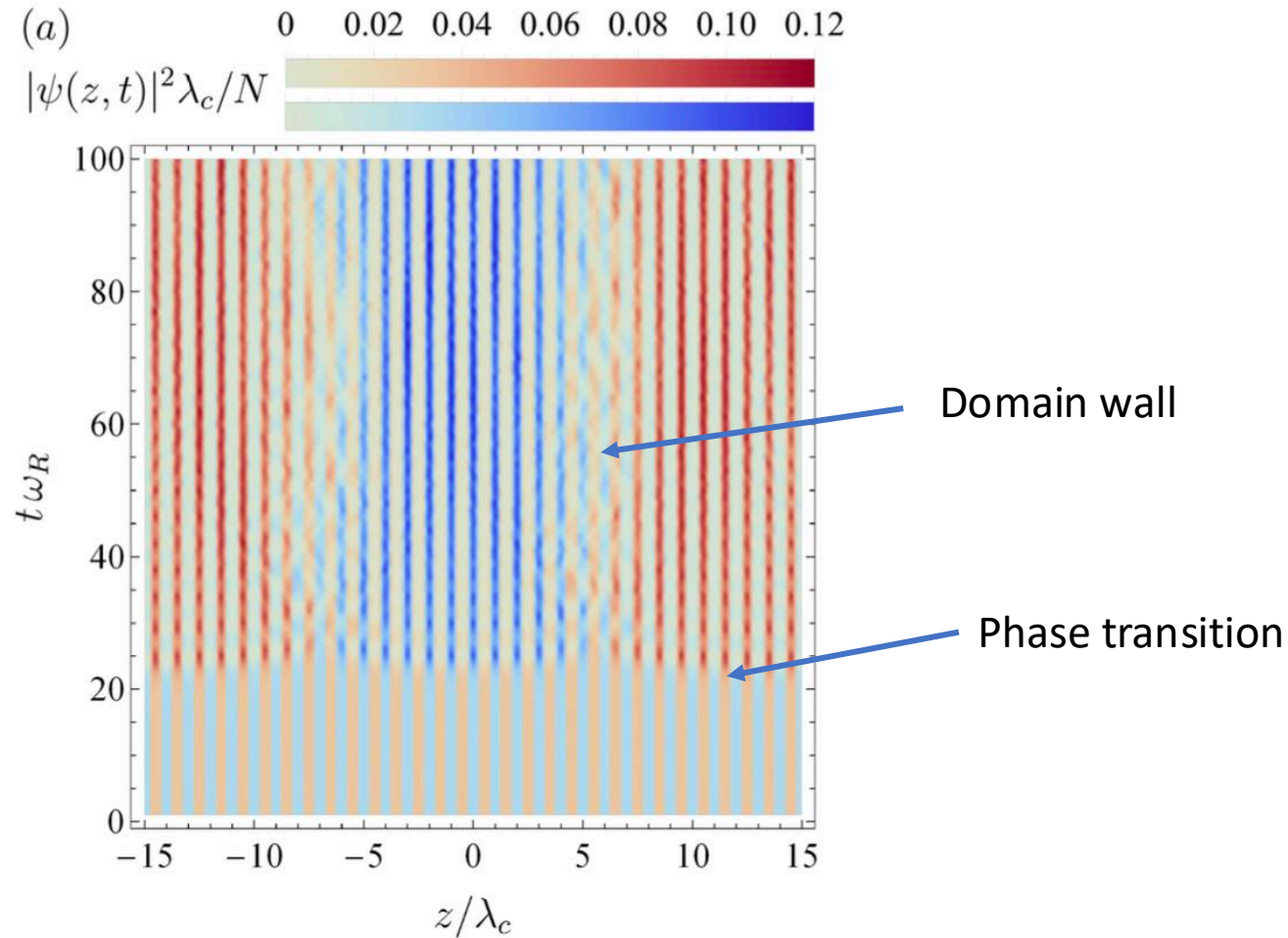
$$\hat{V}(\vec{k}) = \frac{2\Delta_c g_0^2}{\Delta_a^2(\kappa^2 + \Delta_c^2)} \frac{1}{L^2} \hat{\Omega}(\vec{k})^2$$

$$\omega_{\text{rec}} \ll \omega_{\text{scan}} \ll \kappa$$

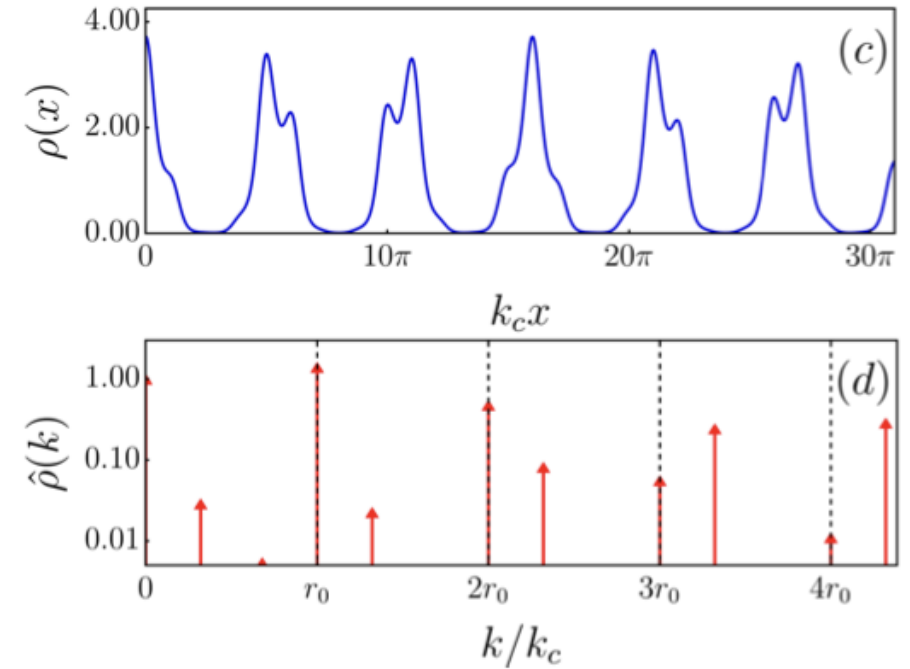
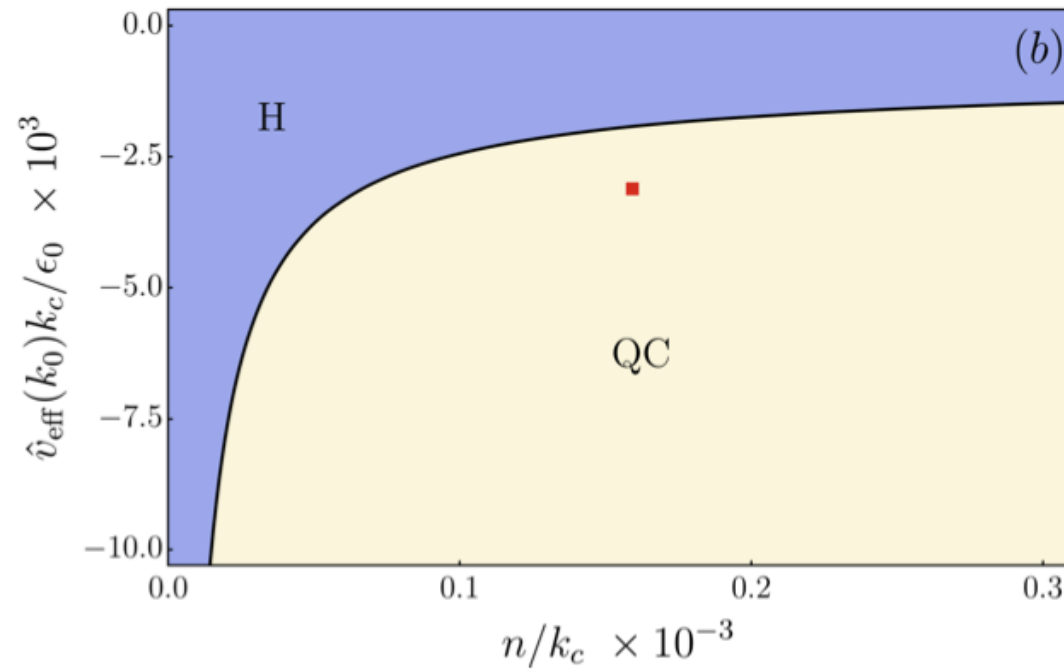
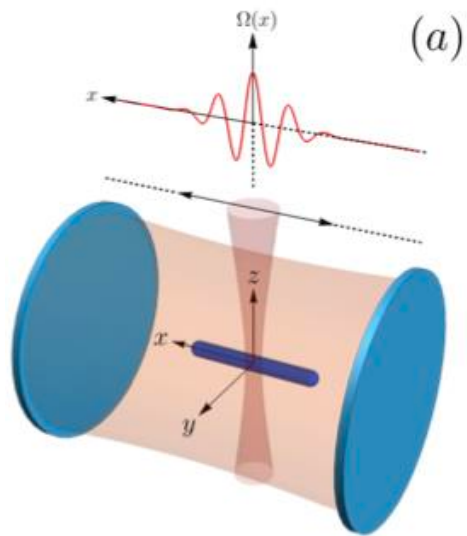
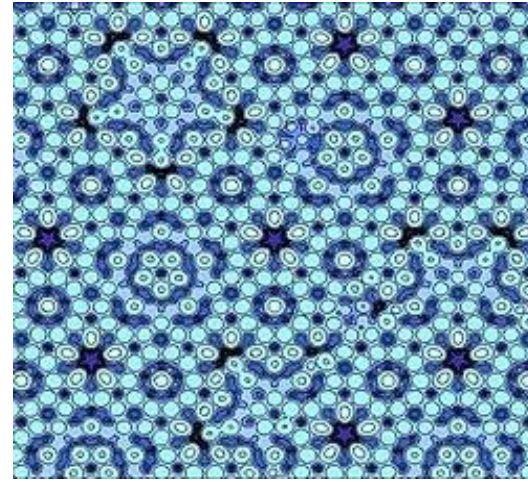
Painted interactions in cavity QED



Painted interactions in cavity QED



Quasi crystallization



The Teams



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Fabian Weis, **Tobias Donner**, **Gabriele Natale**, Simon Hertlein,
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\$\$\$: ERC financed by SERI, QuantEra / Horizon Europe, SNSF

- PRL 136, 140401 (2026)
- PRA 113, 043307 (2026)
- PRL 132, 093402 (2024)
- Nature 608, 494–498 (2022)
- Communications Physics 8, 211 (2025)
- PRX Quantum 5, 040332 (2024)
- arXiv:2607.17334

