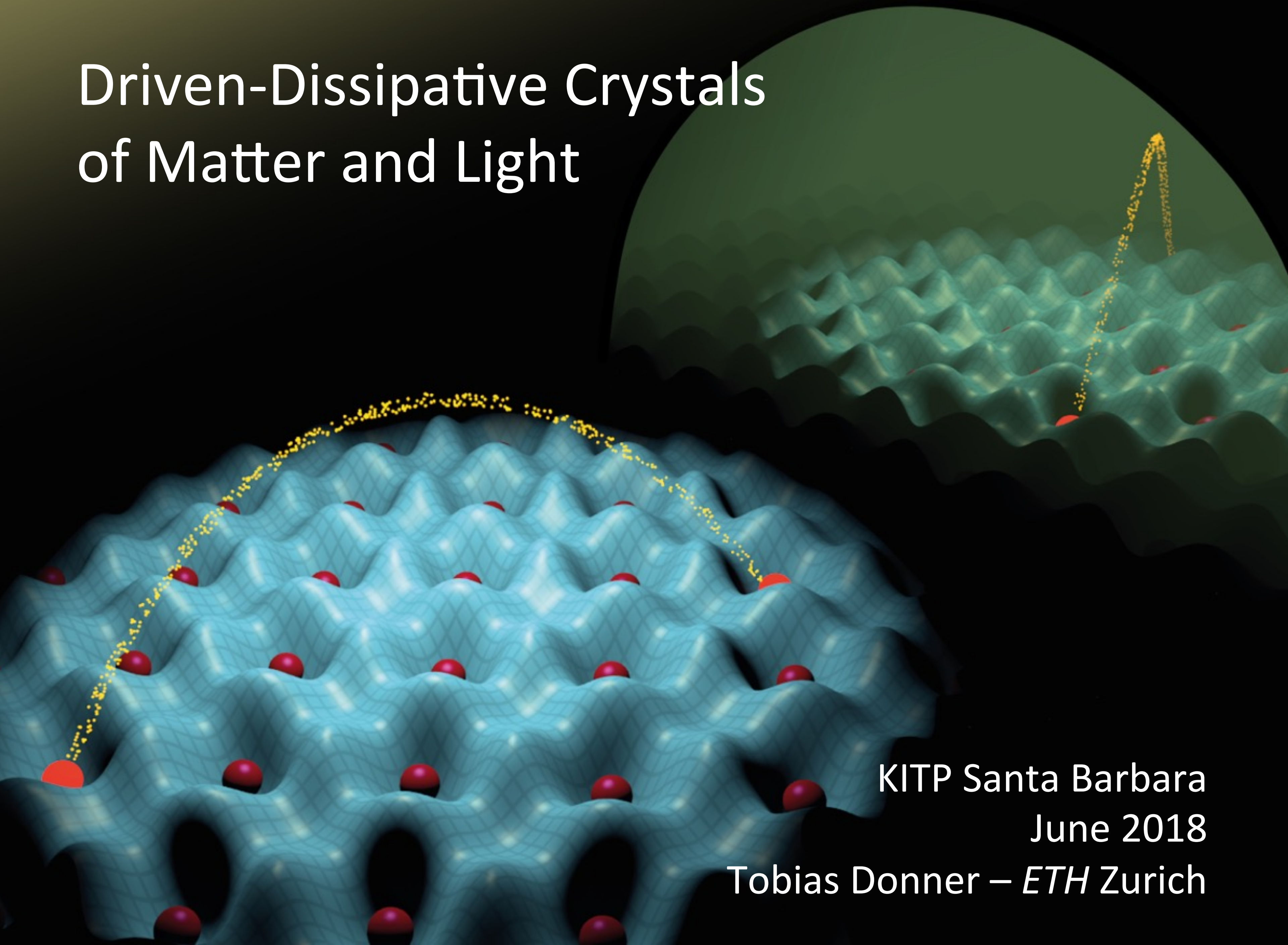
# Driven-Dissipative Crystals of Matter and Light



KITP Santa Barbara
June 2018
Tobias Donner – *ETH* Zurich

# (Thermo-) Dynamics at phase transitions

Competing energy scales can give rise to phase transitions:

$$\hat{H} = A\hat{H}_A + B\hat{H}_B$$

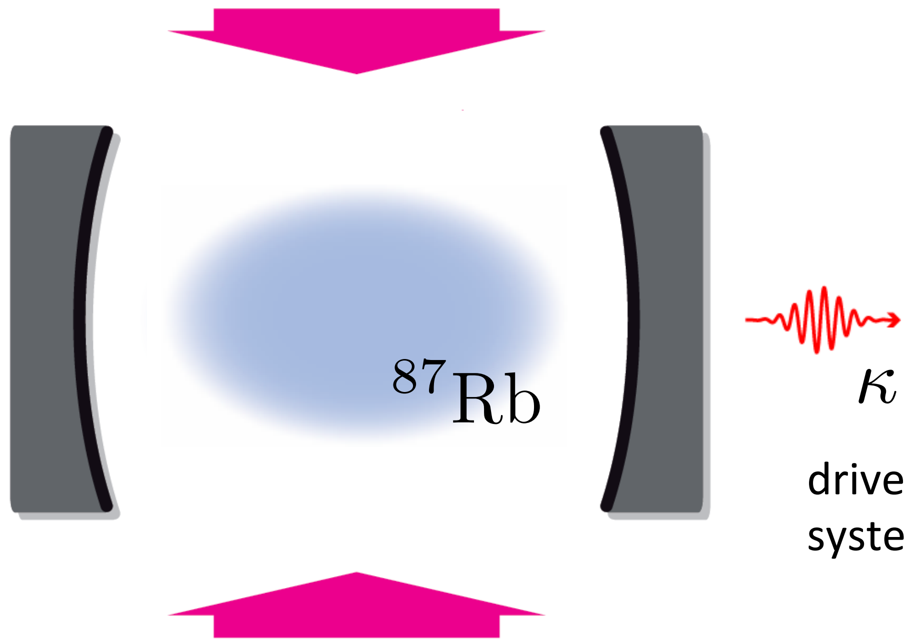
- *Long-range interactions vs kinetic energy*

**Entropy production** at a structural phase transition ($2^{nd}$ order)

- *Long-range interactions vs short-range interactions*

**Quench across a phase transition** in the extended Bose-Hubbard model ($1^{st}$ order)

# Cavity-mediated long-range interactions



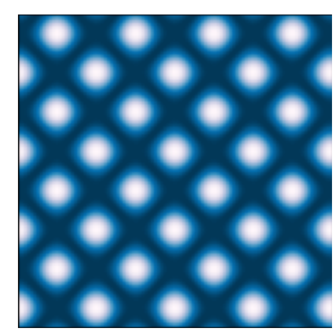

$$V \propto \frac{P}{\Delta_c}$$

driven-dissipative system

Long-range interaction:

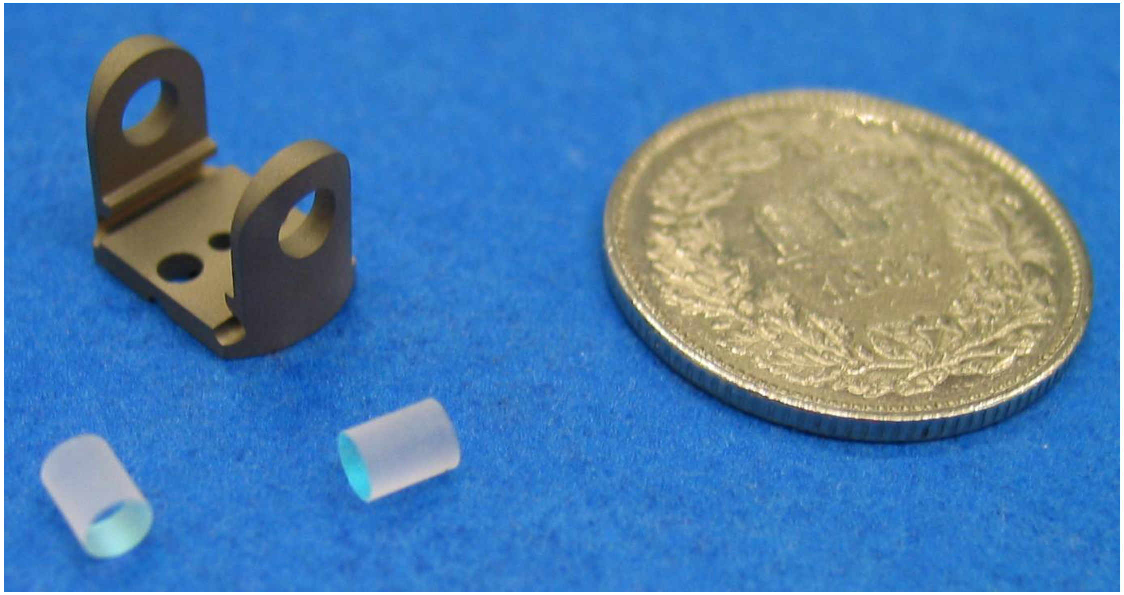
$$V(\mathbf{r},\mathbf{r}') = V\cos(kx)\cos(kz)\cos(kx')\cos(kz')$$

→ Interaction favors checkerboard density modulation.



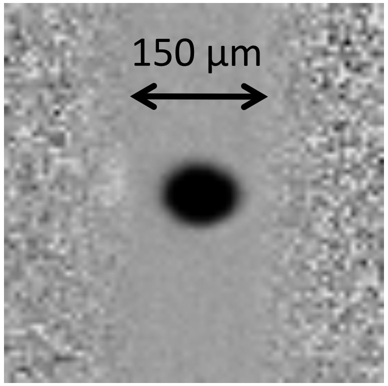
Other groups: Hemmerich group (Hamburg) / Lev group (Stanford)

# High-finesse cavity



Optical Fabry-Perot cavity

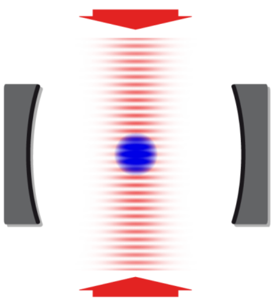
- $L = 178\ \mu m$
- $F = 340.000$
- $(g_0, \kappa, \gamma) = 2\pi \times (10, 1, 3)\mathrm{MHz}$



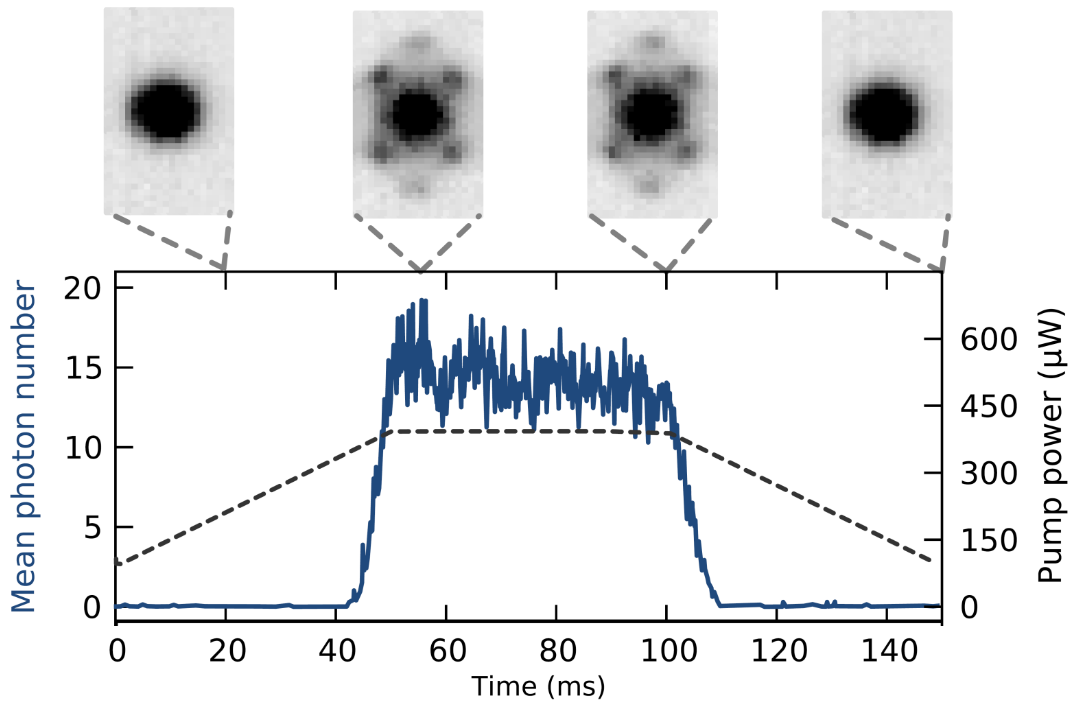

Bose-Einstein condensate

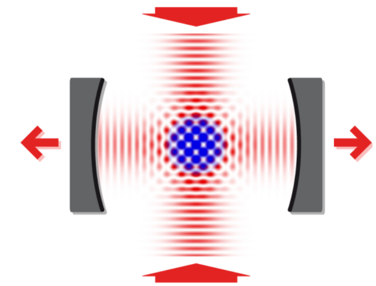
- $10^5$ atoms ($^{87}Rb$)
- $T < 100$ nK

# Structural Phase Transition
# kinetic vs potential energy



$$\langle \hat{a} \rangle = 0$$
$$\langle \hat{a}^\dagger \hat{a} \rangle \neq 0$$



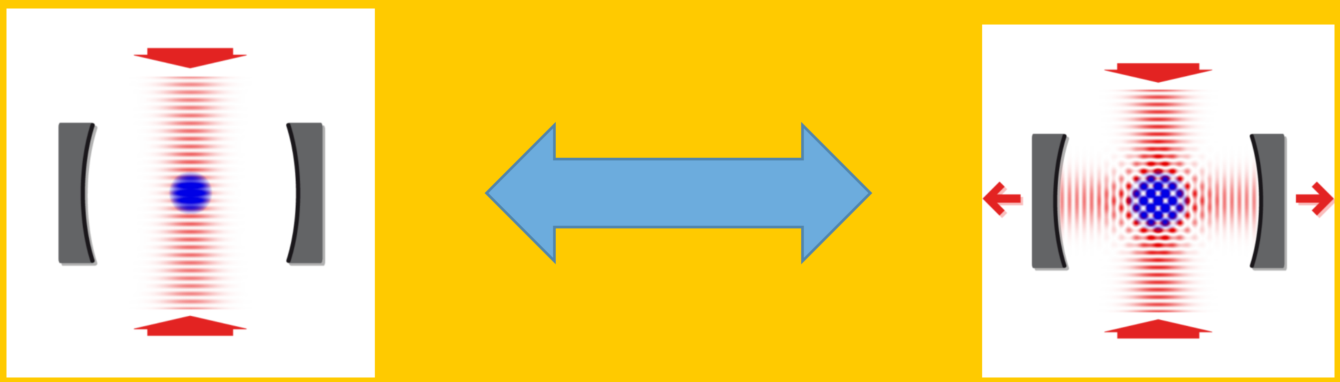



$$\langle \hat{a} \rangle \neq 0$$

**Light field measures order parameter (density modulation):**

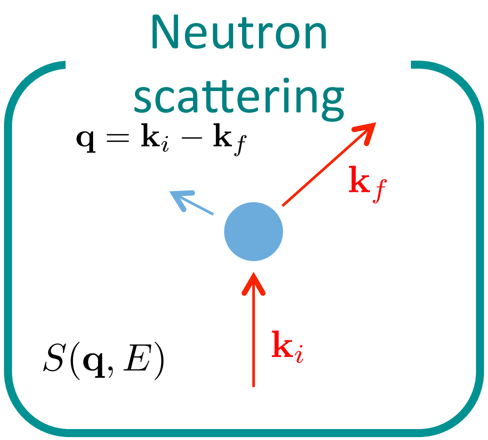
$$\langle \alpha \rangle \propto \langle \Theta \rangle \propto \langle \Psi | \cos(kx) \cos(kz) | \Psi \rangle$$

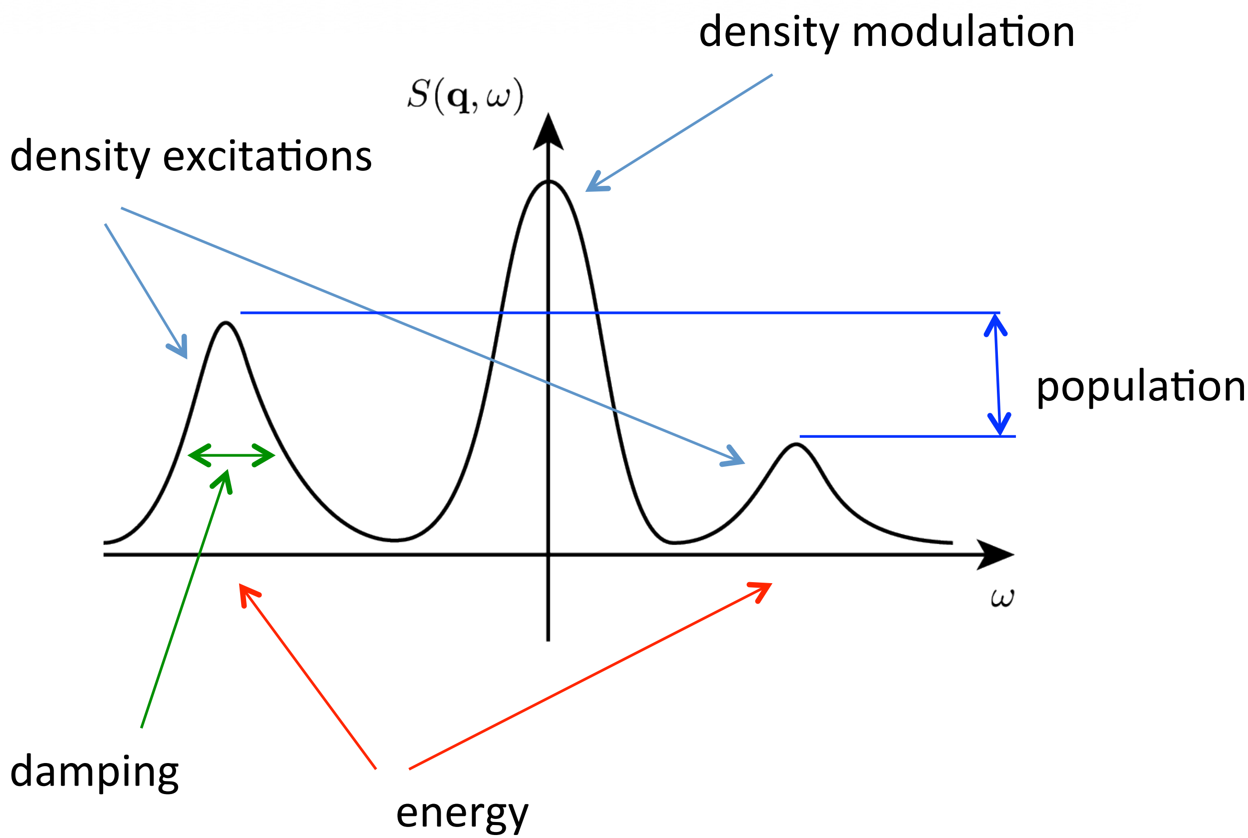
# Fluctuations and entropy production at a structural phase transition



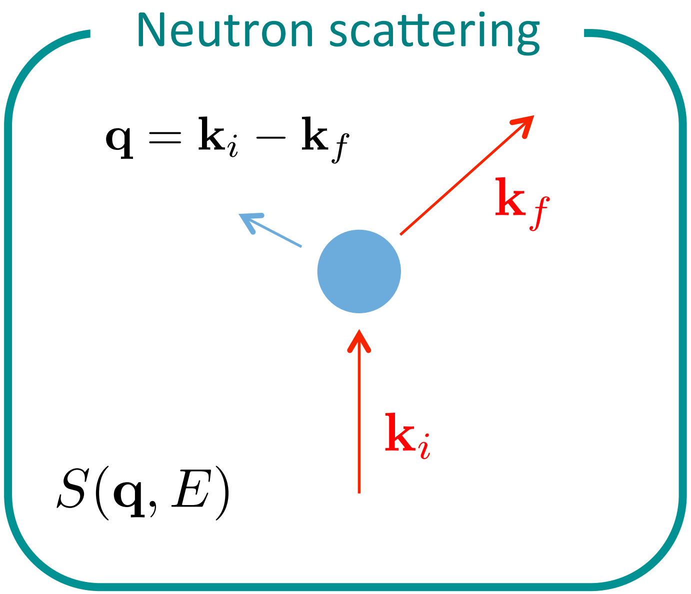
# Dynamic structure factor

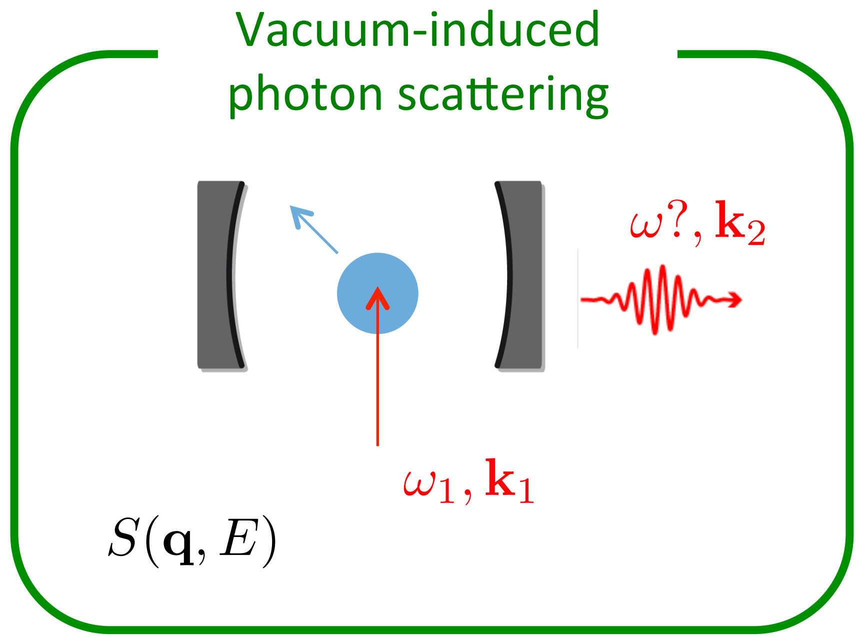
$$S(\mathbf{q},\omega) = \frac{V}{2\pi N}\int \mathrm{d}\mathbf{r}\mathrm{d}t e^{-i(\mathbf{qr}-\omega t)}\langle\rho(\mathbf{r},t)\rho(0,0)\rangle$$



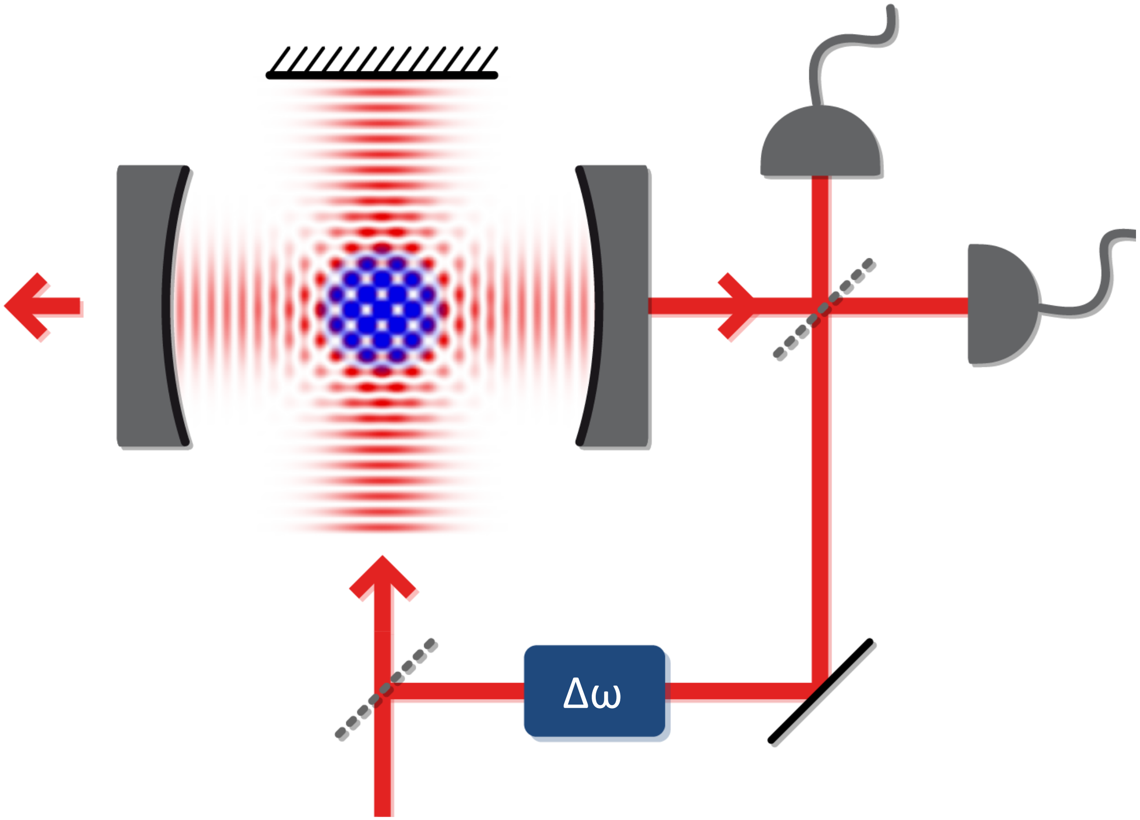
# Dynamic structure factor



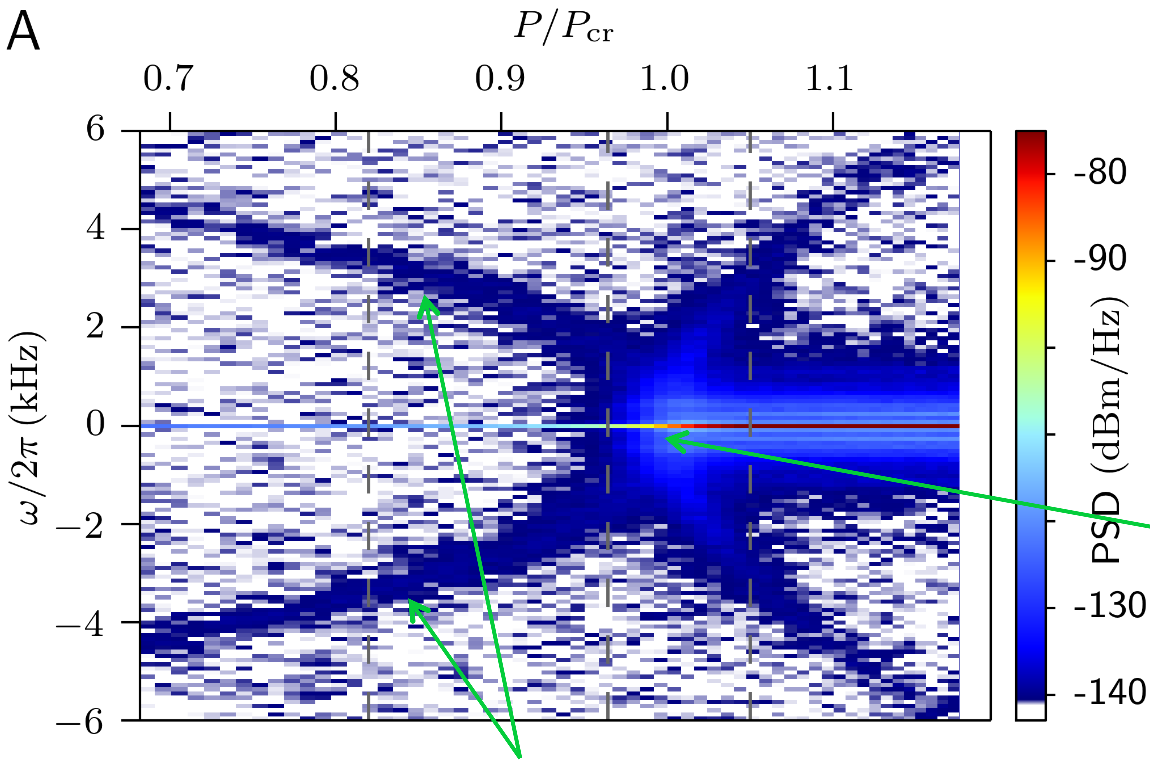



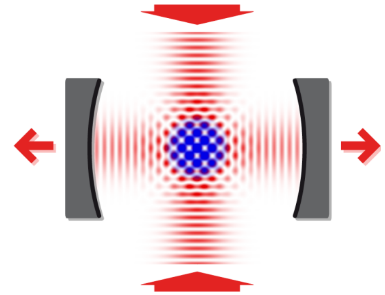

Measures dynamic structure factor at difference wave vector of pump mode and cavity mode.

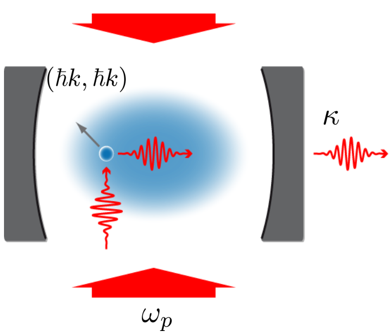
# Phase Sensitive Detection



# Power spectral density of cavity field






**Sidebands:**

fluctuations

creation and annihilation of ***quasiparticles***

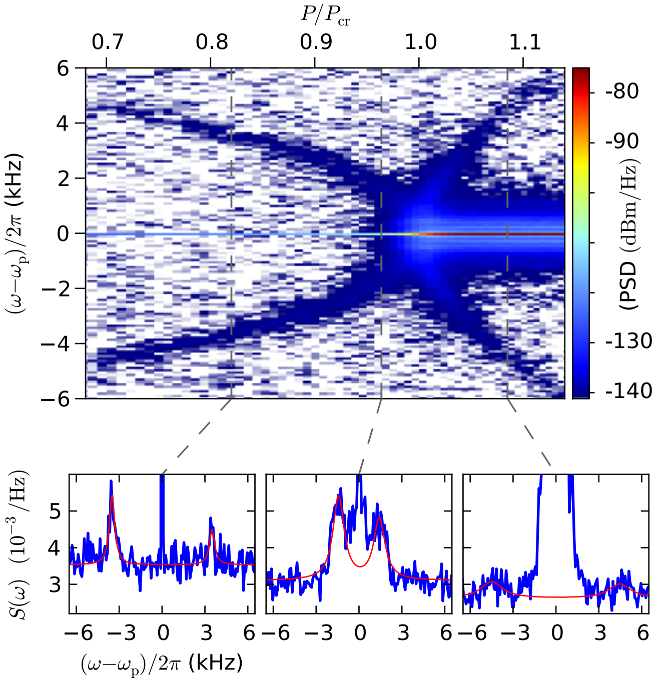
**Carrier:**

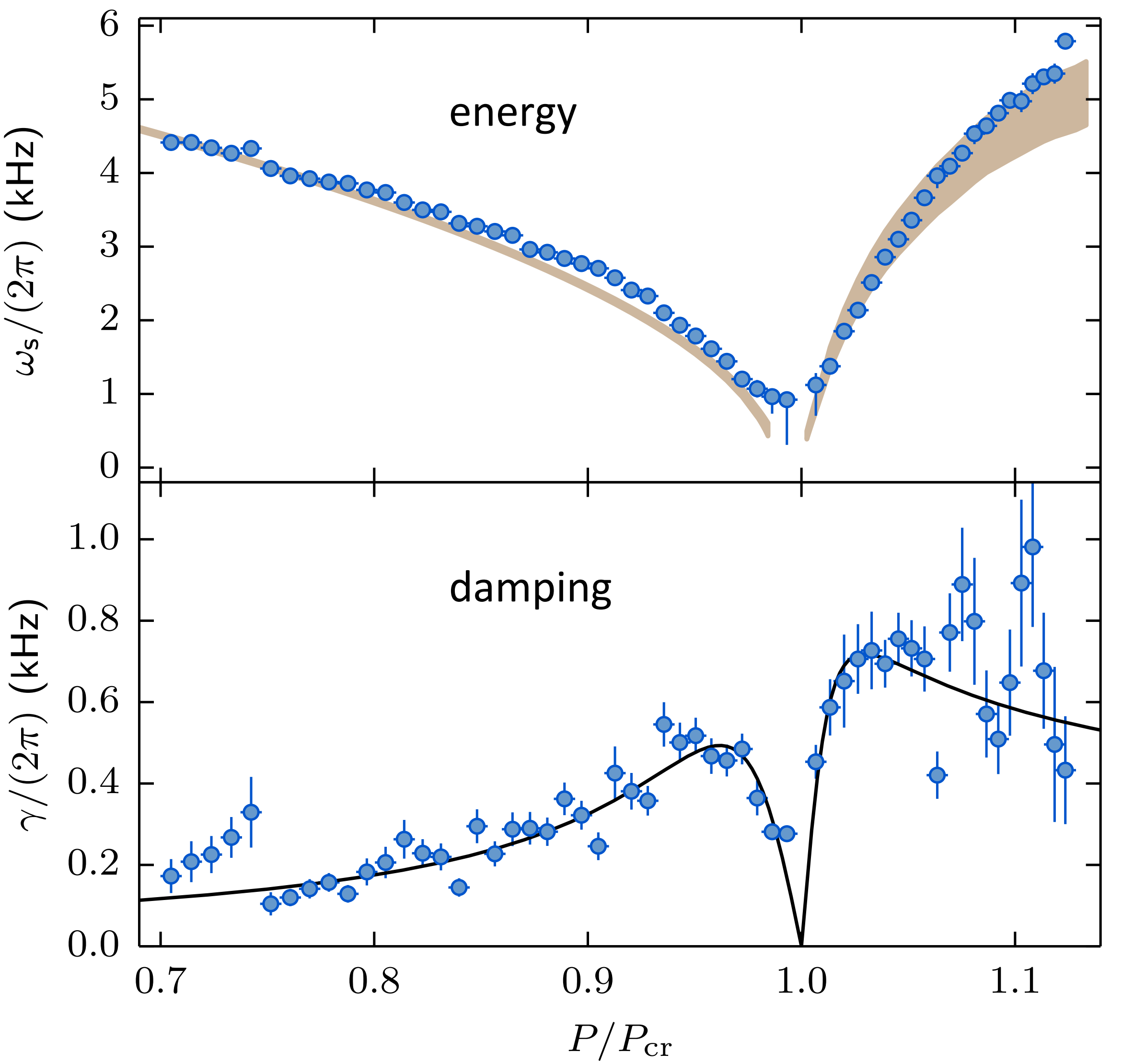
coherent field

Elastic scattering at ***density modulation***

*Nat. Commun.* **6,** 7046 (2015).

# Quasi-particles: excitation energy and lifetime



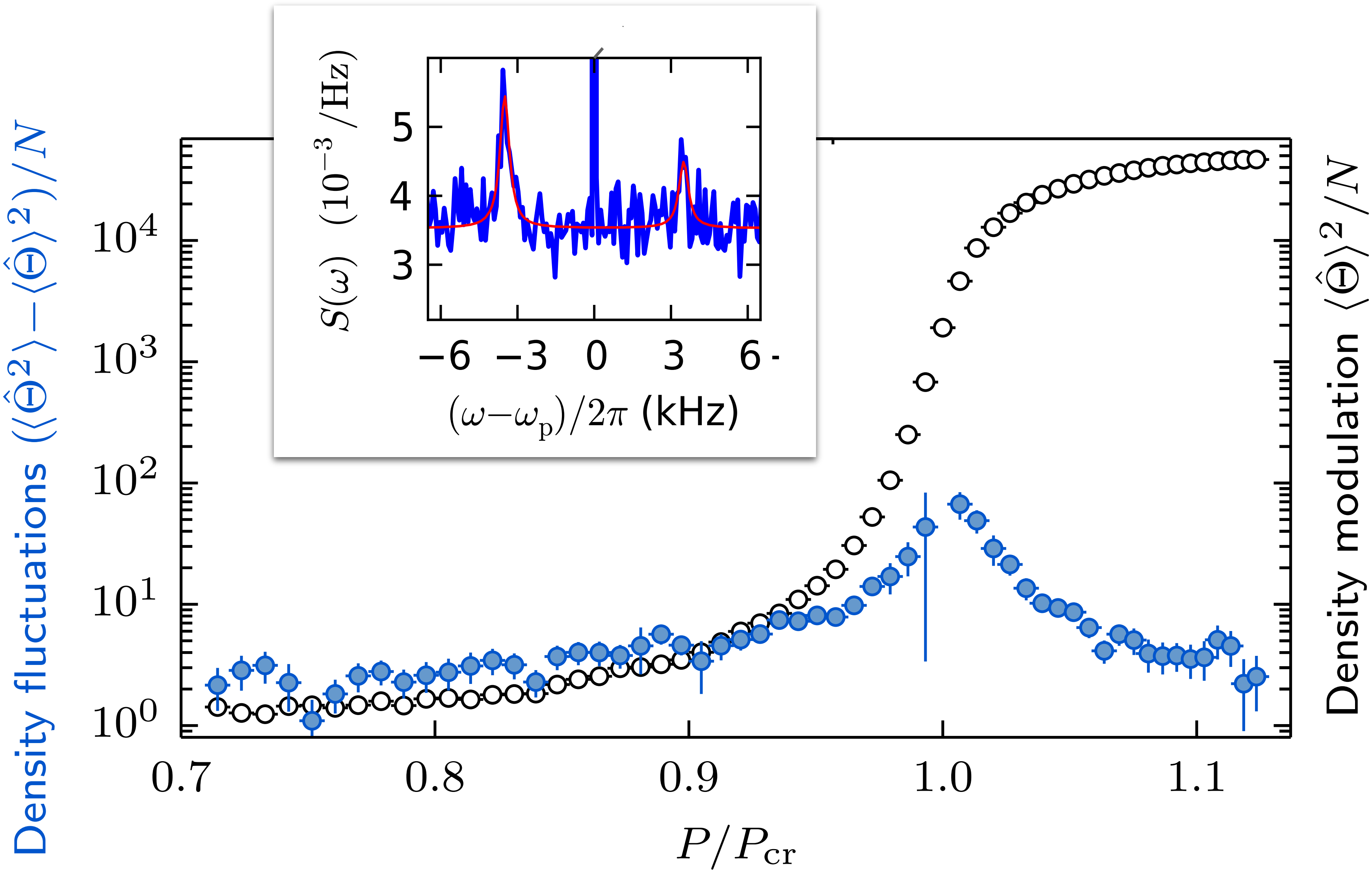




**Theory prediction for damping:**

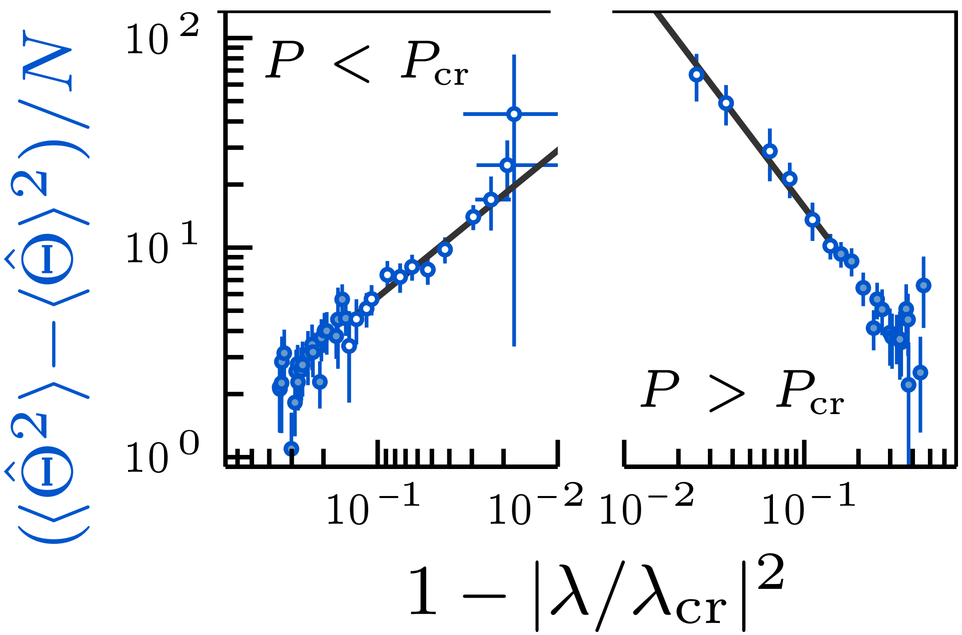
Kulkarni, et al. PRL 111, 220408 (2013)

Konya et al. PRA 90, 013623 (2014)

# Static structure factor



# Scaling of the fluctuations

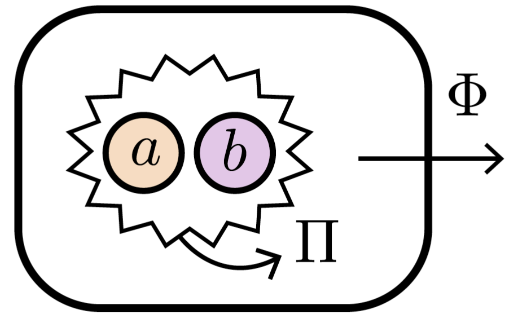



**Exponents of density fluctuations:**
0.7(0.1) in normal phase
1.1(0.1) in organized phase

- **Theory prediction for closed systems: 0.5**
- **Theory prediction for open systems: 1.0**
  *PRA 84, 043637 (2011) (P. Domokos)*
  *New J Phys 14:085011 (2012) (H. Türeci)*
  *Phys. Rev. A 87, 023831 (2013) (P. Strack)*

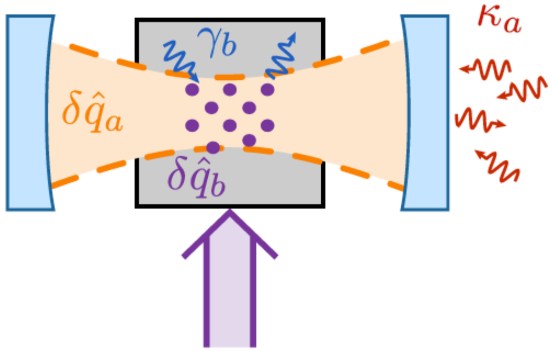
R. Landig, F. Brennecke, R. Mottl, T. Donner, T. Esslinger, *Nat. Commun.* **6,** 7046 (2015).

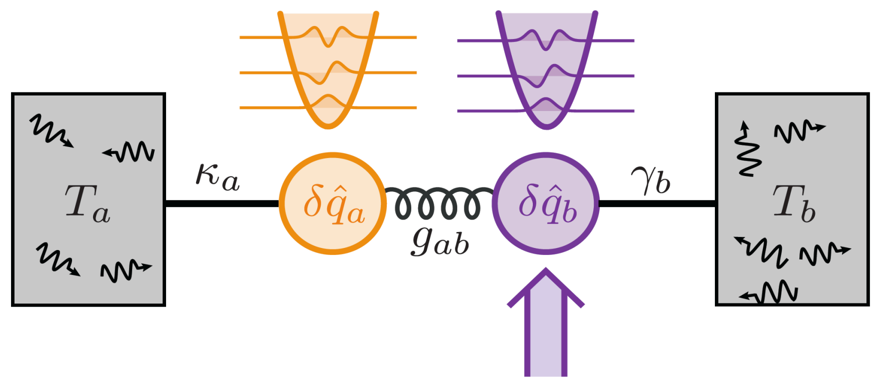
# Entropy production rate




$$\frac{\mathrm{d}S}{\mathrm{d}t} = \Pi(t) - \Phi(t)$$

$$\frac{\mathrm{d}S}{\mathrm{d}t} = 0 \begin{cases} \Pi_s = \Phi_s = 0 & \text{thermal equilibrium} \\ \Pi_s = \Phi_s > 0 & \text{NESS} \end{cases}$$



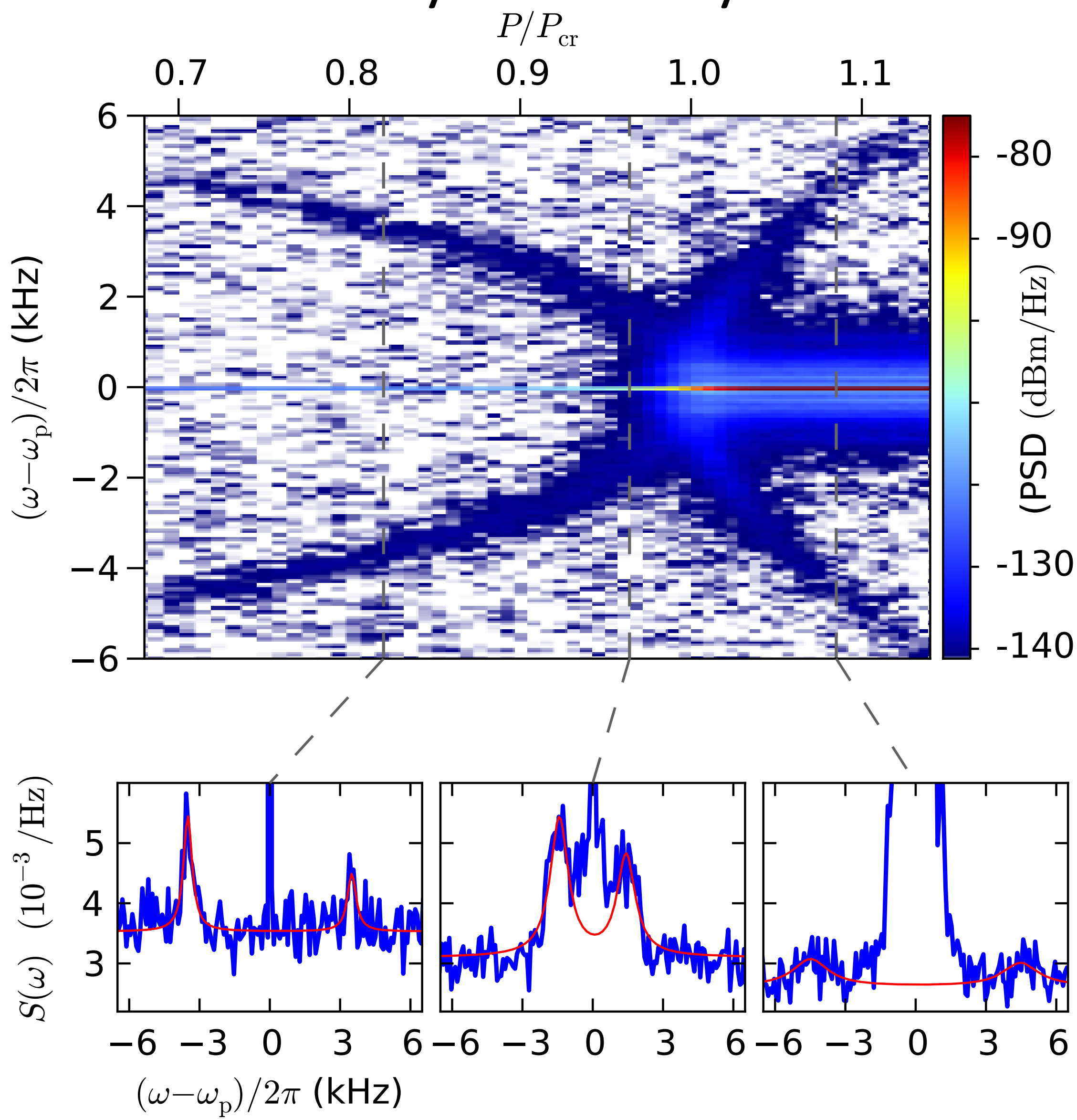




$$\hat{H} = \frac{\hbar\omega_a}{2}(\delta\hat{q}_a^2 + \delta\hat{p}_a^2) + \frac{\hbar\omega_b}{2}(\delta\hat{q}_b^2 + \delta\hat{p}_b^2) + \hbar g_{ab}\delta\hat{q}_a\delta\hat{q}_b$$

$$\Pi_s = 2\gamma_b\left(\frac{n_b + 1/2}{n_{T_b} + 1/2} - 1\right) + 4\kappa_a n_a = \mu_b + \mu_a$$

M. Brunelli, L. Fusco, R. Landig, W. Wieczorek, J. Hoelscher-Obermaier, G. Landi, F. L. Semiao, A. Ferraro, N. Kiesel, T. Donner, G. De Chiara, and M. Paternostro: arXiv:1602.06958

# Sideband asymmetry

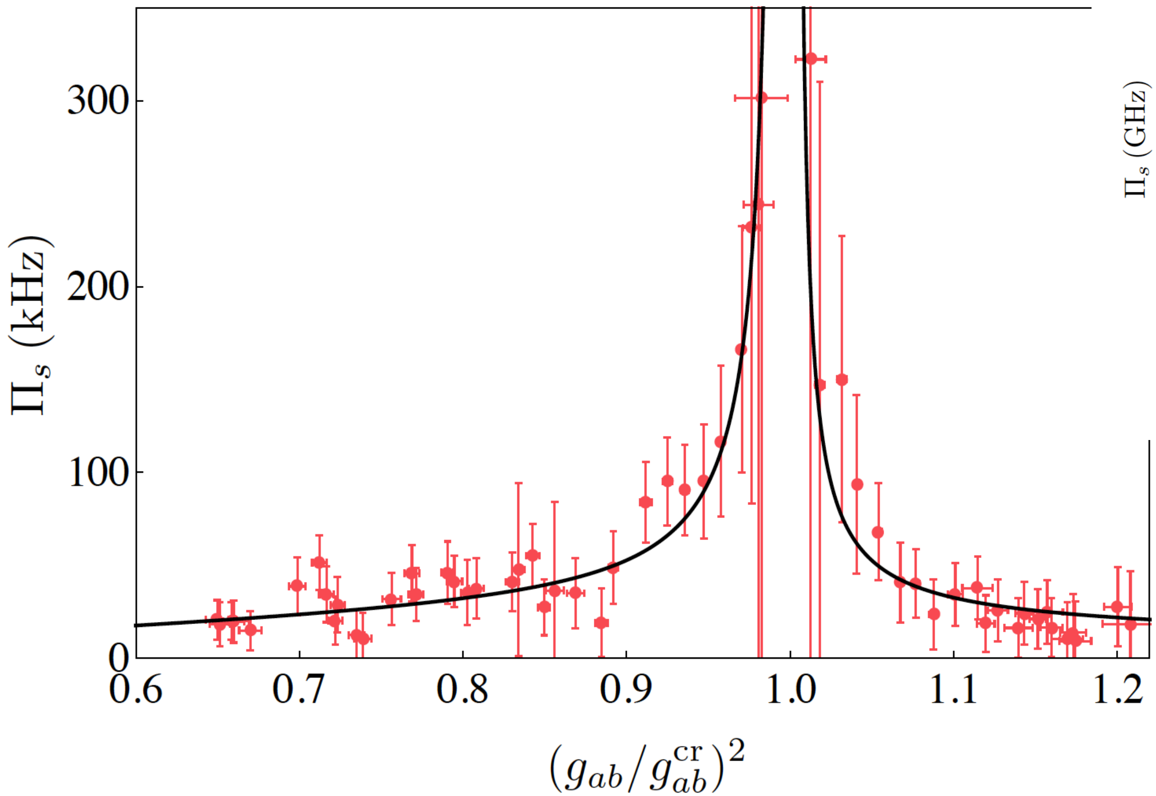



number of quasi-particles

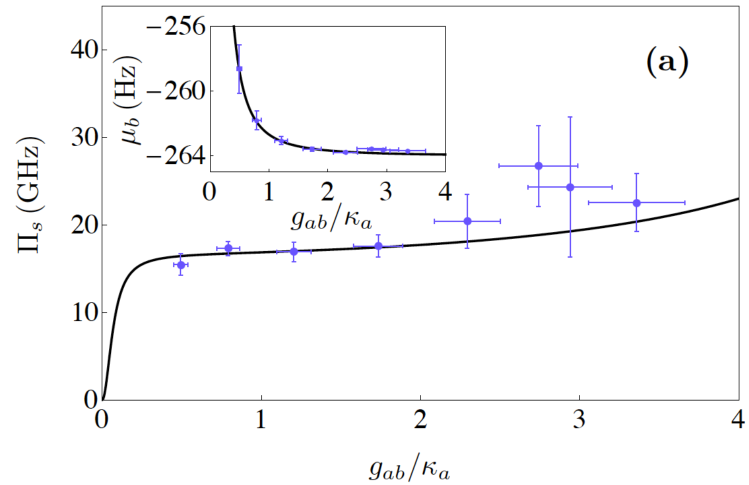
$$2\kappa(\langle\delta\hat{a}^\dagger\delta\hat{a}\rangle_- - \langle\delta\hat{a}^\dagger\delta\hat{a}\rangle_+) = 2\gamma(\langle\hat{c}^\dagger\hat{c}\rangle - n_T)$$

# Entropy production rate at phase transition

$$\Pi_s = 2\gamma_b\left(\frac{n_b + 1/2}{n_{T_b} + 1/2} - 1\right) + 4\kappa_a n_a = \mu_b + \mu_a$$

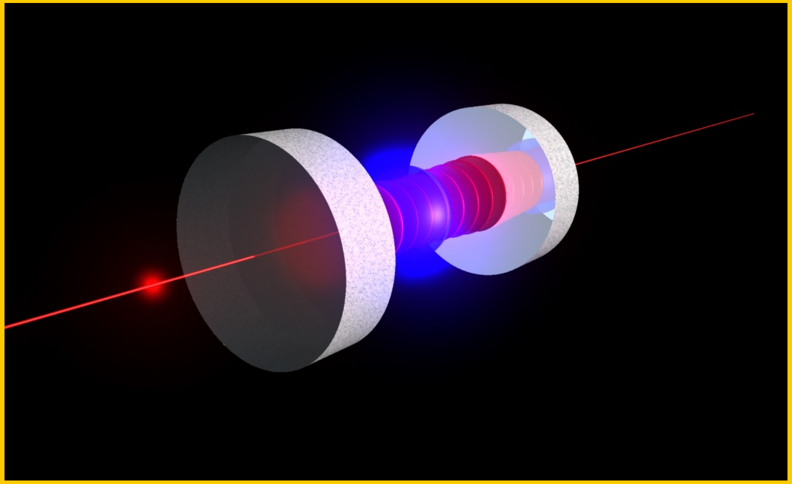



Optomechanics @ Vienna

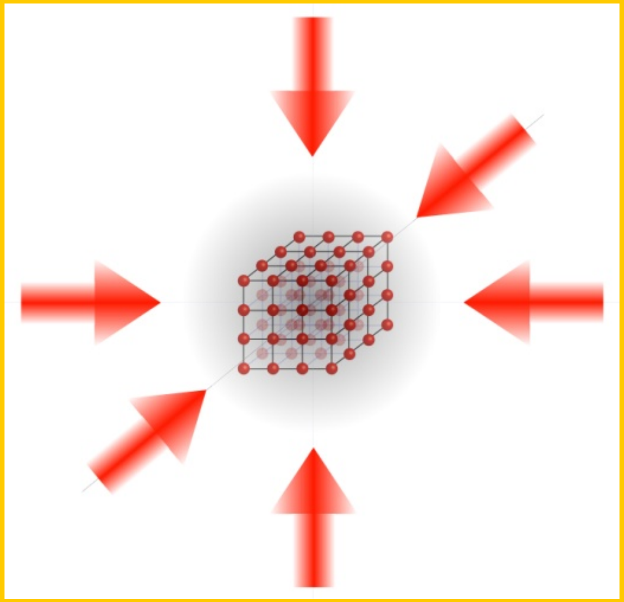



M. Brunelli, L. Fusco, R. Landig, W. Wieczorek, J. Hoelscher-Obermaier, G. Landi, F. L. Semiao, A. Ferraro, N. Kiesel, T. Donner, G. De Chiara, and M. Paternostro: arXiv:1602.06958

# Quenching the Extended Bose-Hubbard model



+



# A possible Hamiltonian

$$H = J \sum_{\langle i,j \rangle} b_i^\dagger b_j + \frac{1}{2} U_0 \sum_i n_i (n_i - 1)$$
$$+ \frac{1}{2} U_{\sigma_1} \sum_{\langle i,j \rangle} n_i n_j + \frac{1}{2} U_{\sigma_2} \sum_{\langle\langle i,j \rangle\rangle} n_i n_j + \cdots$$

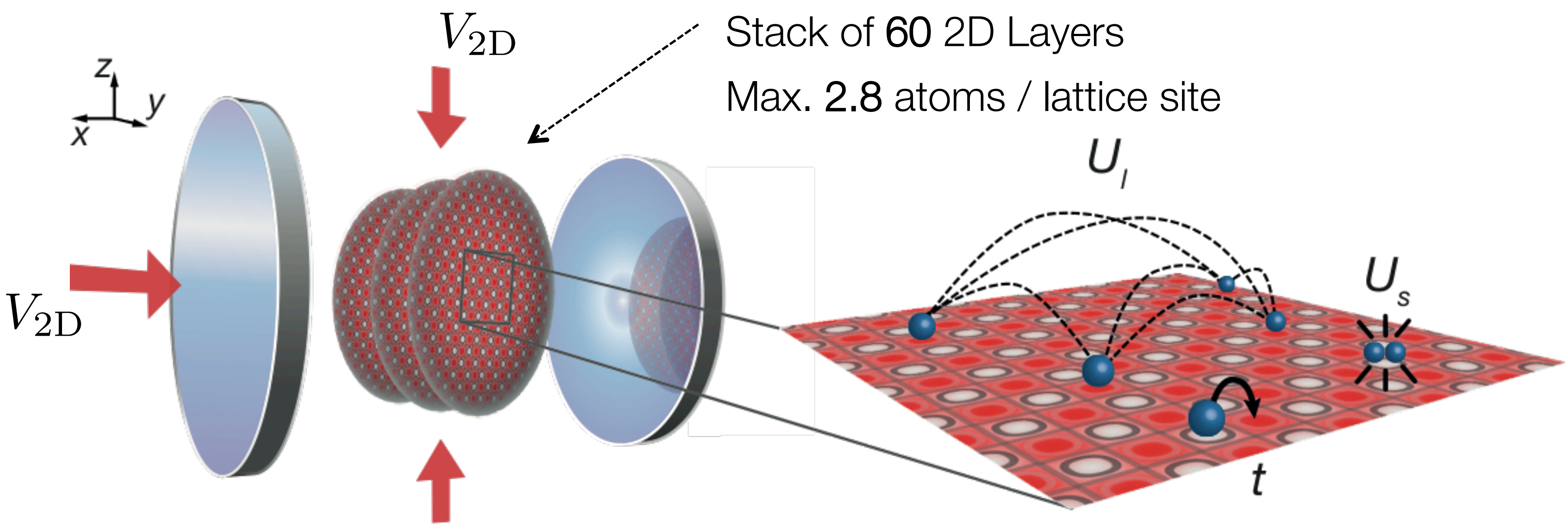

K. Goral, L. Santos, and M. Lewenstein, PRL 88, 170406 (2002)
Scarola, V. W. & Sarma, S. D.. Phys. Rev. Lett. 95, 033003 (2005)

# Lattice model with on-site and global-range interactions

42’000 $^{87}$Rb atoms

Stack of **60** 2D Layers

Max. **2.8** atoms / lattice site

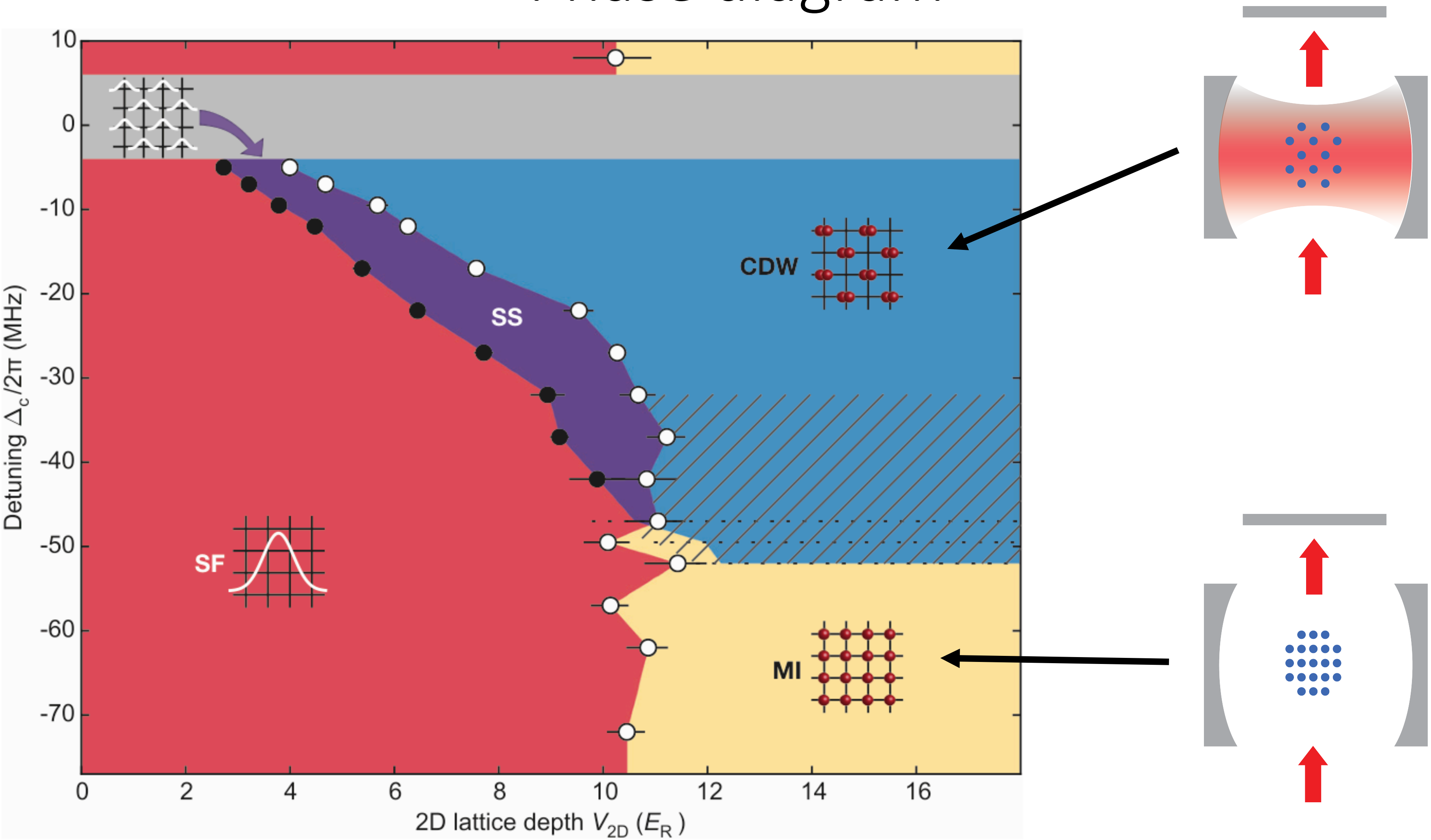



**Tuning interactions:**

$$\boxed{U_s \propto \sqrt{V_{2D}}}$$

$$\boxed{U_l \propto \frac{V_{2D}}{\Delta_c}}$$

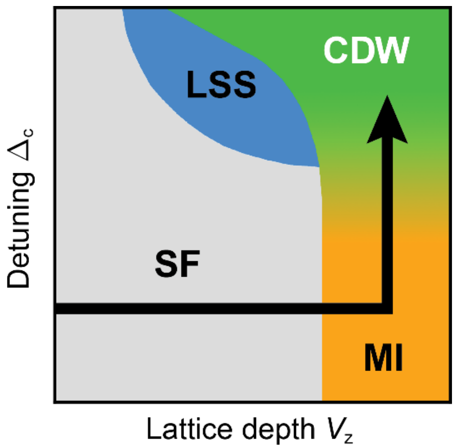
# Phase diagram

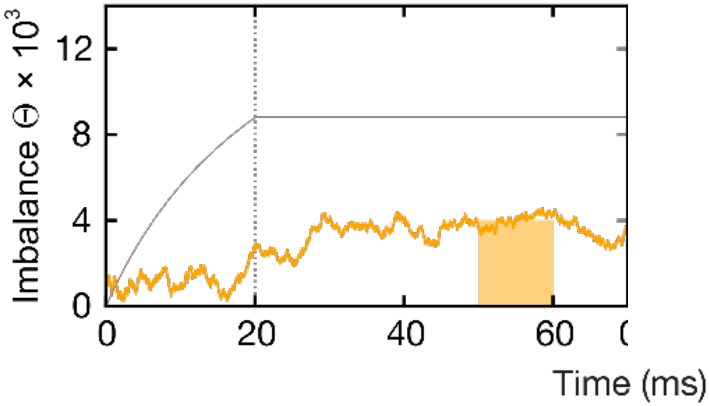



Renate Landig, Lorenz Hruby, Nishant Dogra, Manuele Landini, Rafael Mottl, Tobias Donner, Tilman Esslinger, Nature 532, 476 (2016), arXiv:1511.00007

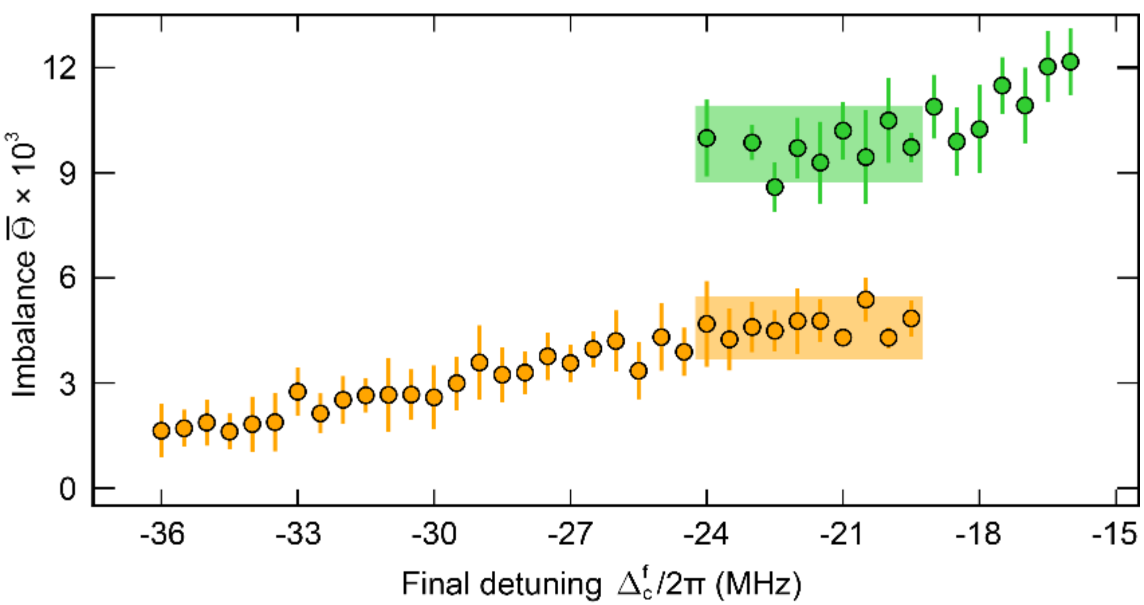
Related work: J. Klinder, H. Keßler, M. Reza Bakhtiari, M. Thorwart, and A. Hemmerich, Phys. Rev. Lett. 115, 230403 (2015), arXiv:1511.00850

# Global-range interaction quenches



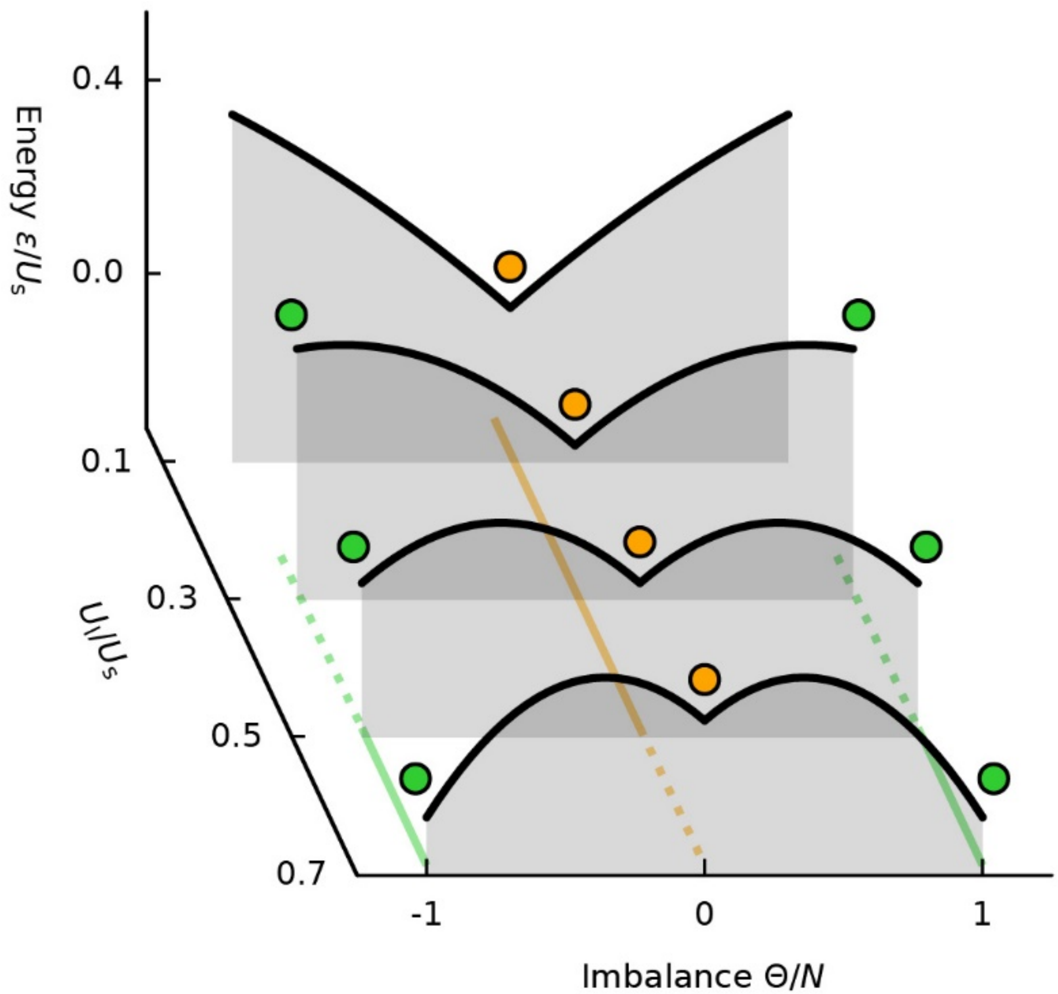

Two distinct final states



# Toy model – Metastability

$$\frac{|\Theta|}{N} = \left| \frac{n_\mathrm{e} - n_\mathrm{o}}{n_\mathrm{e} + n_\mathrm{o}} \right|$$

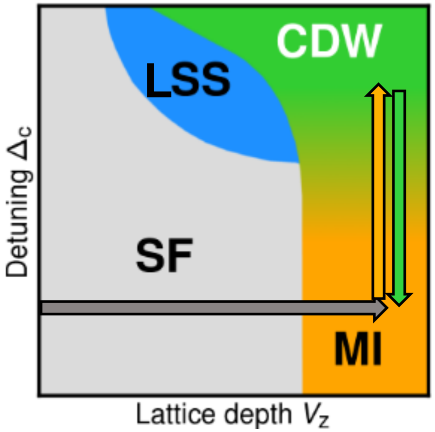
Energy per particle: $$\varepsilon = \frac{1}{2} U_\mathrm{s} \frac{|\Theta|}{N} - U_\mathrm{l} \left( \frac{|\Theta|}{N} \right)^2$$



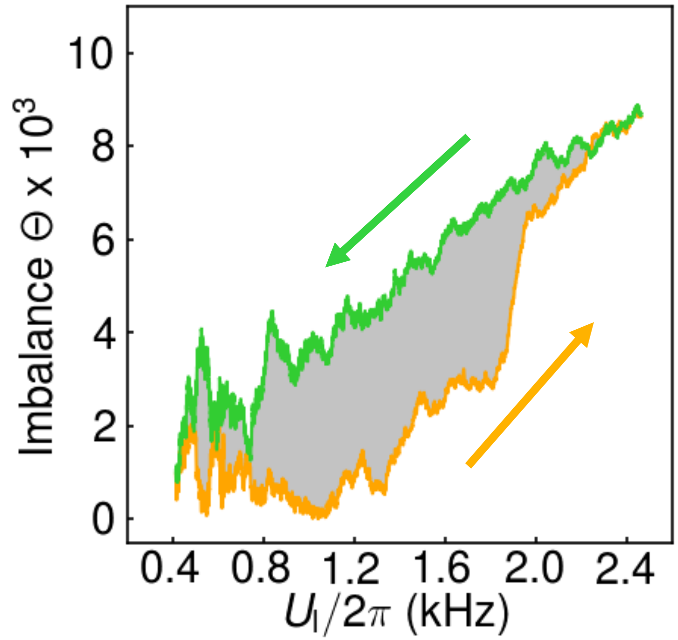

MI
$\Theta = 0$

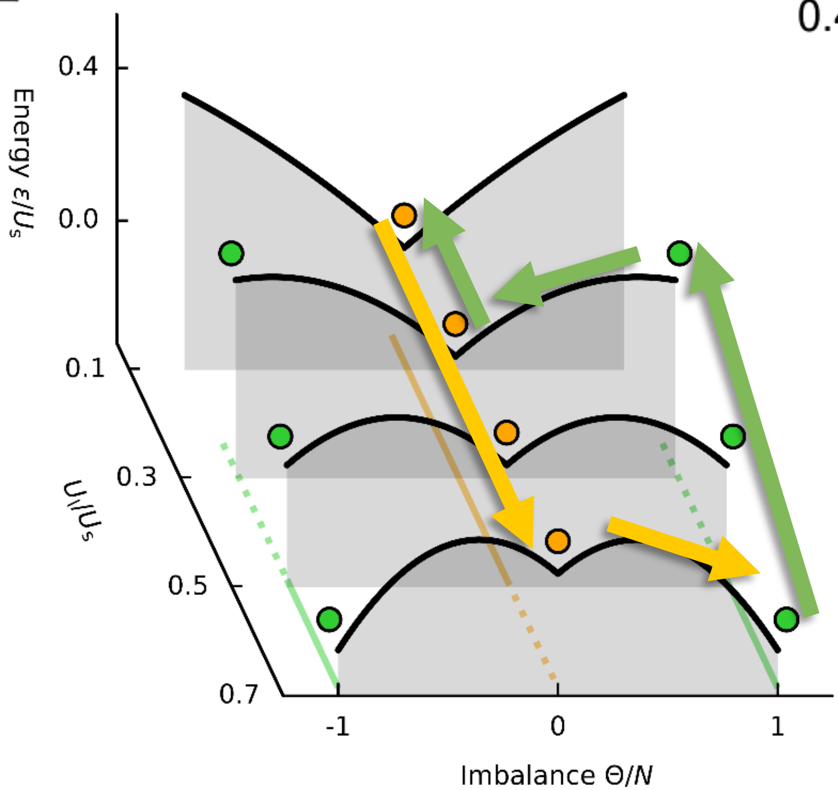
CDW
$\Theta \neq 0$

# Global-range interaction sweeps

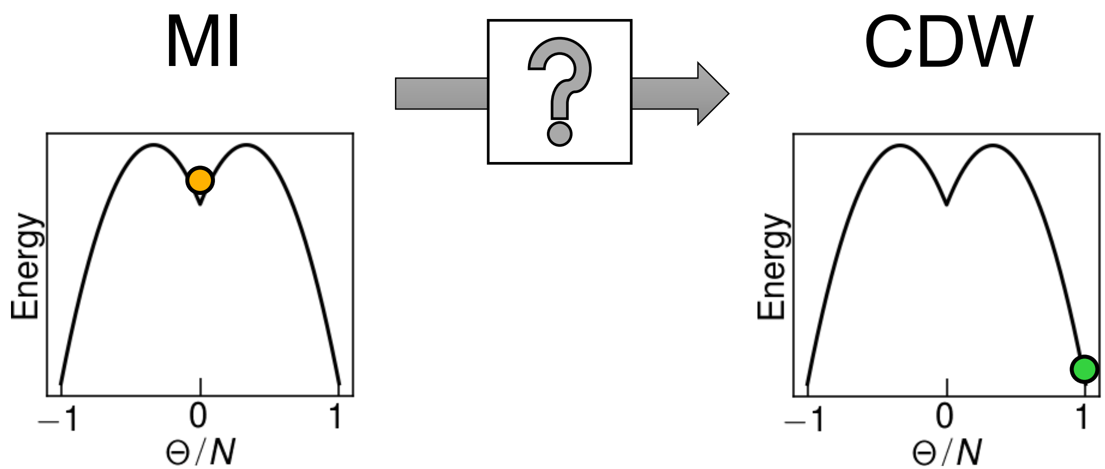


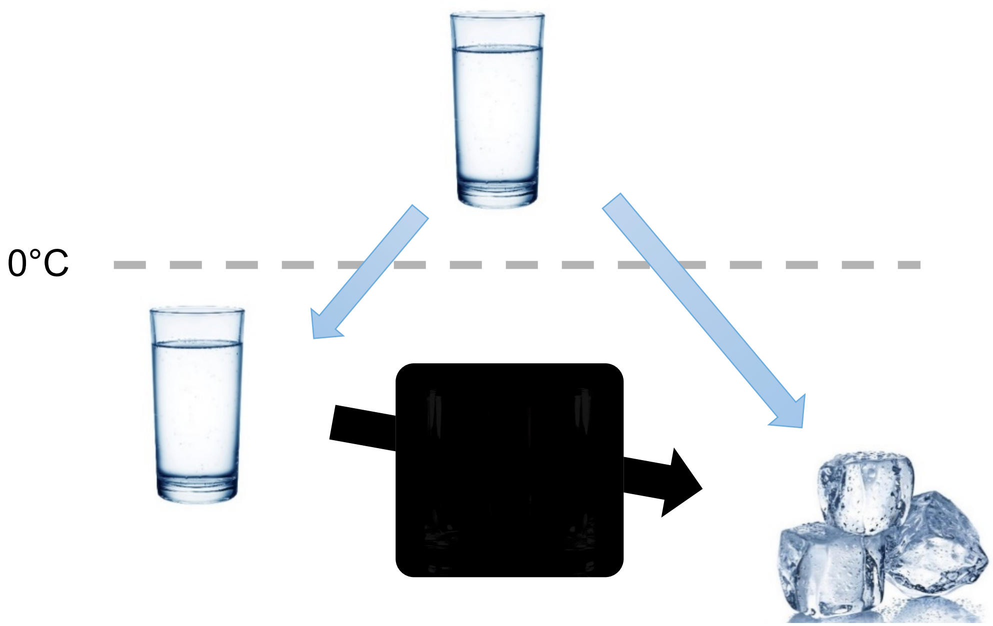

Hysteresis



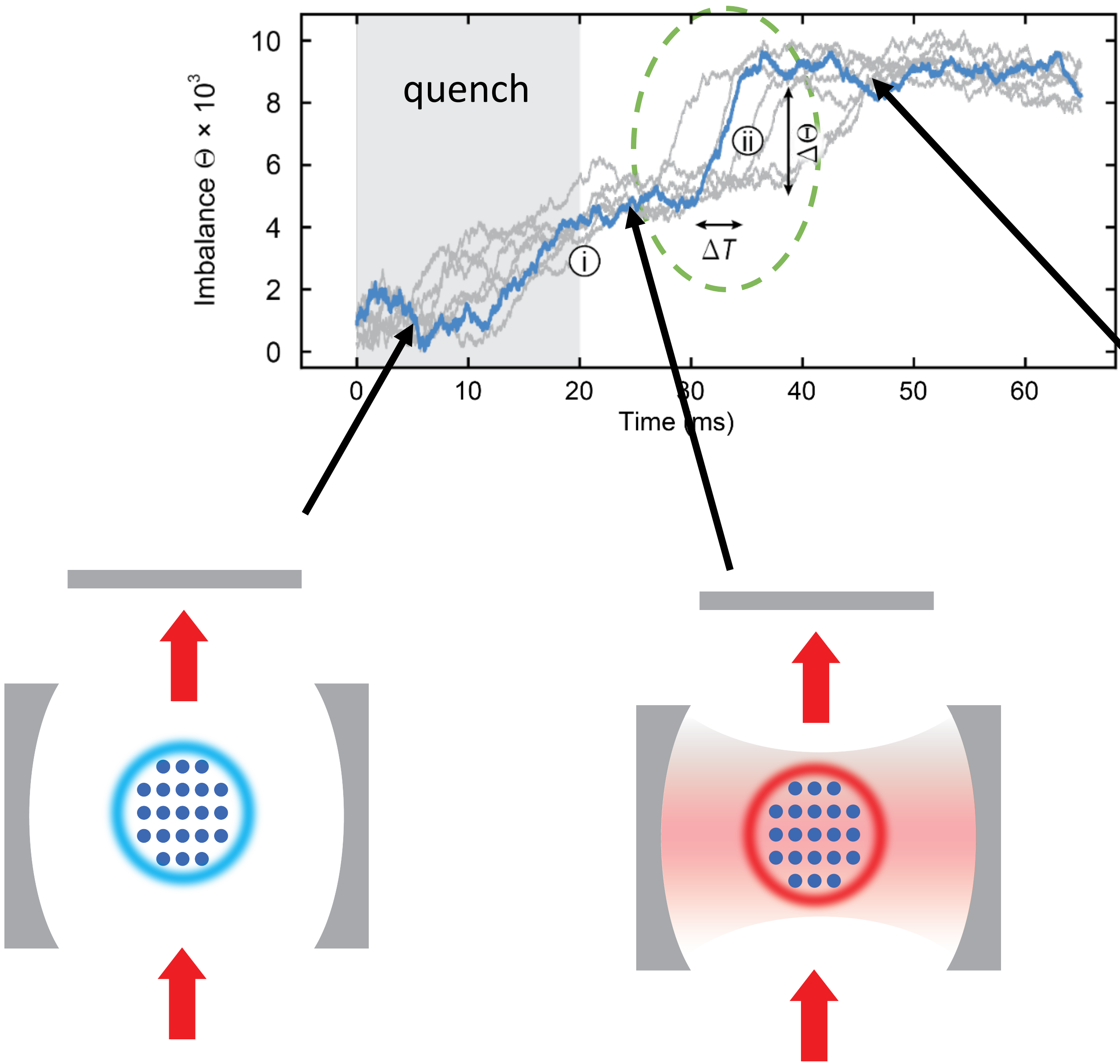



# Dynamics of phase transition



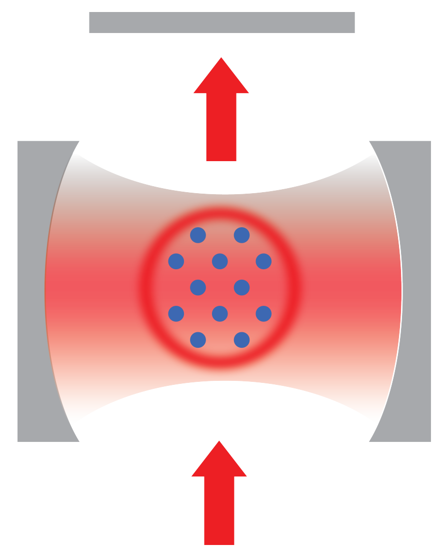



# Imbalance dynamics after the quench

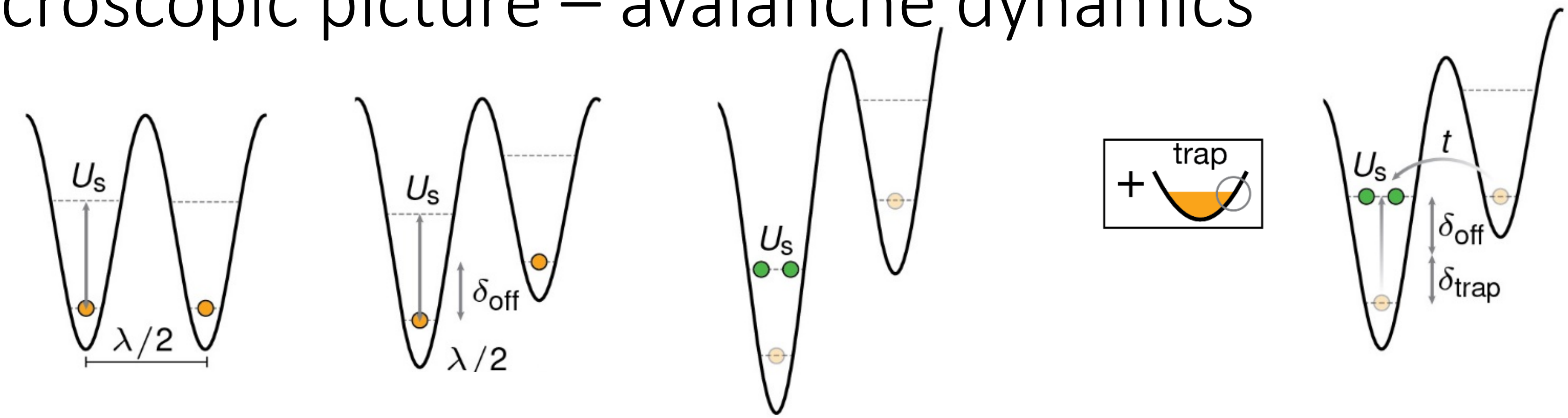


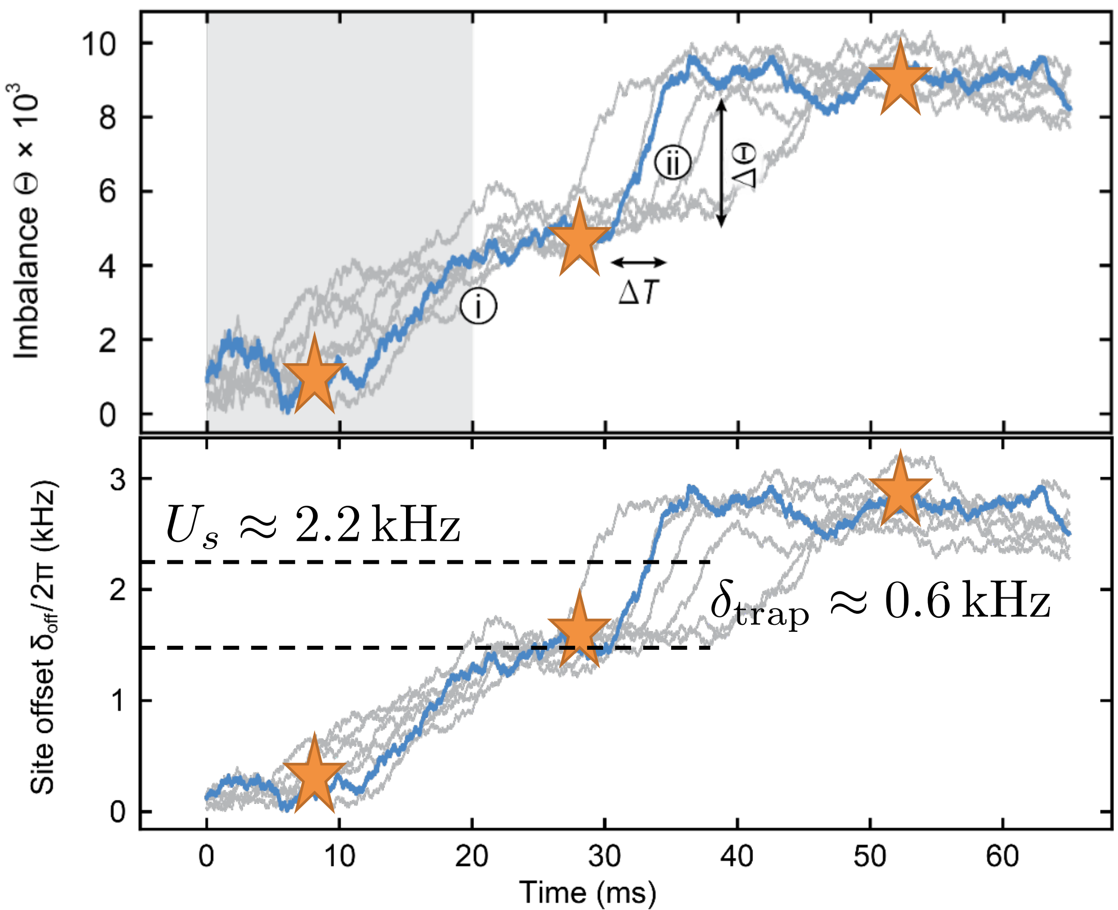

Step duration
ΔT ≈ 4.3 ms

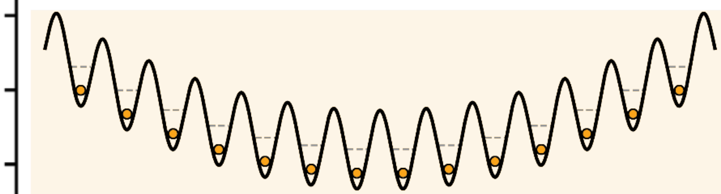
Tunneling time
t ≈ 3.1 ms



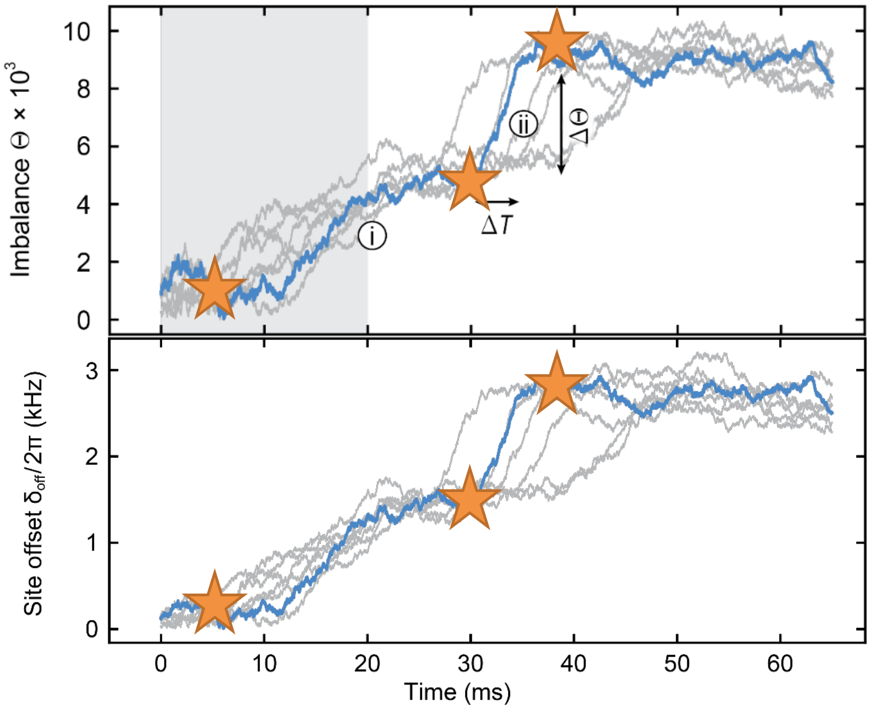
# Microscopic picture – avalanche dynamics

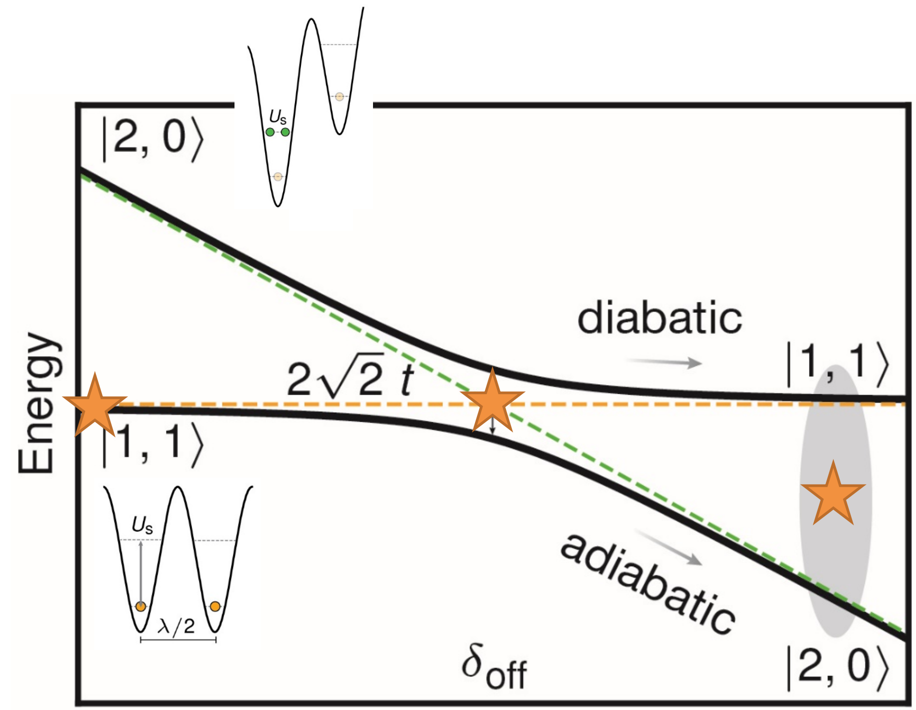


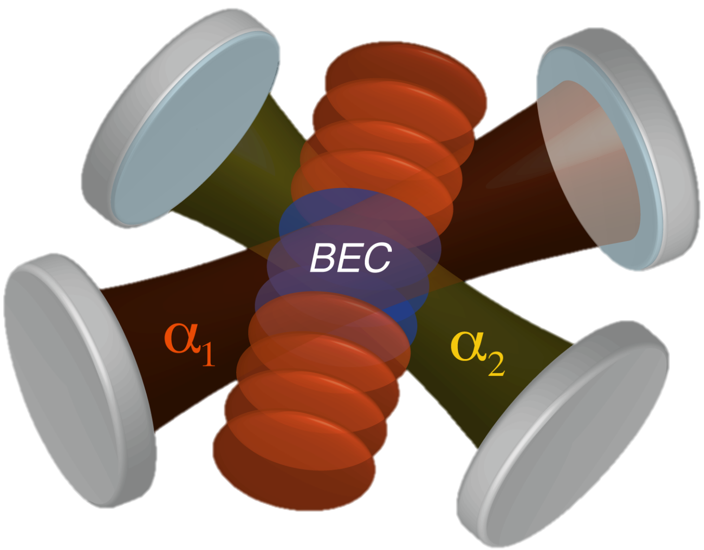
# Microscopic picture – Landau-Zener transitions

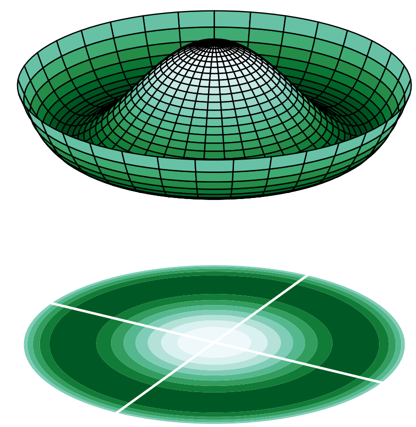


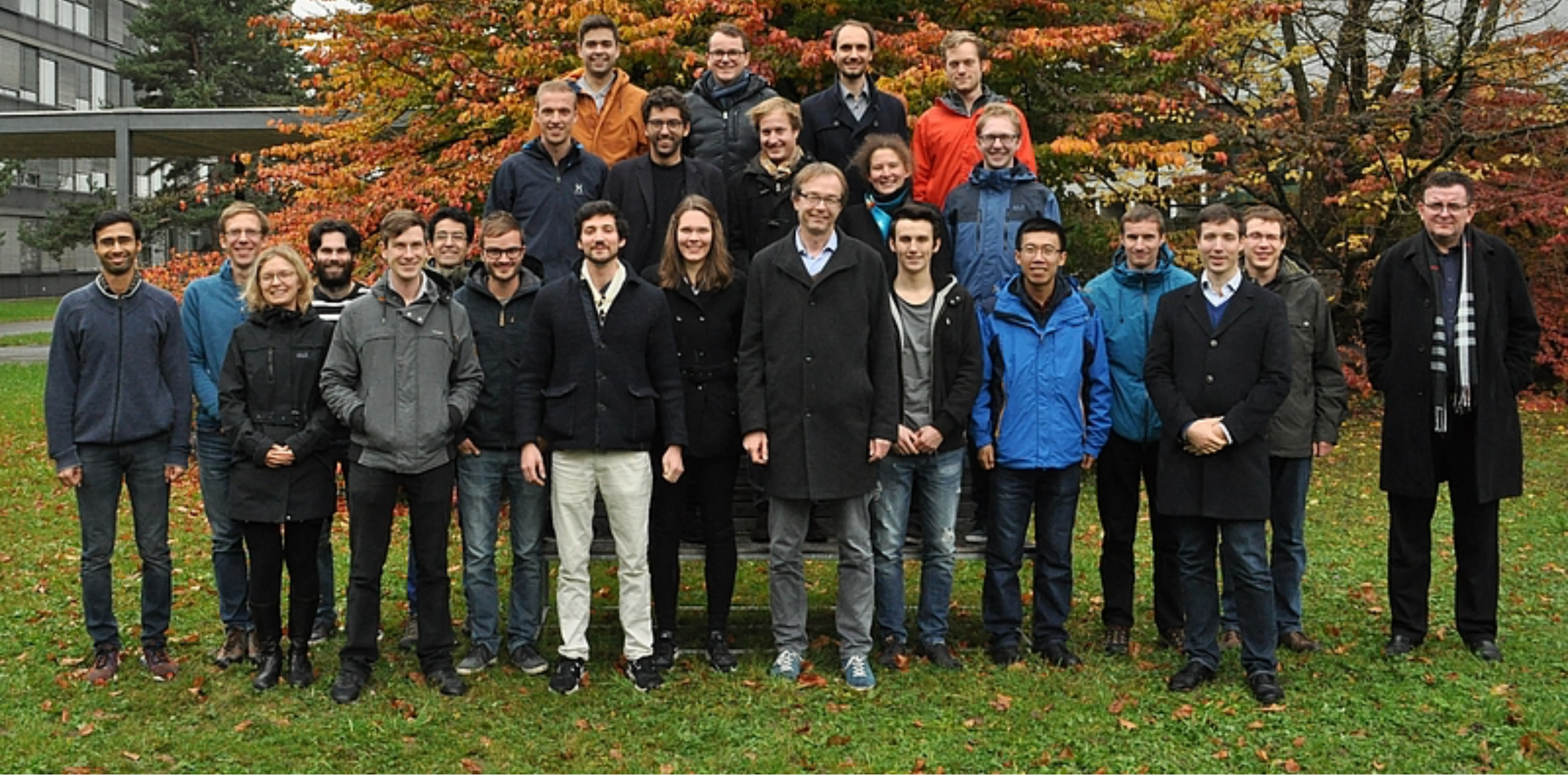




- Time scale (adiabaticity) of parameter change is determined by the system's own dynamics.

# Crossed cavities: from supersolids to coupled order parameters



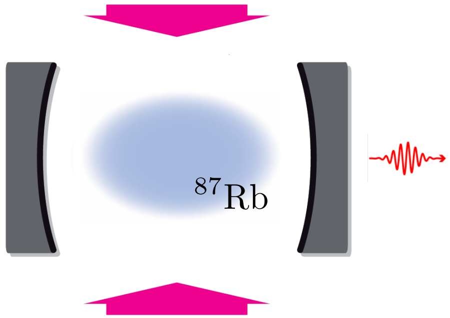



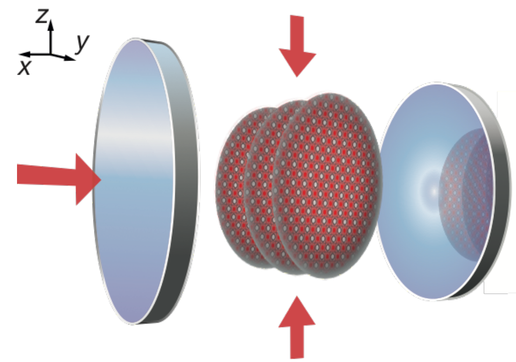


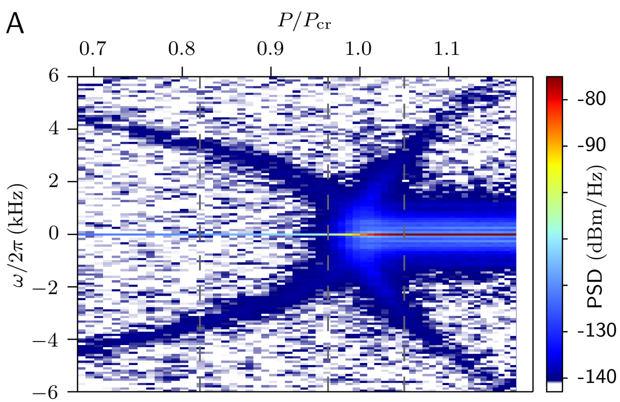
**The current team:**
Lorenz Hruby, Nishant Dogra, Katrin Kröger, Manuele Landini, Tobias Donner, Tilman Esslinger

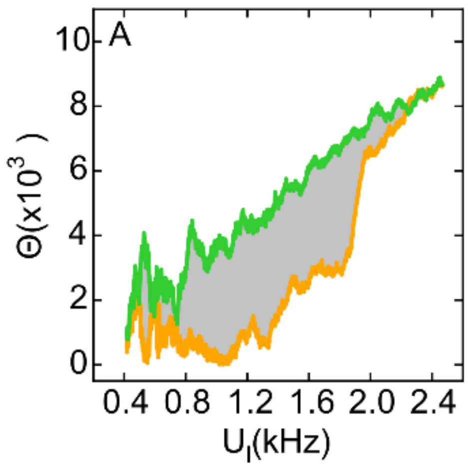
**Former members contributing:**
Kristian Baumann, Rafael Mottl, Renate Landig, Ferdinand Brennecke

Funding: ETH, EU (ERCadv TransQ, SIQS, TherMiQ, QUIC, ColOpt), NCCR QSIT, SNF




*Nat. Commun.* **6,** 7046 (2015)
arXiv:1602.06958

Nature **532**, 476 (2016)
PNAS **115**, 3279 (2018).