The quantum optical Josephson interferometer

&

(non-equilibrium effects in coupled cavities)

Rosario Fazio

NEST, Scuola Normale Superiore, Pisa
Istituto di Nanoscienze - CNR, Pisa

In collaboration with

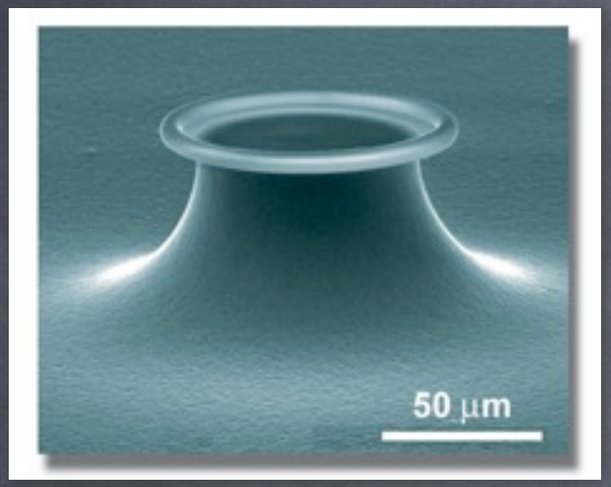
Dario Gerace	Uni-Pavia
Andrea Tomadin	IQOQI -Innsbruck
Vittorio Giovannetti	SNS - Pisa
Iacopo Carusotto	BEC - Trento
Hakan Tureci Atac Imamoglu	ETH-Zurich

- Nature Physics **5**, 281 (2009)
- Phys. Rev. A (2010),arXiv:0904.4437

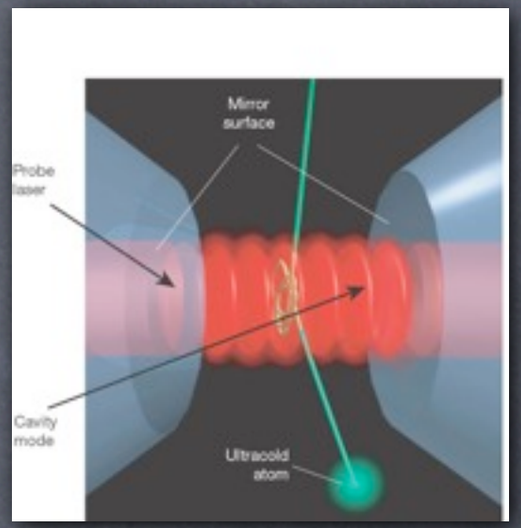
CAVITY-QED

Test for fundaments of Quantum Mechanics

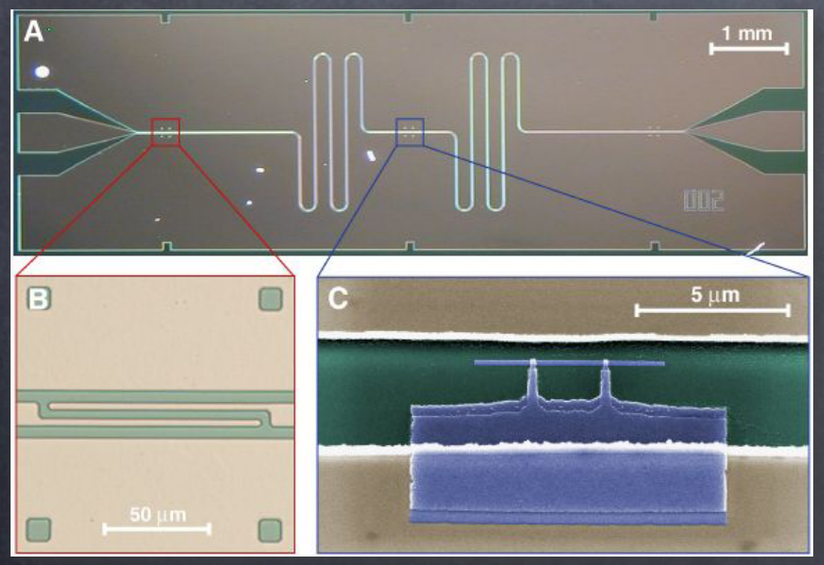
Quantum Information Processing



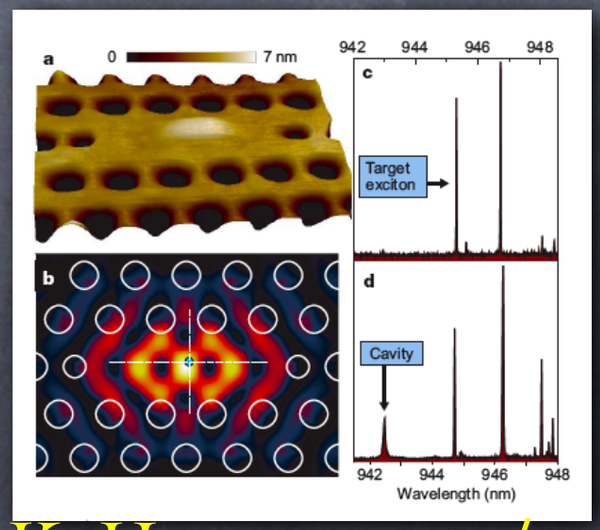
D.K. Armani *et al* Nature **421**, 925



J.M. Raimond *et al* Rev. Mod. Phys **73**, 565 (2001)



A. Wallraff *et al*, Nature **431**, 162 (2004)



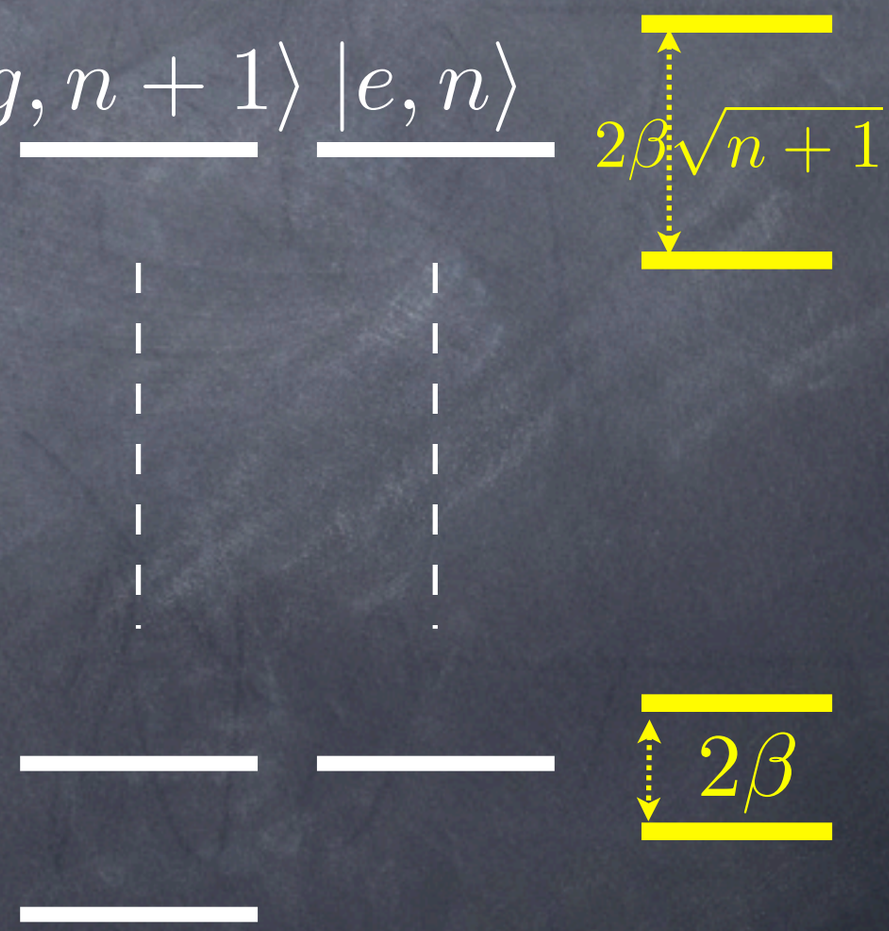
K. Hennessy *et al*, Nature **445**, 895 (2007)

Jaynes-Cummings Model

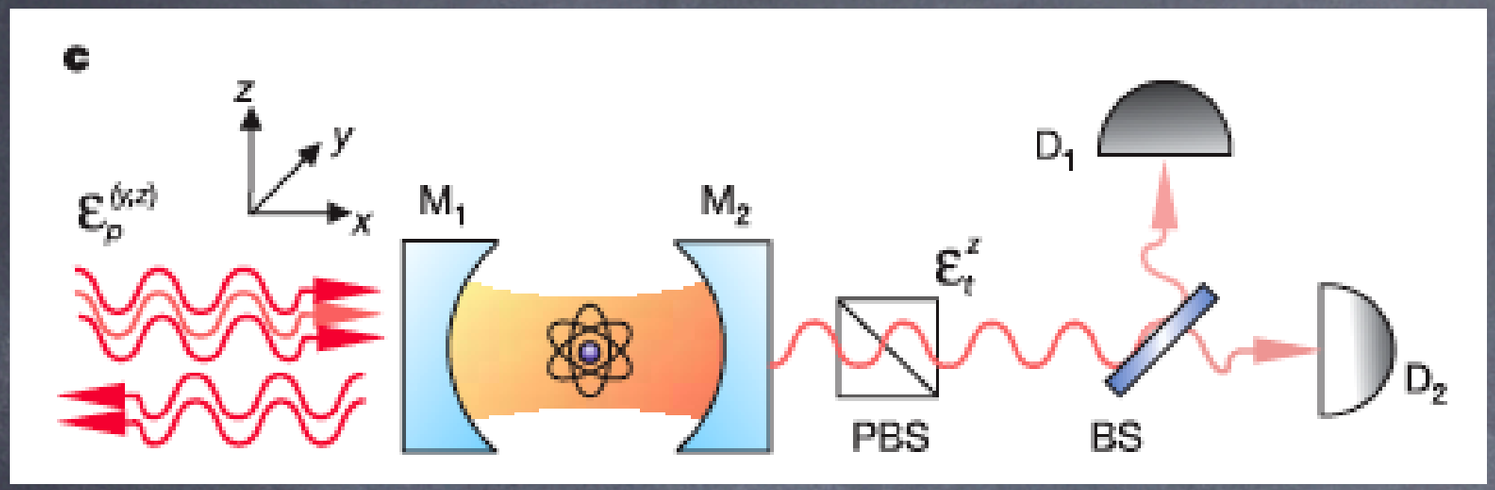
$$\mathcal{H} = \epsilon\sigma_z + \omega a^\dagger a + \beta(a^\dagger\sigma_- + a\sigma_+)$$

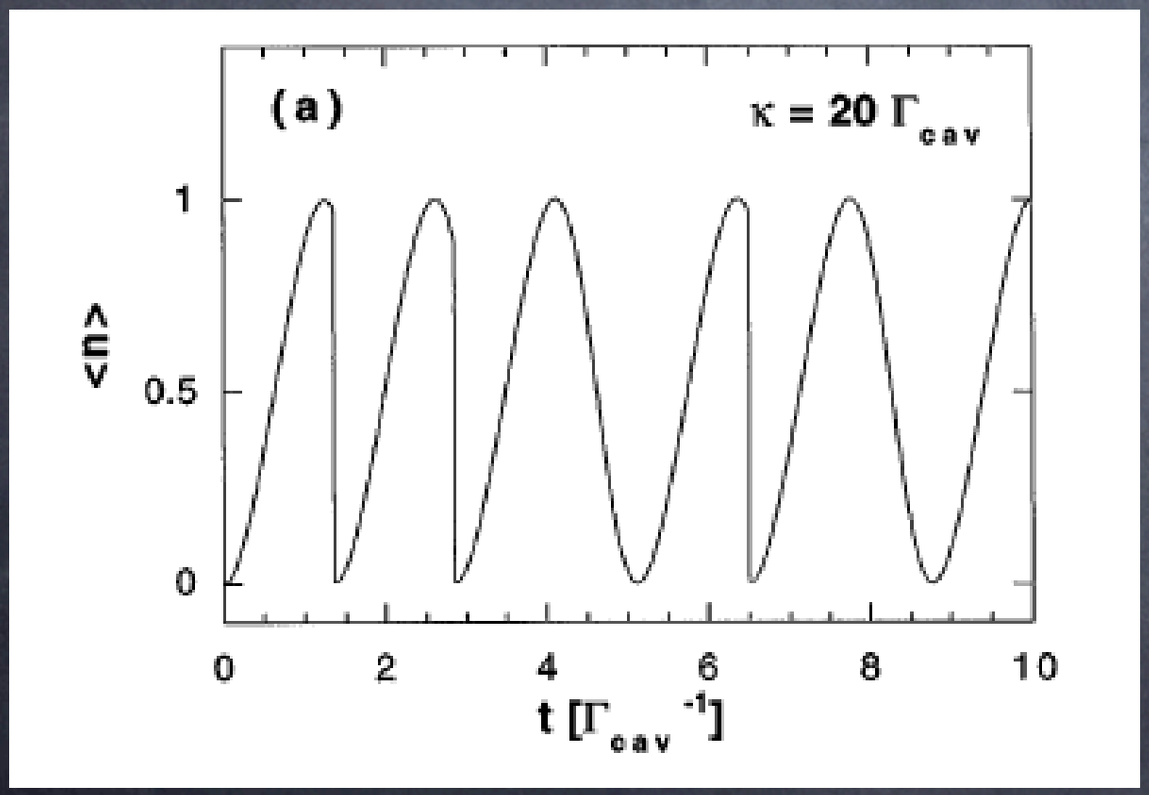
$\epsilon = \omega$

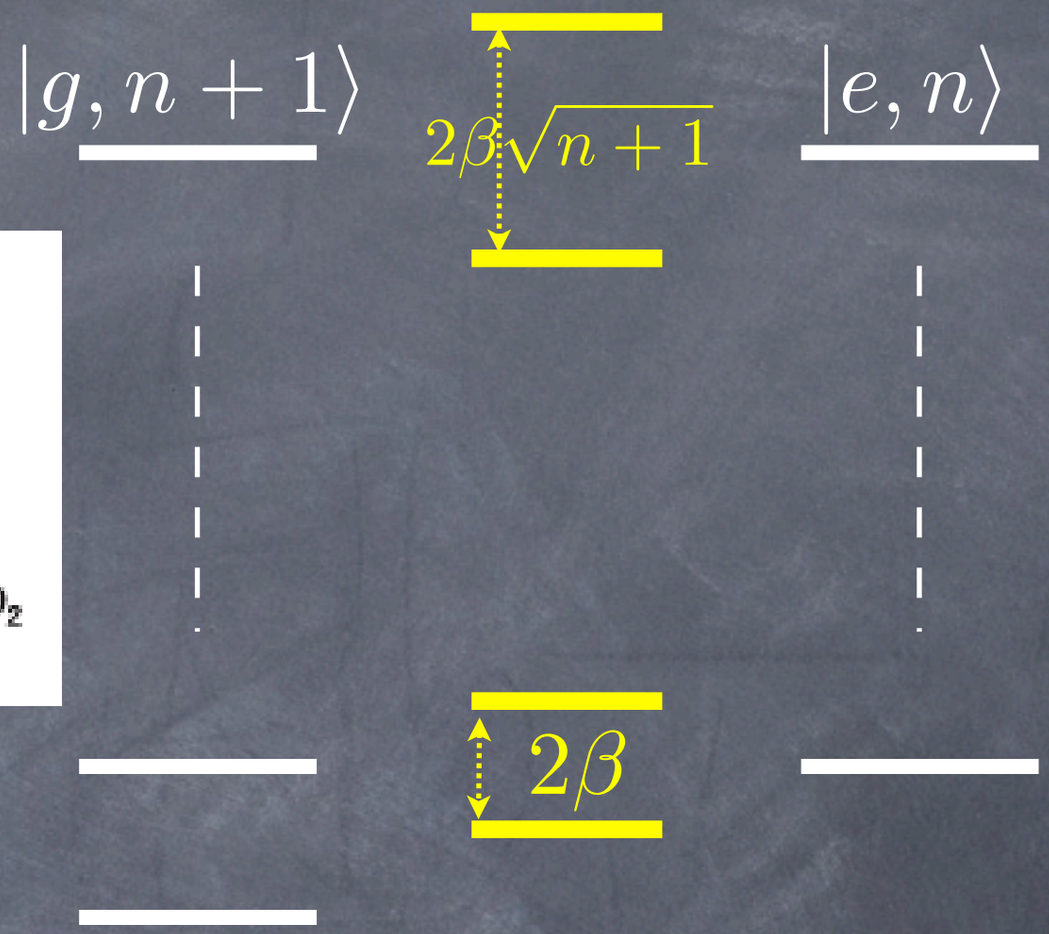
The degeneracy between
$|e, n\rangle$ and $|g, n+1\rangle$
is lifted by the coupling



Photon Blockade

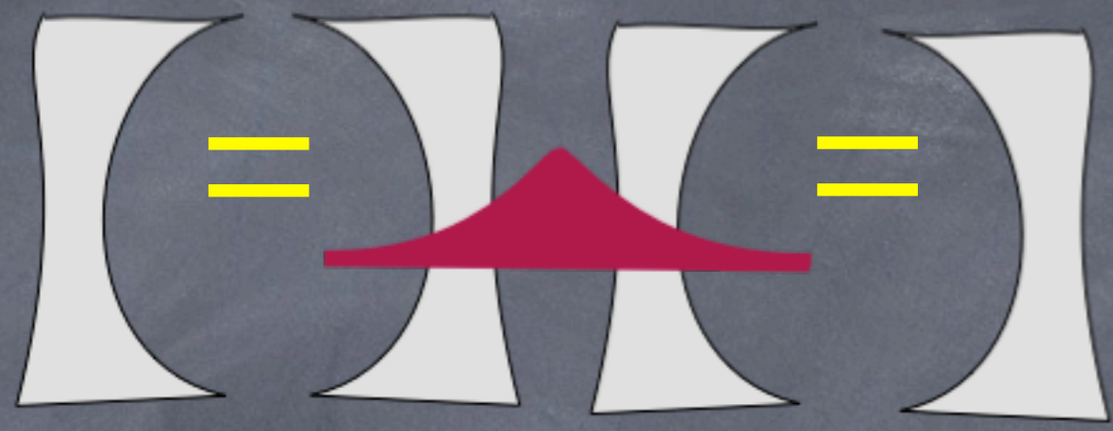






Atom-photon interaction leads to an effec. non-linear medium

A. Imamoglu *et al* 97, S. Rebic *et al* 99, J. Kim *et al* 99, K. Birnbaum *et al* 05



Competition of local non-linearity with photon hopping

Arrays of coupled cavities

- M. J. Hartmann, F.G. Brandao, and M. B. Plenio, Nat. Phys. **2**, 849 (2006)

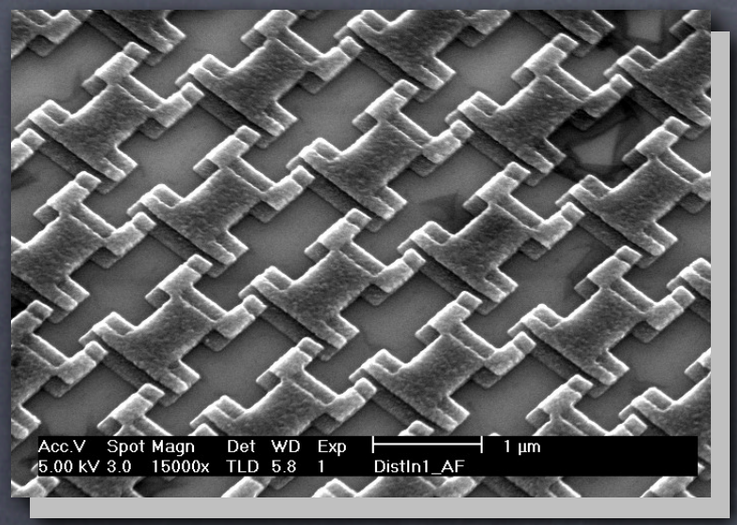
- A.D. Greentree *et al*, Nat. Phys. **2**, 856 (2006)

- D.G. Angelakis, M.F. Santos, and S. Bose, Phys. Rev. A (RC) **76**, 031805 (2007)

Review:
M.J. Hartmann, F.G.S.L. Brandao, and M.B. Plenio, Laser & Photon. Rev. **2**, 527 (2008)

Coupled Cavities

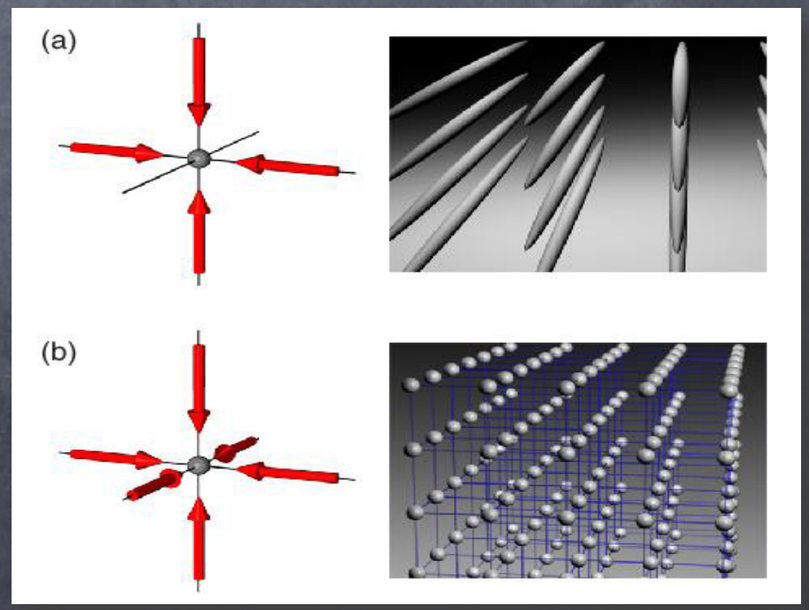
$$\mathcal{H} = \sum_i \mathcal{H}_i^{(JC)} - J \sum_{<ij>} (a_i^\dagger a_j + h.c.)$$



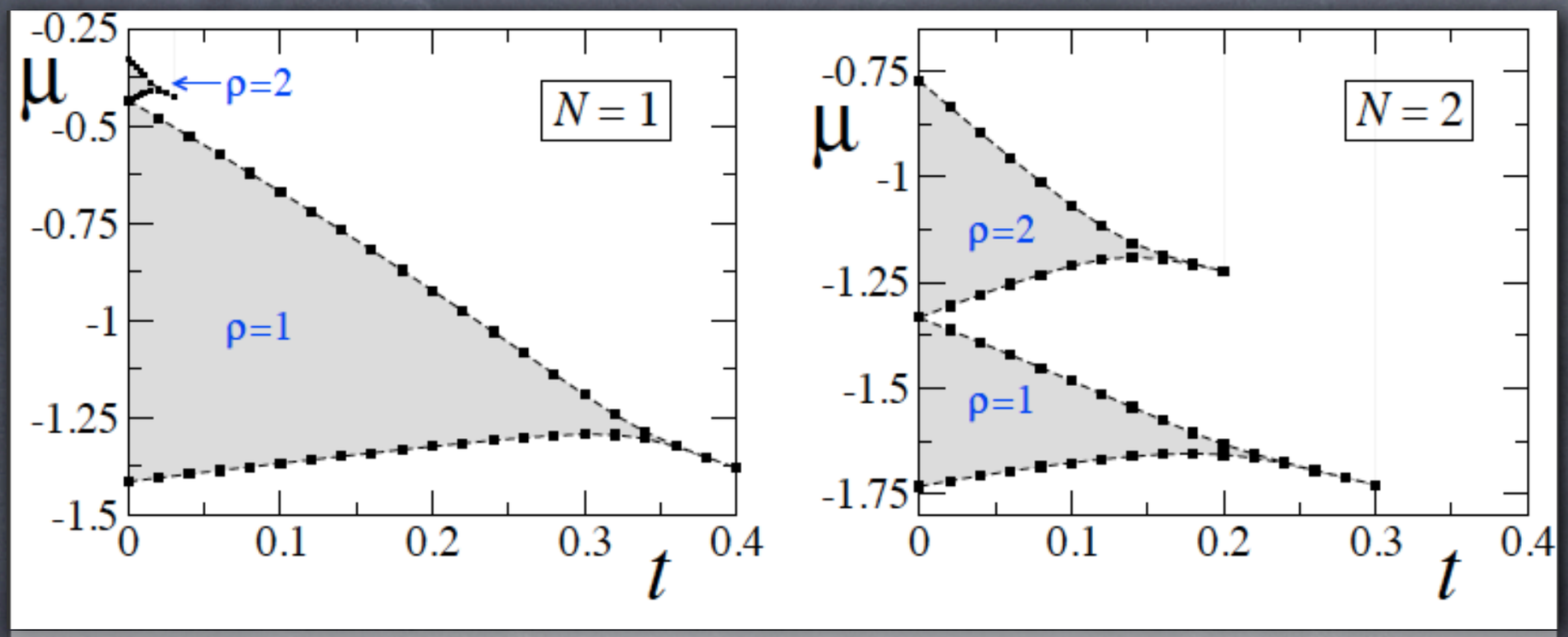
From J.E. Mooij group (TU Delft)

Josephson arrays

Optical Lattices

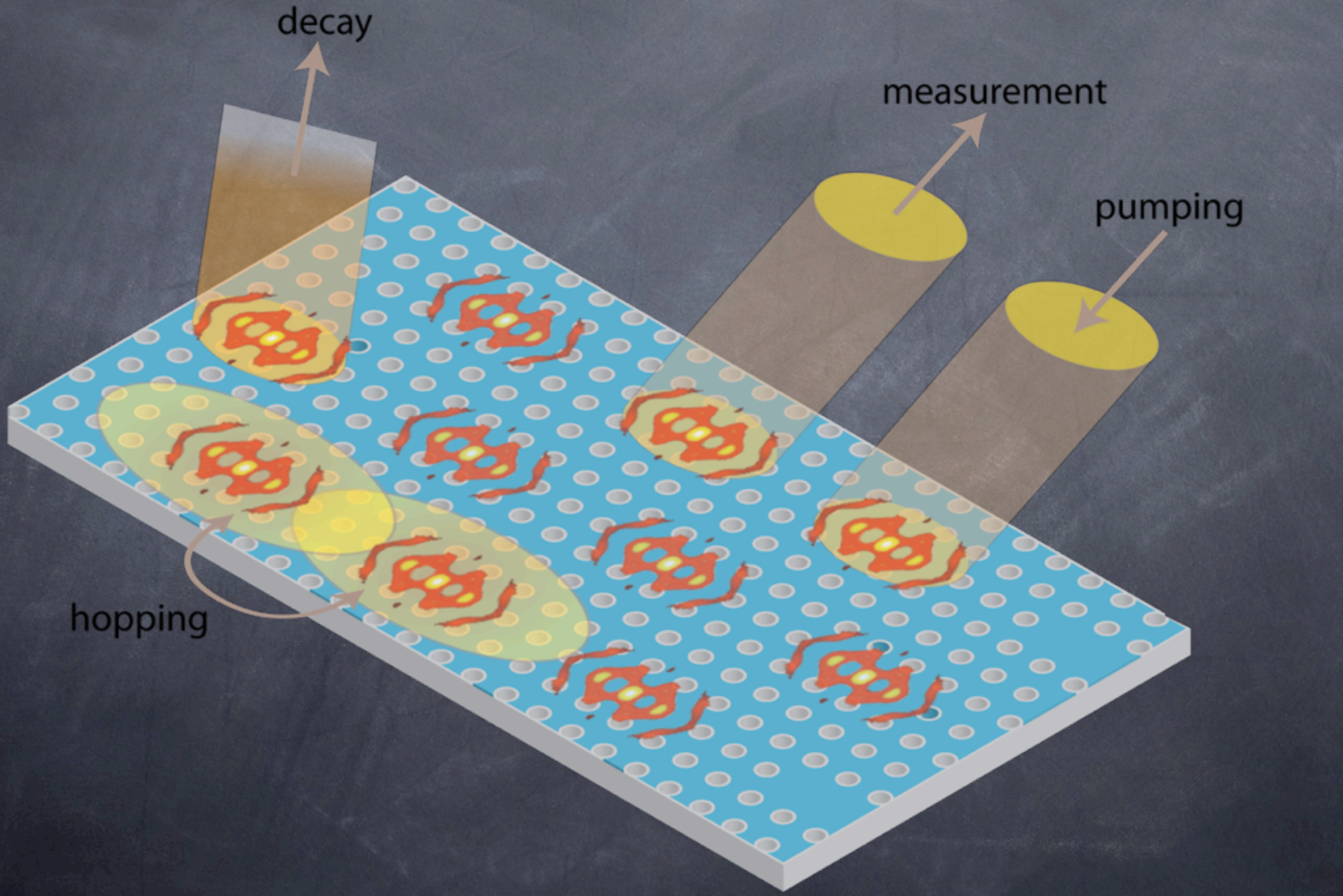


D. Jaksch et al, Phys. Rev. Lett. 81, 3108 (1998)
M. Greiner et al, Nature 415, 39 (2002)



D. Rossini and R. Fazio, Phys. Rev. Lett. **99**, 186401 (2007)

Coupled cavities out of equilibrium



- QED arrays to explore non-equilibrium quantum many-body systems

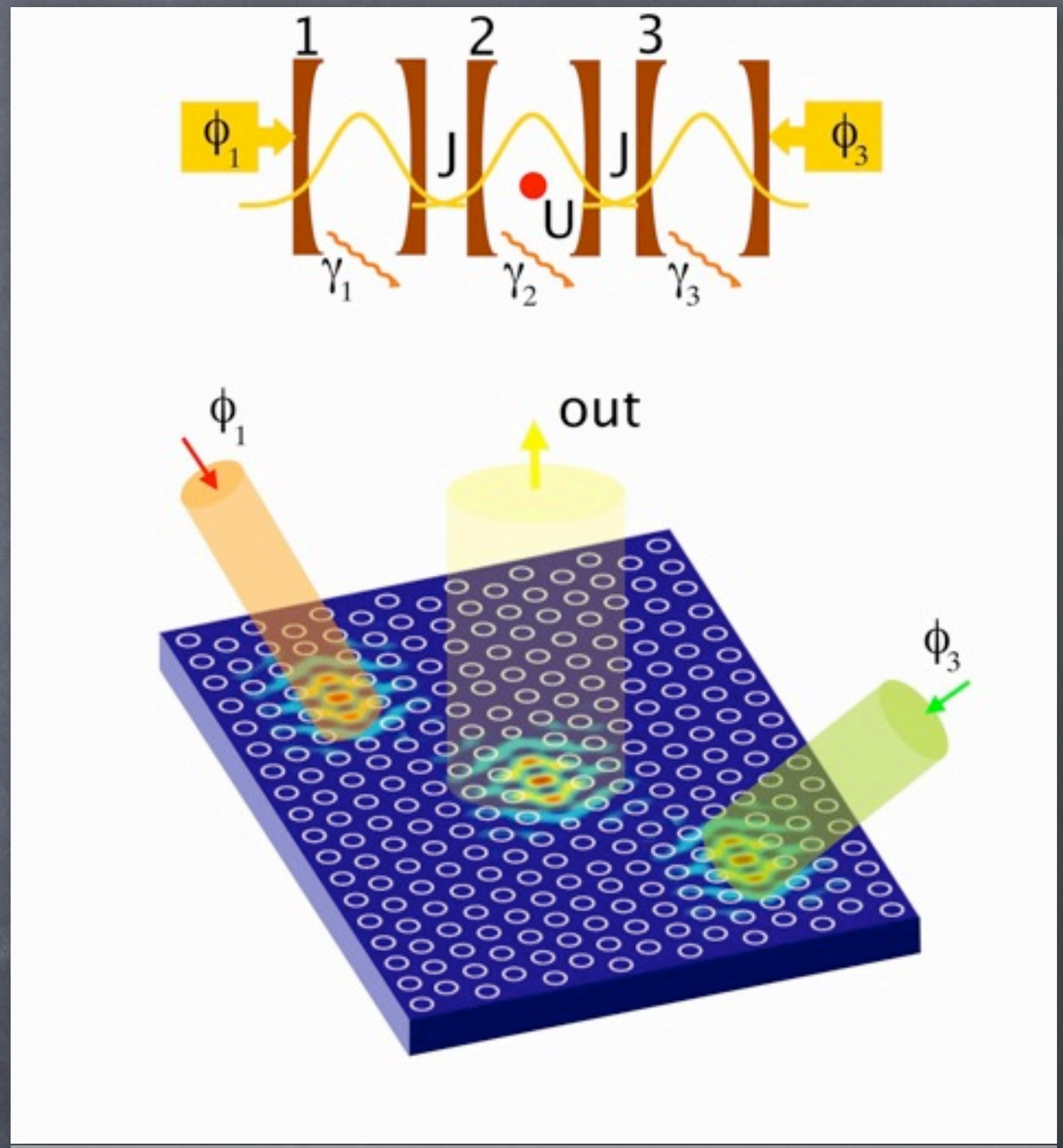
- How to realize and detect, under realistic non-equilibrium conditions, the very rich phase diagram predicted in QED arrays?

- Explore the competition between correlations and hopping in small networks

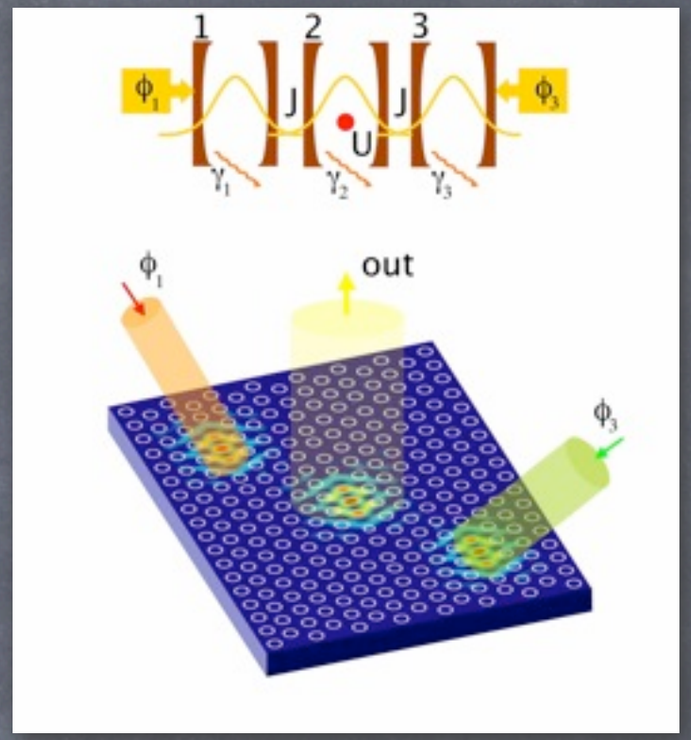
Non-equilibrium effects

Competition between correlations and hopping

THE QUANTUM OPTICAL JOSEPHSON INTERFEROMETER



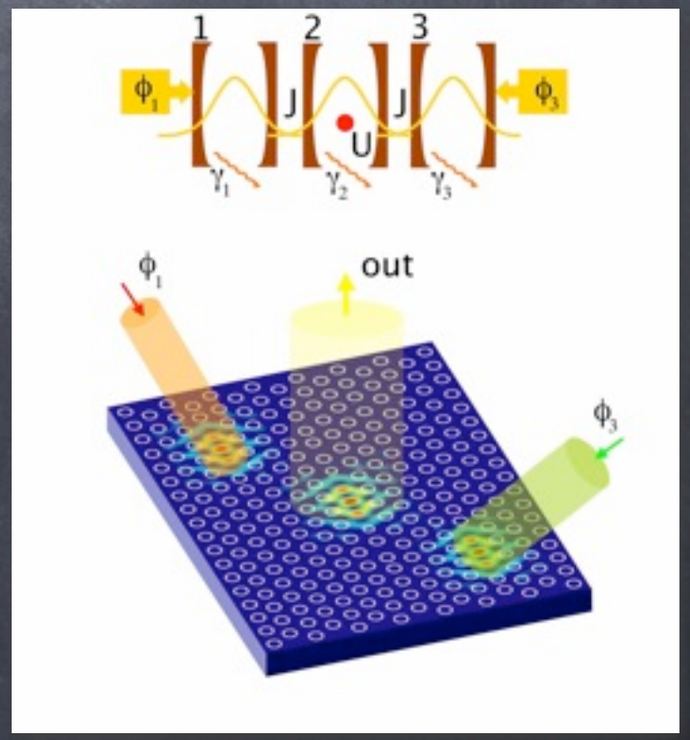
The interplay of tunneling and interactions is analyzed in the steady state of the system, when a dynamical equilibrium between driving and losses is established.



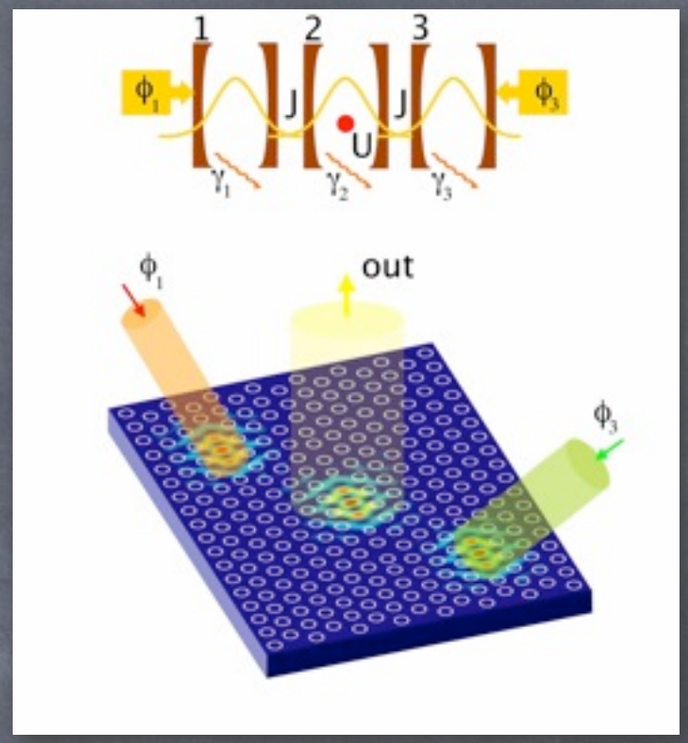
Strong photonic correlations can be identified in the suppression of Josephson-like oscillations of the light emitted from the central cavity as the nonlinearity is increased.

$$\hat{H} = \sum_{k=1}^{3} \Delta_k \hat{p}_k^\dagger \hat{p}_k + J(\hat{p}_1^\dagger \hat{p}_2 + \hat{p}_2^\dagger \hat{p}_3 + \text{h.c.}) + U \hat{p}_2^\dagger \hat{p}_2^\dagger \hat{p}_2 \hat{p}_2 + \sum_{k=1,3} (E_k \hat{p}_k^\dagger + \text{h.c.})$$

$$\frac{\partial \rho}{\partial t} = i[\rho, \hat{H}] + \sum_{k=1}^{3} \frac{\gamma_k}{2} (2\hat{p}_k \rho \hat{p}_k^\dagger - \hat{p}_k^\dagger \hat{p}_k \rho - \rho \hat{p}_k^\dagger \hat{p}_k)$$

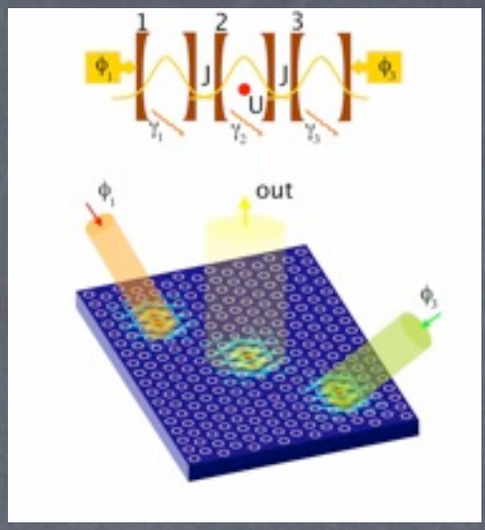


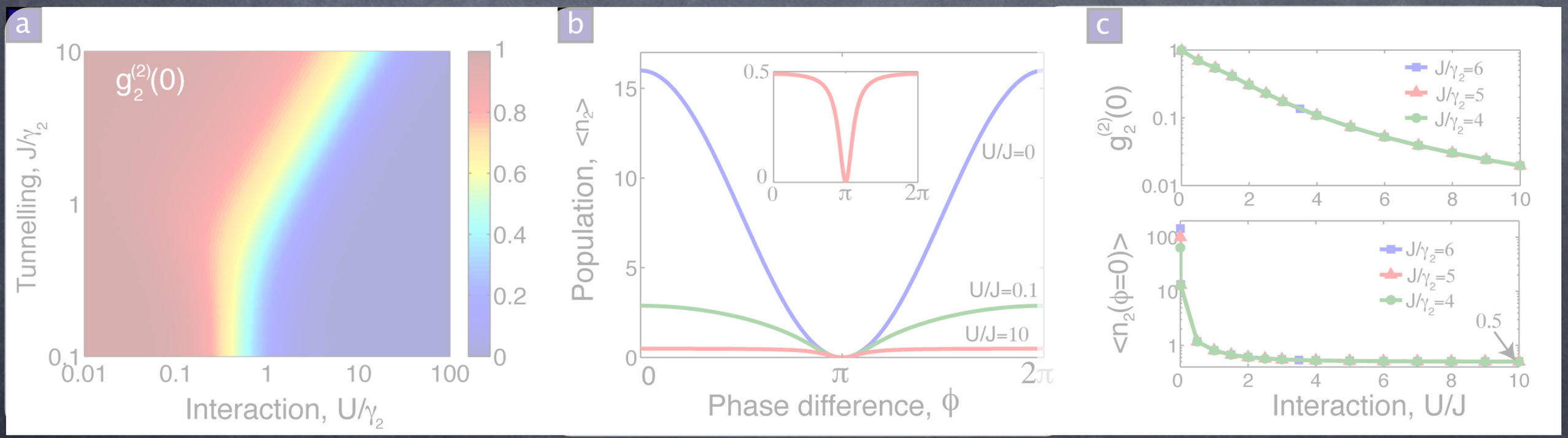
$$\langle n_2 \rangle = Tr\{\hat{p}_2^\dagger \hat{p}_2 \rho_{\rm ss}\}$$



$$g_2^{(2)}(\tau = 0) = Tr\{\hat{p}_2^\dagger \hat{p}_2^\dagger \hat{p}_2 \hat{p}_2 \rho_{\rm ss}\}/\langle n_2 \rangle^2$$

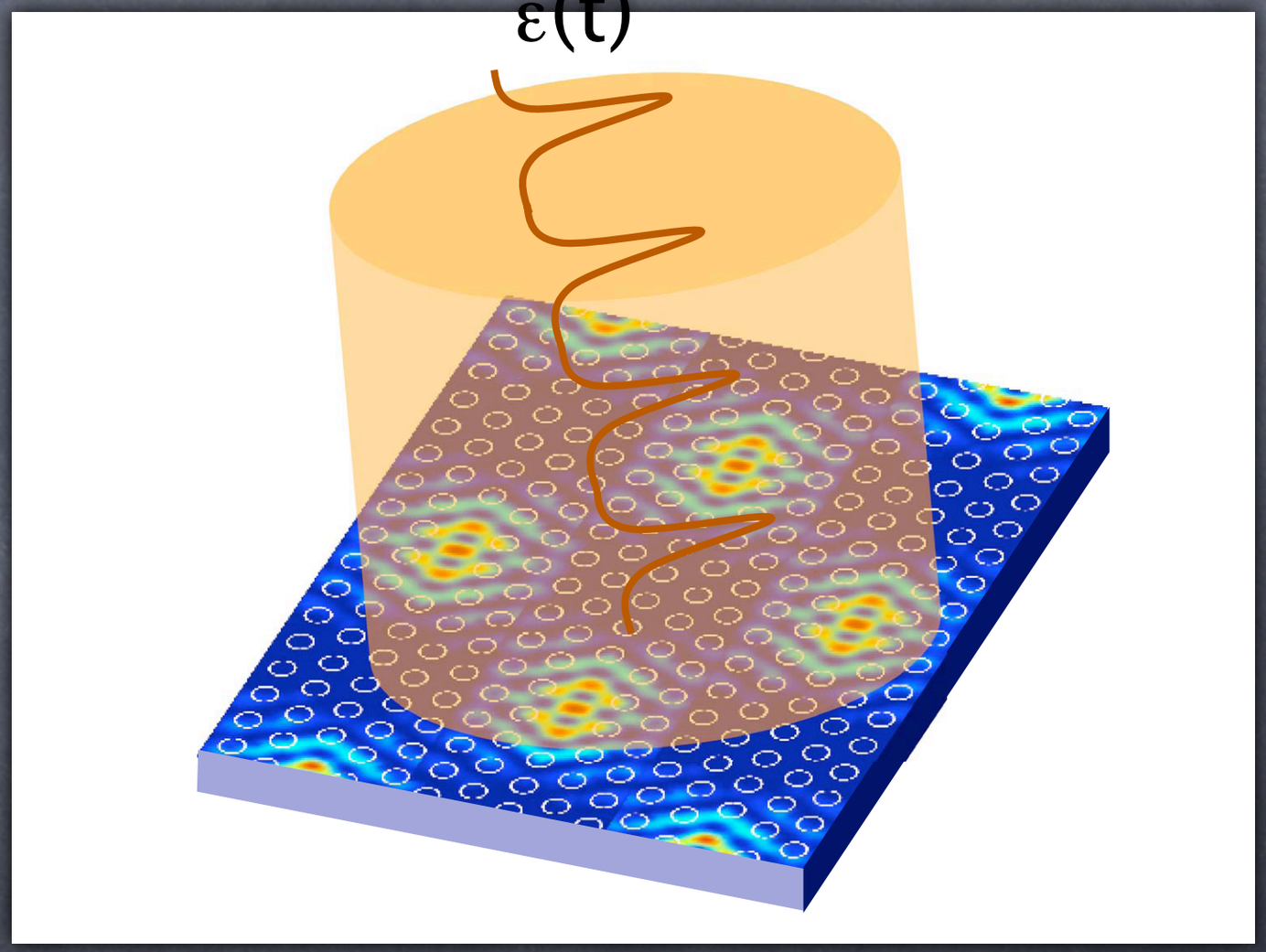
The quantum optical Josephson interferometer



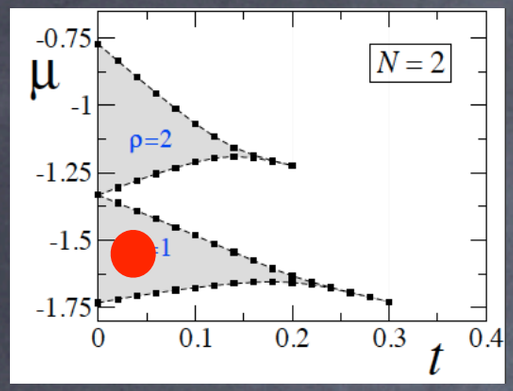


Coupled cavities
&
Quantum quenches

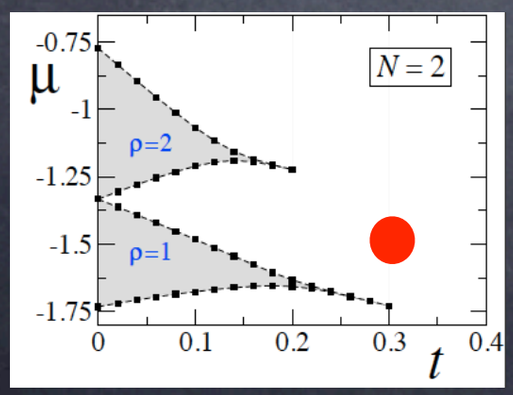
array is driven by a pulsed external laser



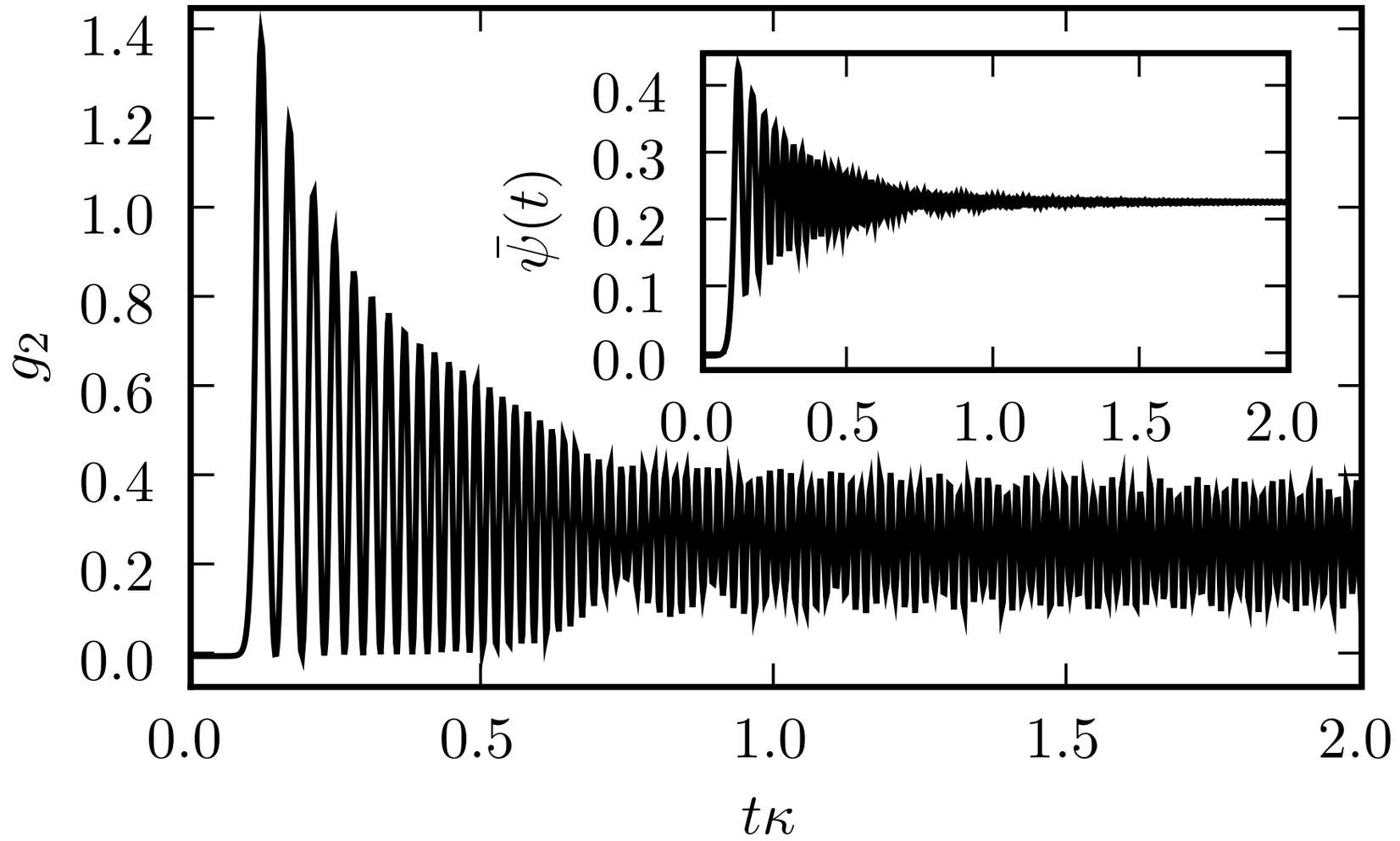
$J < J_{cr}$



$J > J_{cr}$

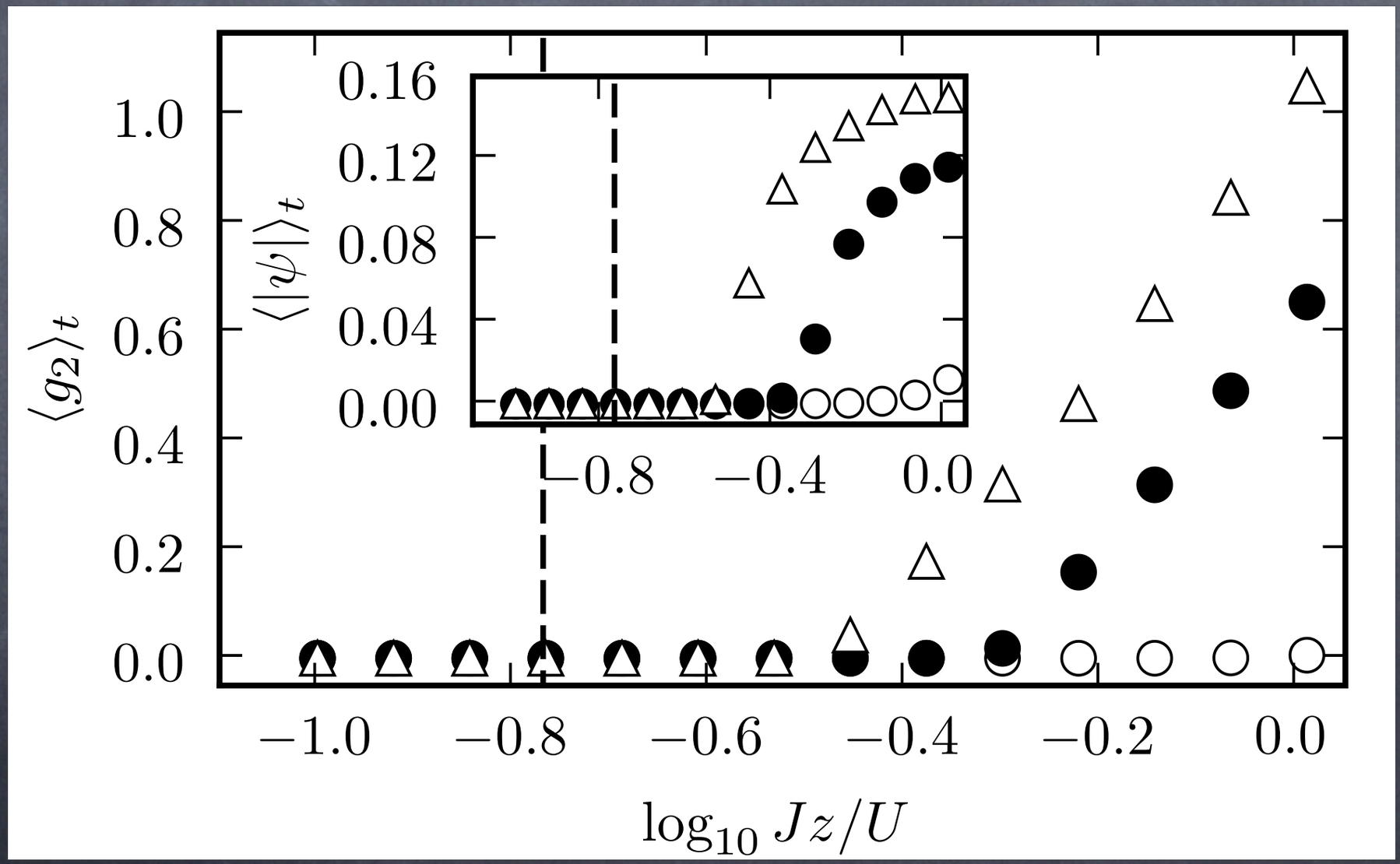


see Altman & Auerbach, PRL (2002)



- At short times, a linear instability sets in and both quantities increase exponentially
- At later times, the collective (non-linear) dynamics of the array leads to oscillations
- Damping at times larger than the photon lifetime

zero-time delay second-order correlation function averaged over a certain interval of time



Conclusions

- Quantum optical Josephson interferometer
- Networks based QED-cavities?
- Non-equilibrium quantum phase transitions?

Funding