Simulating Quantum Simulators

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Critical Phenomena in Open Many-Body systems

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J. Jin, A. Biella, O. Viyuela, L. Mazza, J. Keeling, R. F., D. Rossini, Phys. Rev. X **6**, 031011 (2016)

R. Rota, F. Storme, N. Bartolo, R. F., and C. Ciuti arXiv:1609.02848

Quantum Simulators

Controllable quantum systems

- Detailed microscopic knowledge
- Strong interactions
- Highly tuneable
- High level of coherence over large time scales
- Good access for measurements

Quantum Simulators

Condensed matter physical systems of interests:

Quantum spin chains & ladders
Frustrated quantum magnets
High-Tc superconductors
…

Quantum Simulators

Non-equilibrium dynamics
. . . a number of interesting questions

- Dynamics of collective variables

- Adiabatic dynamics of many-body systems
  - Kibble-Zurek mechanism
  - adiabatic quantum computation

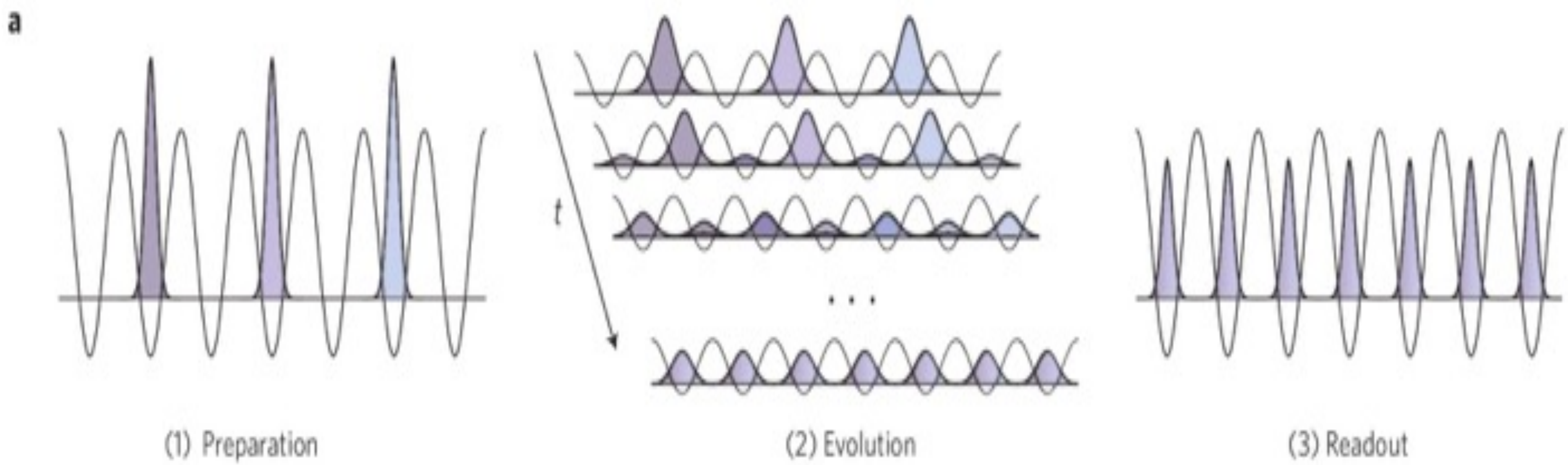
- Thermalization
  - a many-body system being its own bath
  - Generalized Gibbs Ensemble for integrable systems

- ...

Quantum Simulators

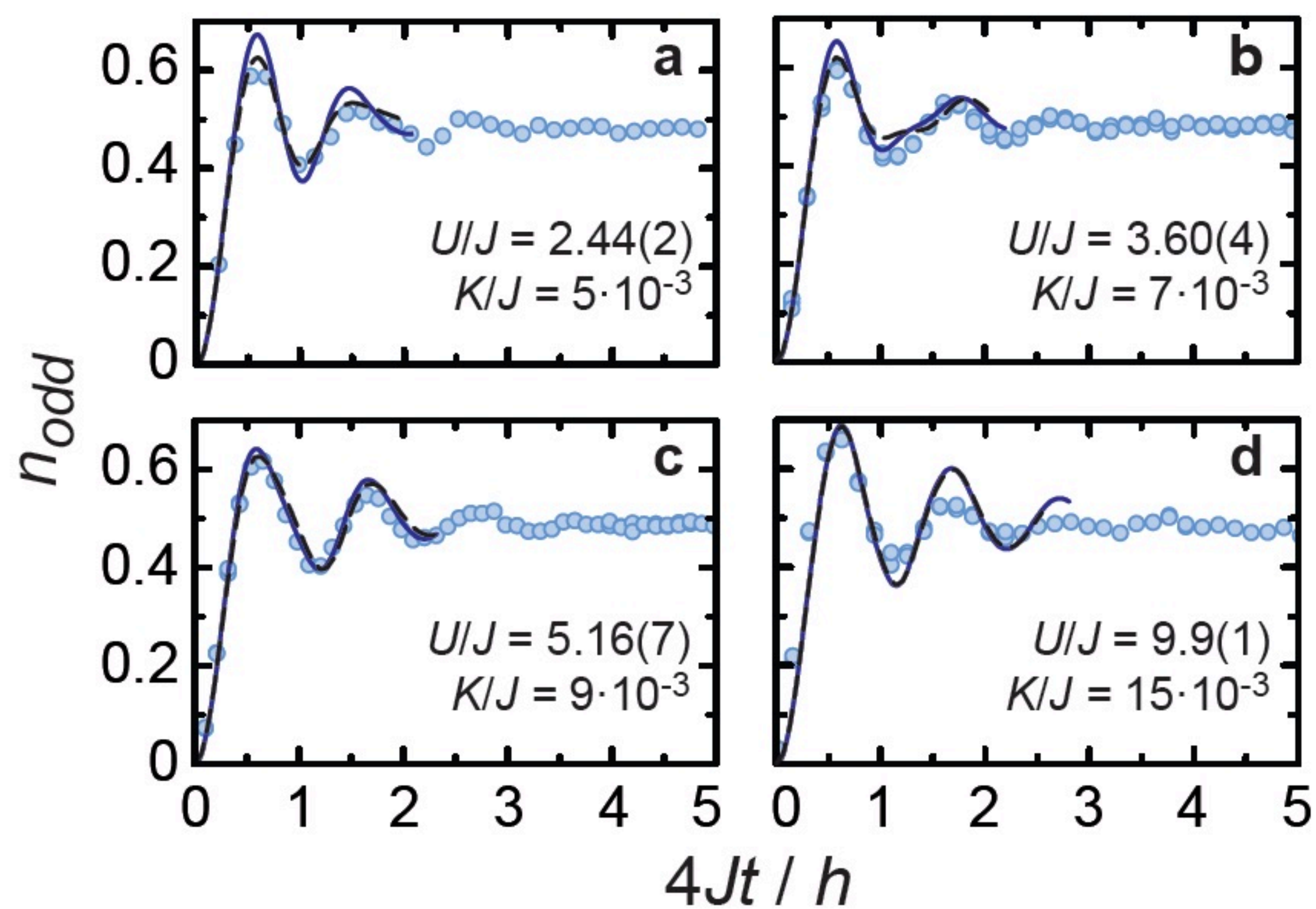
Fast dynamical relaxation in a Bose gas on a 1D lattice

Trotsky, et al Nat. Phys. ***8****, 325 (2012)*



A quantum simulator "beating" a classical simulation

...but "still" numerical simulations are necessary!



This talk…

Open systems quantum simulators

This talk…

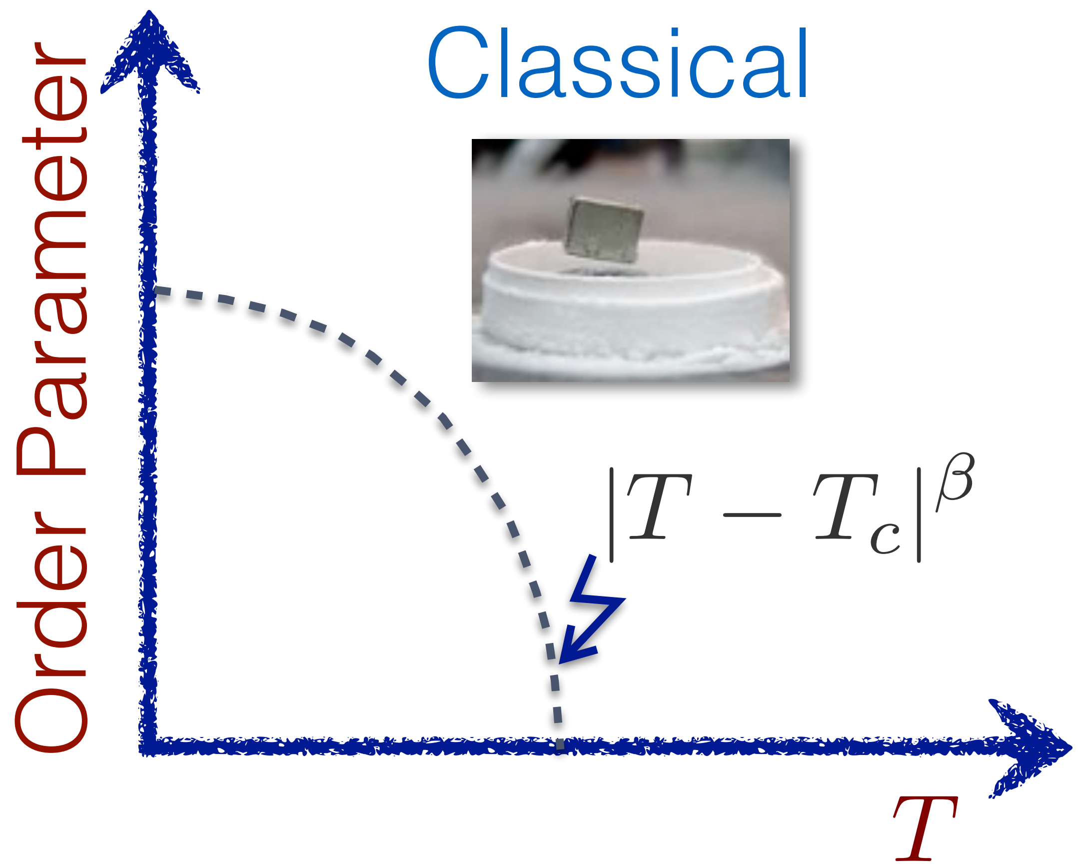
Outline: "Some peculiarities" of phase transitions in dissipative many-body quantum systems

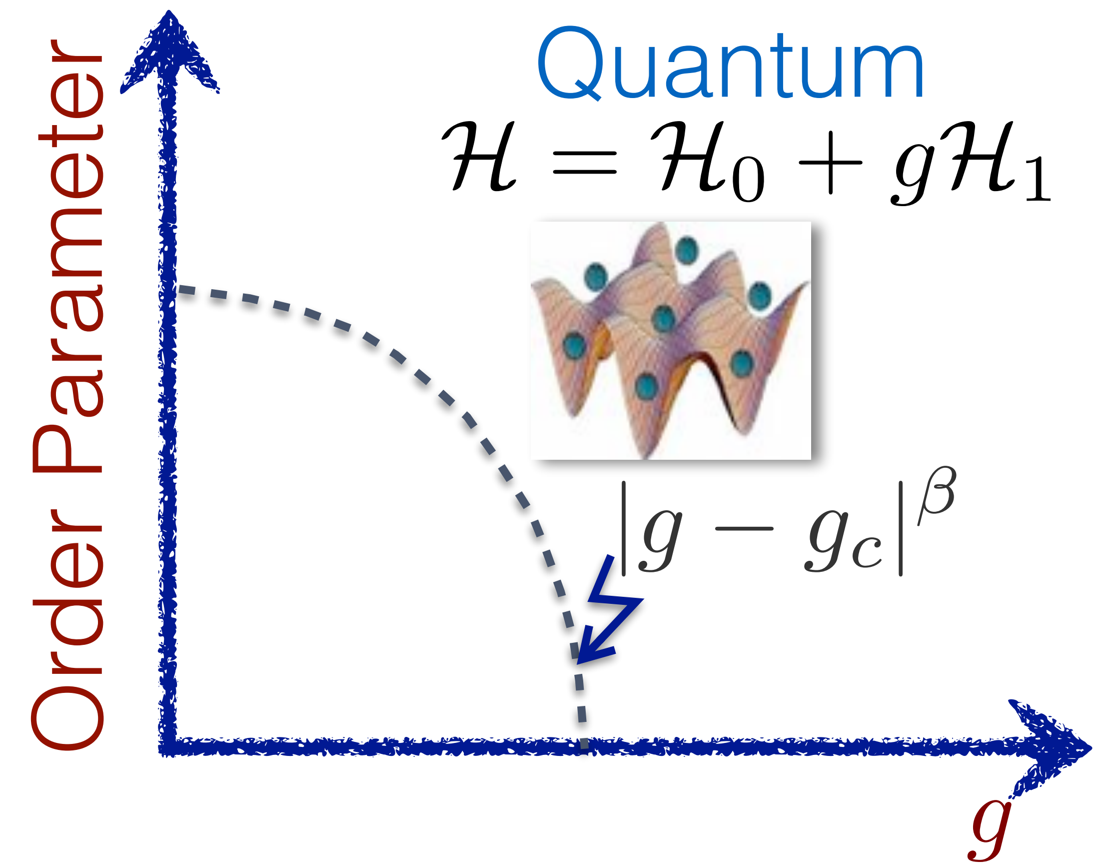
"Most of the action" does **not** occur in one-dimension

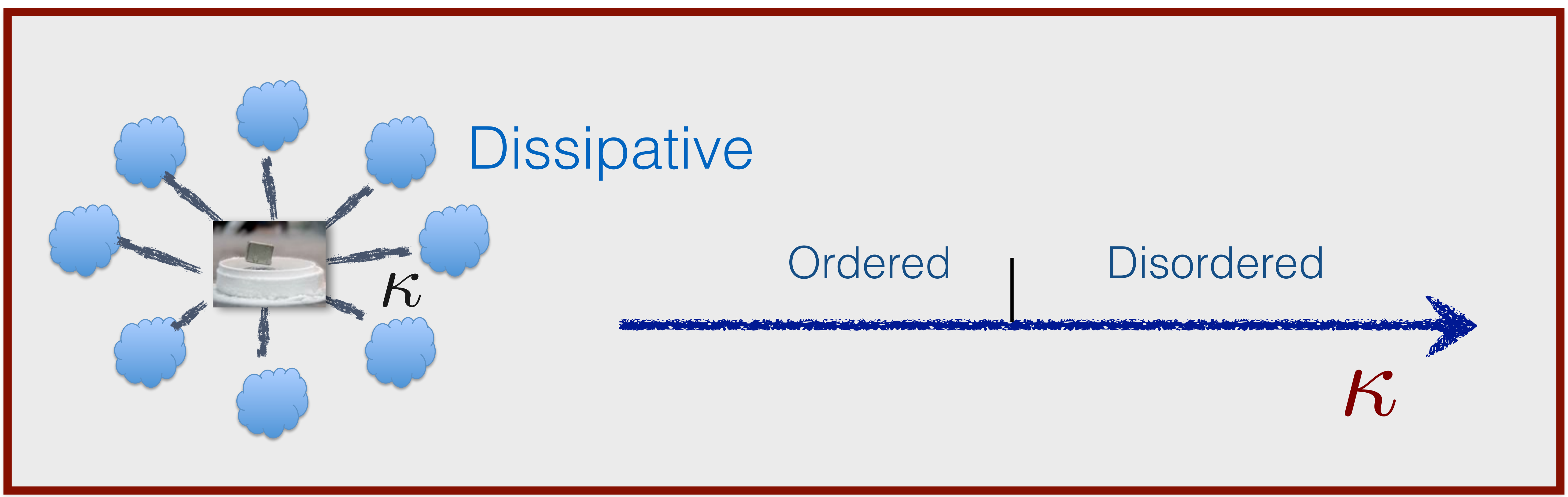
Need for efficient numerical methods to simulate many-body open systems

see e.g. A. Daley (2014)

Phase Transitions







Dissipative phase transitions

- Rich(er) steady-state phase diagram: *(symmetry broken phases, incommensurate phases, limit cycles,…)*

  J. Keeling *et al*, Carusotto & Ciuti, Lee et al, Boitè *et al*, Ludwig & Marquardt, Chan *et al*, …

- Modified critical behaviour: *(coupling to the environment may change the universality class)*

  Della Torre *et al*, Diehl *et al*, Öztop *et al,* Domokos *et al* …

- Equilibrium vs non-equilibrium: *(the steady-state does not need to describe an equilibrium state)*

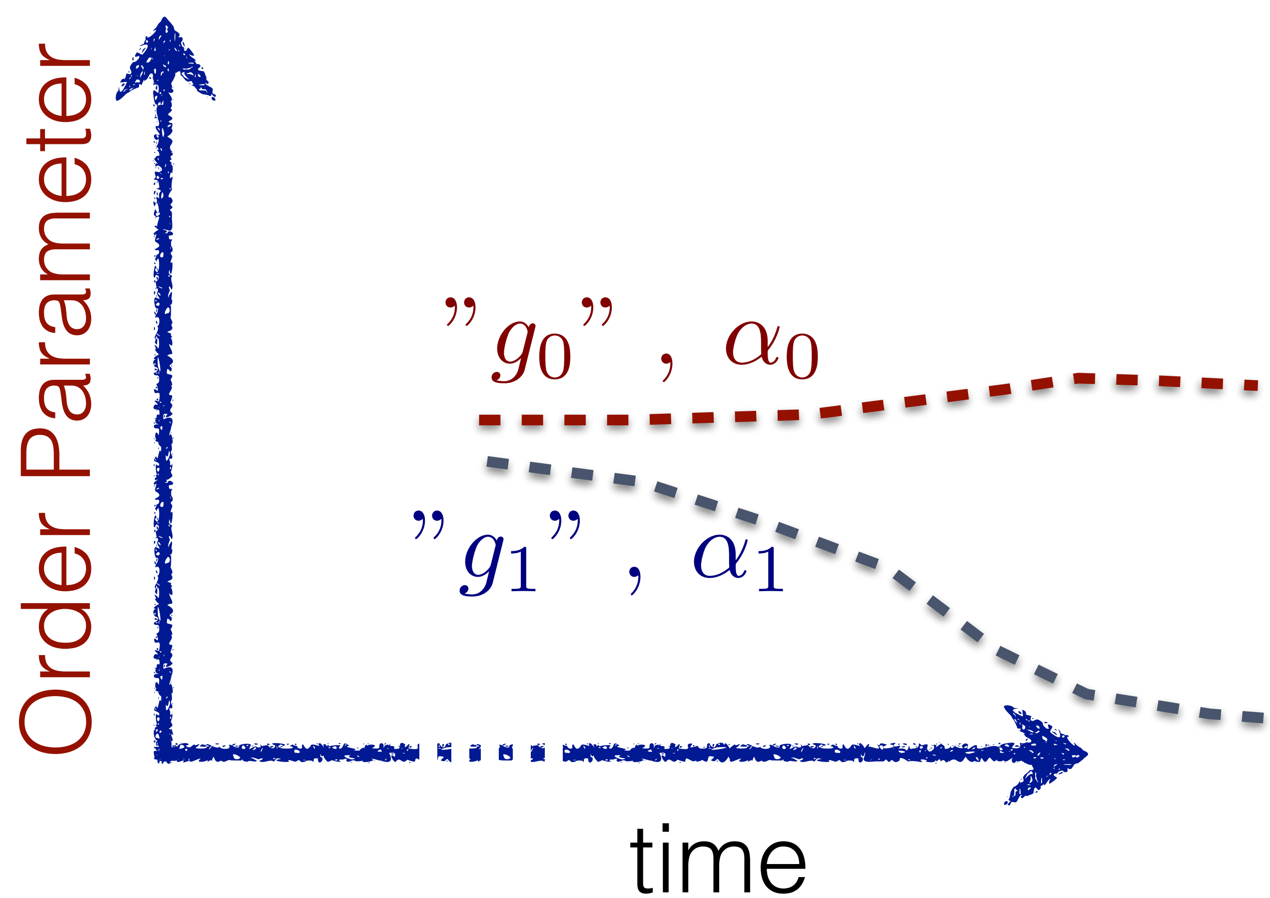
- Control on properties of the bath: *(Cavity arrays, BEC in cavities, Rydberg atoms, trapped ions,…)*

Critical phenomena …Basics

- Diverging correlation length $\xi \sim |g - g_c|^{-\nu}$
- Long-wavelength fluctuations determine the critical behaviour
- Short-wavelength fluctuations affect non-universal properties (e.g. the critical coupling g_c)
- Mean-field ignores fluctuations and will eventually becomes exact as the dimensionality of the system increases
- Quantum fluctuations are irrelevant at finite temperatures and the only important for QCPs

Dissipative phase transitions

$$\dot{\rho} = -i[\overset{g}{\mathcal{H}}, \rho] + \overset{\alpha}{\mathcal{L}}[\rho]$$



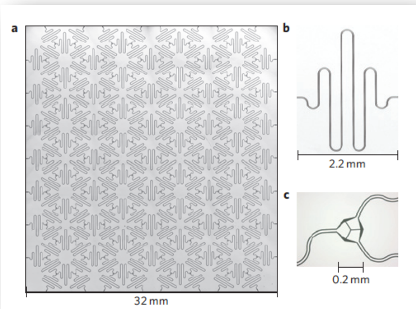
- Competition within the Hamiltonian (e.g. strong local correlation and delocalisation)

$$\mathcal{H} = \mathcal{H}_0 + g\mathcal{H}_1$$

- Competition between unitary dynamics and damping (e.g. photon leakage and external driving)

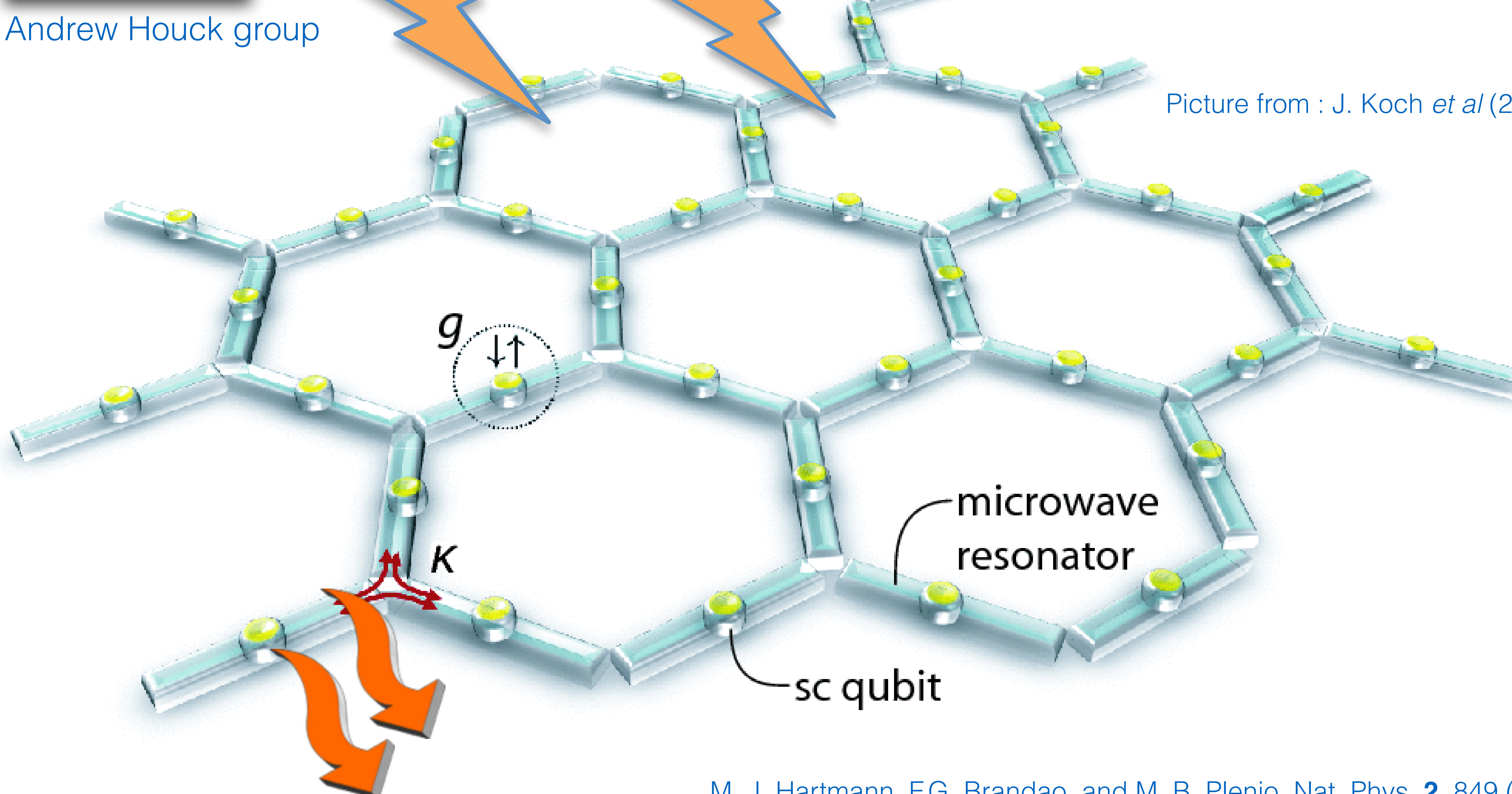
$$\mathcal{H} \longleftrightarrow \mathcal{L}$$

Coupled cavity arrays



Andrew Houck group

Promising platform to study dissipative transitions



Picture from : J. Koch *et al* (2010)

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)

Short-range fluctuations

- Short-range correlations have a dramatic impact on the steady-state phase diagram of quantum driven-dissipative systems.

- This effect, never observed in equilibrium, follows from the fact that ordering in the steady state is of dynamical origin.

From single-site to cluster mean field

$$\dot{\rho} = -i[\mathcal{H}, \rho] + \mathcal{L}[\rho]$$

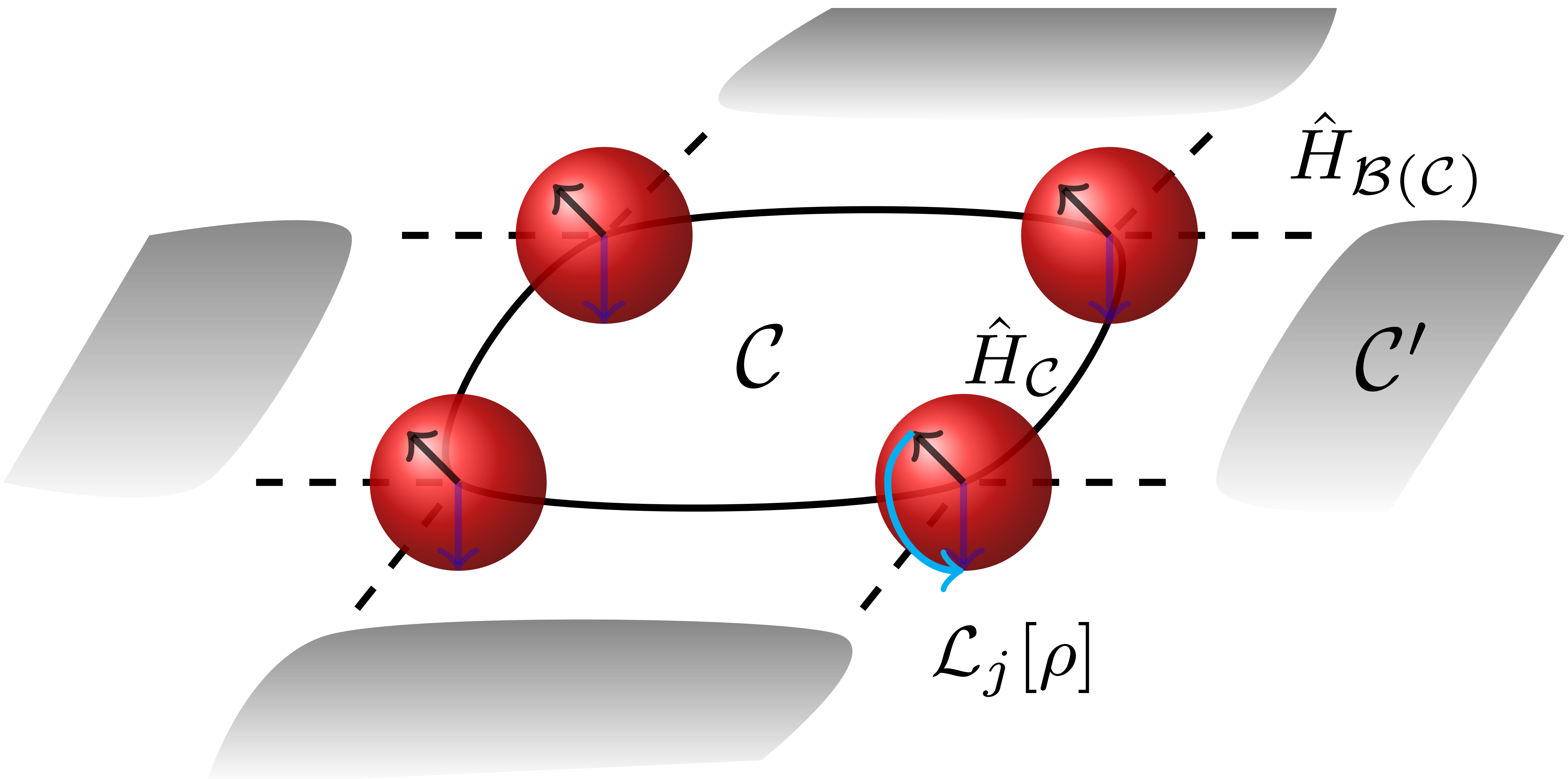
single-site mean field

$$\rho \sim \prod_i \rho_i$$

cluster mean field

$$\rho \sim \prod_{cl} \rho_{cl}$$

From single-site to cluster mean field



From single-site to cluster mean field

$$\hat{H} = \sum_{\langle i,j \rangle} \left(J_x \hat{\sigma}_i^x \hat{\sigma}_j^x + J_y \hat{\sigma}_i^y \hat{\sigma}_j^y + J_z \hat{\sigma}_i^z \hat{\sigma}_j^z \right)$$

$$\sum_j \mathcal{L}_j[\rho] = \gamma \sum_j \left[\hat{\sigma}_j^- \rho \, \hat{\sigma}_j^+ - \frac{1}{2} \left\{ \hat{\sigma}_j^+ \hat{\sigma}_j^-, \rho \right\} \right]$$

Single-site mean field

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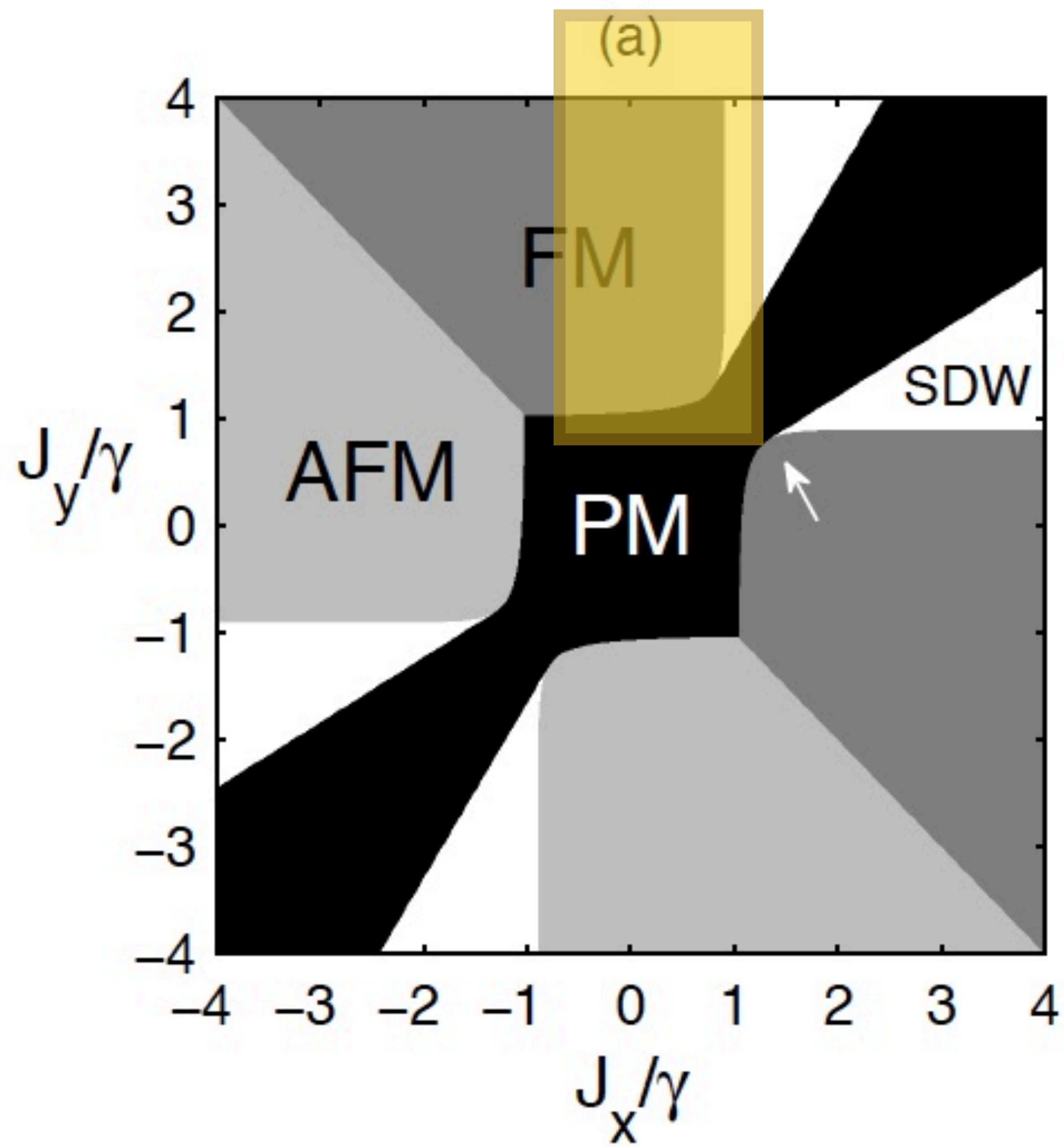
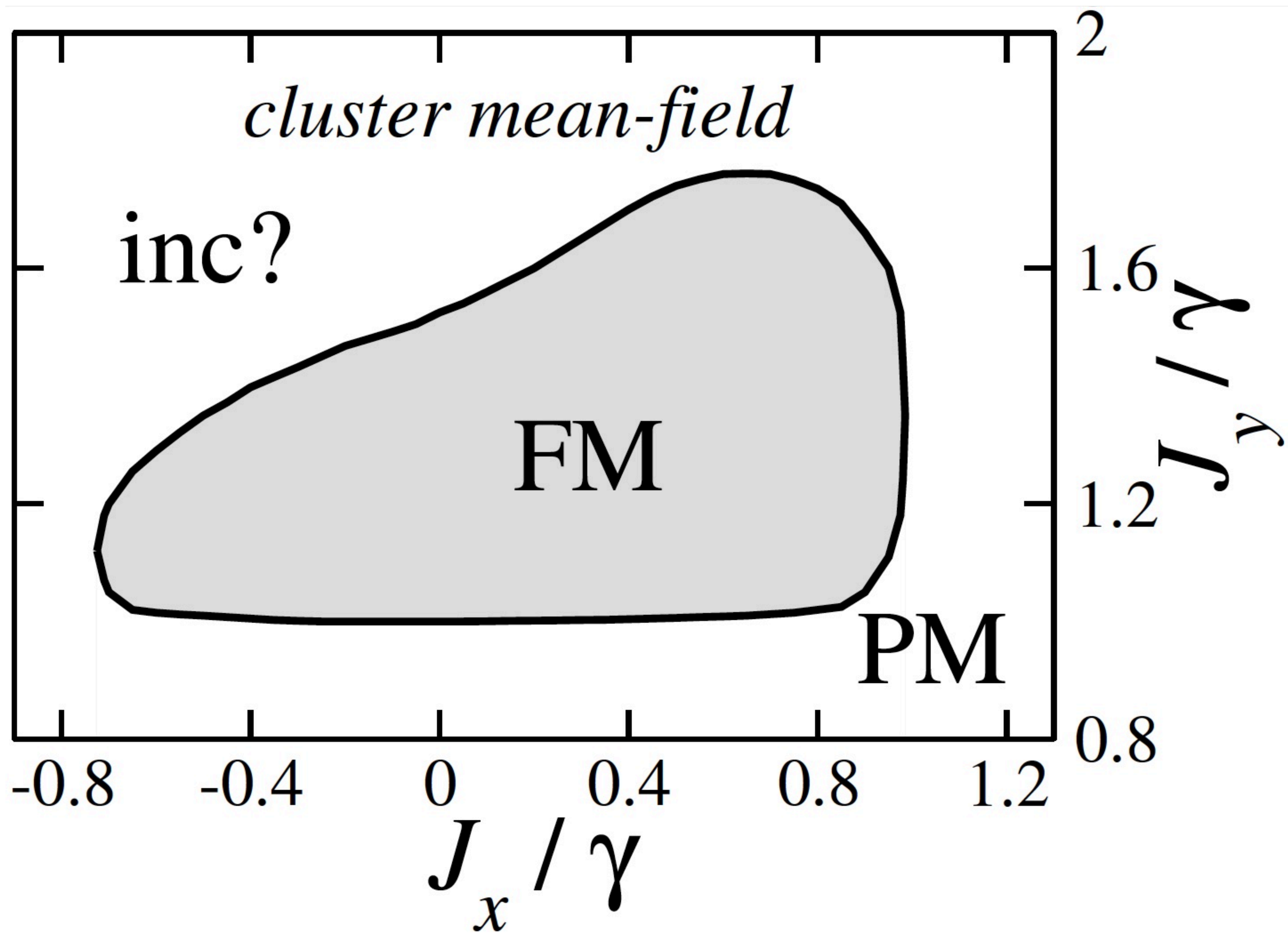
T. E. Lee, S. Gopalakrishnan, and M. D. Lukin, Phys. Rev. Lett. **110**, 257204 (2013).



From single-site to cluster mean field



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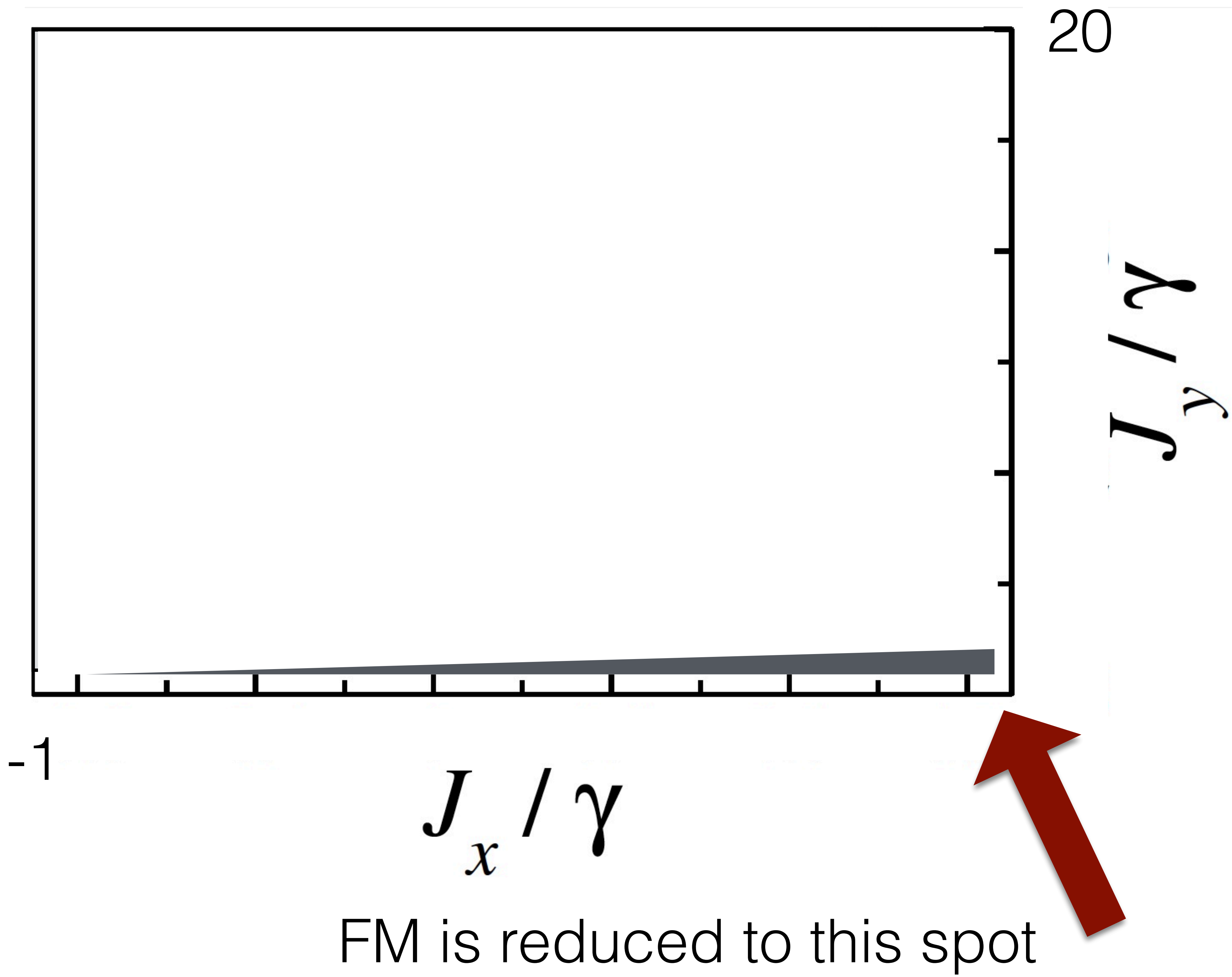
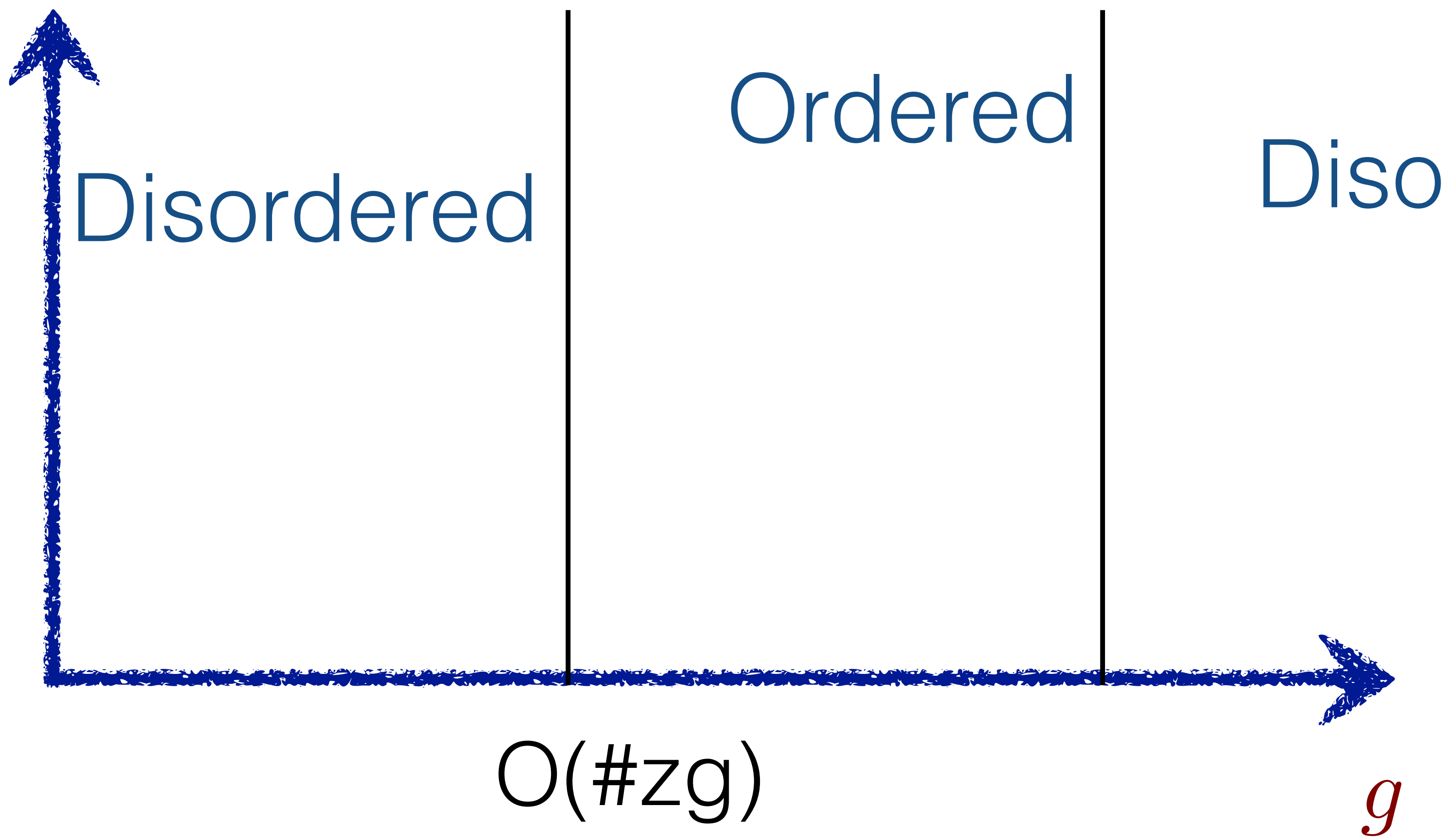


From single-site to cluster mean field

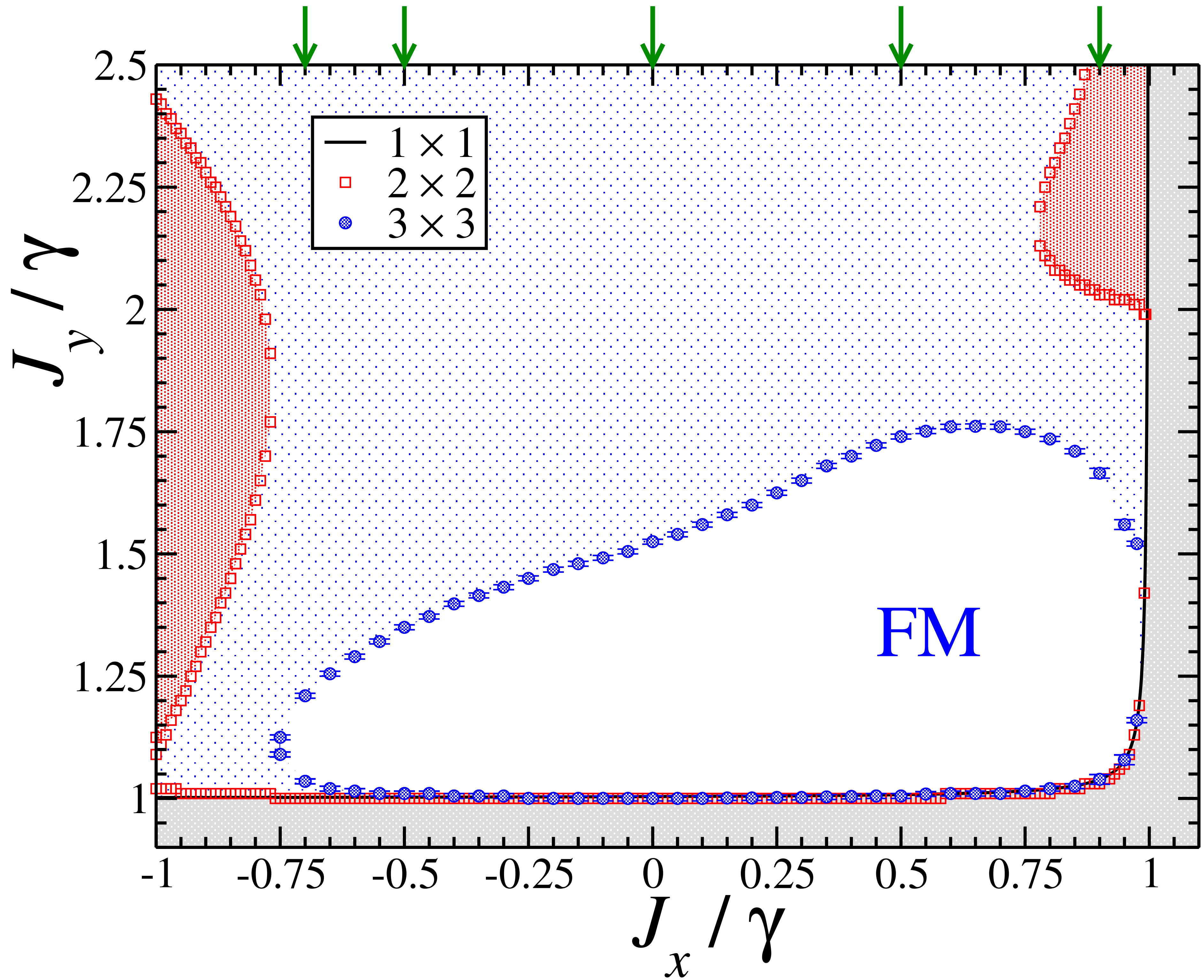


- Methods:

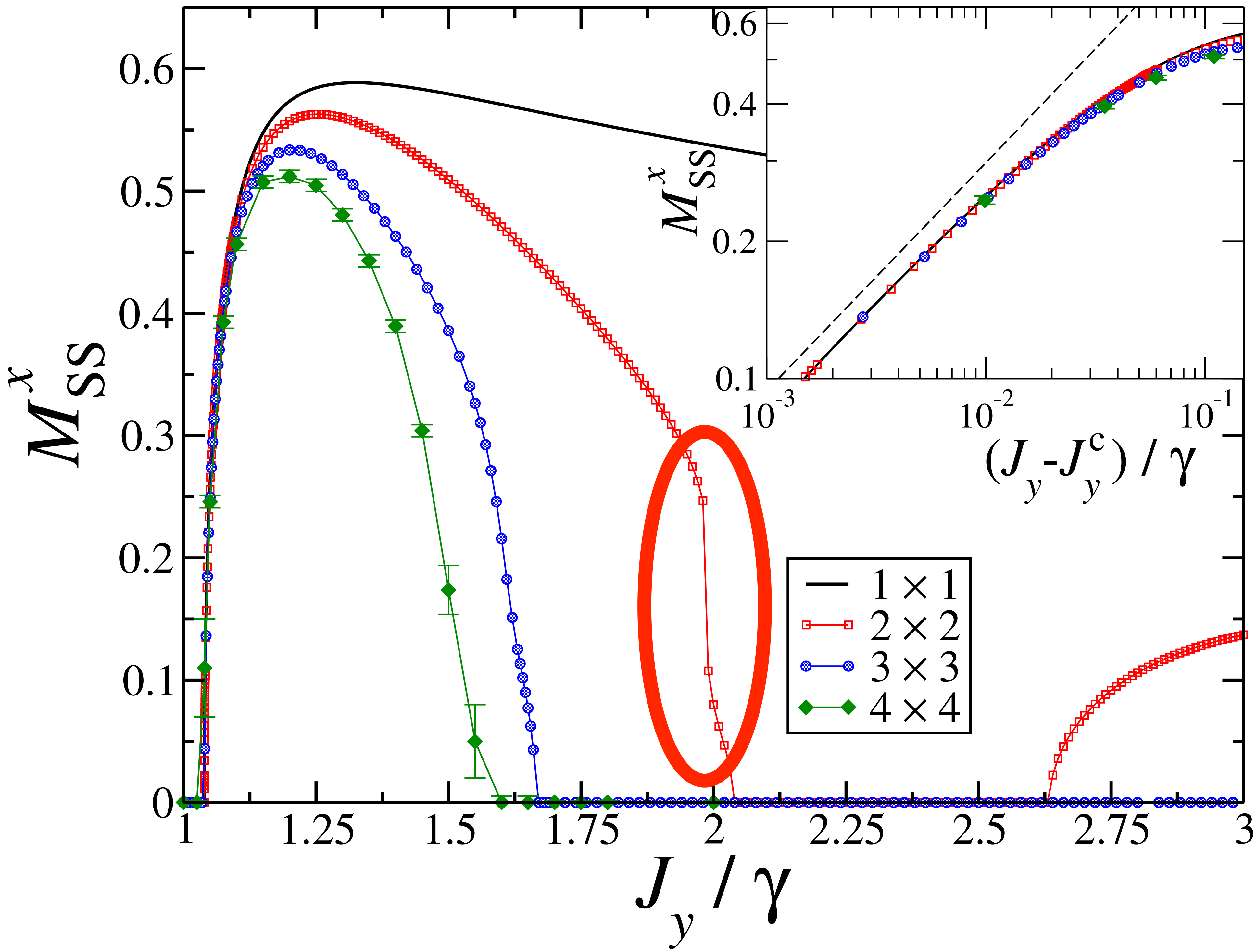
  - Cluster approach + Quantum trajectories
  - Tensor networks techniques
  - Corner renormalisation method S. Finazzi, A. Le Boite, F. Storme, A. Baksic, and C. Ciuti, Phys. Rev. Lett. 115, 080604 (2015).

- In 1D it is possible to show, by a scaling analysis, with the cluster size that the transition disappears

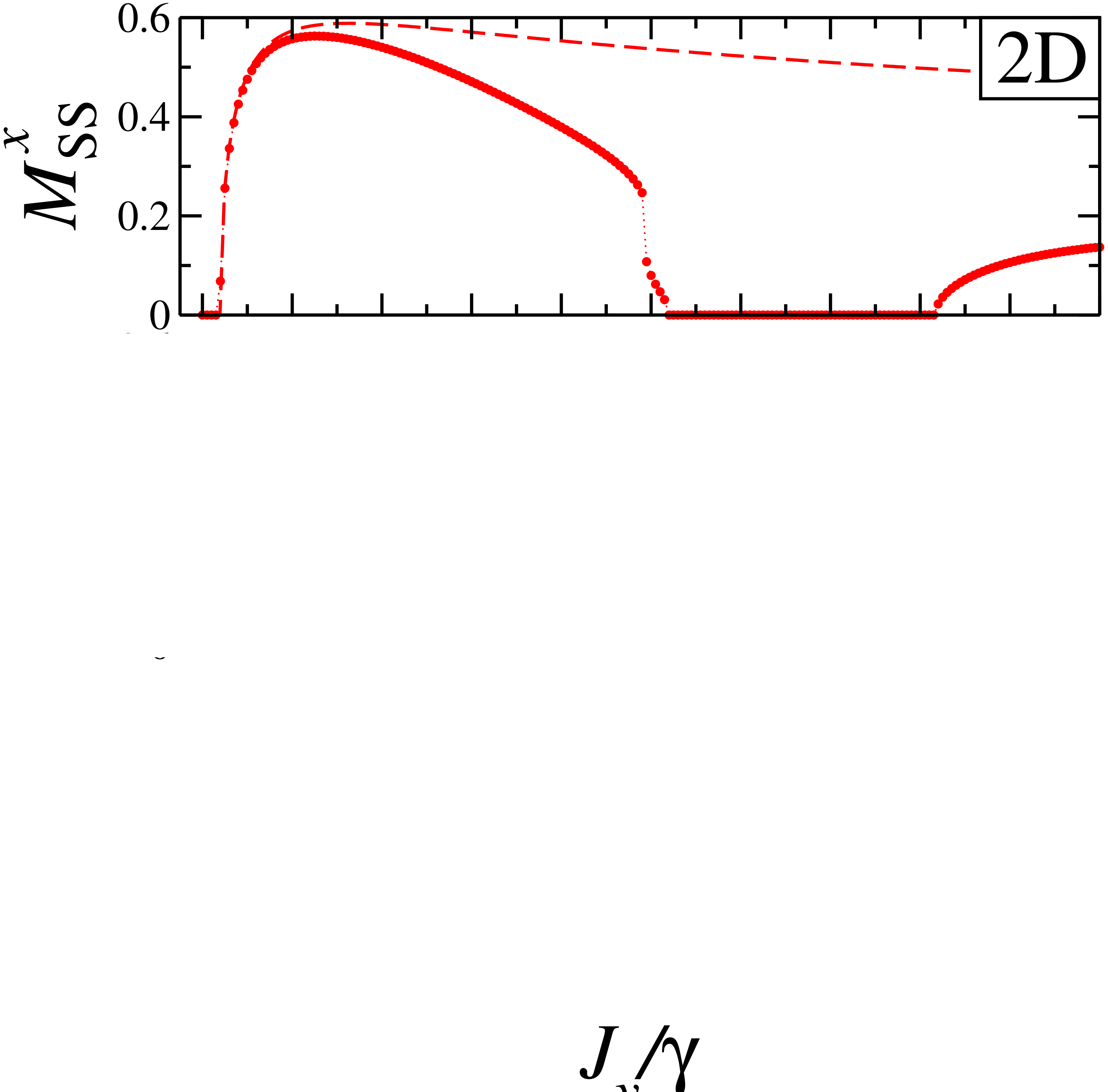
Two-dimensions



Two-dimensions



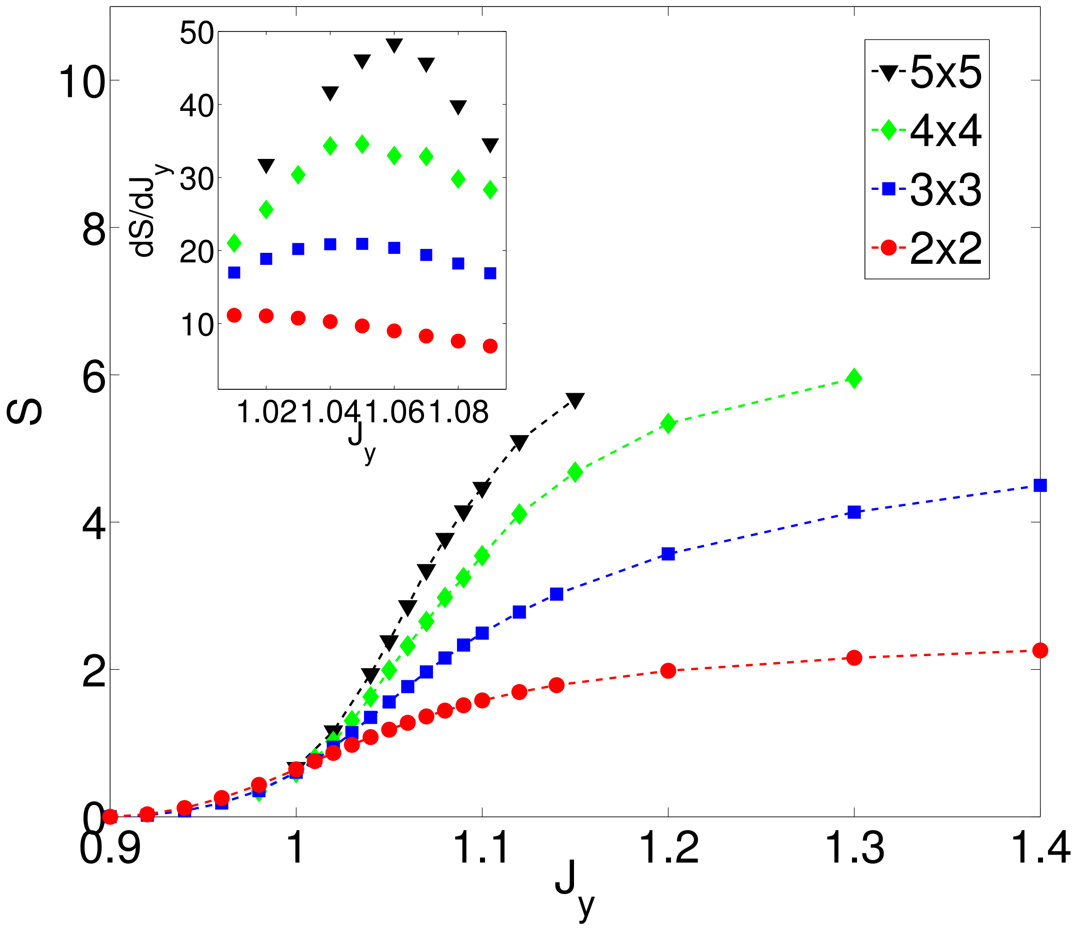
Higher dimensions



Quantum vs thermal fluctuations

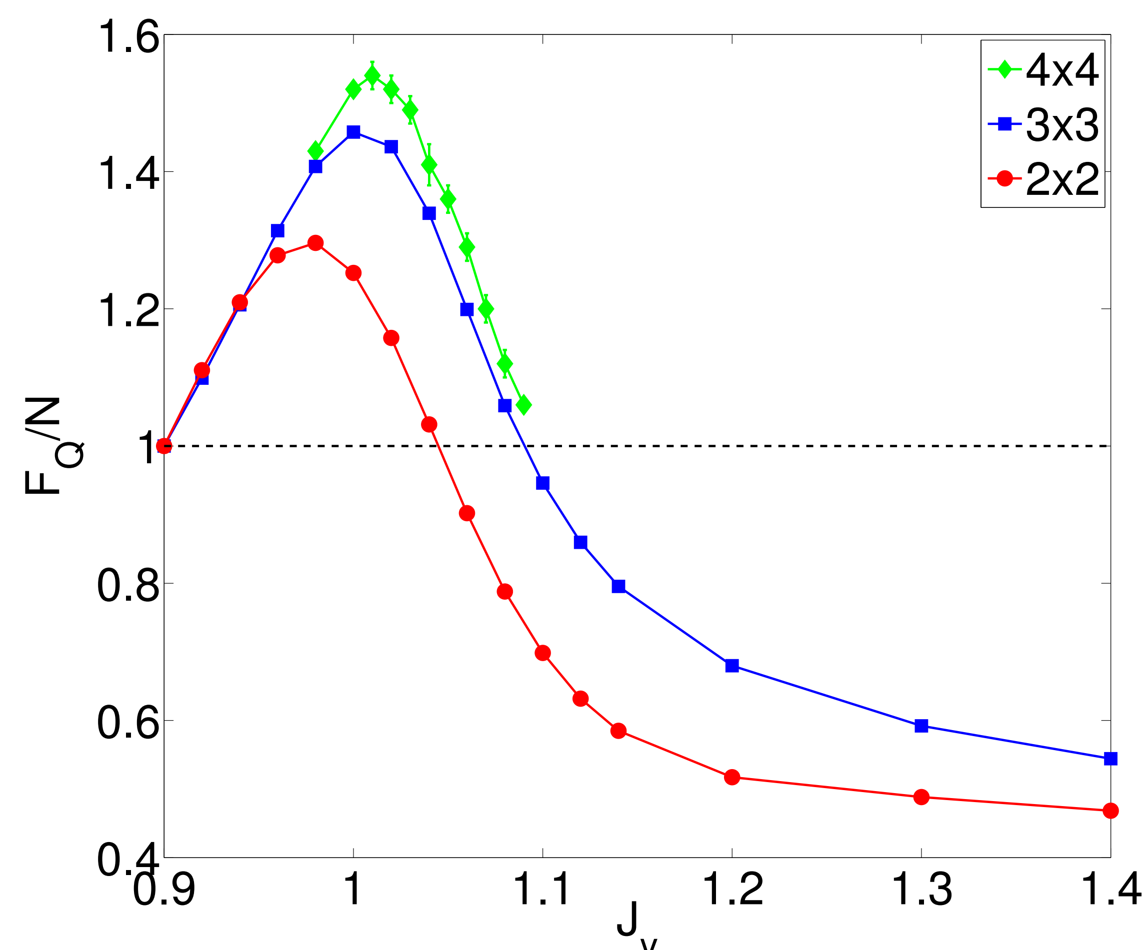
- In the classical case, quantum fluctuations are irrelevant, while in a quantum phase transition, the entanglement properties are critical. A dissipative phase transition can share properties of both classical and quantum phase transitions.

Quantum vs thermal fluctuations



The qualitative behaviour of the Von Neumann entropy S as a function of the coupling parameter Jy in the XYZ model resembles the behaviour of the thermal entropy versus temperature in the equilibrium 2D Ising model.

Quantum Fisher information (measuring the multipartite entanglement) as a function of the coupling shows a critical divergence



Conclusions

- Dramatic changes (quantitatively and in the "topology") in the phase boundaries due to short-range fluctuations

- Enhanced importance is of dynamical origin

- Importance of quantum *and* classical fluctuations