Quantum probing of complex systems

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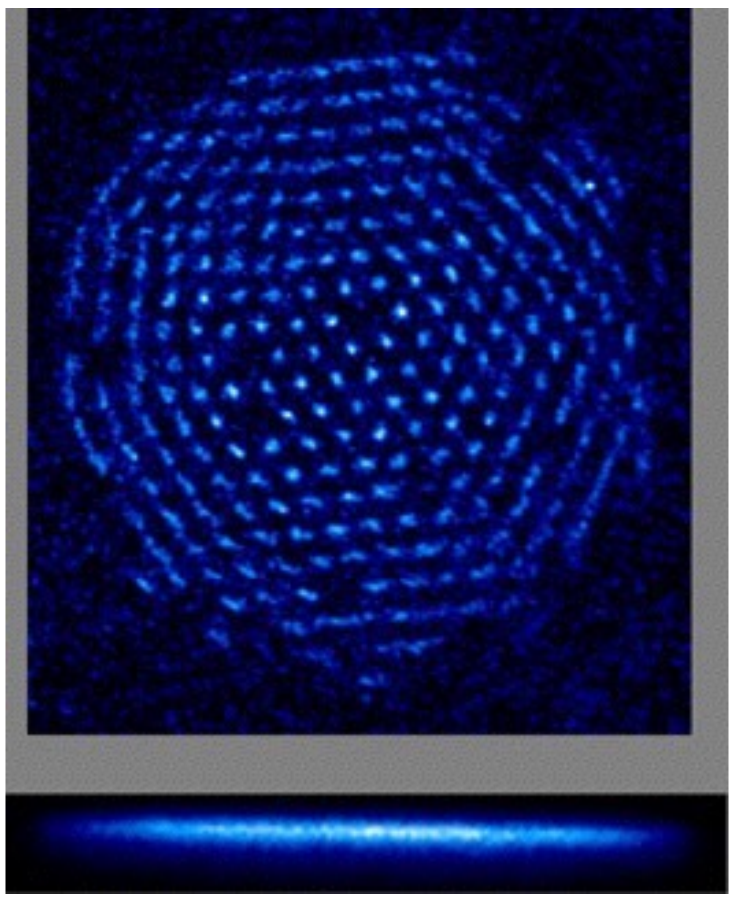
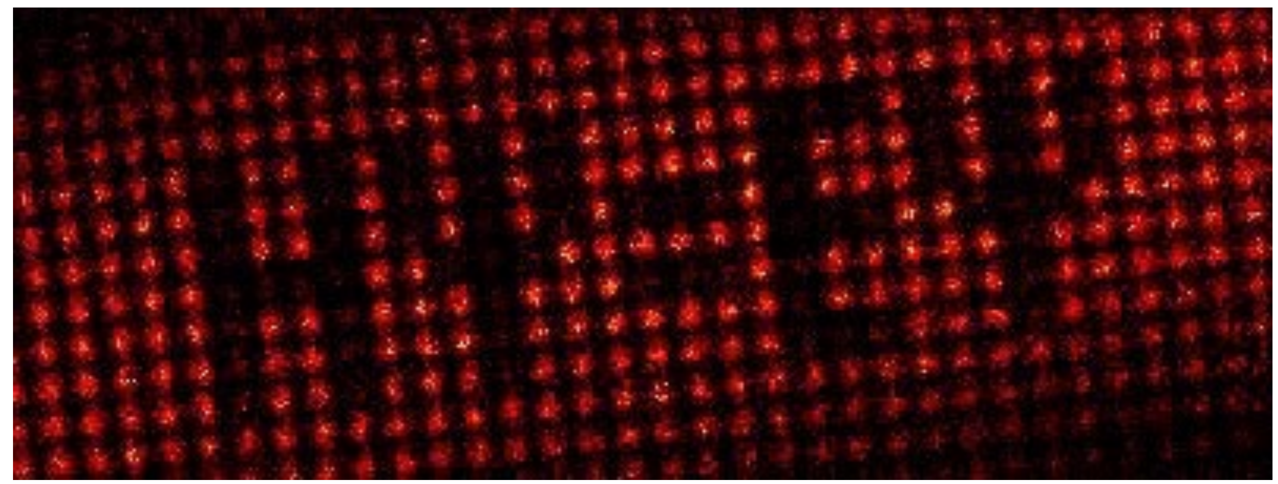
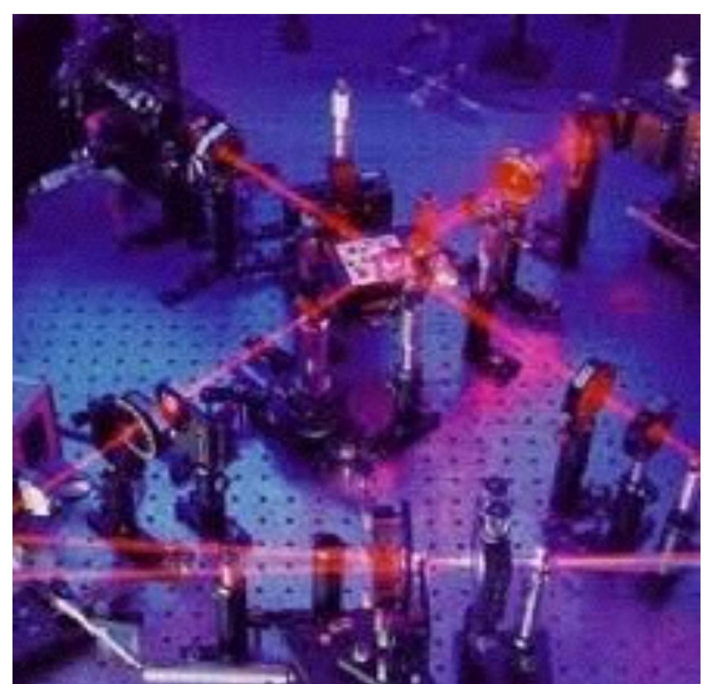
complex systems

ionic crystals



cold atoms in optical lattices





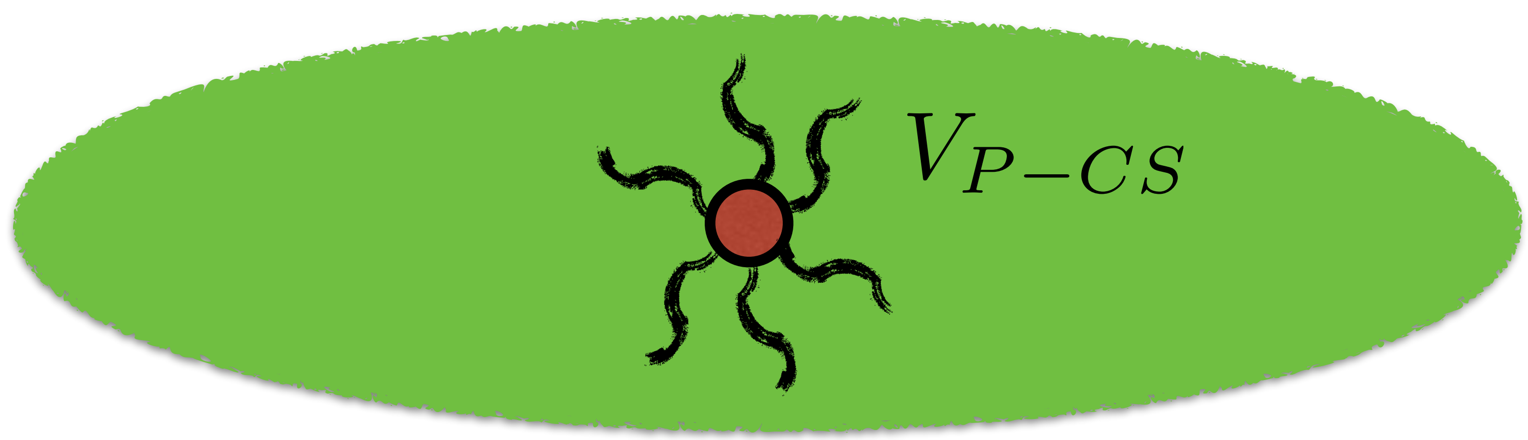
photonic systems

complex system = really messy Hamiltonian!
too many degrees of freedom, non-integrable, etc..

classical response theory…can be rather invasive

can we find a way to probe a complex system without disturbing it too much?

a well-defined, controllable quantum system



V_{P-CS} = engineered interaction that would induce minimum disturbance on CS

Q: can we map some features of CS onto the dynamics of the single quantum system? Also, if this is possible, what kind of information can we extract and how?

tools from
- many-body theory
- open quantum system theory
- statistical physics
- quantum information theory

to investigate
- excitation spectra
- correlations/fluctuations
- decoherence
- non equilibrium properties

controllable quantum simulators

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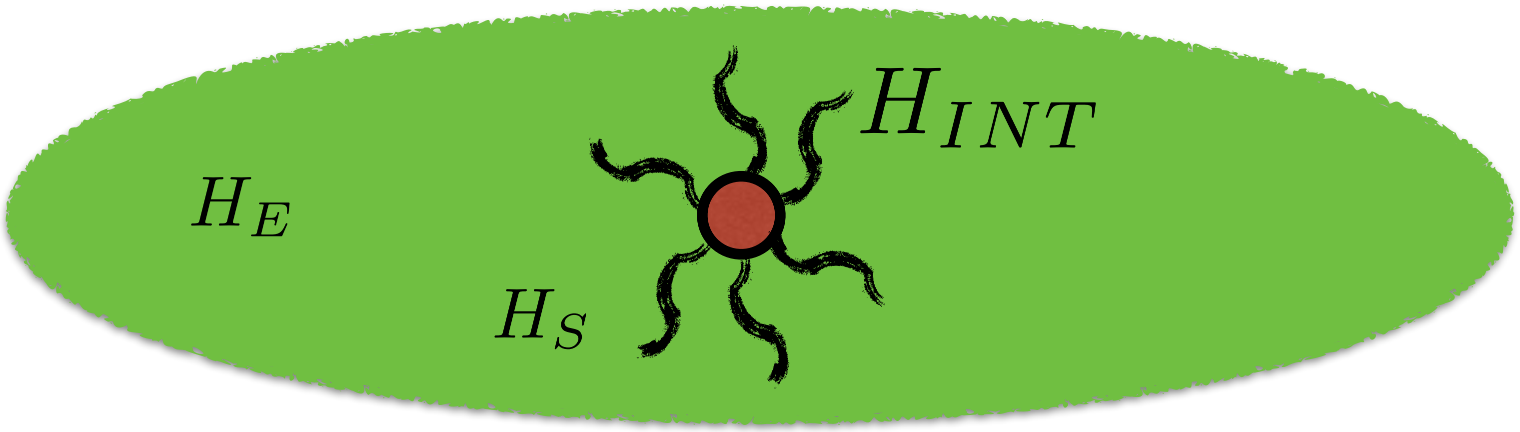
controllable quantum simulators



open quantum system
- dissipation
- decoherence

in a Markovian open system (no memory effects) all the quantum properties are lost within a certain time-scale

$$\boxed{\frac{d}{dt}\rho_S = -i[H,\rho_S] + \sum_j \gamma_j \left(A_j \rho_S A_j^\dagger - \frac{1}{2}\{A_j^\dagger A_j, \rho_S\} \right)}$$

- A_j jump operators
- $\gamma_j \geq 0$

- spontaneous decay
- thermalisation of an e.m. mode in an optical cavity
- random walk

a tool to detect non-Markovian behaviour is the trace distance between quantum states

$$\boxed{D(\hat{\rho}_1, \hat{\rho}_2) \equiv \frac{1}{2}\|\rho_1 - \rho_2\|_1}$$

$$\|\hat{O}\|_1 = \mathrm{Tr}\sqrt{\hat{O}\hat{O}^\dagger}$$

initial states $\rho_1(0), \rho_2(0) \xrightarrow[\text{dynamics}]{\text{Markovian}} \rho_1(t), \rho_2(t)$ Linblad m.e., dynamical map, etc…

$$\downarrow$$

$$\boxed{D(\rho_1(t), \rho_2(t)) \leq D(\rho_1(0), \rho_2(0)) \qquad \forall \rho_1, \rho_2 \forall t \geq 0.}$$

contractivity property

H.-P. Breuer, E.-M. Laine, and J. Piilo, Phys. Rev. Lett. **103**, 210401 (2009).

$$\sigma(t, \rho_{1,2}(0)) \equiv \frac{d}{dt} D(\rho_1(t), \rho_2(t))$$

if $\sigma(t, \rho_{1,2}(0)) > 0$ for some $\rho_1(0), \rho_2(0), t$

the dynamics is non-Markovian

a possible measure for the degree of non-Markovian character is

$$\mathcal{N} = \max_{\rho_{1,2}(0)} \int_{\sigma>0} dt \sigma(t, \rho_{1,2}(0))$$

H.-P. Breuer, E.-M. Laine, and J. Piilo, Phys. Rev. Lett. **103**, 210401 (2009).

analytical results for 2-level systems

H.-P. Breuer, E.-M. Laine, J. Piilo, and B. Vacchini, arXiv:1505.01385 (2015)

how is this relevant for studying complex/many-body systems?

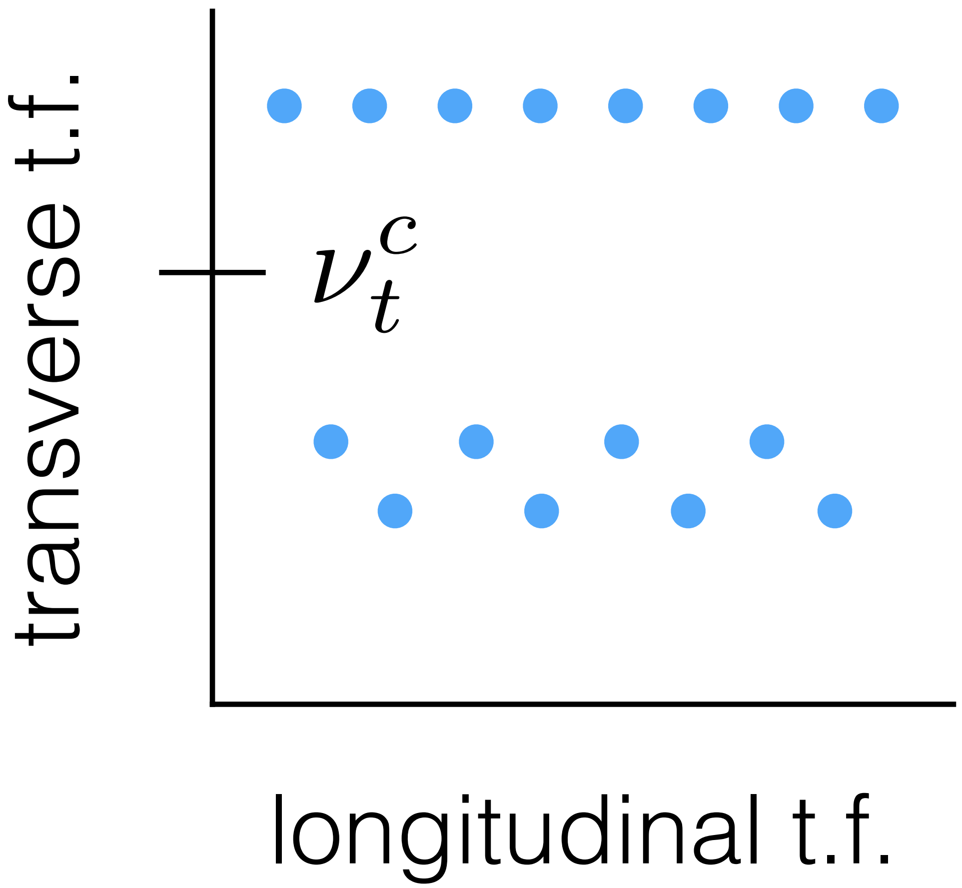
a well-defined, controllable quantum system

V_{P-CS} = engineered interaction that would induce minimum disturbance on CS

the complex/many-body system acts as an environment for the single controllable quantum system! By studying the open system dynamics we can infer some of the environment properties!

critical phenomena

example 1: Coulomb crystals in magnetic traps



- harmonic confinement (magnets)
- Coulomb repulsion (ions)

features:

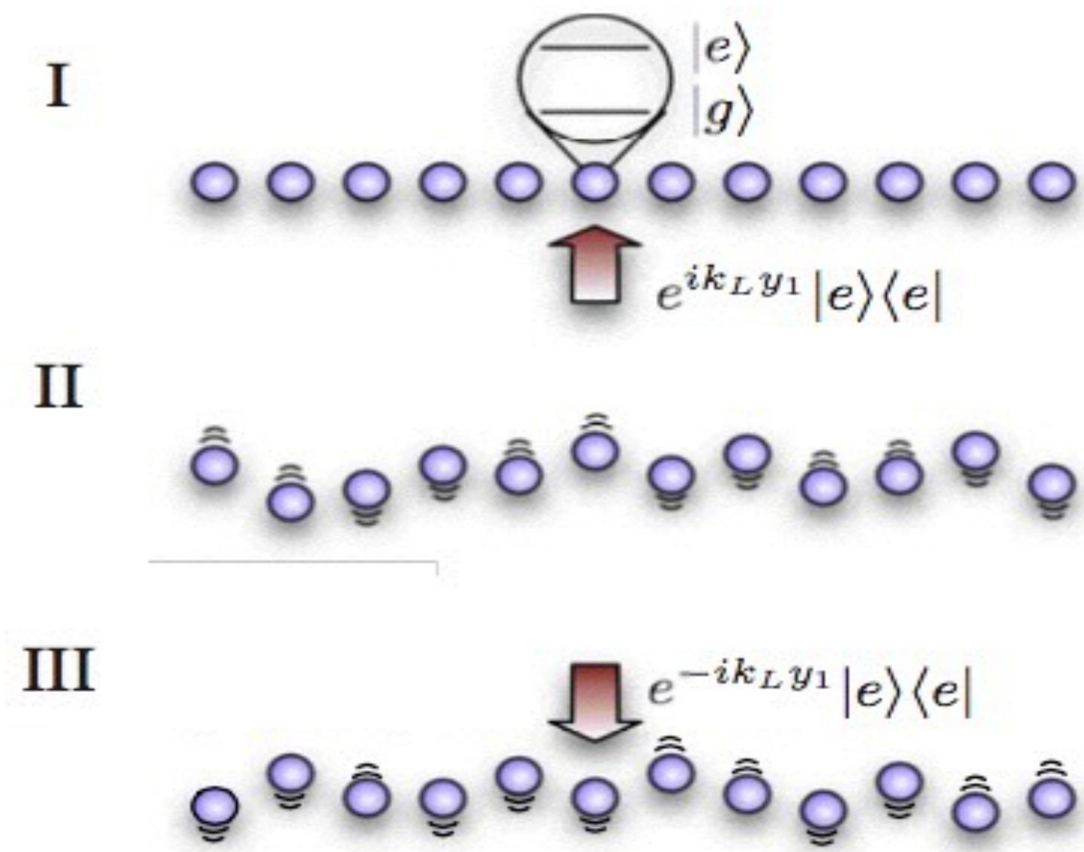
- it is structural
- second order with a closing gap
- same universality class as Ising
- it is quantum (?)

G. De Chiara, T. Calarco, S. Fishman, and G. Morigi, Phys. Rev. A **78**, 043414 (2008)

can we find a quantum probing scheme for this phase transition? what do we get out of it?

probing protocol: Ramsey interferometry with a single quit

the dynamics of the qubit is both dissipative and decoherent and (quite a mess)



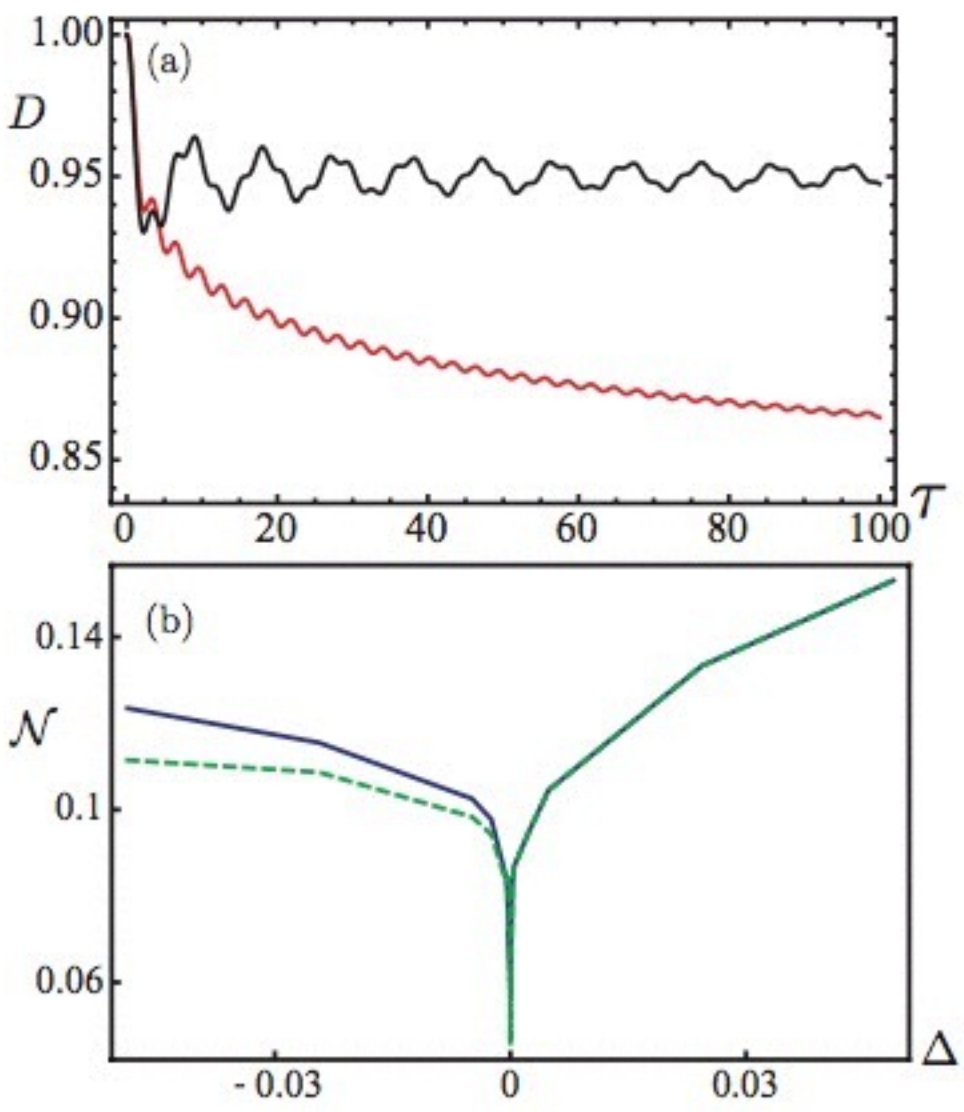
however, we can calculate the non-Markovianity properties and, even better, connect them the visibility of the Ramsey fringes (experimental shortcut to measure non-Markovianity)

G. De Chiara, T. Calarco, S. Fishman, and G. Morigi, Phys. Rev. A **78**, 043414 (2008)

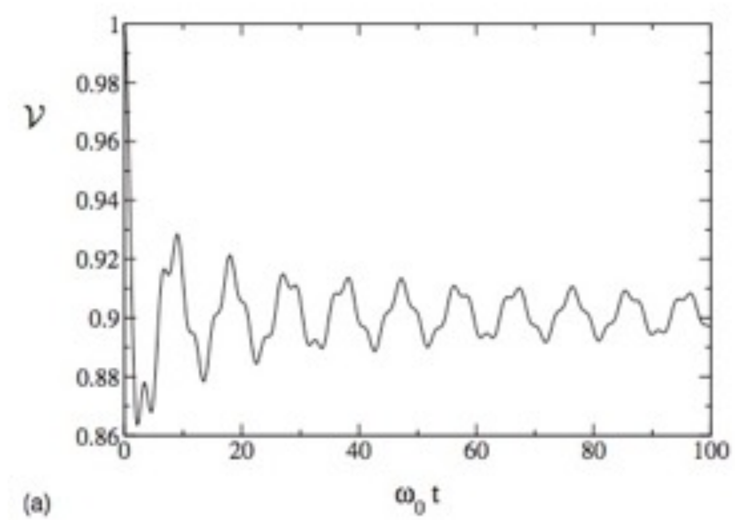
$$D_{\rm opt}(t) = \frac{1}{4}\left|1 + 2\cos B(t)\left[\mathcal{V}(t) - \xi^4\mathcal{V}^{-1}(t)\right] + \mathcal{V}^4(t) + 2\xi^4\right|$$

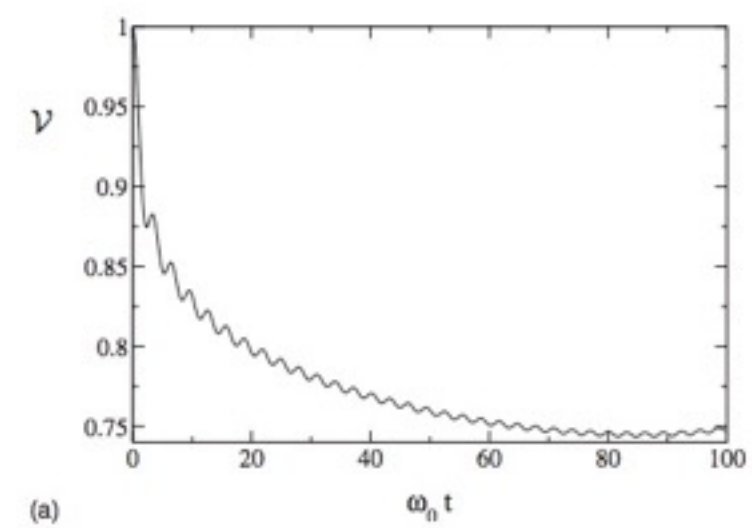
the optimal trace distance is a function of the visibility fringes!

M. Borrelli, P. Haikka, G. De Chiara, and S. Maniscalco, Phys. Rev. A **88**, 010101 (R) (2013)



near the critical point the dynamics becomes almost non-Markovian





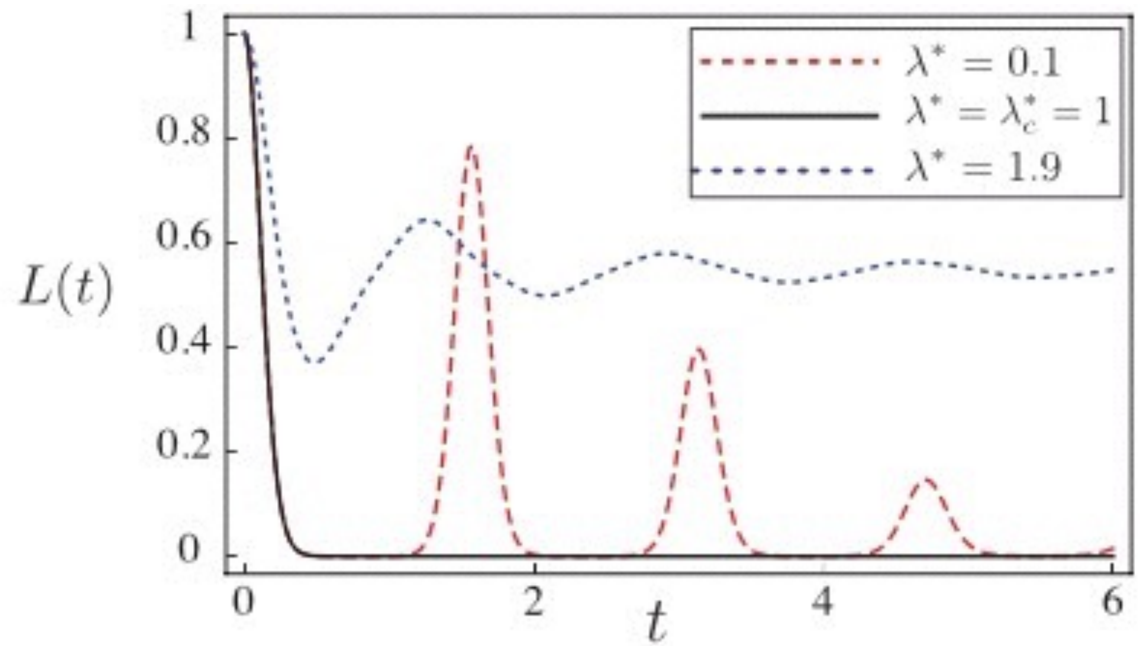
G. De Chiara, T. Calarco, S. Fishman, and G. Morigi, Phys. Rev. A **78**, 043414 (2008)

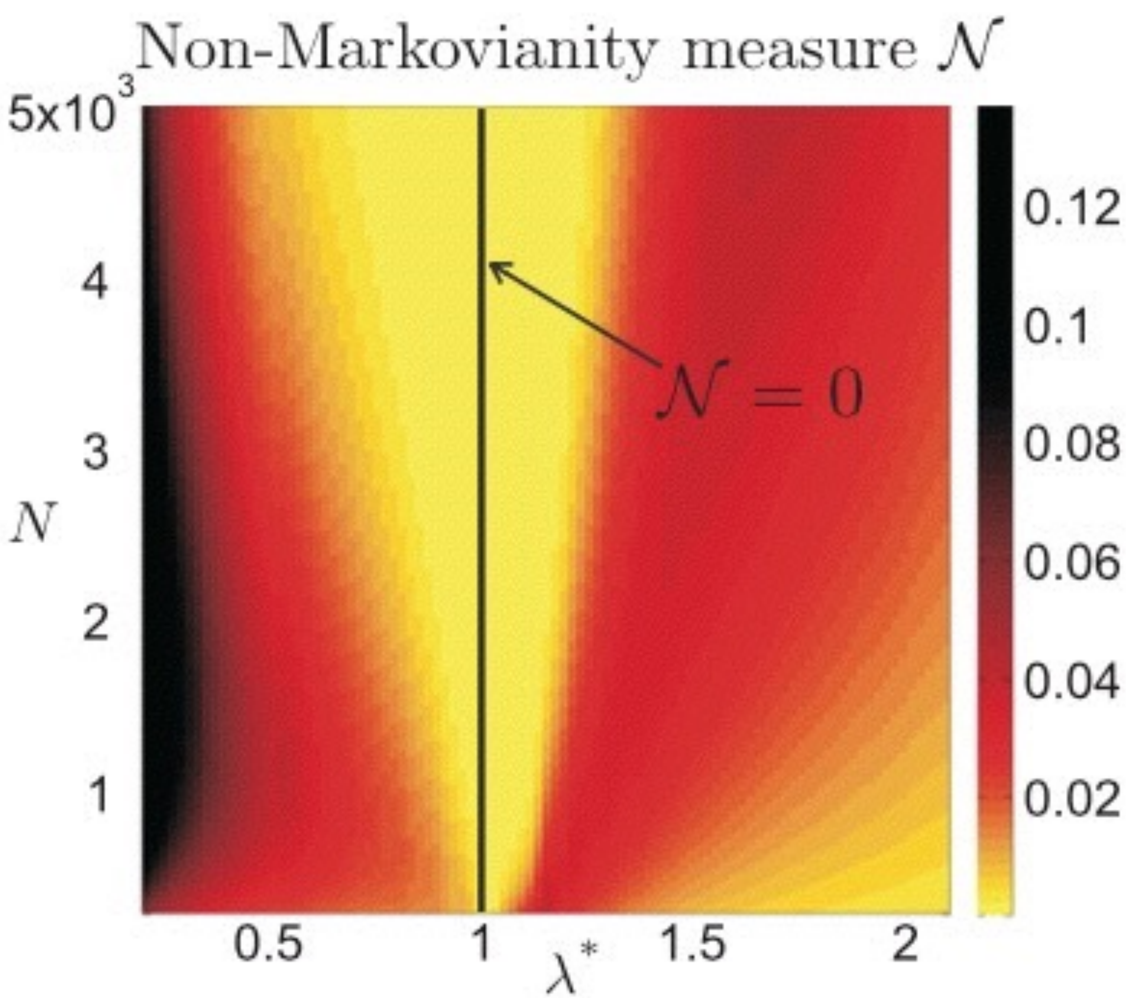
example 2: decoherence in a transverse Ising model

$$H = -J\sum_i \sigma_i^z\sigma_{i+1}^z + \lambda\sigma_i^x + \delta|e\rangle\langle e|\sigma_i^x$$

$$D_{\mathrm{opt}}(t) = \sqrt{L(t)}$$

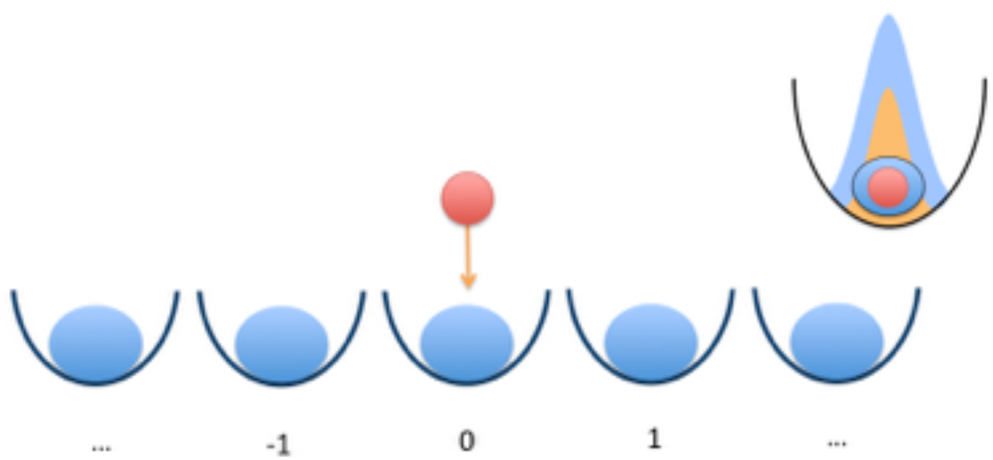
P. Haikka *et* al., Phys. Rev. A **85**, 060101(R) (2012)





at criticality the dynamics is completely Markovian

example 2: Bose-Hubbard model in ultracold atoms



- lasers creating a standing wave pattern
- an atomic impurity that does not significantly perturb the lattice

$$H_{BH} = -J \sum_{i=1}^{N_S} (a_{i+i}^{\dagger} a_i + a_i^{\dagger} a_{i+1}) + \frac{U}{2} \sum_{i=1}^{N_S} n_i (n_i - 1) - \mu \sum_{i=1}^{N_S} n$$

kinetic interaction

transition from a superfluid $J \gg U$ to a insulating phase $J \ll U$ depending on the ratio J/U and filling factor $\bar{n}(J/U, \mu/U)$

Wanna hear the results?
Wait for the next talk :-)

preliminary results show that a quantum probe based approach to many-body systems might be promising

- none or very little perturbation of the many-body Hamiltonian
- the decoherence in the open system dynamics signals critical features of the may-body environment
- some statistical knowledge of the environment can be achieved by looking at the system only

to do’s next:

- higher order correlation functions
- possibility of mapping entanglement in the environment onto the state of probe/s

Thank you for your attention!
Grazie per l’attenzione!
Kiitos!
Vielen Dank für Ihre Aufmerksamkeit!
İlginiz için teşekkürler!
Dziękuję za uwagę!