Quasiperiodic lattices as tunable quantum environments: memory effects and work statistics

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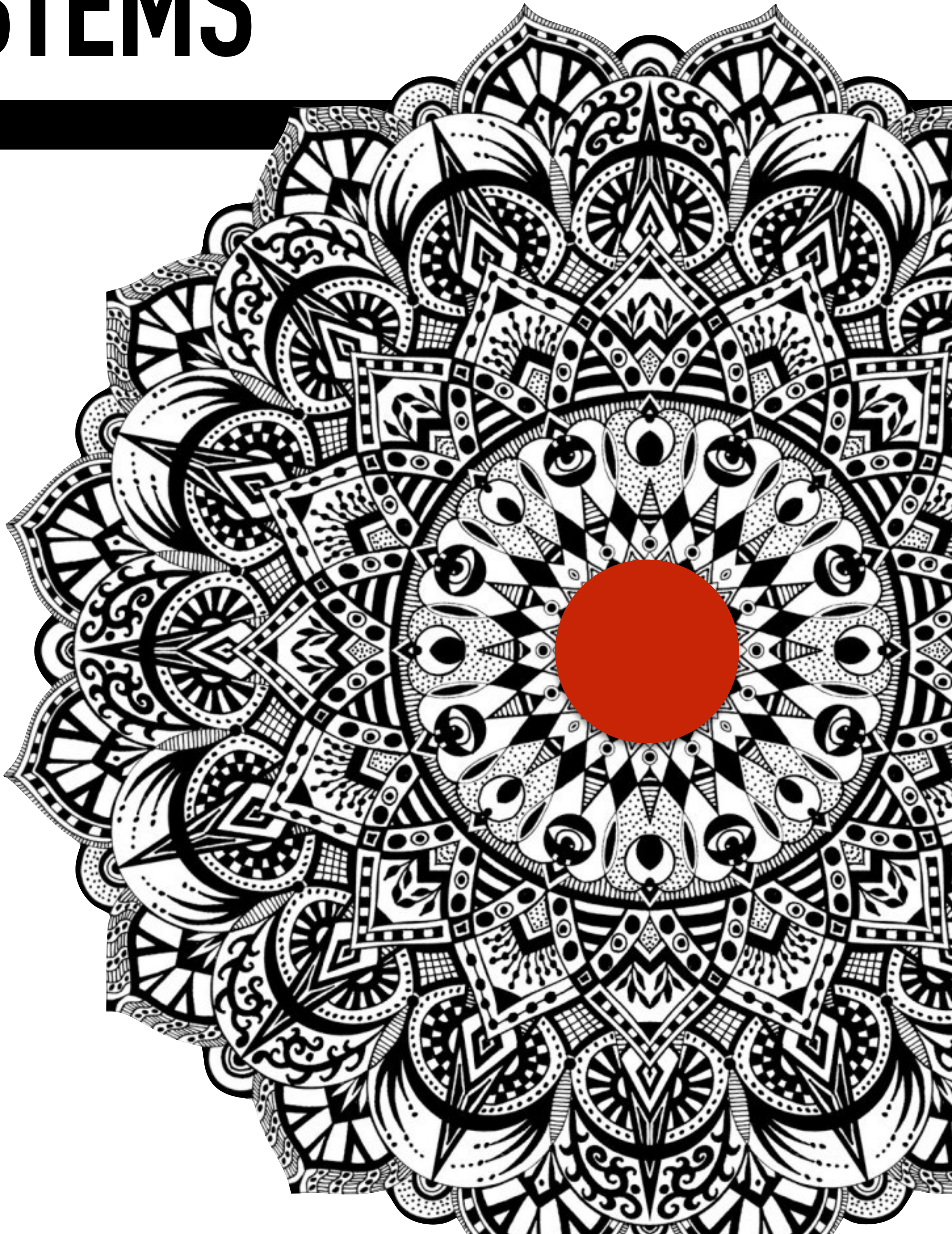
OPEN QUANTUM SYSTEMS



ENVIRONMENT

S

150210 Zentangle © Emerlye Arts

IDENTIFY S

ENVIRONMENT

S

Examples of environment?

the first and main assumption

No initial correlations

$$\rho_T(0) = \rho_S \otimes \rho_E$$

time

generally correlations are created

$$\rho_T(t) \qquad \rho_S(t) = Tr_E(\rho_T(t))$$

the goal of OQS theory

Dynamics

$$\rho_S(0) \rightarrow \rho_S(t)$$

master equation

dynamical map

dynamical map

$$\rho_S(t) = \Lambda_t \rho_S(0)$$

t-parametrised family of quantum channels (CPTP linear maps)

$$t \geq 0 \qquad \Lambda_0 = \mathbb{1}_n$$

master equation – dynamical map

the connection

$$\rho_S(t) = \Lambda_t \rho_S(0)$$

$$\frac{d\rho_S(t)}{dt} = L_t \rho_S(t)$$

$$\dot{\Lambda}_t = L_t \Lambda_t \ , \qquad \Lambda_0 = \mathbb{1}_n$$

solution

the generator

$$\Lambda_t = \mathrm{T}\exp\left(\int_0^t L_\tau \, d\tau\right)$$

the most important OQS theorem

Gorini-Kossakowski-Sudarshan-Lindblad (GKSL theorem)

$$\frac{d\rho_S(t)}{dt} = L_t \rho_S(t) \quad \Rightarrow \quad \frac{d\rho_S(t)}{dt} = L \rho_S(t)$$

$$\Lambda_t = \mathrm{T}\exp\left(\int_0^t L_\tau \, d\tau\right) \quad \Rightarrow \quad \Lambda_t = e^{-Lt}$$

the most important OQS theorem

Gorini–Kossakowski–Sudarshan–Lindblad (GKSL theorem)

decay rates $\gamma_k \geq 0$

$$L(\rho) = -i[H,\rho] + \sum_k \gamma_k \left(V_k \rho V_k^\dagger - \frac{1}{2}\{V_k^\dagger V_k, \rho\} \right)$$

jump (or Lindblad) operators

MARKOVIAN OPEN QUANTUM SYSTEMS

What if

$$\frac{d\rho_S(t)}{dt} = L_t \rho_S(t)$$

time dependent

GKSL theorem still holds!

decay rates $\gamma_k(t) \geq 0$

$$L(\rho) = -i[H,\rho] + \sum_k \gamma_k(t) \left(V_k \rho V_k^\dagger - \frac{1}{2}\{V_k^\dagger V_k, \rho\} \right)$$

MARKOVIAN

what happens to
the dynamical map

dynamical map

semigroup

$$\Lambda_t = e^{Lt} \qquad \Lambda_{t+s} = \Lambda_t \Lambda_s$$

divisibility

$$\Lambda_t = \Lambda_{t,s} \Lambda_s$$

CP

GKSL theorem does not hold anymore!

decay rates can be temporarily negative

$$L(\rho) = -i[H,\rho] + \sum_k \gamma_k(t) \left(V_k \rho V_k^\dagger - \frac{1}{2}\{V_k^\dagger V_k, \rho\} \right)$$

NON-MARKOVIAN

dynamical map

non-divisibility

$$\Lambda_t = \Lambda_{t,s}\Lambda_s$$

not CP

the “intermediate map” is not CP

GKSL theorem does not hold anymore!

decay rates can be temporarily negative

$$L(\rho) = -i[H, \rho] + \sum_k \boxed{\gamma_k(t)} \left(V_k \rho V_k^\dagger - \frac{1}{2}\{V_k^\dagger V_k, \rho\} \right)$$

NON-MARKOVIAN

dynamical map

non-divisibility

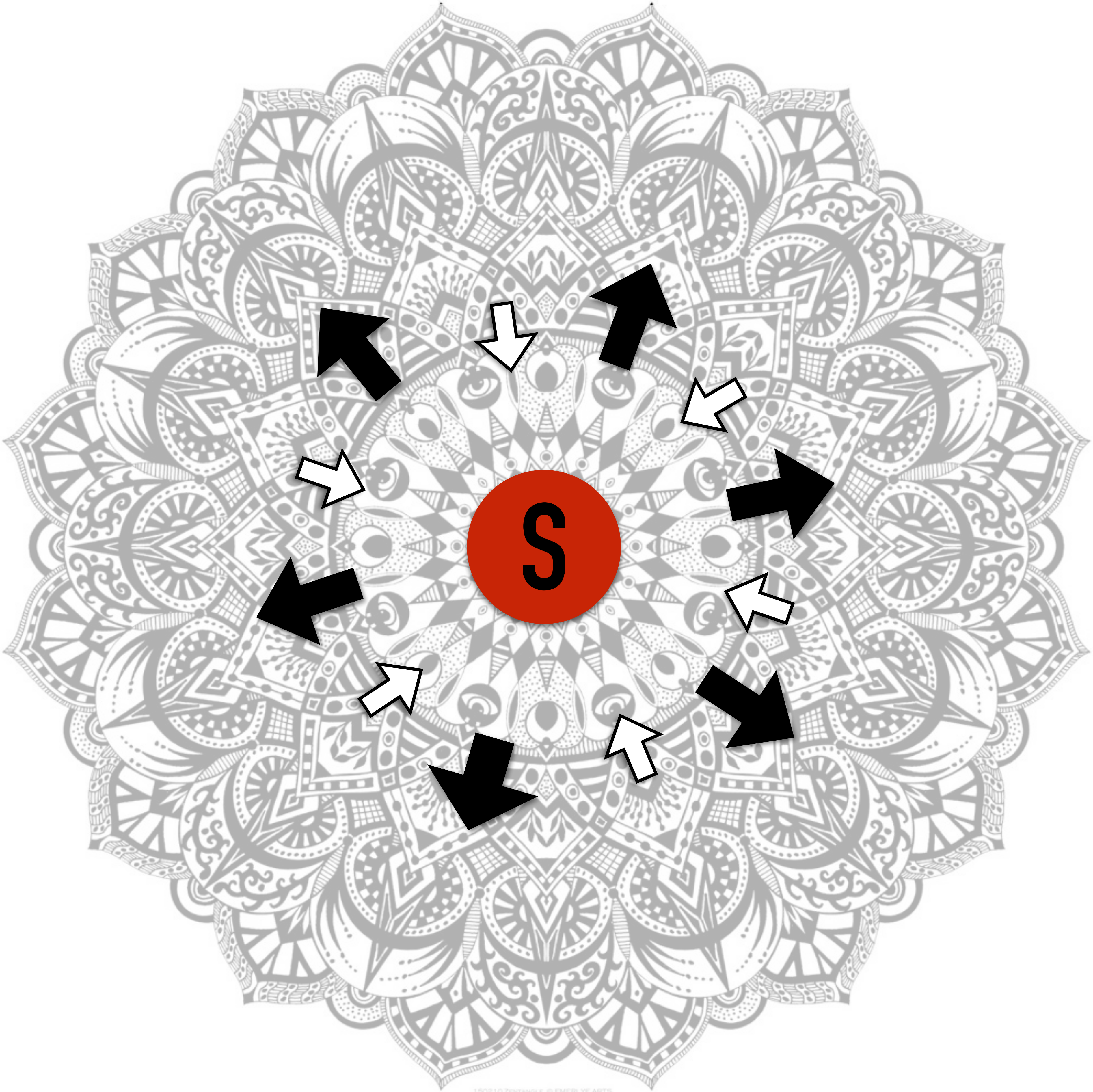
$$\Lambda_t = \Lambda_{t,s}\Lambda_s$$

not CP

the “intermediate map” is not CP

NON-MARKOVIAN DYNAMICS IN TERMS OF INFORMATION FLOW

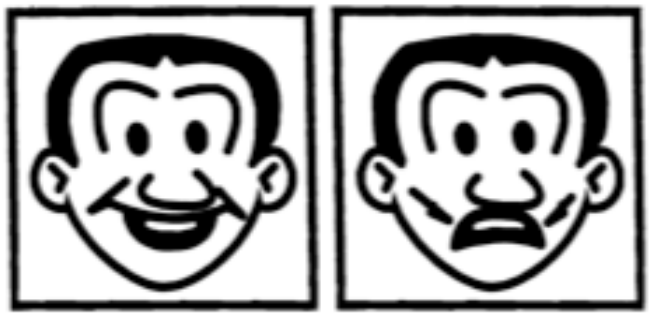
MEMORY EFFECTS AS INFORMATION BACK-FLOW


S

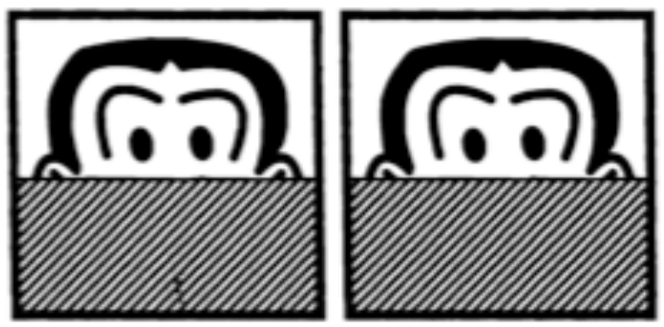
Trace distance (BLP) measure

Distinguishability between two quantum states

$$D(\rho_1, \rho_2) = \frac{1}{2}\mathrm{Tr}|\rho_1 - \rho_2|,$$



more distinguishability
more information



less distinguishability
less information

H.-P. Breuer, E.-M. Laine and J. Piilo, PRL 103, 210401 (2009)

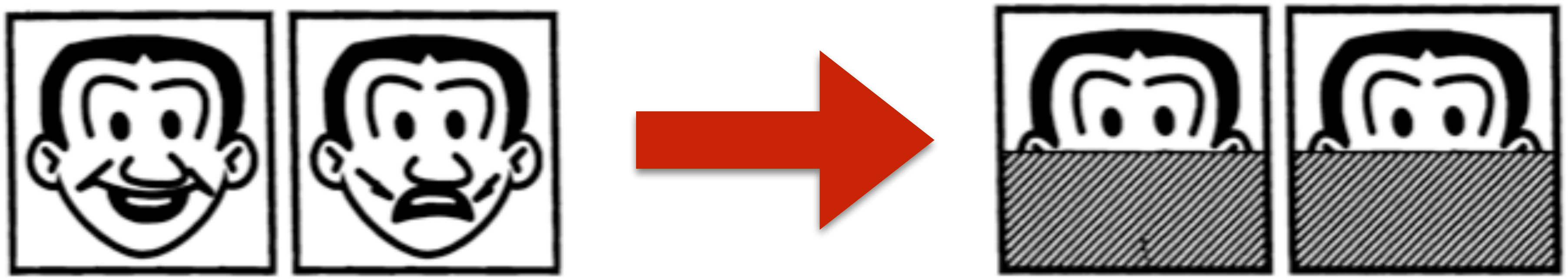
Trace distance (BLP) measure

Distinguishability between two quantum states

$$D(\rho_1, \rho_2) = \frac{1}{2}\mathrm{Tr}|\rho_1 - \rho_2|,$$

$$D(\Phi\rho_1, \Phi\rho_2) \leq D(\rho_1, \rho_2)$$

Φ CPTP map



information loss

Trace distance (BLP) measure

Distinguishability between two quantum states

$$D(\rho_1, \rho_2) = \frac{1}{2}\mathrm{Tr}|\rho_1 - \rho_2|,$$

$$D(\Phi\rho_1, \Phi\rho_2) \leq D(\rho_1, \rho_2)$$

Φ **CPTP map**

Rate of change of the trace distance

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

Trace distance (BLP) measure

information flow

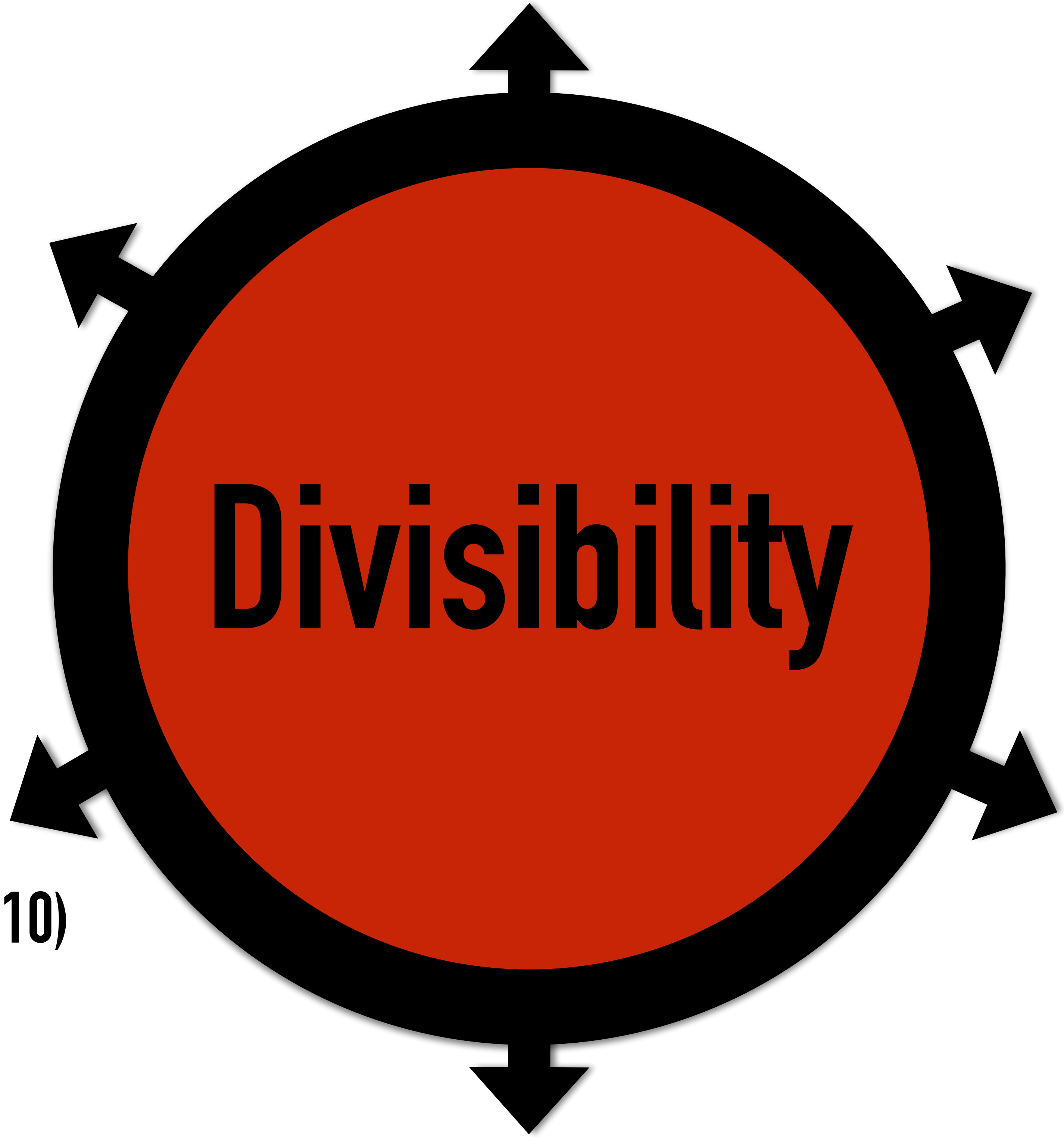
$$\sigma(t,\rho_{1,2}(0)) = \frac{d}{dt} D(\rho_1(t),\rho_2(t))$$

$$\sigma(t,\rho_{1,2}(0)) \leq 0$$ **Markovian**

$$\sigma(t,\rho_{1,2}(0)) > 0$$ **Non-Markovian**

Backflow of information

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



Divisibility

PRL 103, 210401 (2009)
Trace distance

Mutual information
PRA 86, 044101 (2012)

Fisher information
PRA 86, 044101 (2012)

Fidelity
PRA 84, 052118 (2011)

Entanglement
with ancilla
PRL 105, 050403 (2010)

Channel capacities
Scientific Reports 4 5720 (2014)

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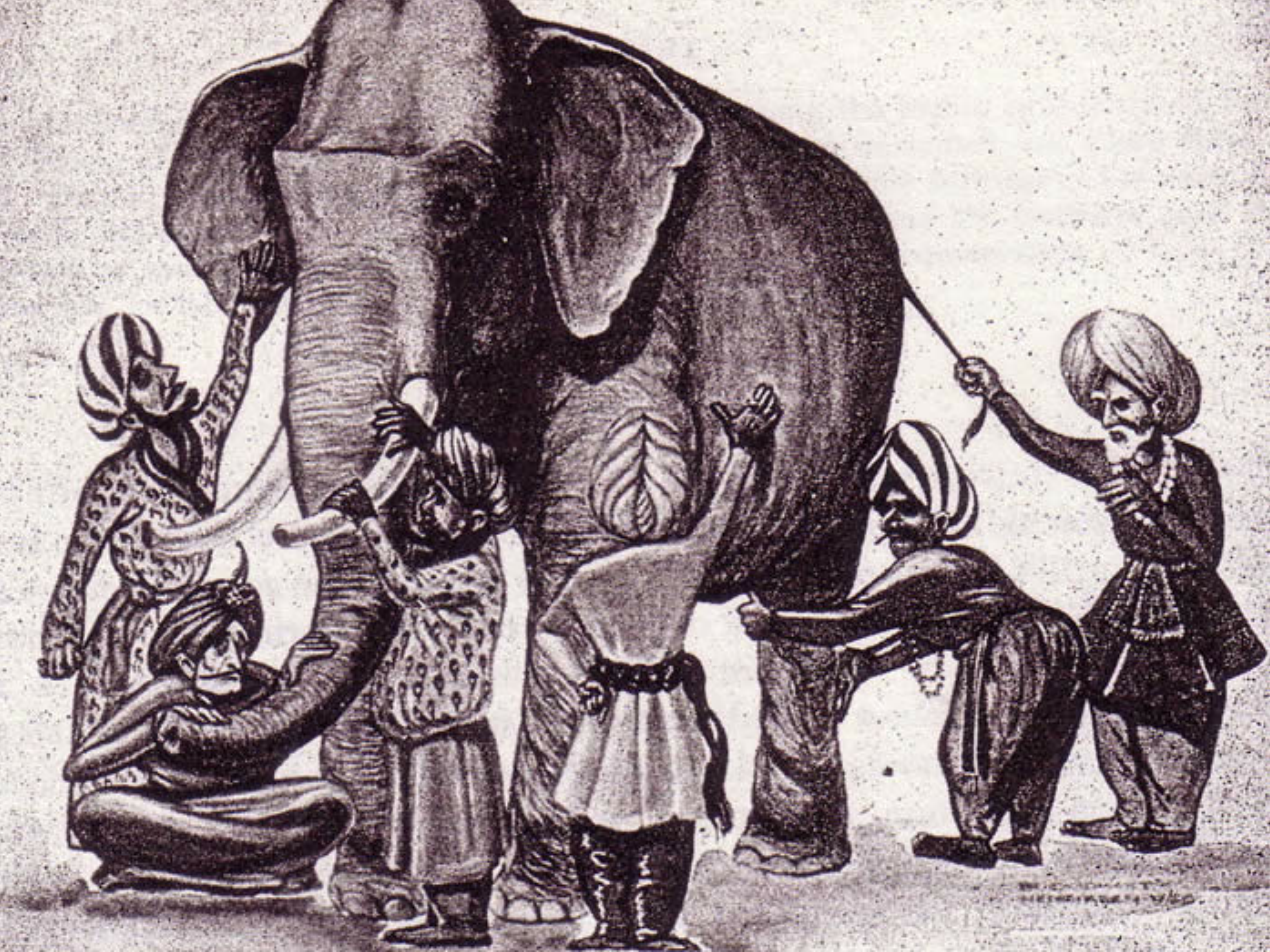
H.–P. Breuer, et al., Rev. Mod. 88, 021002 (2016)

A. Rivas, et al., Rep. Prog. Phys. 77, 094001 (2014)

I. de Vega and D. Alonso, Rev. Mod. Phys. 89, 015001 (2017)

L. Li, M. J. W. Hall, H. M. Wiseman, arXiv:1712.08879

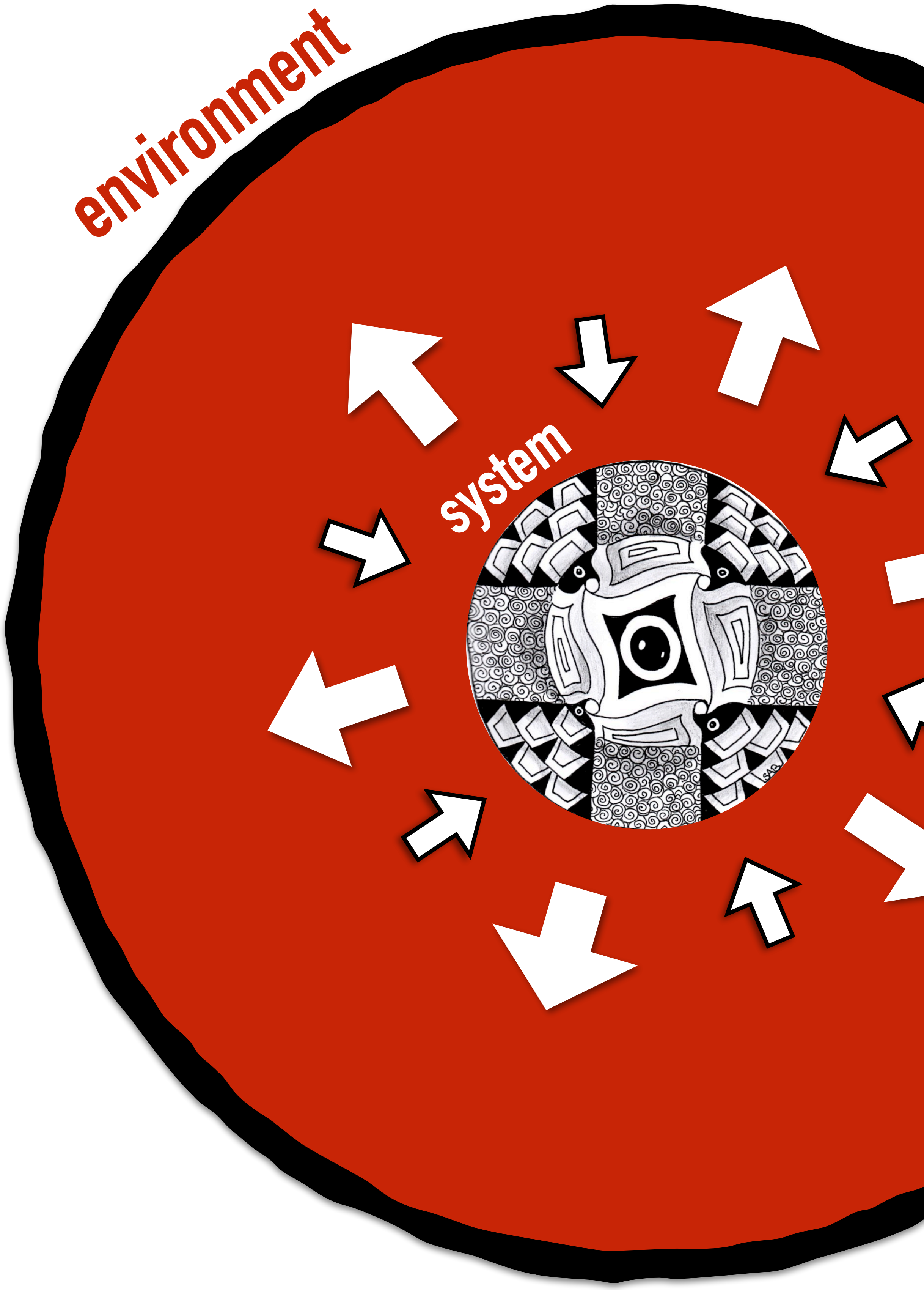



k-Divisibility

Degree of non-Markovianity

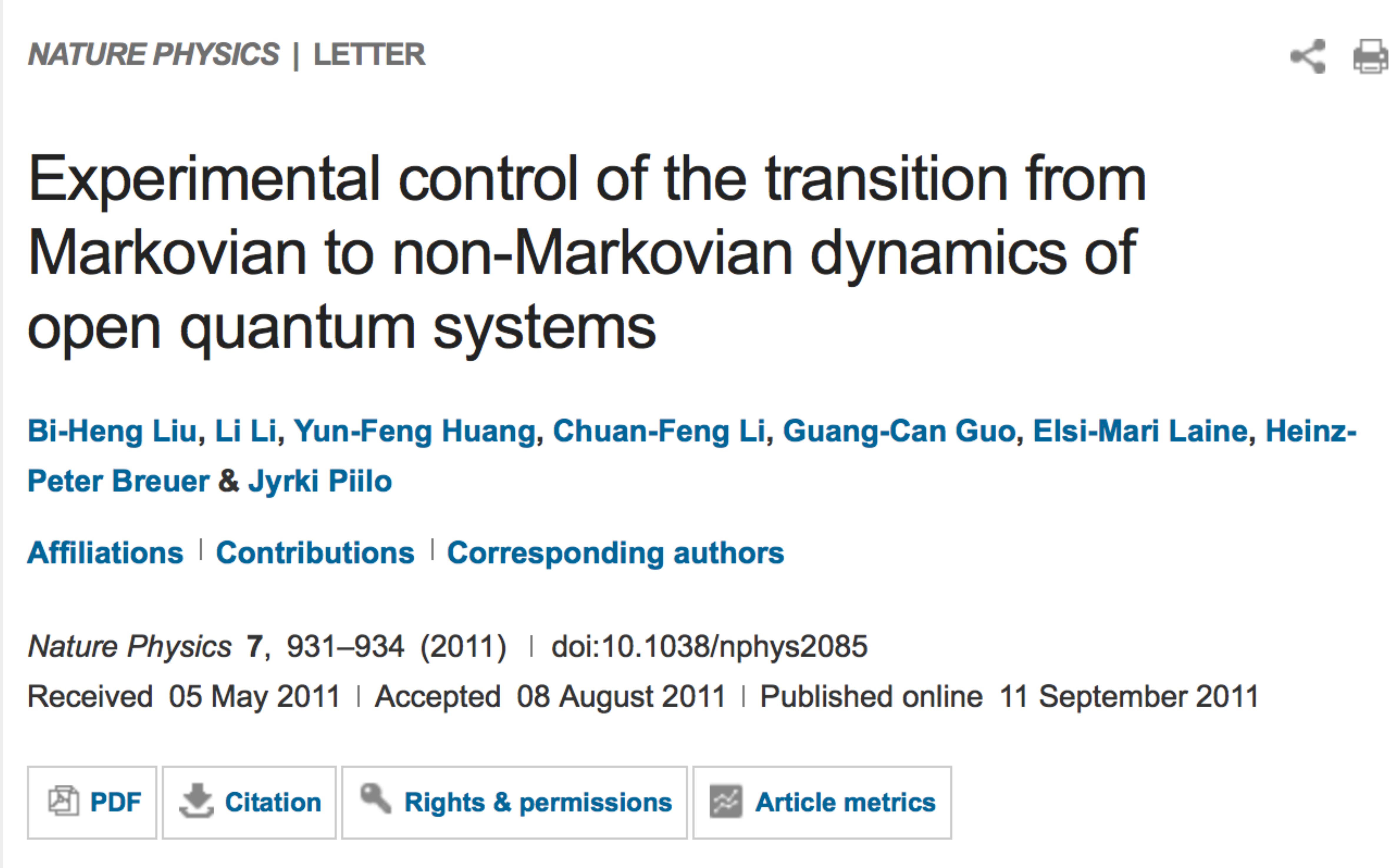
D. Chruscinski and S. Maniscalco, Phys. Rev. Lett. 112, 120404 (2014)

Detecting non-Markovianity



D. Chruscinski, C. Macchiavello and S. Maniscalco, Phys. Rev. Lett. 118, 080404 (2017)

Experiment Nature Physics, 2011



NATURE PHYSICS | LETTER

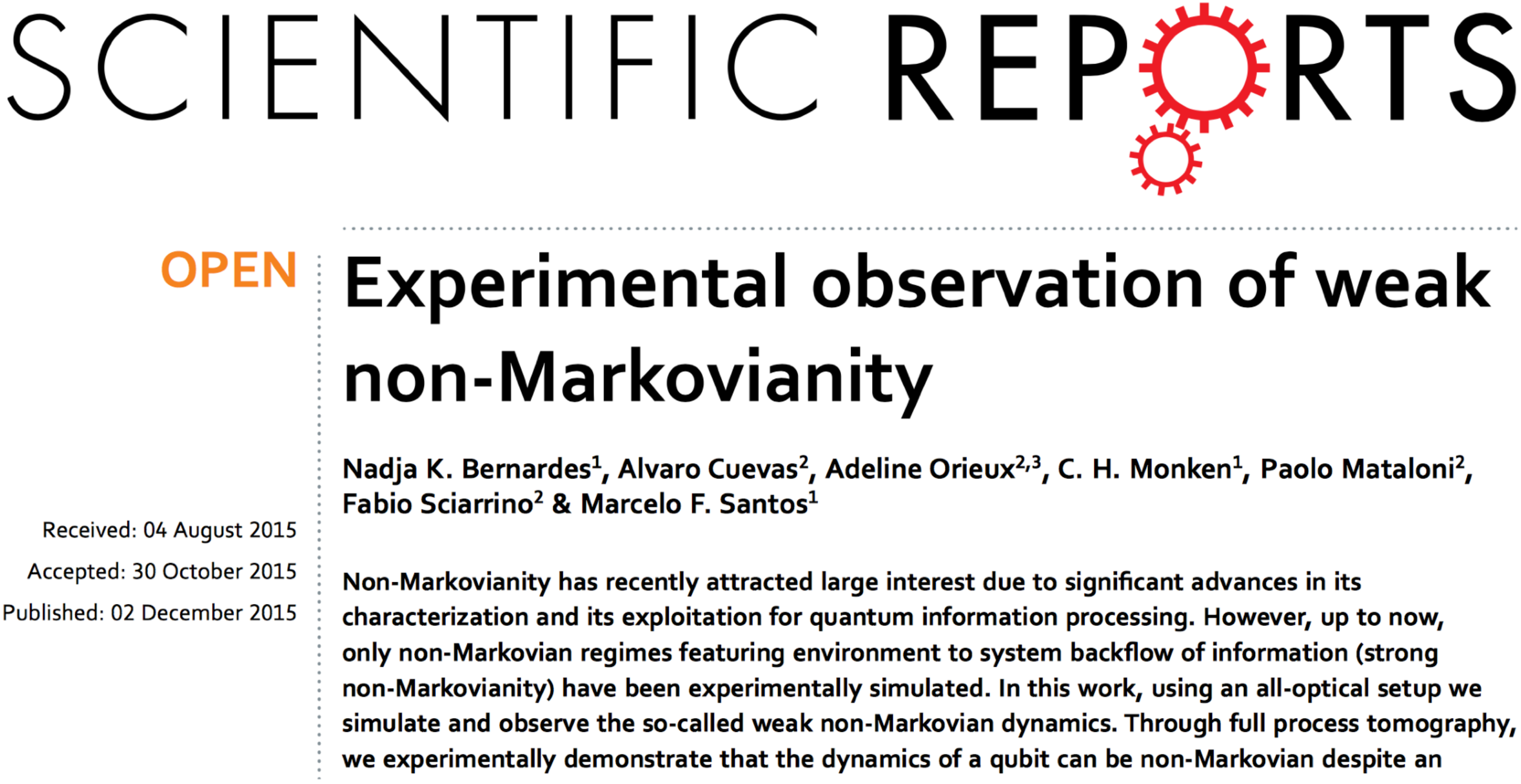
Experimental control of the transition from Markovian to non-Markovian dynamics of open quantum systems

Bi-Heng Liu, Li Li, Yun-Feng Huang, Chuan-Feng Li, Guang-Can Guo, Elsi-Mari Laine, Heinz-Peter Breuer & Jyrki Piilo

Affiliations | Contributions | Corresponding authors

Nature Physics **7**, 931–934 (2011) | doi:10.1038/nphys2085
Received 05 May 2011 | Accepted 08 August 2011 | Published online 11 September 2011

Experiment Scientific Reports, 2015



SCIENTIFIC REPORTS

OPEN

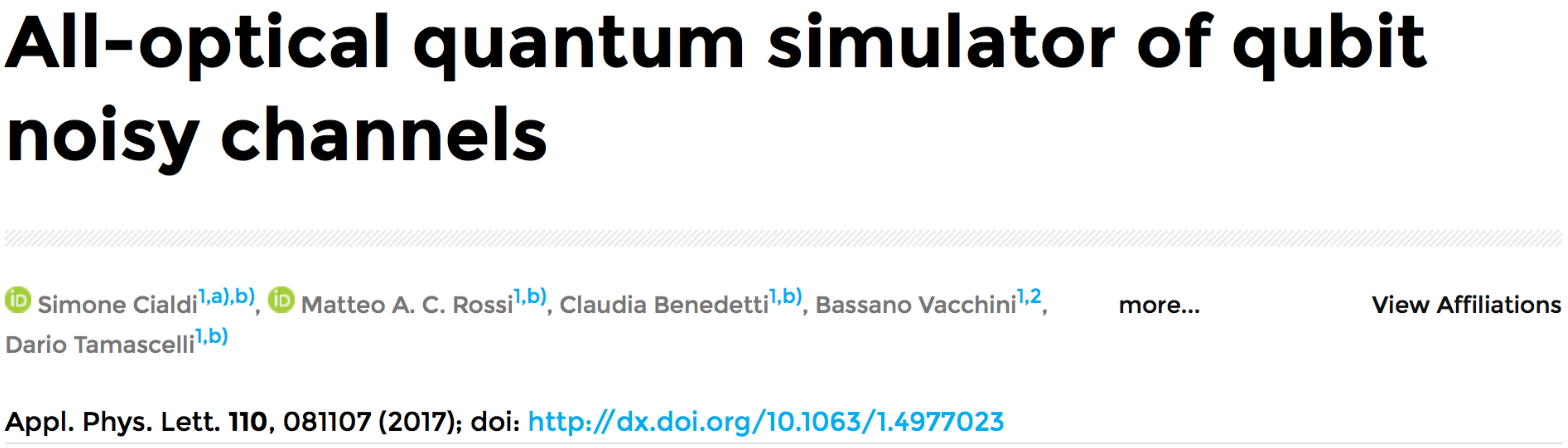
Experimental observation of weak non-Markovianity

Nadja K. Bernardes[1], Alvaro Cuevas[2], Adeline Orieux[2,3], C. H. Monken[1], Paolo Mataloni[2], Fabio Sciarrino[2] & Marcelo F. Santos[1]

Received: 04 August 2015
Accepted: 30 October 2015
Published: 02 December 2015

Non-Markovianity has recently attracted large interest due to significant advances in its characterization and its exploitation for quantum information processing. However, up to now, only non-Markovian regimes featuring environment to system backflow of information (strong non-Markovianity) have been experimentally simulated. In this work, using an all-optical setup we simulate and observe the so-called weak non-Markovian dynamics. Through full process tomography, we experimentally demonstrate that the dynamics of a qubit can be non-Markovian despite an

Experiment APL, 2017



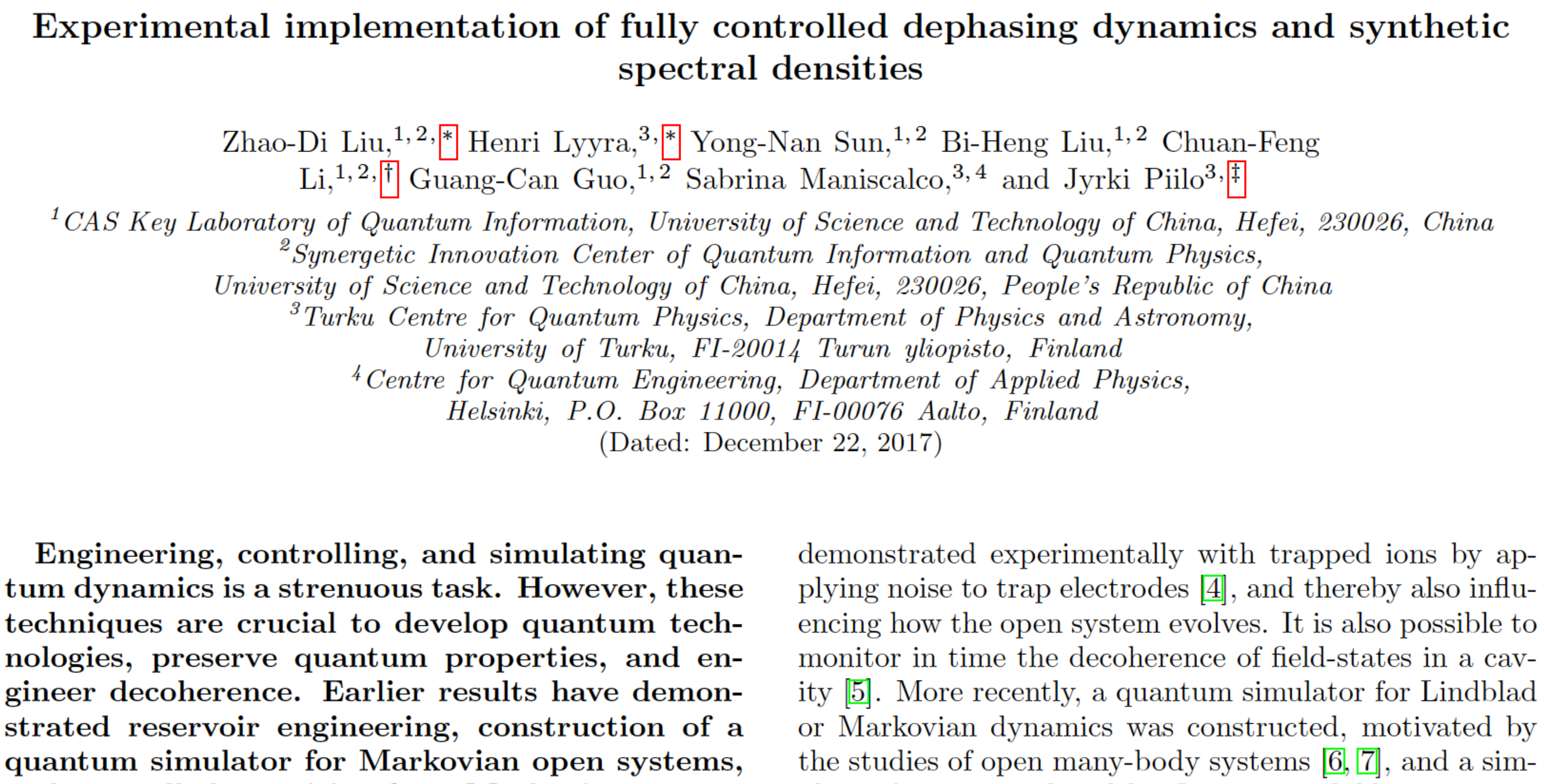
All-optical quantum simulator of qubit noisy channels

Simone Cialdi[1,a),b)], Matteo A. C. Rossi[1,b)], Claudia Benedetti[1,b)], Bassano Vacchini[1,2], Dario Tamascelli[1,b)]

Appl. Phys. Lett. **110**, 081107 (2017); doi: http://dx.doi.org/10.1063/1.4977023

Experiment

arXiv:1712.08071



Experimental implementation of fully controlled dephasing dynamics and synthetic spectral densities

Zhao-Di Liu,[1,2,*] Henri Lyyra,[3,*] Yong-Nan Sun,[1,2] Bi-Heng Liu,[1,2] Chuan-Feng Li,[1,2,†] Guang-Can Guo,[1,2] Sabrina Maniscalco,[3,4] and Jyrki Piilo[3,‡]
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(Dated: December 22, 2017)

Engineering, controlling, and simulating quantum dynamics is a strenuous task. However, these techniques are crucial to develop quantum technologies, preserve quantum properties, and engineer decoherence. Earlier results have demonstrated reservoir engineering, construction of a quantum simulator for Markovian open systems,

demonstrated experimentally with trapped ions by applying noise to trap electrodes [4], and thereby also influencing how the open system evolves. It is also possible to monitor in time the decoherence of field-states in a cavity [5]. More recently, a quantum simulator for Lindblad or Markovian dynamics was constructed, motivated by the studies of open many-body systems [6, 7], and a sim-

What do all these papers have in common?

VERY SIMPLE OPTICAL MODELS

PHOTONIC ENVIRONMENT

COLD GASES AS ENVIRONMENTS OF IMMERSED IMPURITIES

Bose-Hubbard Hamiltonian

1D gas of cold bosonic atoms trapped in an optical lattice and confined to the lowest Bloch band

arXiv:1706.09148

Phys. Rev. A 97, 040101 (2018)

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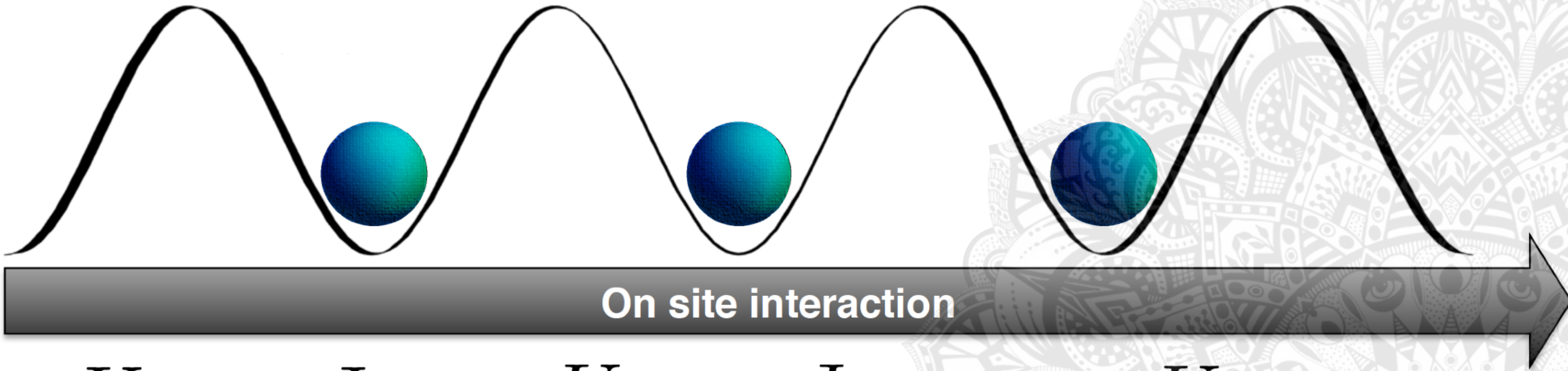
THE ENVIRONMENT

$$\hat{H}_{BH} = -J\sum_{\langle i,j\rangle}(\hat{a}_i^\dagger\hat{a}_j + \hat{a}_j^\dagger\hat{a}_i) + \frac{U}{2}\sum_i \hat{n}_i(\hat{n}_i - 1)$$



$U << J$

superfluid

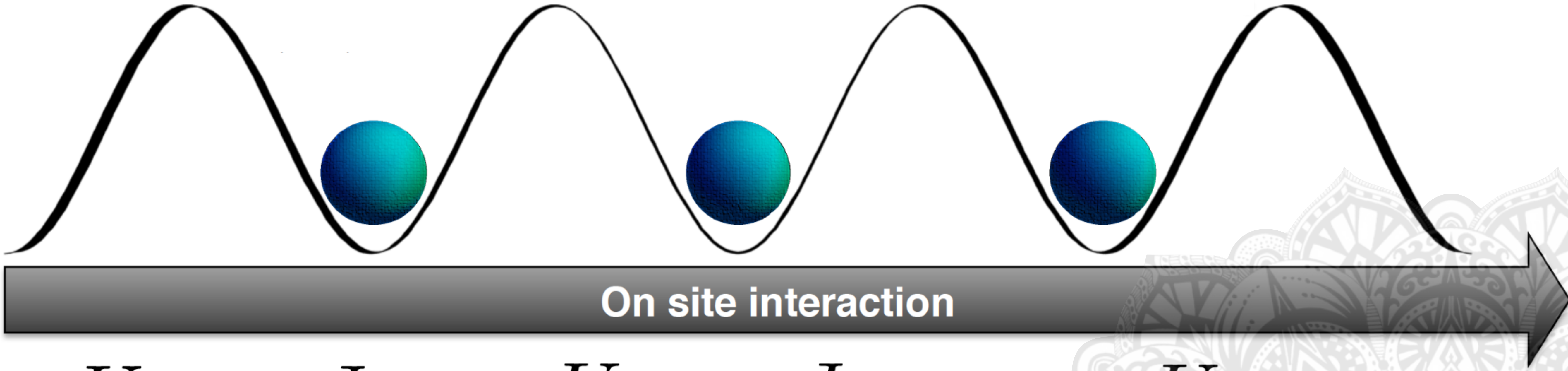
$U >> J$

Mott-insulator

$U \to \infty$

Free fermions

THE ENVIRONMENT



$U << J$ $U >> J$ $U \to \infty$

quantum phase transition

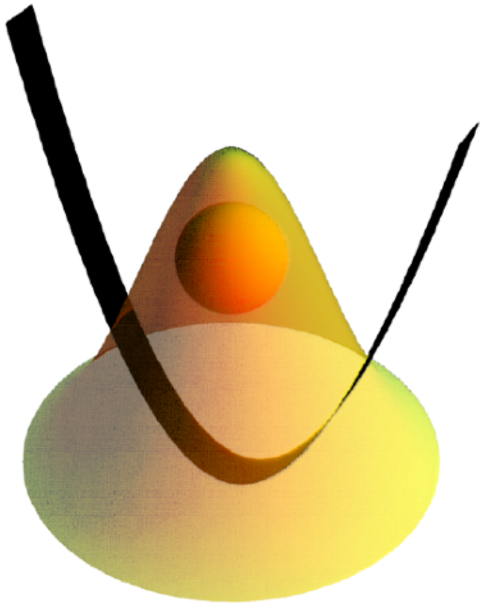
superfluid

DELOCALISED

Mott-insulator

LOCALISED

THE OPEN SYSTEM: Impurity



motional ground state

$$\hat{H} = \frac{\omega_0}{2}\hat{\sigma}_z$$

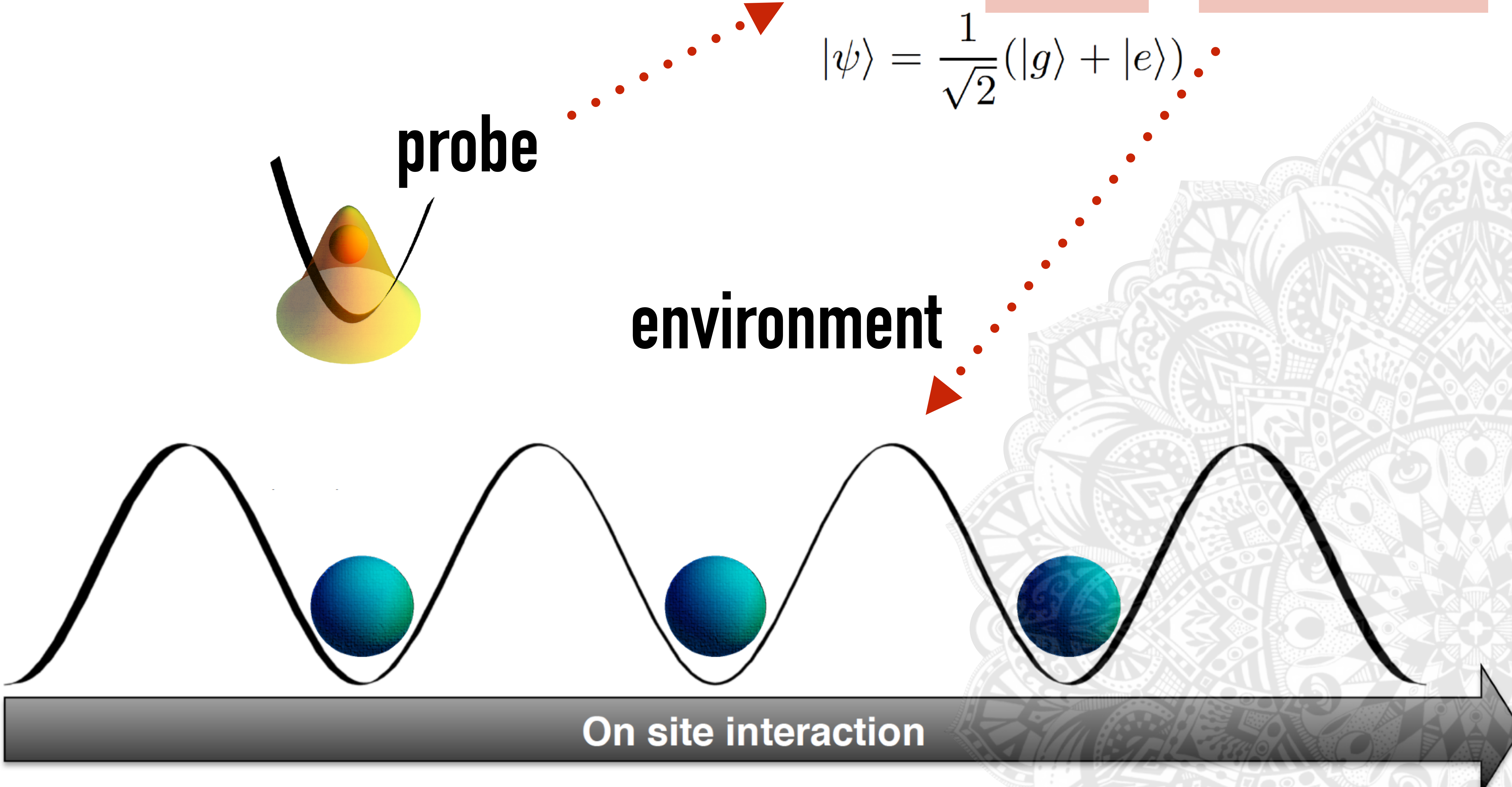
two lowest internal states

$$|e\rangle \; |g\rangle$$

THE INITIAL STATE

$$\rho(0) = \boxed{|\psi\rangle\langle\psi|} \otimes \boxed{|\Phi_{GS}\rangle\langle\Phi_{GS}|}$$

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)$$

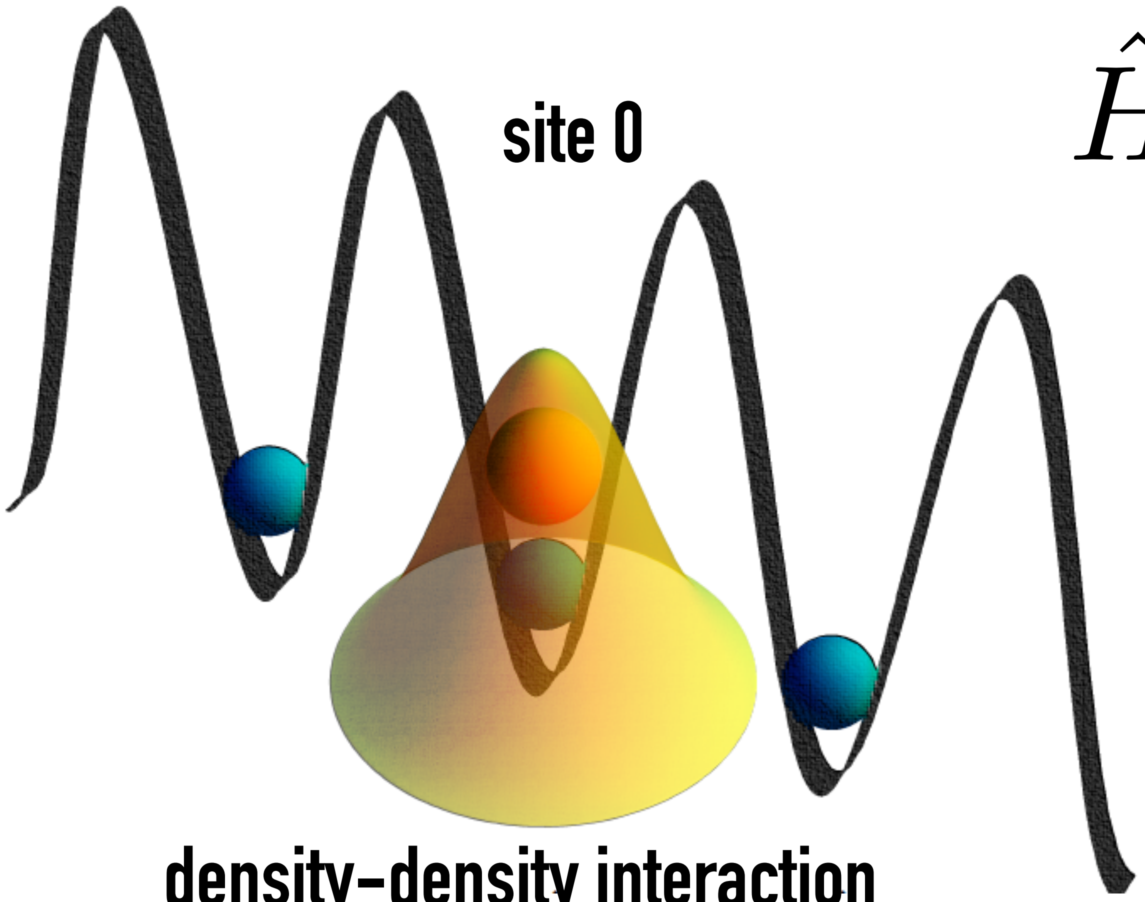


probe

environment

On site interaction

THE SYSTEM-ENVIRONMENT INTERACTION



density-density interaction

$$\hat{H}_{int} = U_e |e\rangle\langle e| \otimes \boxed{\hat{a}_0^\dagger \hat{a}_0}$$

local number operator $\hat{n}_0$

THE OPEN SYSTEM DYNAMICS

total closed system

$$\hat{H} = \underbrace{\frac{\omega_0}{2}\hat{\sigma}_z}_{\text{system}} + \underbrace{\hat{H}_{BH}}_{\text{environment}} + \underbrace{U_e|e\rangle\langle e| \otimes \hat{a}_0^\dagger \hat{a}_0}_{\text{interaction}}$$

time convolutionless projection operator technique

open system

impurity

$$\frac{d\rho}{dt} = -\frac{i\omega_0}{2}[\hat{\sigma}_z, \rho] + \gamma(t)(\hat{\sigma}_z \rho \hat{\sigma}_z - \rho)$$

MASTER EQUATION

for the impurity (open system)

$$\frac{d\rho}{dt} = -\frac{i\omega_0}{2}[\hat{\sigma}_z, \rho] + \boxed{\gamma(t)}(\hat{\sigma}_z\rho\hat{\sigma}_z - \rho)$$

$$\gamma(t) = U_e^2 \mathrm{Re} \int_0^t dt' \boxed{\langle \hat{n}_0(t')\hat{n}_0(0)\rangle}$$

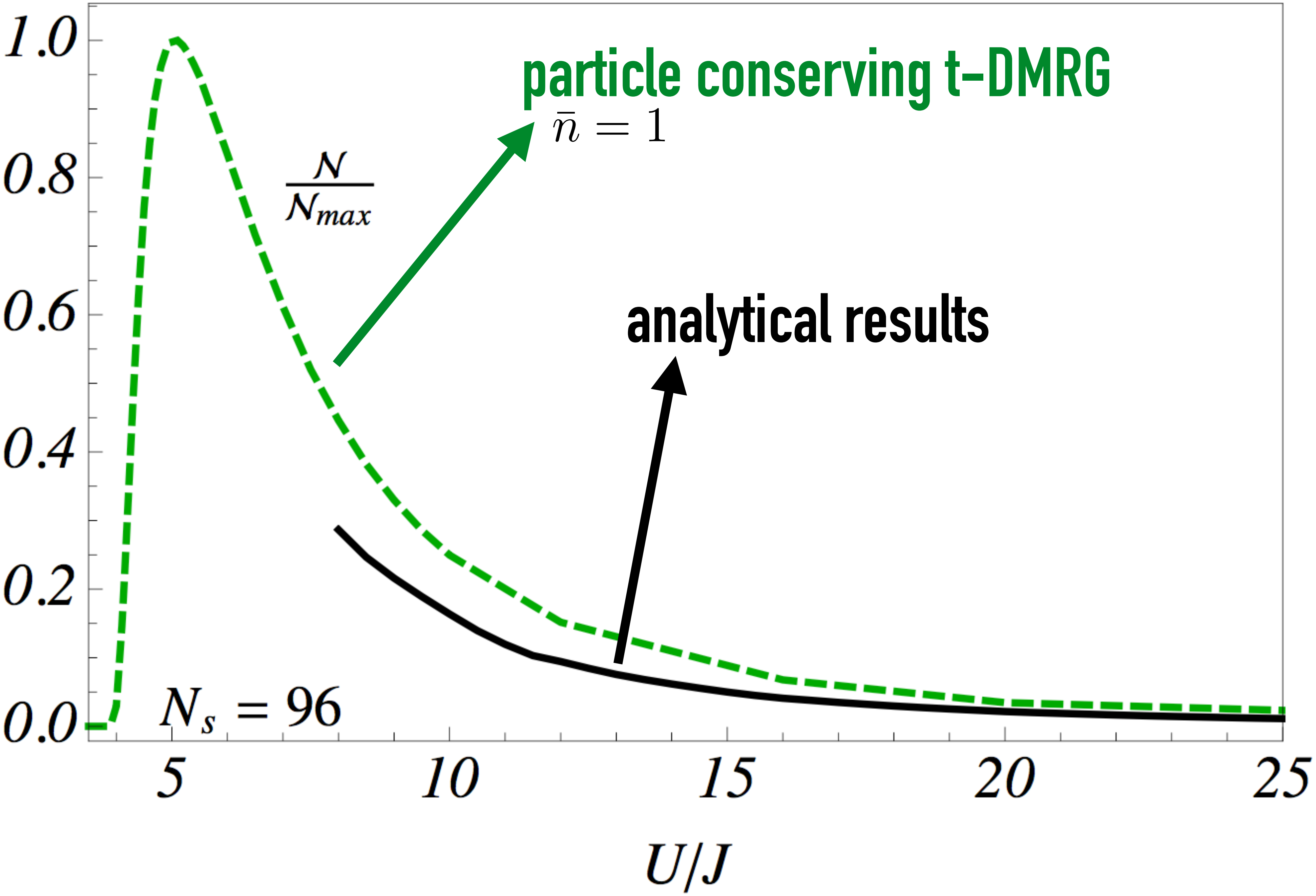
density-density fluctuations of the Bose gas

$\gamma(t) \geq 0$ **Markovian dynamics**

$\gamma(t) < 0$ **Non-Markovian dynamics**

Markovian – Nonmarkovian crossover

$N_s = 96$



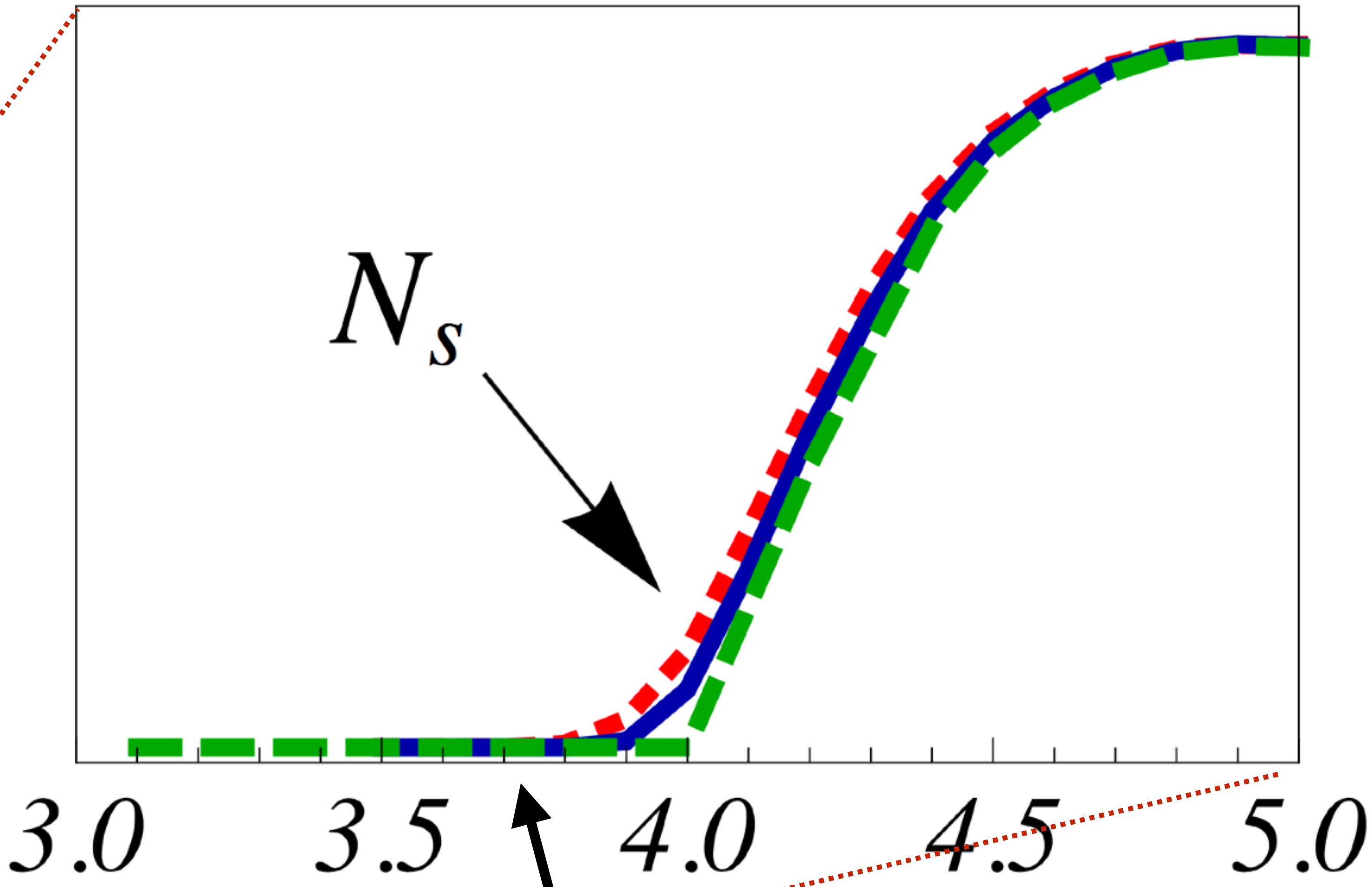
particle conserving t-DMRG

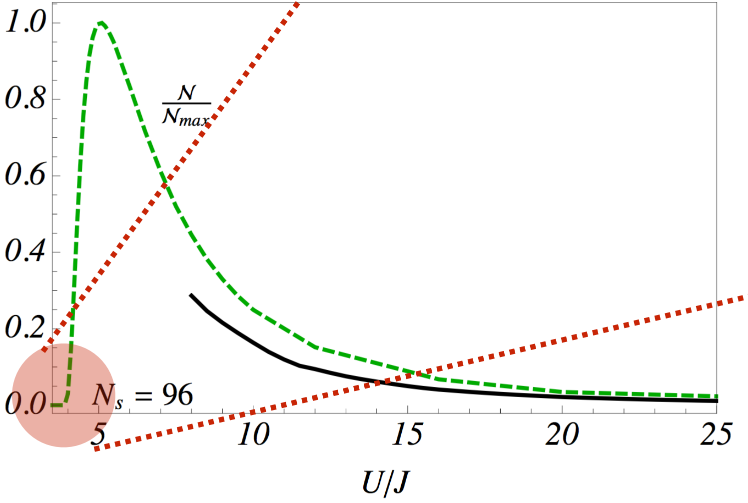
$\bar{n} = 1$

analytical results

Markovian - Nonmarkovian crossover

$N_s = 80, 96, 128$

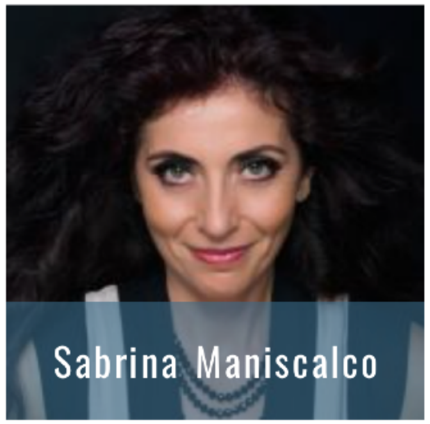




agreement with analytical approach

Take home message

Bose lattices are non trivial controllable environment allowing us to induce both Markovian and non-Markovian dynamics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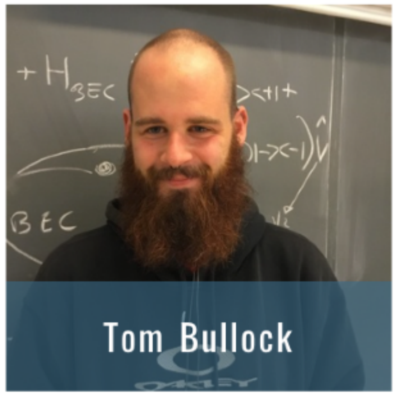
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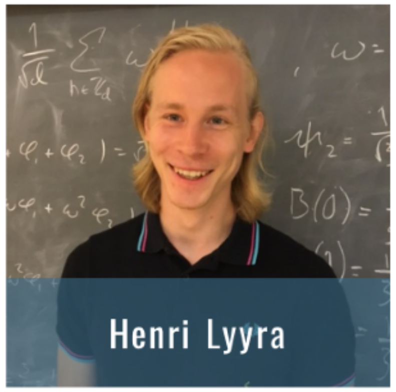
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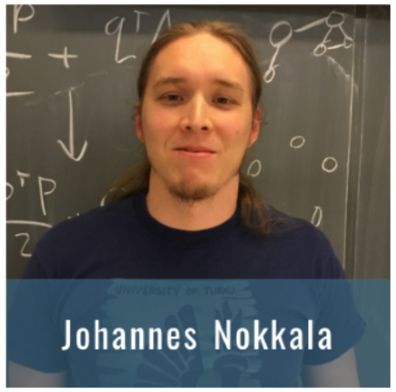
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Funding:

European Commission

QuProCS

Magnus Ehrnrooth foundation

Finnish Centre of Excellence for Quantum Technologies

ACADEMY OF FINLAND