Extreme decoherence and quantum chaos

Adolfo del Campo

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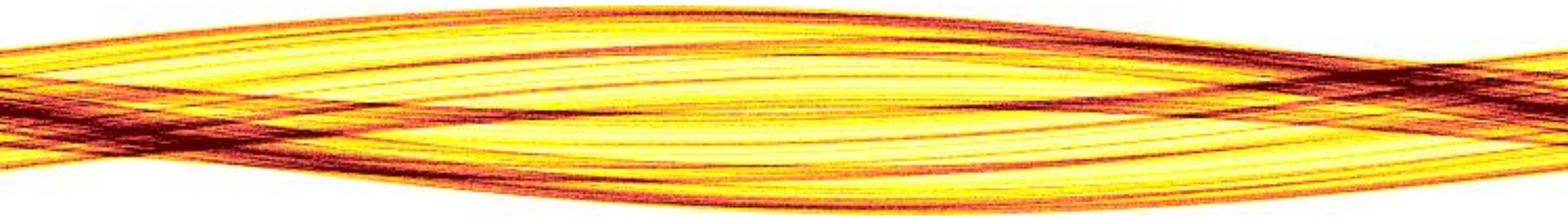

QIST2019
Yukawa Institute for Theoretical Physics,
Kyoto University, May 29th, 2019

ikerbasque
Basque Foundation for Science

QST group from Boston to Bilbao

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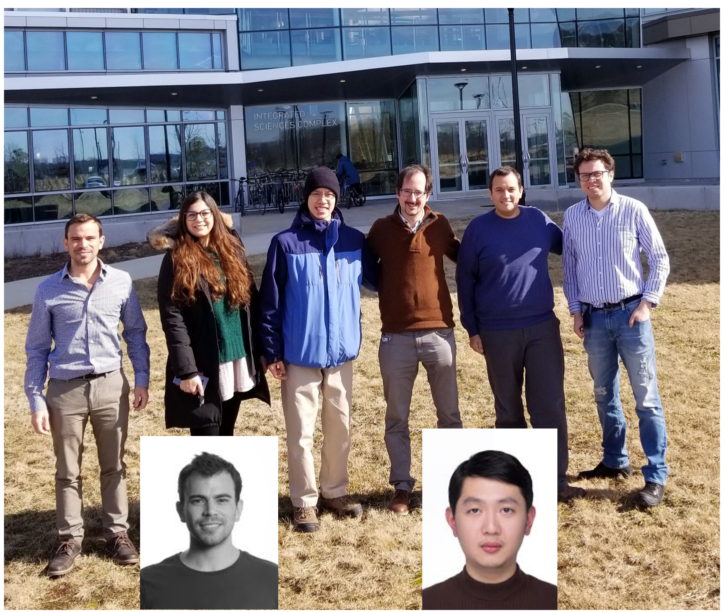
DIPC

QST group from Boston to Bilbao



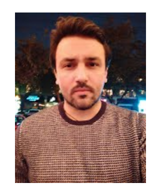
Dr. LP Garcia-Pintos Prof Zhenyu Xu

A Chenu

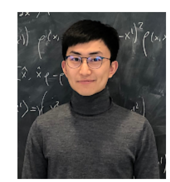
AdC

F Gomez-Ruiz

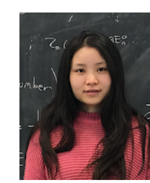
L Dupays



Dr N Gentil



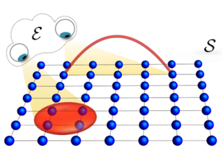
TY Huang

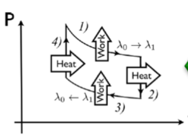


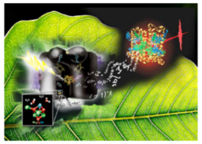
J Zhu

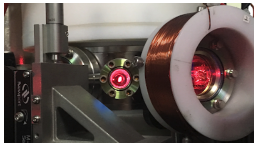
Research

- Quantum open Systems
- Time, Quantum Speed Limits & Metrology
- Quantum Control: Shortcuts to Adiabaticity
- Dynamics of phase transitions: Kibble Zurek mechanism
- Quantum Computation: adiabatic, open
- Quantum Thermodynamics: engines, finite-time
- Trapped ions, cold atoms
- Integrable models, RMT, …



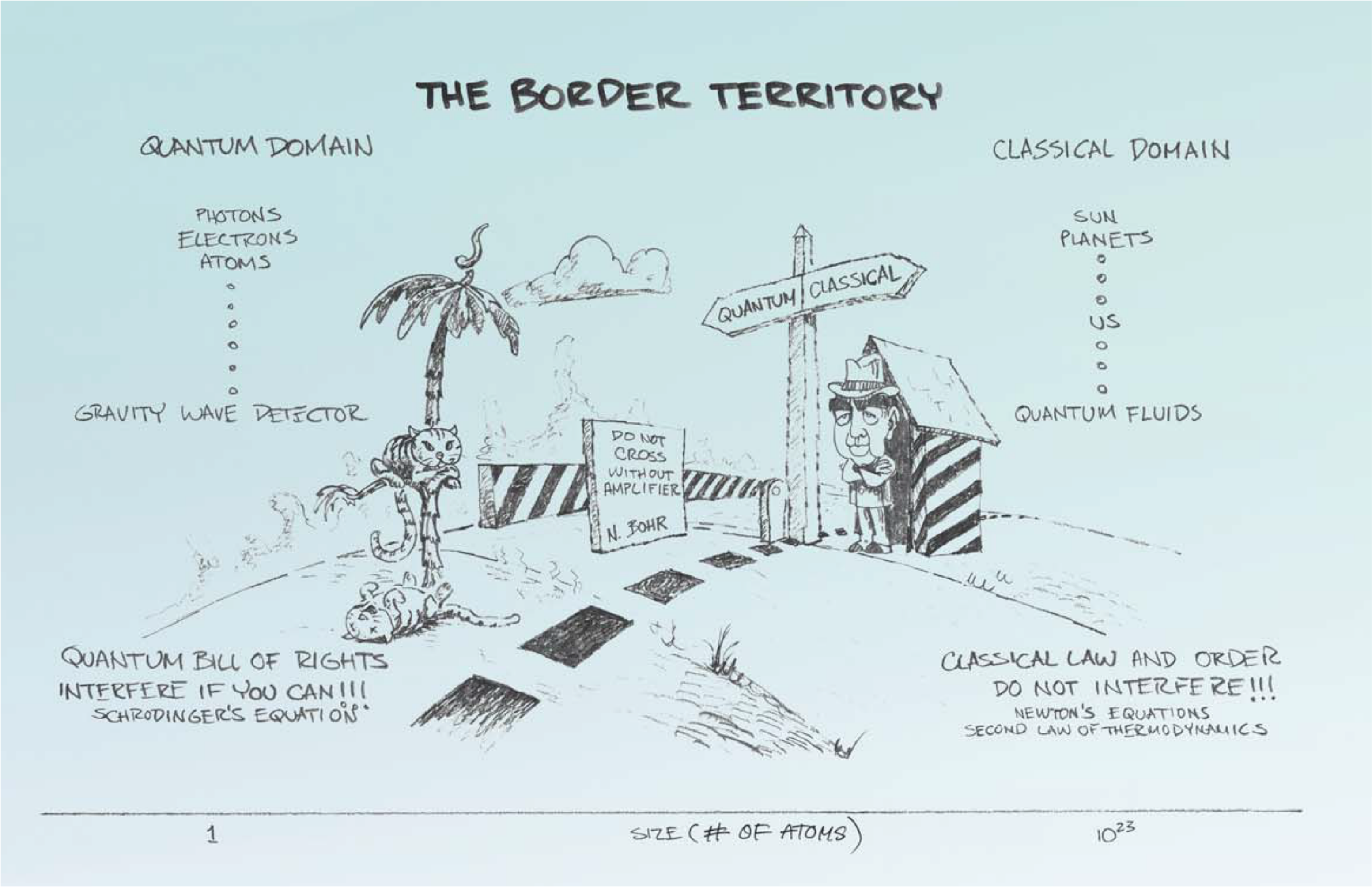







Adolfo del Campo: adolfo.delcampo@umb.edu

Open Quantum Systems: Decoherence



e.g. Zurek, Physics Today

Contents

- Extreme decoherence
  - Noise as a resource for Open Quantum Systems
  - Noise coupled to local interactions
  - Noise coupled to Random Matrix Theory
- Work statistics of complex systems
  - Loschmidt echo and p(W)
  - P(W) and scrambling
  - Work pdf & chaos/RMT
  - Work pdf for time-reversal

Open Quantum Systems

System of interest embedded in an environment: composite system-environment

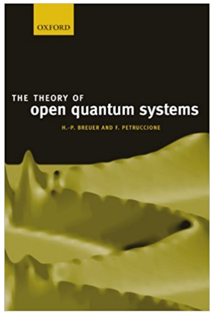
$$\rho(t) = \hat{U}_{SE}(t,0)\rho_S(0) \otimes \rho_E \hat{U}_{SE}(t,0)^\dagger$$

Reduced dynamics via master equation

$$\frac{d}{dt}\rho_S = \frac{-i}{\hbar}\left[\hat{H}_S, \rho_S\right] + \mathcal{D}(\rho_S)$$

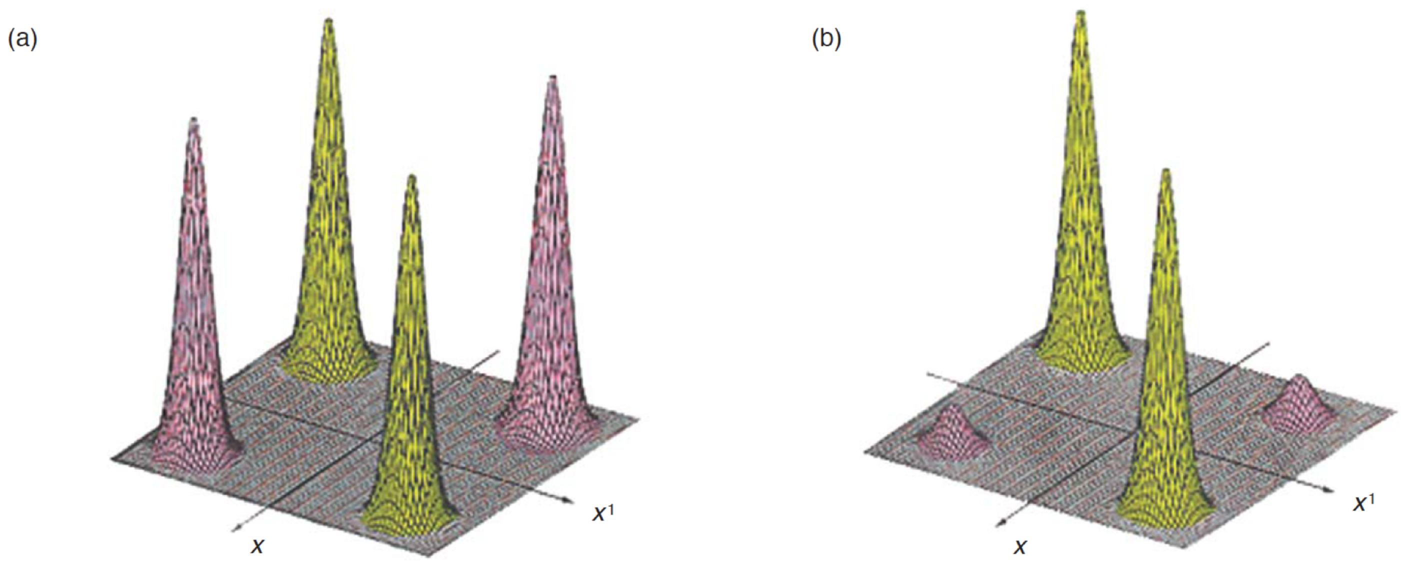
Markovian limit: Universal Lindblad form

$$\frac{d}{dt}\rho_S = \frac{-i}{\hbar}\left[\hat{H}_S, \rho_S\right] + \sum_\alpha \gamma_\alpha \left[L_\alpha \rho_S L_\alpha^\dagger - \frac{1}{2}\left\{L_\alpha^\dagger L_\alpha, \rho_S\right\}\right]$$



Open Quantum Systems: Decoherence

Decay of coherences of density matrix, e.g. of a Schrodinger cat state

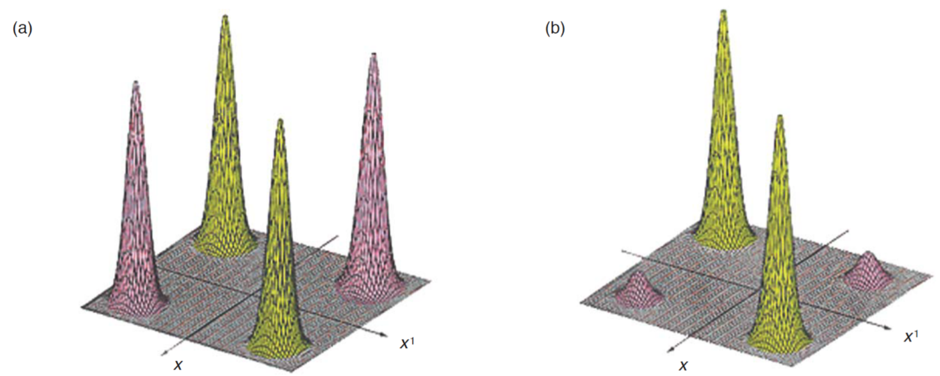


$$\psi_0(x) = \mathcal{N}_\sigma \left[e^{-\frac{(x-r)^2}{2\sigma^2}} + e^{-\frac{(x+r)^2}{2\sigma^2}} \right]$$

e.g. Zurek, Physics Today

Open Quantum Systems: Decoherence

Decay of coherences of density matrix, e.g. of a Schrodinger cat state



Quantum Brownian Motion

$$\frac{d}{dt}\rho_S(t) = \frac{1}{i\hbar}[H, \rho_S(t)] - \frac{i\gamma}{\hbar}[x, \{p, \rho_S(t)\}] - \frac{2m\gamma k_B T}{\hbar^2}[x, [x, \rho_S(t)]]$$

Decoherence time in the high-temperature limit

$$\tau_D = \frac{\lambda_\beta^2}{2\gamma\Delta x^2}$$

e.g. Zurek, Physics Today

Decoherence from Quantum Decay: Fidelity

Survival probability

$$\mathcal{S}(t) := F[\rho_S(0), \rho_S(t)] = \langle \Psi_0 | \rho_S(t) | \Psi_0 \rangle$$

Master equation

$$\frac{d}{dt}\rho_S = \frac{-i}{\hbar}\left[\hat{H}_S, \rho_S\right] + \sum_\alpha \gamma_\alpha \left[L_\alpha \rho_S L_\alpha^\dagger - \frac{1}{2}\left\{L_\alpha^\dagger L_\alpha, \rho_S\right\}\right]$$

Short time decay

$$\mathcal{S}(t) = 1 - \frac{t}{\tau_D} + \mathcal{O}(t^2)$$

Universal decoherence time for Markovian evolutions

$$\boxed{\tau_D = \frac{1}{\sum_\alpha \gamma_\alpha \mathrm{Cov}\left(L_\alpha, L_\alpha^\dagger\right)} \qquad \mathrm{Cov}(A,B) = \langle AB \rangle - \langle A \rangle \langle B \rangle}$$

M. Beau, J. Kiukas, I. L. Egusquiza, AdC, Phys. Rev. Lett. 119, 130401 (2017)

Decoherence from Quantum Decay: Purity

Purity

$$P_t = \mathrm{tr}\rho_S^2 \in [1/d, 1]$$

Master equation

$$\frac{d}{dt}\rho_S = \frac{-i}{\hbar}\left[\hat{H}_S, \rho_S\right] + \sum_\alpha \gamma_\alpha \left[L_\alpha \rho_S L_\alpha^\dagger - \frac{1}{2}\left\{L_\alpha^\dagger L_\alpha, \rho_S\right\}\right]$$

Short time decay

$$P_t = P_0[1 - Dt + \mathcal{O}(t^2)]$$

Universal decoherence time & rate

$$\boxed{\tau_D = \frac{1}{\sum_\alpha \gamma_\alpha \mathrm{Cov}\left(L_\alpha, L_\alpha^\dagger\right)} \qquad D = \frac{2}{P_0}\frac{1}{\tau_D}}$$

M. Beau, J. Kiukas, I. L. Egusquiza, AdC, Phys. Rev. Lett. 119, 130401 (2017)

Decoherence from Quantum Decay

Survival probability

$$\mathcal{S}(t) := F[\rho_S(0), \rho_S(t)] = \langle\Psi_0|\rho_S(t)|\Psi_0\rangle$$

Quantum Brownian motion

$$\frac{d}{dt}\rho_S(t) = \frac{1}{i\hbar}[H, \rho_S(t)] - \frac{i\gamma}{\hbar}[x, \{p, \rho_S(t)\}] - \frac{2m\gamma k_B T}{\hbar^2}[x, [x, \rho_S(t)]]$$

Short time decay

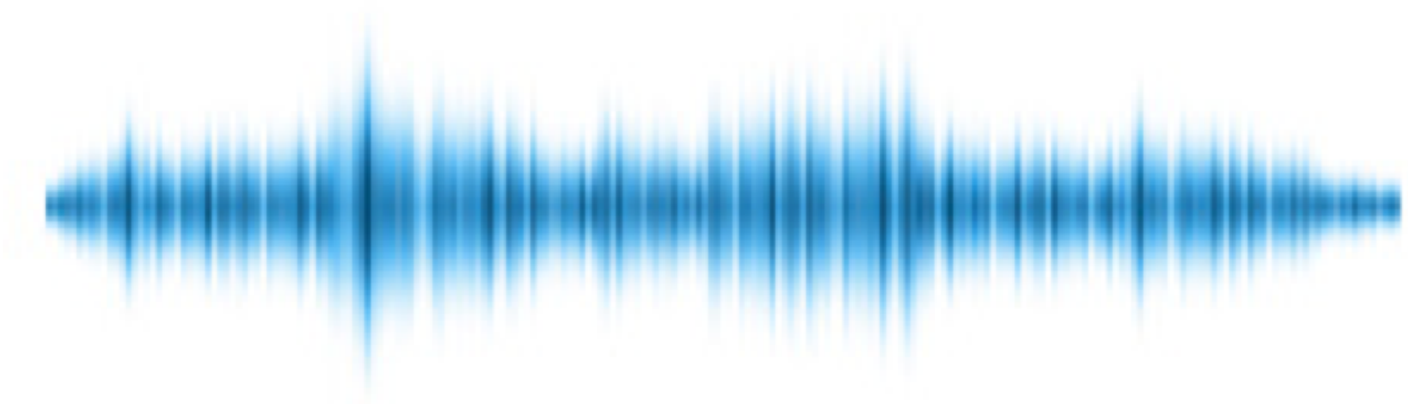
$$\mathcal{S}(t) = 1 - \frac{t}{\tau_D} + \mathcal{O}(t^2)$$

Recover  estimate for decoherence time

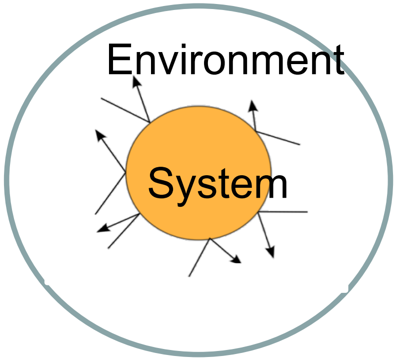
$$\tau_D = \frac{\lambda_\beta^2}{2\gamma\Delta x^2}$$

M. Beau, J. Kiukas, I. L. Egusquiza, AdC, Phys. Rev. Lett. 119, 130401 (2017)

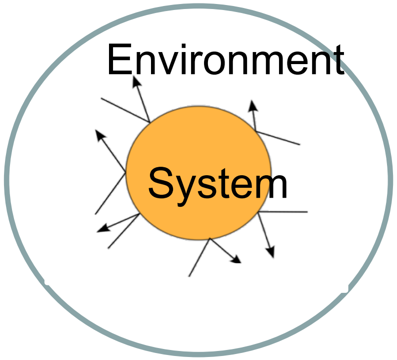
Decoherence
in Noisy Quantum systems

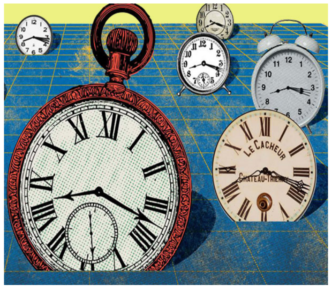


Sources of noise

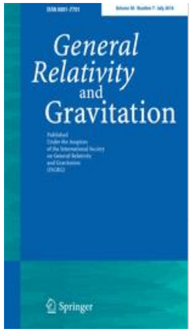


Sources of noise

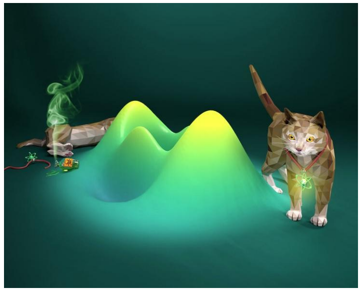




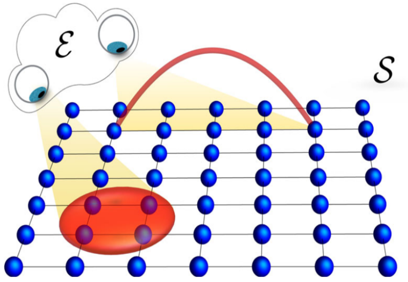
I. L. Egusquiza *et al*., Quantum evolution according to real clocks, Phys. Rev. A **59**, 3236 (1999).



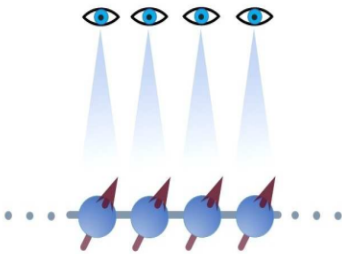
R. Gambini *et al*., Fundamental decoherence from quantum gravity: a pedagogical review, J. Gen Relativ Gravit **39**, 1143 (2007).



Wavefunction Collapse models
(GRW theory, Milburn model, …)
A. Bassi et al. Rev. Mod. Phys. **85**, 471 (2013)



A. Chenu *et al*., Quantum Simulation of Generic Many-Body Open System Dynamics Using Classical Noise, PRL **118**, 140403 (2017).



L. P. García-Pintos *et al*., Spontaneous symmetry breaking induced by quantum monitoring, arXiv:1808.08343.

Stochastic Hamiltonians

Full system

Deterministic part + stochastic part with real Gaussian process

$$H(t) = H_0(t) + \gamma(t)V$$

Stochastic Schrodinger equation

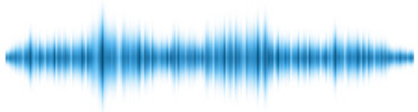
$$i\frac{d}{dt}|\psi(t)\rangle = [H_0(t) + \gamma(t)V]\,|\psi(t)\rangle$$

Extensive literature

G. J. Milburn, PRA 44, 5401 (1991)
H. Moya-Cessa, V. Bužek, M. S. Kim, and P. L. Knight, PRA 48, 3900 (1993)
A. Budini, PRA 64, 052110 (2001)
[...]
A. Chenu, M. Beau, J. Cao, AdC, Phys. Rev. Lett. 118, 140403 (2017)

Noise-Averaged dynamics

Density matrix averaged over realizations



$$\rho(t) = \langle \rho_{\rm st}(t) \rangle = \Big\langle |\psi(t)\rangle\langle\psi(t)| \Big\rangle$$

Master equation requires stochastic unravelling

$$\frac{d}{dt}\rho(t) = -i[H_0(t),\rho] - \int_0^t ds \langle \gamma(t)\gamma(s)\rangle \left[V, \langle [\hat{U}_{\rm st}(t,s) V \hat{U}^\dagger_{\rm st}(t,s), \rho_{\rm st}(t)]\rangle\right]$$

Simplified via Novikov's theorem for white noise $\quad \langle \gamma(t)\gamma(t')\rangle = W^2\delta(t-t')$

$$\boxed{\frac{d}{dt}\rho(t) = -i[H_0(t),\rho(t)] - \frac{W^2}{2}[V,[V,\rho(t)]]}$$

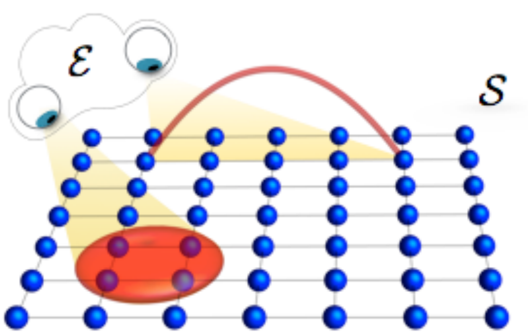
A. Chenu, M. Beau, J. Cao, AdC, Phys. Rev. Lett. 118, 140403 (2017)

Experimental tests?

Quantum simulation of open systems with many-body dissipators

Target Hamiltonian: Ising chain

$$\hat{H}_I = -\sum_{i<j} J_{ij}\,\sigma_i^z\sigma_j^z - h\sum_{i=1}^{N}\sigma_i^x.$$



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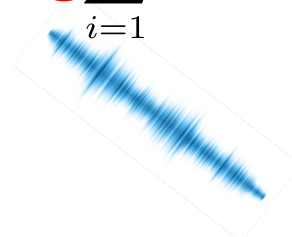

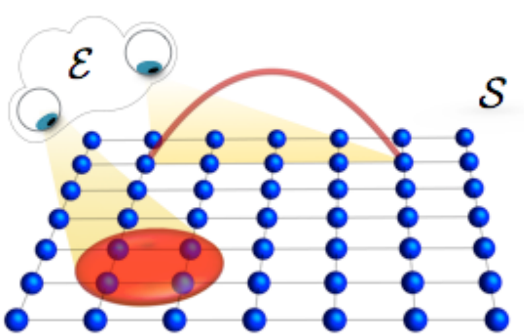

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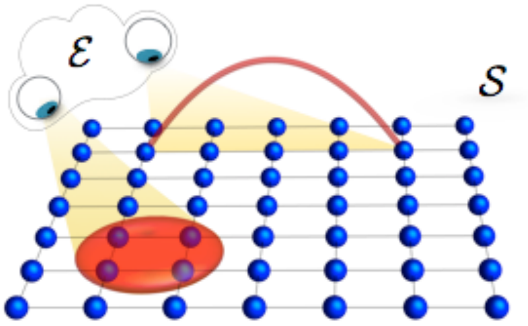
Modulating magnetic field

$$\mathcal{D}[\rho(t)] = -\gamma \sum_{ij} [\sigma_i^x [\sigma_j^x, \rho(t)]]$$

Nonlocal "2-body" dissipator

$$\tau_D \sim 1/N^2$$



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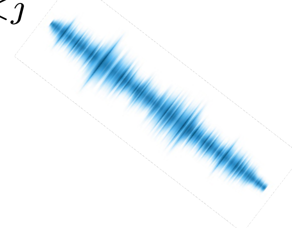

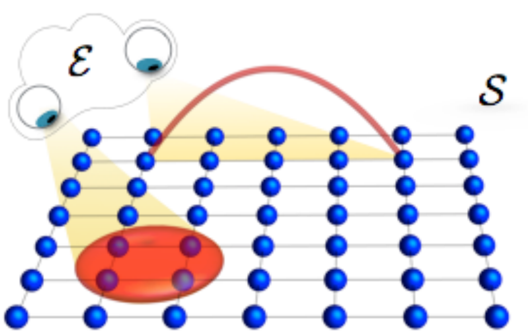

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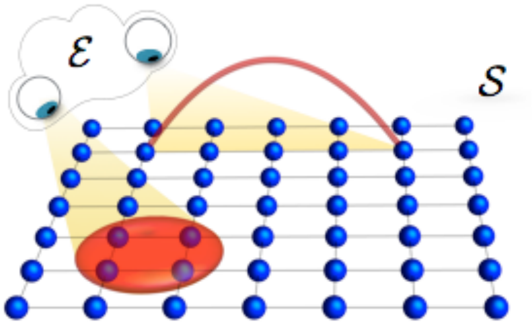
Target Hamiltonian: Ising chain

$$\hat{H}_I = -\sum_{i<j} J_{ij}\,\sigma_i^z \sigma_j^z - h\sum_{i=1}^{N} \sigma_i^x .$$

Modulating ferromagnetic couplings

$$\mathcal{D}[\rho(t)] = -\gamma \sum_{i<j} \sum_{i'<j'} \left[\sigma_i^z \sigma_j^z, \left[\sigma_{i'}^z \sigma_{j'}^z, \rho(t)\right]\right]$$



Nonlocal "4-body" dissipator

$$\tau_D \sim 1/N^4$$

A. Chenu, M. Beau, J. Cao, AdC, Phys. Rev. Lett. 118, 140403 (2017)

Stochastic k-body Hamiltonians

Stochastic Hamiltonian

$$\hat{H}_S(t) = \hat{H}_T(t) + \sum_\alpha \lambda_\alpha(t)\, \hat{L}_\alpha$$

k-body operators

$$\hat{L}_\alpha = \sum_{i_1<\cdots<i_k} \mathbb{L}^{(\alpha,k)}_{i_1,\ldots,i_k}$$

"2k-body" dissipators

$$\mathcal{D}(\rho) = -\sum_\alpha \sum_{i_1<\cdots<i_k} \sum_{i'_1<\cdots<i'_k} \frac{\gamma_\alpha}{2} [\mathbb{L}^{(\alpha,k)}_{i_1,\ldots,i_k}, [\mathbb{L}^{(\alpha,k)}_{i'_1,\ldots,i'_k}, \rho]]$$

Double sum over indices vs usual single sum ~ correlated environment

A. Chenu, M. Beau, J. Cao, AdC, Phys. Rev. Lett. 118, 140403 (2017)

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k-body operators

$$\hat{L}_\alpha = \sum_{i_1 < \cdots < i_k} \mathbb{L}^{(\alpha,k)}_{i_1,\dots,i_k}$$

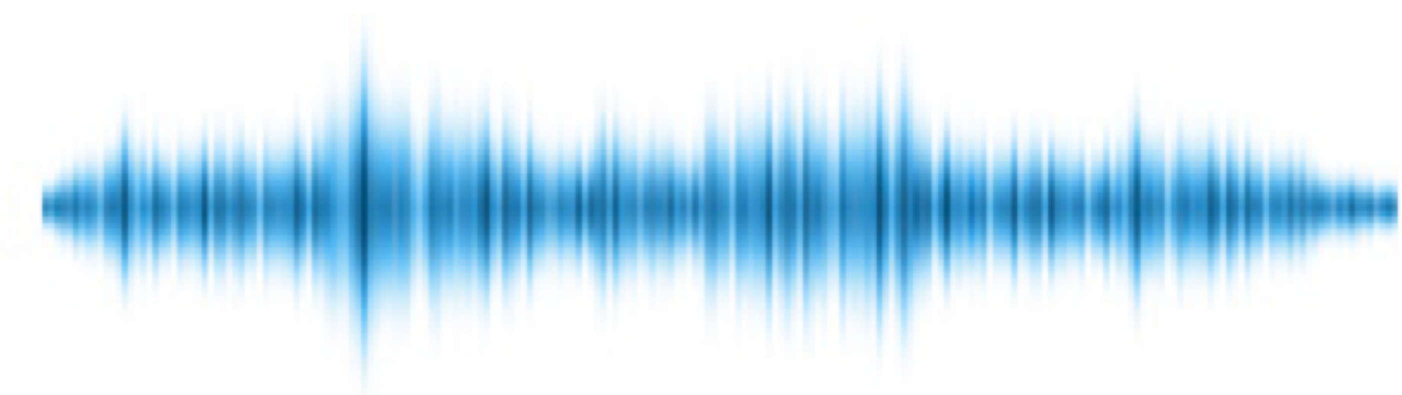
“2k-body” dissipators

$$\tau_D \sim 1/N^{2k}$$

Polynomial scaling

A. Chenu, M. Beau, J. Cao, AdC, Phys. Rev. Lett. 118, 140403 (2017)

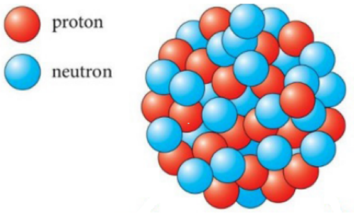
Extreme Decoherence



Chaos & Complex systems

Chaotic systems as a paradigm of **complex systems** and test-bed for **information scrambling**

Described by Random Matrix Theory

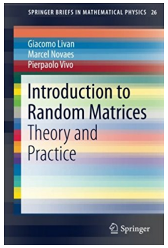


Heavy Nucleus Systems

Ensembles of random matrices

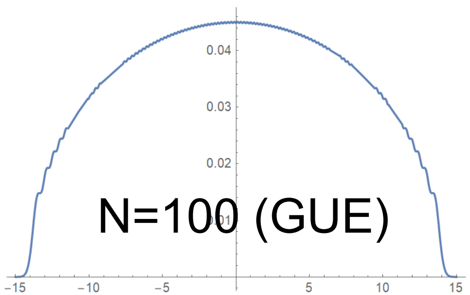
Gaussian Unitary Ensembles (GUE): Hermitian Hamiltonians

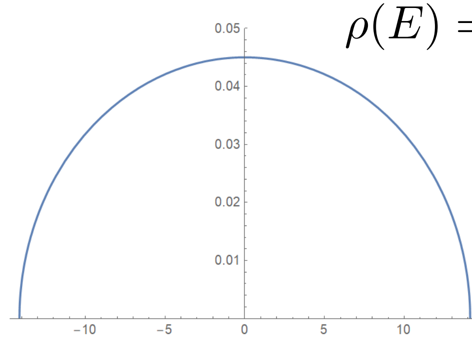
Gaussian Orthogonal Ensembles (GOE): Real Symmetric Hamiltonians with time-reversal symm



Chaos & Complex systems

Density of states: Universal for large Hilbert space dimension “d”





$$\rho(E) = \frac{\sqrt{2d}}{\pi}\sqrt{1-\left(\frac{E}{\sqrt{2d}}\right)^2}$$

Eigenvalues spacing

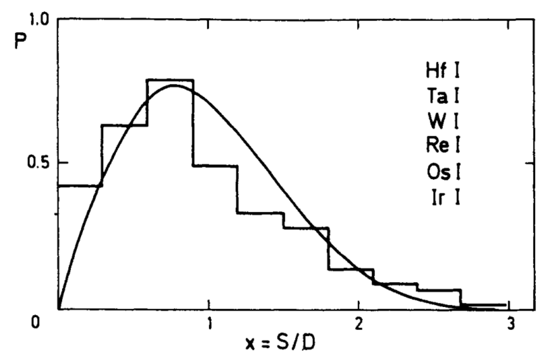


Figure 1.6. Plot of the density of nearest neighbor spacings between odd parity atomic levels of a group of elements in the region of osmium. The levels in each element were separated according to angular momentum, and separate histograms were constructed for each level series, and then combined. The elements and the number of contributed spacings are HfI, 74; TaI, 180; WI, 262; ReI, 165; OsI, 145; IrI, 131 which lead to a total of 957 spacings. The solid curve corresponds to the Wigner surmise, Eq. (1.5.1). Reprinted with permission from Annales Academiae Scientiarum Fennicae, Porter C.E. and Rosenzweig N., Statistical properties of atomic and nuclear spectra, *Annale Academiae Scientiarum Fennicae, Serie A VI, Physica* 44, 1–66 (1960).

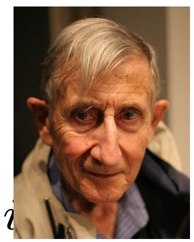
Stochastic k-body Hamiltonians

Stochastic Hamiltonian

$$\hat{H}_S(t) = \hat{H}_T(t) + \sum_\alpha \lambda_\alpha(t)\,\hat{L}_\alpha$$

RMT-body operators

$$\hat{L}_\alpha$$

Decoherence rate?

Z. Xu, L. P. García-Pintos, A. Chenu, and AdC, PRL 122, 014103 (2019)

Stoch RMT Hamiltonians: noise & ensemble averages

GUE average

$$\langle f(X)\rangle_{\mathrm{GUE}} := \int \prod_{k=1}^{d} \mathrm{d}x_k \varrho_{\mathrm{GUE}}(x_1,\ldots,x_d)\,\langle f(X)\rangle_{\mathrm{Haar}}$$

$$\langle f(X)\rangle_{\mathrm{Haar}} := \int_{\mathcal{U}(d)} f(UHU^{-1})\mathbf{d}\mu(U)$$

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Decoherence rate of "fixed" initial state

$$D_{\mathrm{GUE}} = \frac{2d}{d+1}\sum_{\mu}\gamma_\mu\langle \mathrm{var}_{\rho_{\beta=0}}(V_\mu)\rangle_{\mathrm{GUE}} \simeq \Gamma d$$

$$\Gamma = \sum_{\mu}\gamma_\mu$$

Z. Xu, L. P. García-Pintos, A. Chenu, and AdC, PRL 122, 014103 (2019)

Decoherence rate in RMT: GUE

Noise-averaged master equation

$$\frac{d}{dt}\rho(t) = \frac{1}{i\hbar}[\hat{H}_T, \rho(t)] - \sum_\alpha \lambda_\alpha(t)[\hat{L}_\alpha, [\hat{L}_\alpha, \rho(t)]]$$

Decoherence rate

$$D = \frac{2}{P_0}\frac{1}{\tau_D} = \sum_\alpha \lambda_\alpha(t)\Delta\hat{L}_\alpha^2$$

Ensemble average

$$\hat{L}_\alpha \in \mathrm{GUE}(d)$$

$$D_{\mathrm{GUE}} \sim \Gamma d \sim 2^N$$

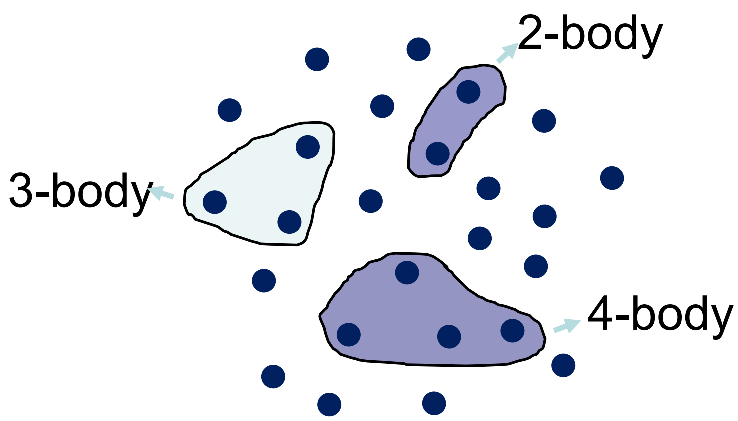
$$\Gamma = \sum_\alpha \lambda_\alpha$$

Exponential dependence on particle number!

Extreme decoherence

Z. Xu, L. P. García-Pintos, A. Chenu, and AdC, PRL 122, 014103 (2019)

k-body Stochastic Hamiltonians & Lindbladians



Stochastic k-body Hamiltonians lead to k-body Lindblad operators

$$D_{k\text{-body}} \lesssim \frac{2\gamma\epsilon^2 \|\Lambda_{l_1<\cdots<l_k}\|^2}{(k!)^2} n^{2k} \qquad (k \ll n) \qquad \textbf{Not Extreme!}$$

Decoherence rate scales polynomially on system size

Z. Xu, L. P. García-Pintos, A. Chenu, and AdC, PRL 122, 014103 (2019)

Entangled states: the thermofield double state

Two copies of the system, independent fluctuations

$$\tilde{H}_t = H \otimes \mathbf{1} + \mathbf{1} \otimes H + \hbar\sqrt{\gamma}(\xi_t^L H \otimes \mathbf{1} + \mathbf{1} \otimes \xi_t^R H)$$

Z. Xu, L. P. García-Pintos, A. Chenu, and AdC, PRL 122, 014103 (2019)

Entangled states: the thermofield double state

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Lindblad operators

$$\tilde{V}_1 = H \otimes \mathbf{1} \quad \tilde{V}_2 = \mathbf{1} \otimes H$$

Initial state: purified thermal density matrix, defined via the Hamiltonian (not fixed)

$$|\Phi_0\rangle := \frac{1}{\sqrt{Z(\beta)}} \sum_k e^{-\frac{\beta E_k}{2}} |k\rangle |k\rangle$$

Z. Xu, L. P. García-Pintos, A. Chenu, and AdC, PRL 122, 014103 (2019)

Entangled states: exact evolution

Time-dependent density matrix

$$\rho_t = \frac{1}{Z(\beta)} \sum_{j,k} e^{-\frac{\beta}{2}(E_j+E_k) - i\frac{2t}{\hbar}(E_j-E_k) - \gamma t(E_j+E_k)^2} |j\rangle|j\rangle\langle k|\langle k|$$

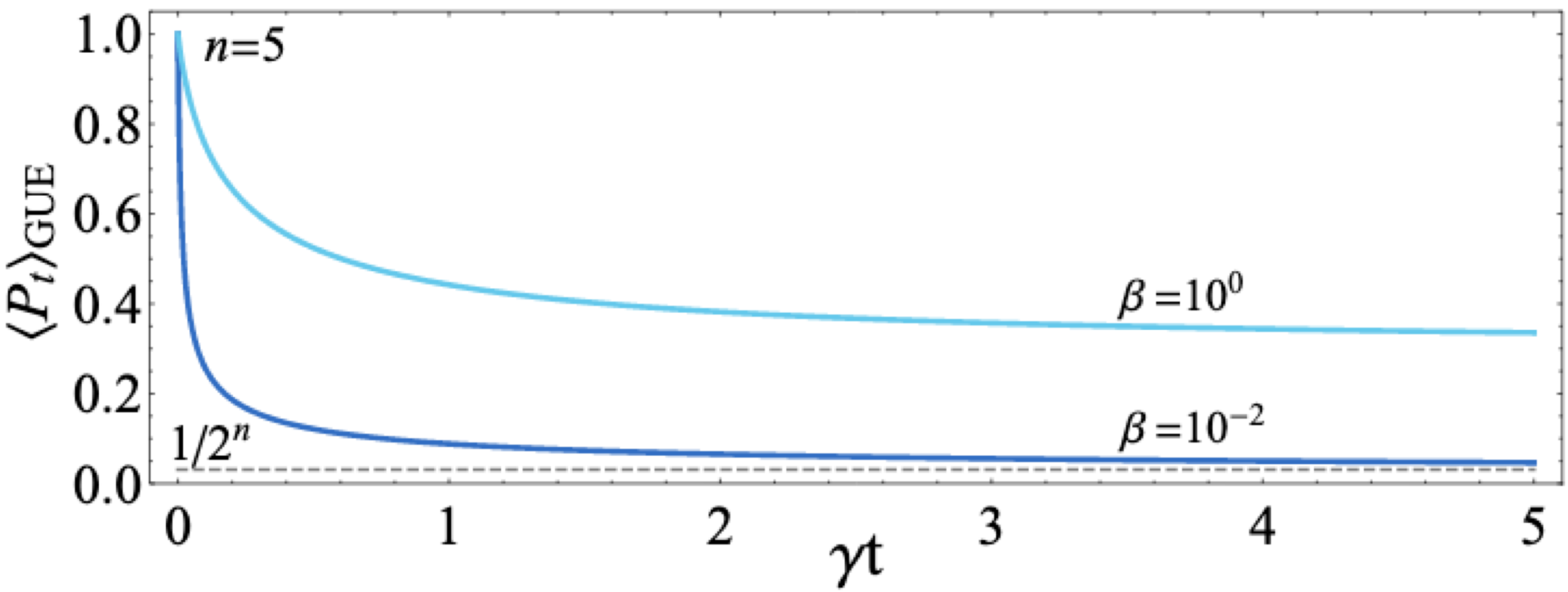
Decay of the purity

$$P_t = \sqrt{\frac{1}{8\pi\gamma t}} \int_{-\infty}^{\infty} e^{-\frac{y^2}{8\gamma t}} \left| \frac{Z(\beta - iy)}{Z(\beta)} \right|^2$$

Decoherence rate

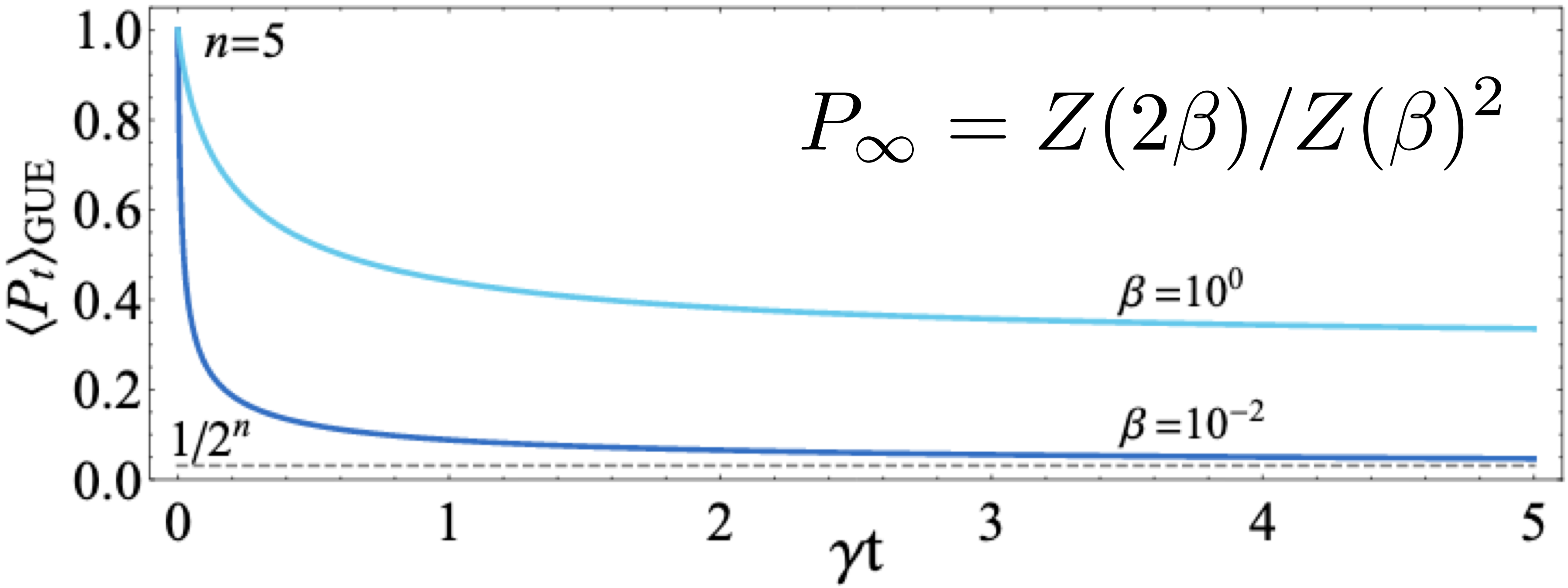
$$\tilde{D} = 4\gamma \mathrm{var}_{\rho_\beta}(H) = 4\gamma \frac{\mathrm{d}^2}{\mathrm{d}\beta^2} \ln\left[Z(\beta)\right]$$

Entangled states: exact evolution



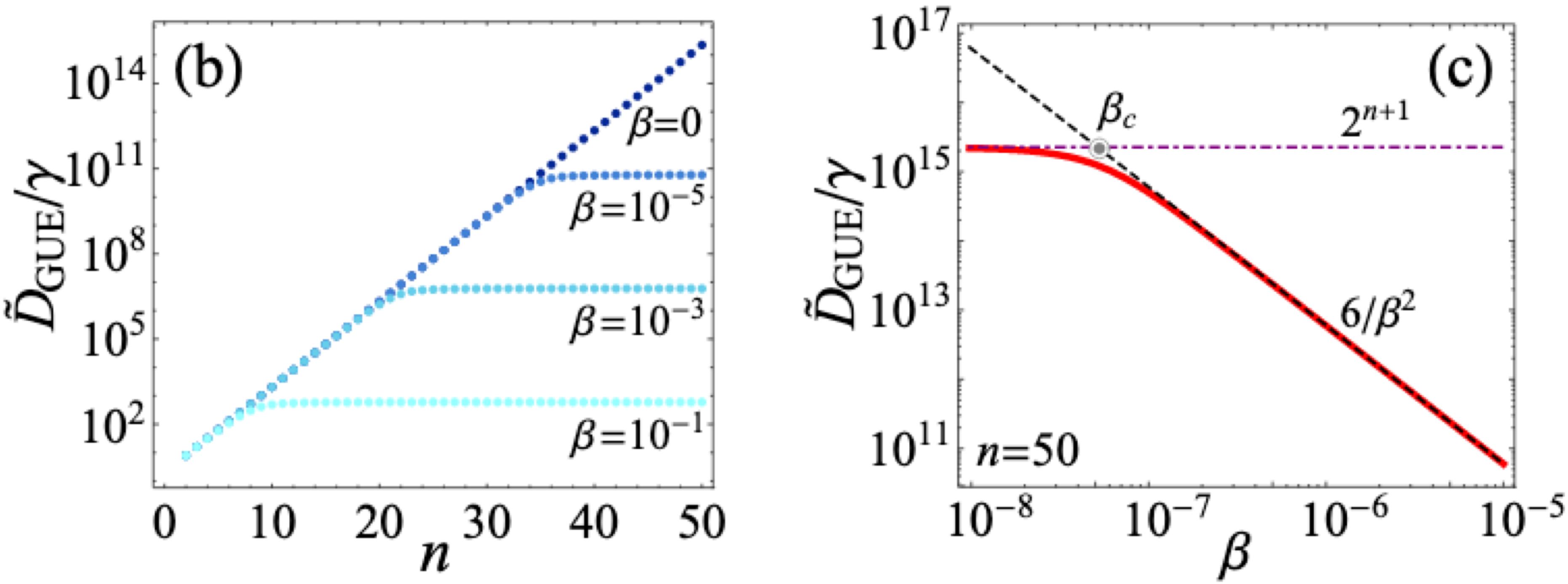
Z. Xu, L. P. García-Pintos, A. Chenu, and AdC, PRL 122, 014103 (2019)

Entangled states: exact evolution



Z. Xu, L. P. García-Pintos, A. Chenu, and AdC, PRL 122, 014103 (2019)

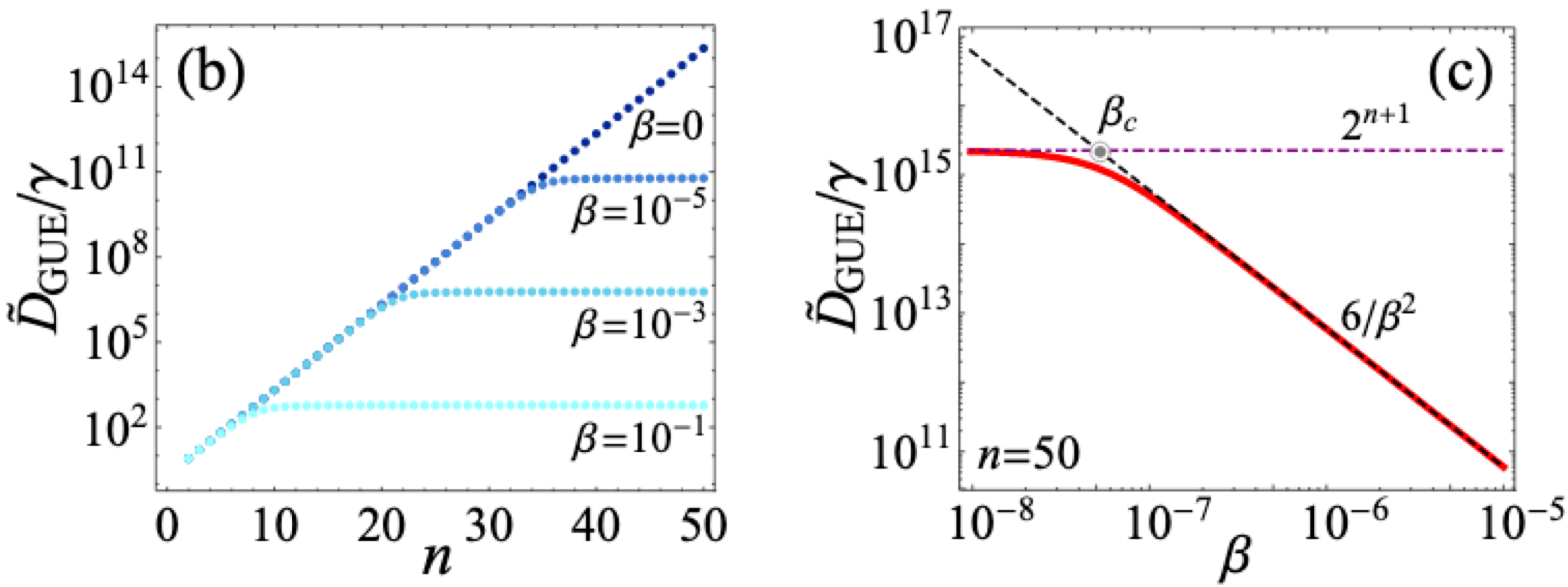
Entangled states: decoherence rate



$$\tilde{D}_{\rm GUE} \simeq \begin{cases} 2\gamma d, & \left(\beta \ll \sqrt{3/d}\,\right) \\ \frac{6\gamma}{\beta^2}, & \left(\beta \gg \sqrt{3/d}\,\right) \end{cases}$$

Z. Xu, L. P. García-Pintos, A. Chenu, and A. del Campo, PRL **122**, 014103 (2019).

Thermofield double states: decoherence rate



For a TDS extreme decoherence is restricted to

infinite temperature or small system sizes

Z. Xu, L. P. García-Pintos, A. Chenu, and A. del Campo, PRL **122**, 014103 (2019)

Black holes in AdS/CFT: decoherence rate

Decoherence rate proportional to heat capacity of CFT

$$\tilde{D} = 4\gamma C/(k_B \beta^2)$$

Heat capacity proportional to entropy/scales with #dof

[Papadodimas & Raju]

Z. Xu, L. P. García-Pintos, A. Chenu, and A. del Campo, PRL **122**, 014103 (2019).

Contents

- **Noise** a resource for quantum simulation of open systems

- In Local Interactions

  polynomial scaling of decoherence rate with system size

  Chenu et al. PRL 118, 140403 (2017); 119,130401 (2017)

- In RMT Operators

  exponential scaling of decoherence rate with system size

  Xu et al., PRL 122, 014103 (2019)

Part II

Work statistics in complex systems & information scrambling

A. Chenu, I. L. Egusquiza, J. Molina-Vilaplana, AdC, Sci. Rep. 8, 12634 (2018)
A. Chenu, J. Molina-Vilaplana, AdC, Quantum 3, 127 (2019)

Work pdf

Driven isolated system $$\hat{H}_s = \sum_n E_n^s |n_s\rangle\langle n_s|$$

Unitary evolution: **physical time of evolution "s"**

$$\hat{U}(\tau) = \mathcal{T}\exp\left[-i\int_0^\tau ds\hat{H}_s\right]$$

Work probability distribution

$$p_\tau(W) = \sum_{n,m} p_n^0\, p_{m|n}^\tau \delta\left[W - \left(E_m^\tau - E_n^0\right)\right]$$

J. Kurchan, ArXiv:0007360 (2000); P. Talkner, E. Lutz, P. Hanggi, PRE 75, 050102(R) (2007)

Work pdf: characteristic function

Fourier transform = moment-generating function

$$\chi(t,\tau) = \int_{-\infty}^{\infty} dW p_\tau(W)\, e^{iWt}.$$

Variable "t" different from the physical time of evolution "s"

Explicit expression

$$\chi(t,\tau) = \sum_n p_n^0 \langle n_0 | e^{it\hat{H}_\tau^{\rm eff}} e^{-it\hat{H}_0} | n_0 \rangle \qquad \hat{H}_\tau^{\rm eff} = \hat{U}^\dagger(\tau)\hat{H}_\tau\hat{U}(\tau)$$

resembles a Loschmidt echo

J. Kurchan, ArXiv:0007360 (2000); P. Talkner, E. Lutz, P. Hanggi, PRE 75, 050102(R) (2007)

From Work pdf to dynamics

Silva 2008:

If

system prepared in an eigenstate at s=0

sudden quench

think of "t" as a second time of evolution in a Loschmidt echo

$$\chi(t,\tau) = \langle n_0 | e^{it\hat{H}_\tau} e^{-it\hat{H}_0} | n_0 \rangle$$

Avoids explicit computation of transition probabilities in

$$p_\tau(W) = \sum_{n,m} p_n^0 \, p_{m|n}^\tau \delta \left[W - \left(E_m^\tau - E_n^0 \right) \right]$$

A. Silva, PRL 101, 120603 (2008)

From Work pdf to dynamics: arbitrary setting

Chenu et al 2017:

Purification of arbitrary initial mixed state purification

$$\rho_0 \longrightarrow |\Psi_0\rangle = \sum_n \sqrt{p_n^0}\, |n_0\rangle_L \otimes |n_0\rangle_R$$

A. Chenu et al., Sci. Rep. 8, 12634 (2018); Quantum 3, 127 (2019)

From Work pdf to dynamics: arbitrary setting

Chenu et al 2017:

Purification of arbitrary initial mixed state purification

$$\rho_0 \longrightarrow |\Psi_0\rangle = \sum_n \sqrt{p_n^0}\, |n_0\rangle_L \otimes |n_0\rangle_R$$

Characteristic function as a Loschmidt echo amplitude

$$\begin{aligned}\chi(t,\tau) &= \sum_n p_n^0 \langle n_0| e^{it\hat{H}_\tau^{\rm eff}} e^{-it\hat{H}_0} |n_0\rangle \\ &= \langle \Psi_0|\Psi_t\rangle = \langle \Psi_0| e^{+it\hat{H}_\tau^{\rm eff}} e^{-it\hat{H}_0} \otimes \mathbf{1}_R |\Psi_0\rangle\end{aligned}$$

A. Chenu et al., Sci. Rep. 8, 12634 (2018); Quantum 3, 127 (2019)

From Work pdf to dynamics: arbitrary setting

Chenu et al 2017:

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$$\chi(t,\tau) = \sum_n p_n^0 \langle n_0| e^{it\hat{H}_\tau^{\rm eff}} e^{-it\hat{H}_0} |n_0\rangle$$

$$= \langle\Psi_0|\Psi_t\rangle = \langle\Psi_0| e^{+it\hat{H}_\tau^{\rm eff}} e^{-it\hat{H}_0} \otimes \mathbf{1}_R |\Psi_0\rangle$$

Loschmidt echo

$$\mathcal{L}(t) = |\langle\Psi_0|\Psi_t\rangle|^2 = \left|\int_{-\infty}^{\infty} dW p_\tau(W)\, e^{iWt}\right|^2$$

A. Chenu et al., Sci. Rep. 8, 12634 (2018); Quantum 3, 127 (2019)

Work statistics and information scrambling

Scrambling:

Spreading of quantum correlations across many degrees of freedom

Papadodimas-Raju: decay dynamics of purified state, e.g., survival amplitude

$$\mathcal{L}(t) = |\langle\Psi_0|\Psi_t\rangle|^2 = |\langle\Psi_0|\hat{U}_L(t,0)\otimes\mathbf{1}_R|\Psi_0\rangle|^2$$

K Papadodimas, S. Raju, PRL 115, 211601 (2015)

Work statistics and information scrambling

Scrambling:

Spreading of quantum correlations across many degrees of freedom

Papadodimas-Raju: decay dynamics of purified state, e.g., survival amplitude

$$\mathcal{L}(t) = |\langle \Psi_0 | \Psi_t \rangle|^2 = |\langle \Psi_0 | \hat{U}_L(t,0) \otimes \mathbf{1}_R | \Psi_0 \rangle|^2$$

Decay dynamics in Loschmidt echo $\hat{U}_L(t,0) = e^{+it\hat{H}_\tau^{\rm eff}} e^{-it\hat{H}_0}$

Scrambling from work pdf

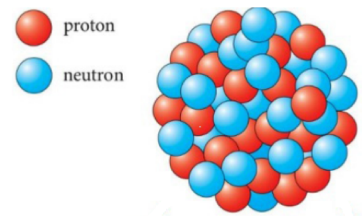
$$\mathcal{L}(t) = |\langle \Psi_0 | \Psi_t \rangle|^2 = \left| \int_{-\infty}^{\infty} dW p_\tau(W) \, e^{iWt} \right|^2$$

A. Chenu et al., Sci. Rep. 8, 12634 (2018); Quantum 3, 127 (2019)
AdC, J. Molina-Vilaplana, J. Sonner, PRD 95, 126008 (2017)

Chaos & Complex systems

Chaotic systems as a paradigm of **complex systems** and test-bed for **information scrambling**

Described by Random Matrix Theory

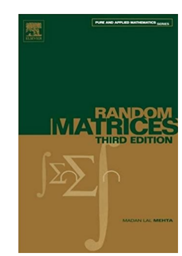


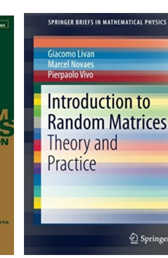
Heavy Nucleus Systems

Ensembles of random matrices

Gaussian Unitary Ensembles (GUE): Hermitian Hamiltonians

Gaussian Orthogonal Ensembles (GOE): Real Symmetric Hamiltonians with time-reversal symm





Work pdf & RMT

Example: Quantum quenches between two RMT Hamiltonians

A. Chenu et al. Quantum work statistics, Loschmidt echo and information scrambling, arXiv:1711.01277

A. Chenu et al.

Work Statistics, Loschmidt Echo and Information Scrambling in Chaotic Quantum Systems arXiv:1804.09188

See related work:

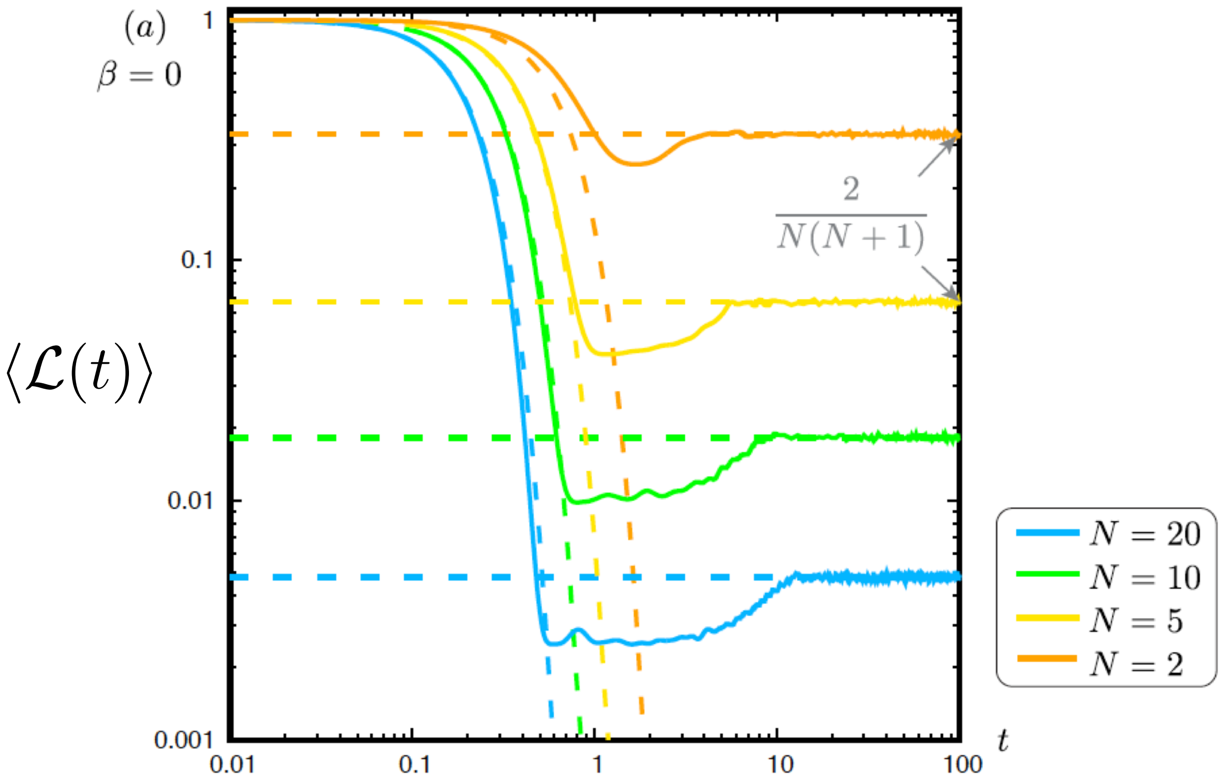
RMT large N asymptotics: M. Łobejko, J. Łuczka, P. Talkner PRE 95, 052137 (2017)

Disordered many-body systems: Y Zheng and D. Poletti, arXiv:1806.02555

Chaos & Complex systems

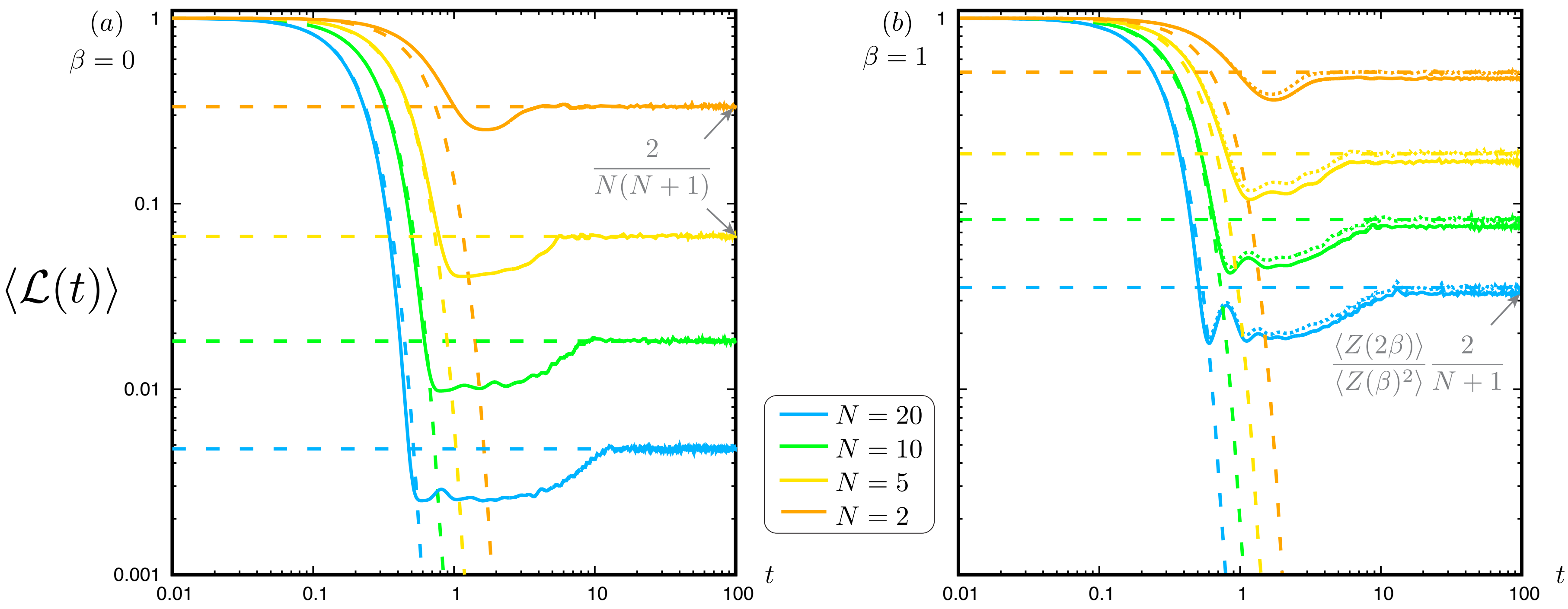
Initial thermal state $$|\Psi_0\rangle = \frac{1}{\sqrt{Z(\beta)}}\sum_n e^{-\frac{\beta}{2}\hat{H}_0 \otimes \mathbf{1}_R}|n_0\rangle_L \otimes |n_0\rangle_R$$

Sudden quench: $$\hat{H}_0 \to \hat{H}_f \qquad \hat{H}_0, \hat{H}_f \in \mathrm{GUE(N)}$$



A. Chenu et al., Quantum 3, 127 (2019)

Chaos & Complex systems



Short-times $\langle \mathcal{L}(t) \rangle_{\mathrm{GUE}} = \left\langle e^{-t^2\sigma_W^2 + \mathcal{O}(t^4)} \right\rangle \geq e^{-t^2\langle \sigma_W^2 \rangle + \mathcal{O}(t^4)}$

Long-times $\langle \mathcal{L}(t) \rangle_{\mathrm{GUE}} \to \dfrac{\langle Z(2\beta) \rangle}{\langle Z(\beta)^2 \rangle} \dfrac{2}{(N+1)}$

A. Chenu et al., Quantum 3, 127 (2019)

Work for time-reversal operation

Time-reversal operation

Negation of system Hamiltonian (e.g. in GOE)

$$\hat{H}_0 \to \hat{H}_f = -\hat{H}_0 \qquad \hat{H}_0 \in \mathrm{GOE(N)}$$

Loschmidt echo from partitio function

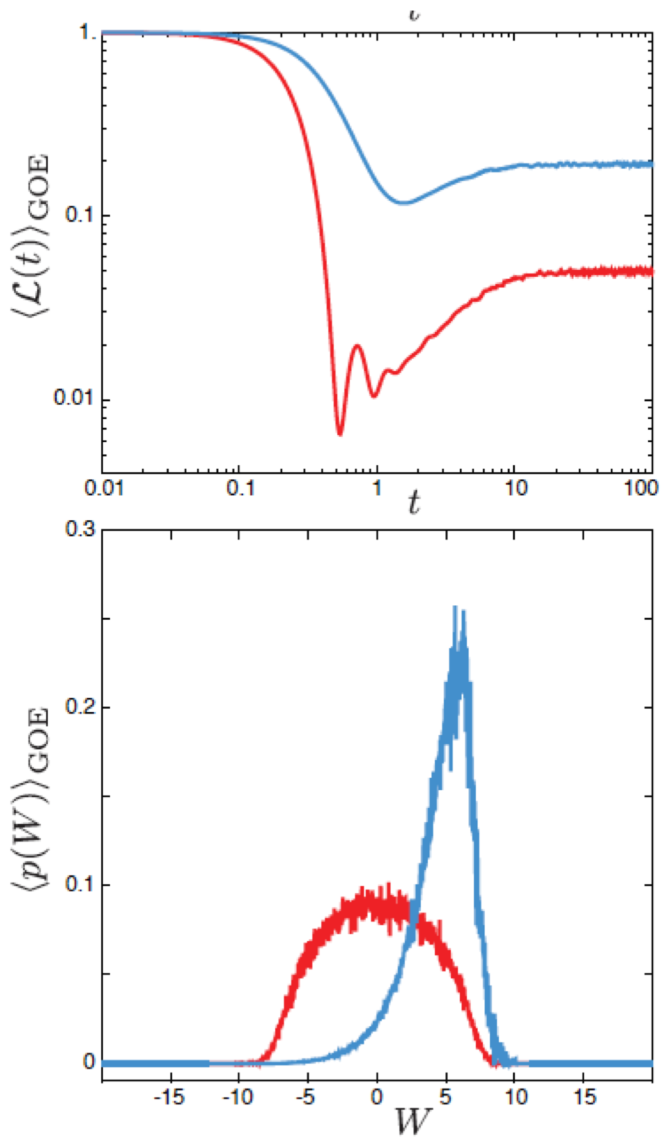
$$\mathcal{L}(t) = |\langle \Psi_0 | \Psi_0(t) \rangle|^2 = \left| \frac{Z(\beta + i2t)}{Z(\beta)} \right|^2$$

Work pdf

$$p(W) = \frac{1}{2} \langle \rho(E) \rangle_\beta \Big|_{E=-W/2}$$

Mean work

$$\langle W \rangle = -2 \langle \hat{H}_0 \rangle_\beta$$



A. Chenu et al., Sci. Rep. 8, 12634 (2018)

Loschmidt echo, work pdf and scrambling

$$\hat{H}_0 \rightarrow \hat{H}_f = -\hat{H}_0$$

$$\mathcal{L}(t) = |\langle TDS(0)|TDS(t)\rangle|^2 = \left|\int dW p(W) e^{iWt}\right|^2 = \left|\frac{Z(\beta + i2t)}{Z(\beta)}\right|^2$$

A. Chenu et al., Sci. Rep. 8, 12634 (2018); A. Chenu et al., Quantum 3, 127 (2019)

Loschmidt echo, work pdf and scrambling

$$\hat{H}_0 \rightarrow \hat{H}_f$$

GUE averaged Loschmidt echo

$$\langle \mathcal{L}(t) \rangle = \frac{1}{\langle Z(\beta)^2 \rangle} \frac{1}{N^2-1} \Big(g(0,t) g(\beta,t) + N \langle Z(2\beta) \rangle - \frac{1}{N} \langle Z(2\beta) \rangle g(0,t) - \frac{1}{N} g(\beta,t) N \Big)$$

Spectral form factor

$$g(\beta,t) \equiv \langle Z(\beta+it) Z(\beta-it) \rangle$$

A. Chenu et al., Sci. Rep. 8, 12634 (2018); A. Chenu et al., Quantum 3, 127 (2019)

Loschmidt echo, work pdf and scrambling

GUE averaged Loschmidt echo: infinite temperature

$$\langle \mathcal{L}(t) \rangle = \frac{1}{N^2} \mathcal{F}^{(1)}_{\mathrm{GUE}}(t) \qquad (\beta = 0)$$

Frame potential

$$\mathcal{F}^{(k)}_{\mathcal{E}} = \int_{\hat{A},\hat{B}\in\mathcal{E}} D\hat{A} D\hat{B} \left| \mathrm{tr} \hat{A}^{\dagger} \hat{B} \right|^{2k}$$

A. Chenu et al., Sci. Rep. 8, 12634 (2018); A. Chenu et al., Quantum 3, 127 (2019)

Loschmidt echo, work pdf and scrambling



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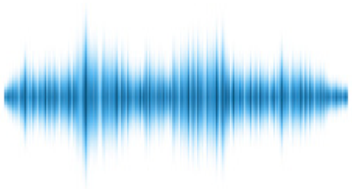
Cotler et al
JHEP 1711 (2017) 048

A. Chenu et al., Sci. Rep. 8, 12634 (2018); A. Chenu et al., Quantum 3, 127 (2019)

Summary



- Extreme decoherence
  - Noise as a resource for QOS
  - Noise coupled to local interactions
  - Noise coupled to RMT

- Work statistics of complex systems
  - Loschmidt echo and p(W)
  - P(W) and scrambling
  - Work pdf & chaos/RMT
  - Work pdf for time-reversal

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