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Workshop on
Noise and Instabilities in Quantum Mechanics

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Quantum noise in algorithms and transport

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Plan

- Open quantum systems: master equation

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- Solving the master equation with quantum trajectories

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- Possible experimental realization of a quantum ratchet

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- Possible experimental realization of a quantum ratchet
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- Future plans

Open quantum systems

- Real systems interact with the environment, this leads to what is known as *quantum noise*. Open quantum systems cannot be described by means of a pure state, it is necessary to use the density operator. In general, a Markovian type of evolution is assumed (without memory effects):

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- H_s is the system's Hamiltonian, $\{\ ,\ \}$ denotes the anticommutator and L_μ are the Lindblad operators, with $\mu \in [1, \ldots, M]$ (the number M depending on the particular model of interaction with the environment)

Open quantum systems

- A pure state $\rho(t_0) = |\phi(t_0)\rangle\langle\phi(t_0)|$, evolves to:

$$\rho(t_0 + dt) = (1 - \sum_\mu dp_\mu)\ |\phi_0\rangle\langle\phi_0|\ + \sum_\mu dp_\mu |\phi_\mu\rangle\langle\phi_\mu|,$$

with the probabilities dp_μ given by: $dp_\mu = \langle\phi(t_0)|L_\mu^\dagger L_\mu|\phi(t_0)\rangle dt$, and the new states by:

$$|\phi_0\rangle = \frac{(1 - iH_{\rm eff}\, dt/\hbar)|\phi(t_0)\rangle}{\sqrt{1 - \sum_\mu dp_\mu}} \quad and \quad |\phi_\mu\rangle = \frac{L_\mu|\phi(t_0)\rangle}{||L_\mu|\phi(t_0)\rangle||}.$$

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- With probability dp_μ the system "jumps" to the state $|\phi_\mu\rangle$. With probability $1 - \sum_\mu dp_\mu$ there are no jumps and the system evolves according to $H_{\text{eff}} = H_s + iK$, where $K = -\hbar/2 \sum_\mu L_\mu^\dagger L_\mu$. This suggests to simulate the equation by means of the quantum jumps scheme (quantum trajectories).

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- We repeat this $n_{\rm steps} = \Delta t/dt$ times
- Average over different runs to recover, up to statistical errors, the probabilities obtained using the density operator. Given an operator A, we can write the mean value $\langle A\rangle_t = {\rm Tr}[A\rho(t)]$ as the average over $\mathcal{N}$ trajectories:
  $\langle A\rangle_t = {\rm Tr}[A\rho(t)] = \lim_{\mathcal{N}\to\infty} \frac{1}{\mathcal{N}} \sum_{i=1}^{\mathcal{N}} \langle\phi_i(t)|A|\phi_i(t)\rangle$
  There is also an advantage in computation time: in general $\mathcal{N} \approx 100 - 500$ trajectories are needed in order to obtain statistical convergence, there is an advantage in computer time if the Hilbert space dimension N satisfies $N > \mathcal{N}$

Noise models

Amplitude damping (dissipation or energy loss)

$$\begin{aligned} |0\rangle_s|0\rangle_e &\rightarrow |0\rangle_s|0\rangle_e, \\ |1\rangle_s|0\rangle_e &\rightarrow \sqrt{1-p}\;|1\rangle_s,|0\rangle_e + \sqrt{p}\;|0\rangle_s|1\rangle_e \end{aligned}$$

- We study in detail two possible generalizations of the amplitude damping to the case of n qubits.
- Both consider one-qubit processes only.
- In the first case the jump probability for the system is fixed.
- In the other, the jump probability depends on the internal state.
- Each case corresponds to a different branching process.

Noise models (A. damping 1)

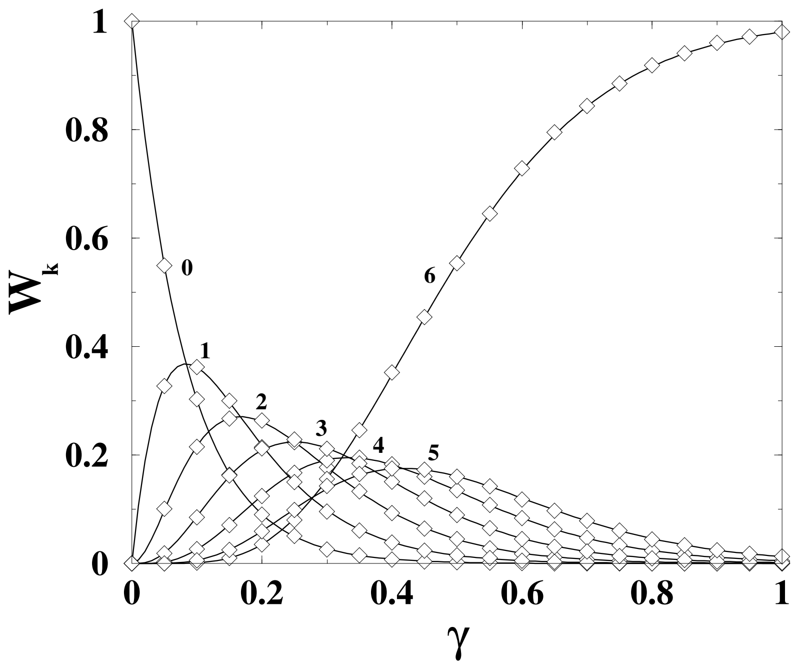
$$\rho(t_0+dt) = \left(1-\frac{\Gamma dt}{\hbar}\right)|1011\rangle\langle 1011| + \frac{\Gamma dt}{3\hbar}(|0011\rangle\langle 0011|$$

$$+|1001\rangle\langle 1001| + |1010\rangle\langle 1010|).$$

Define probability classes of probability W_k (n_k = qubits "up" and $n_k = n_0 - k = m - k$):

$$W_k = \frac{(\Gamma t/\hbar)^k}{k!}\exp\left(-\frac{\Gamma t}{\hbar}\right)$$

$$W_m = 1 - \sum_{k=0}^{m-1} W_k$$



Noise models (A. damping 2)

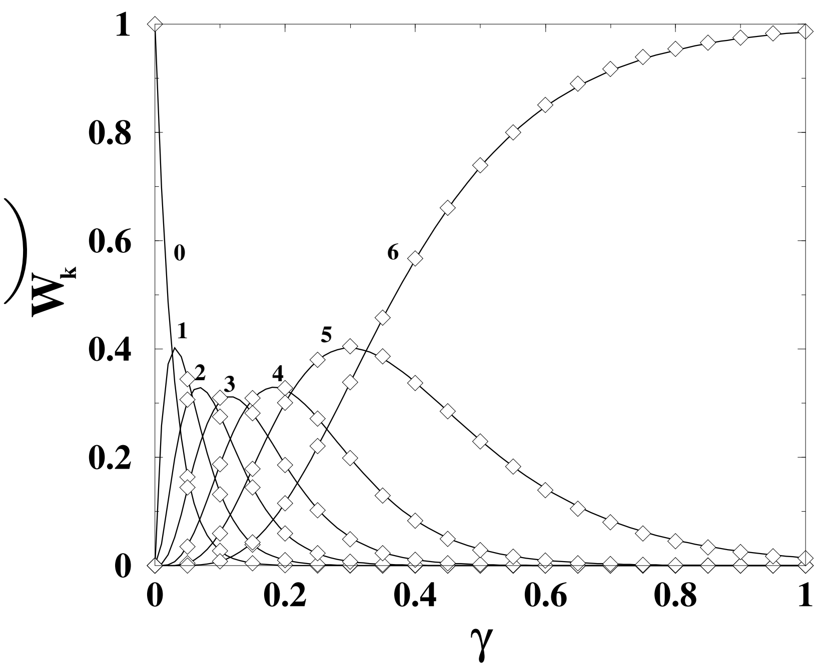
$$\rho(t_0+dt) = \left(1 - \frac{3\Gamma dt}{\hbar}\right)|1011\rangle\langle 1011| + \frac{\Gamma dt}{\hbar}(|0011\rangle\langle 0011|$$

$$+|1001\rangle\langle 1001| + |1010\rangle\langle 1010|).$$

Evolution of W_k:

$$W_k = \frac{n!}{n_k!}\sum_{i=0}^{k}\frac{(-1)^{(k-i)}}{i!\,(k-i)!}\ \exp\left(-\frac{n_i\,\Gamma t}{\hbar}\right)$$

$$W_m = 1 - \sum_{k=0}^{m-1} W_k$$



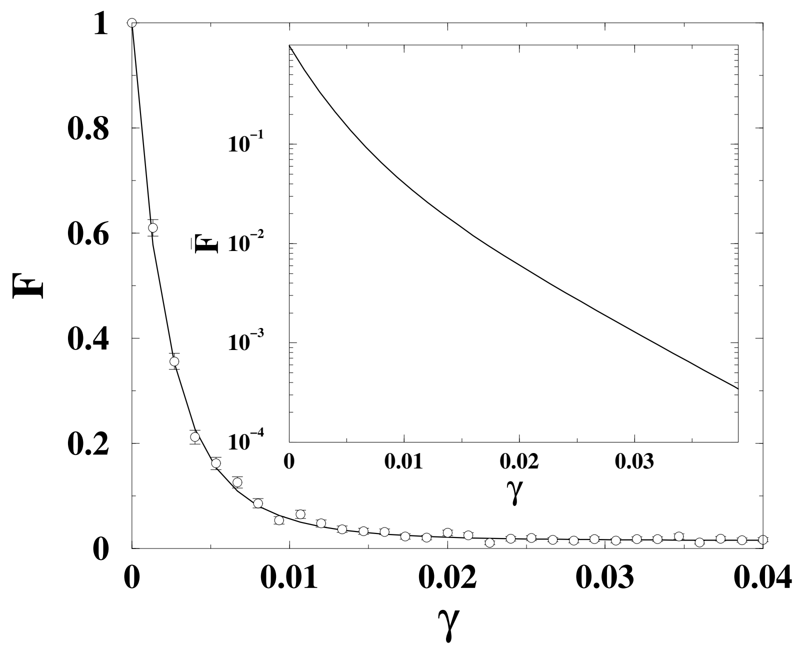
Noise models (P. flip)

Phase flip (information loss)

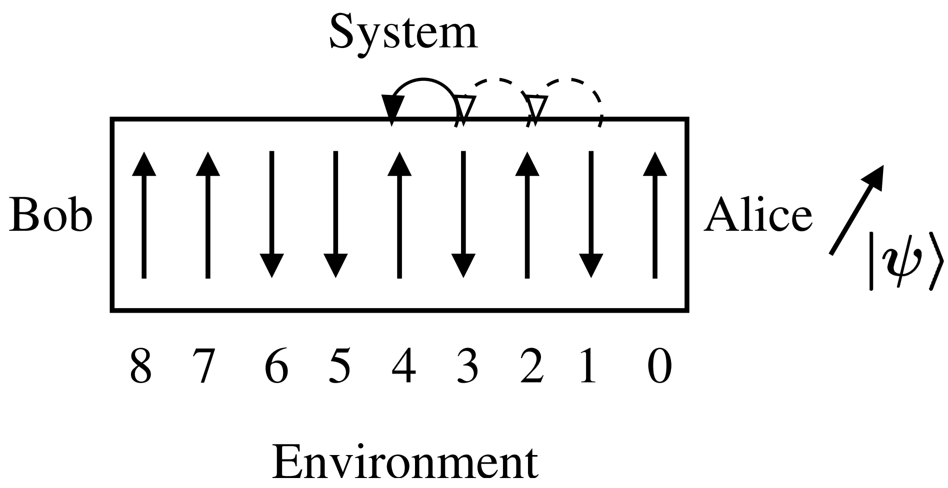
$$
\begin{aligned}
|0\rangle_s|0\rangle_e &\rightarrow \sqrt{1-p}\,|0\rangle_s|0\rangle_e + \sqrt{p}\,|0\rangle_s|1\rangle_e,\\
|1\rangle_s|0\rangle_e &\rightarrow \sqrt{1-p}\,|1\rangle_s|0\rangle_e - \sqrt{p}\,|1\rangle_s|1\rangle_e
\end{aligned}
$$

Generalize like case 2; $|\psi_0\rangle$, random complex numbers of modulus $1/\sqrt{2^n}$

$$F(t) = \frac{1}{2^n} + \frac{n!}{2^n}\sum_{i=1}^{n}\frac{1}{i!\,(n-i)!}\exp\left(-\frac{2i\,\Gamma t}{\hbar}\right)$$



Noise in algorithms: teleportation



Initial state

$$\sum_{i_{n-1},\ldots,i_2} c_{i_{n-1},\ldots,i_2} |i_{n-1}\ldots i_2\rangle \otimes \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle).$$

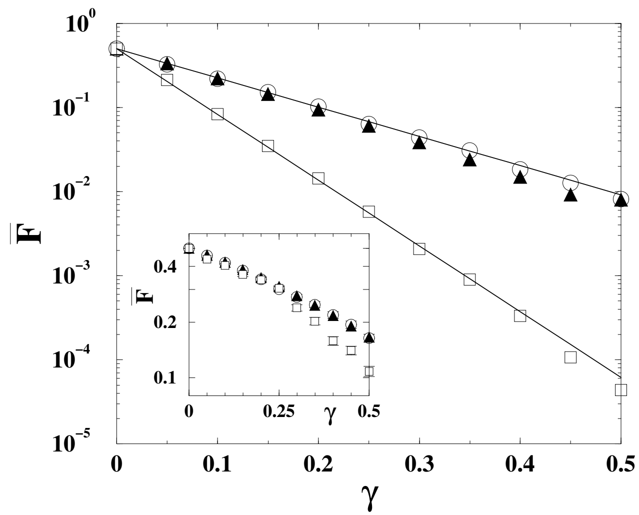
We take $c_{i_{n-1},\ldots,i_2}$ (modulus $1/\sqrt{2^{n-2}}$, random phases).

teleportation

$$\rho_k^{(n)} = U_{\rm sw}^{k,k+1} \left[\sum_{\mu_1,\ldots,\mu_k=0}^{\mathcal{M}} M_{\mu_k}^{(n)}(dt) \cdots M_{\mu_1}^{(n)}(dt) \right.$$

$$\left. \rho_{k-1}^{(n)} \; (M_{\mu_1}^{(n)})^\dagger(dt) \cdots (M_{\mu_k}^{(n)})^\dagger(dt) \right] U_{\rm sw}^{k,k+1\,\dagger},$$

Fidelity of amplitude damping 2 (10 and 20 qubits):



Noise in algorithms: the baker's map

The baker's map acts on $0 \leq q, p < 1$:

$$\begin{aligned} q_{k+1} &= 2q_k - [2q_k], \\ p_{k+1} &= (p_k + [2q_k])/2, \end{aligned}$$

Using the discrete Fourier transform

$$\langle q_k | F_n | q_j \rangle \equiv \frac{1}{\sqrt{2^n}} \exp\left(\frac{2\pi i k j}{2^n} \right),$$

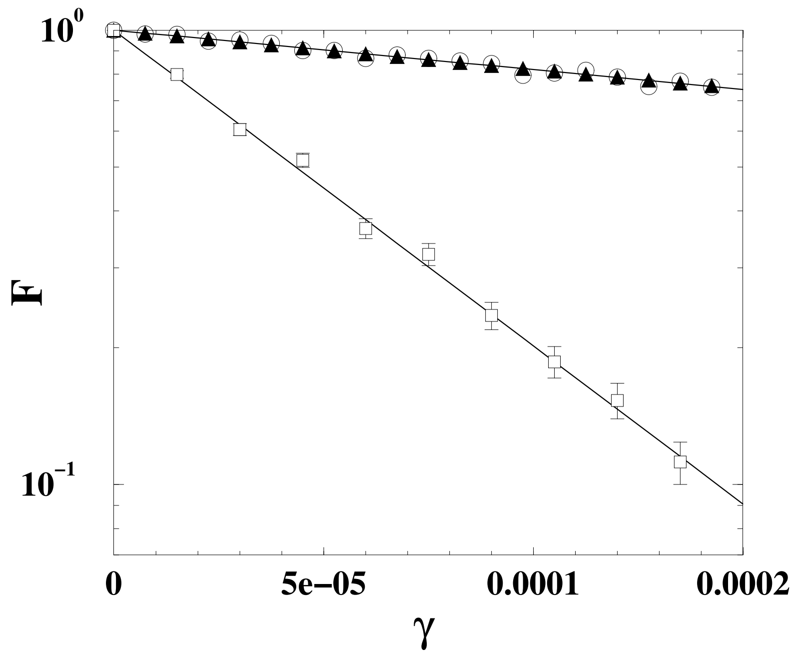
the quantum map becomes

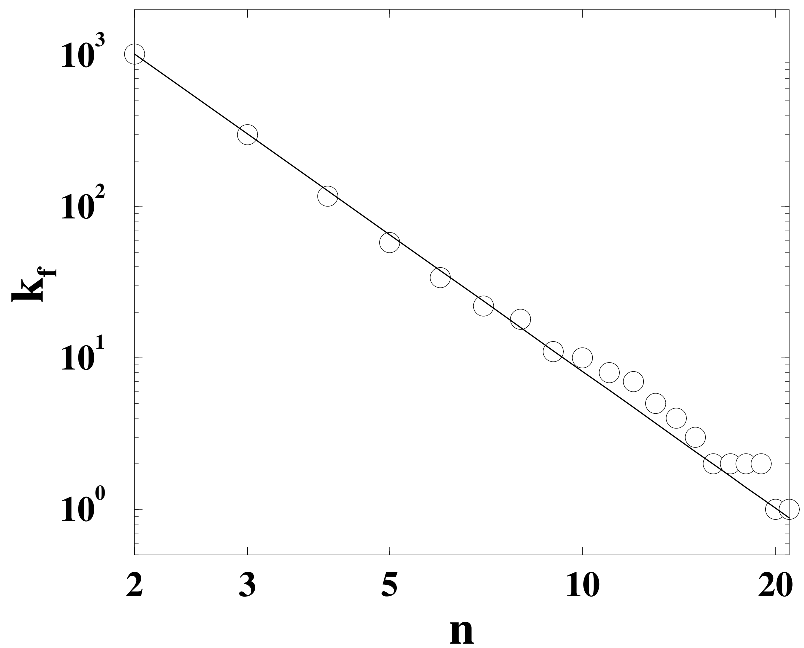
$$|\psi_{k+1}\rangle = B\,|\psi_k\rangle = F_n^{-1} \begin{bmatrix} F_{n-1} & 0 \\ 0 & F_{n-1} \end{bmatrix} |\psi_k\rangle$$

the baker's map

Fidelity with p. flip $F = \exp\left(-n\gamma N_g\right) = \exp(-2\gamma n^3 k)$.

Time scale $(A = 0.9)$ $k_f = -\frac{\ln A}{2\gamma n^3}$.





Noise in transport: quantum ratchets

- In recent years there have been several works in the field of periodic systems that present directed transport due to a broken spatio-temporal symmetry.
- This phenomenon, the ”ratchet” effect, is important in technological applications such as rectifiers, pumps, particle separation devices, molecular motors in biology, etc.
- There have been several proposals in order to model this effect: systems with external noise, chaotic systems with dissipation and purely Hamiltonian ones.

A model for quantum ratchets

- The system to be shown here presents asymmetry in the potential and dissipation.
- The presence of strange attractors is a common feature of chaotic dissipative systems.
- In quantum systems the fractal structure of the attractor is smoothed in the Planck scale.
- It is interesting to see how this fact affects quantum ratchets.
- Moreover, $\langle p \rangle_{-\phi} = -\langle p \rangle_{\phi}$ due to the fact that $V_{\phi}(x, \tau) = V_{-\phi}(-x, \tau)$.

A model for quantum ratchets

We study the movement in one dimension [$x \in (-\infty, +\infty)$] with dissipation an potential

$$V(x,\tau) = k\left[\cos(x) + \frac{a}{2}\cos(2x+\phi)\right]\sum_{m=-\infty}^{+\infty}\delta(\tau - mT),$$

where T is the period. This is equivalent to the map:

$$\begin{cases} \overline{n} = \gamma n + k(\sin(x) + a\sin(2x+\phi)), \\ \overline{x} = x + T\overline{n}, \end{cases}$$

(we use $p = Tn$).

A model for quantum ratchets

In the quantum case we have: $x \to \hat{x}$, $n \to \hat{n} = -i(d/dx)$, $\hbar_{\text{eff}} = T$.

$$\dot{\hat{\rho}} = -i[\hat{H}_s, \hat{\rho}] - \frac{1}{2}\sum_{\mu=1}^{2}\{\hat{L}_\mu^\dagger \hat{L}_\mu, \hat{\rho}\} + \sum_{\mu=1}^{2} \hat{L}_\mu \hat{\rho} \hat{L}_\mu^\dagger.$$

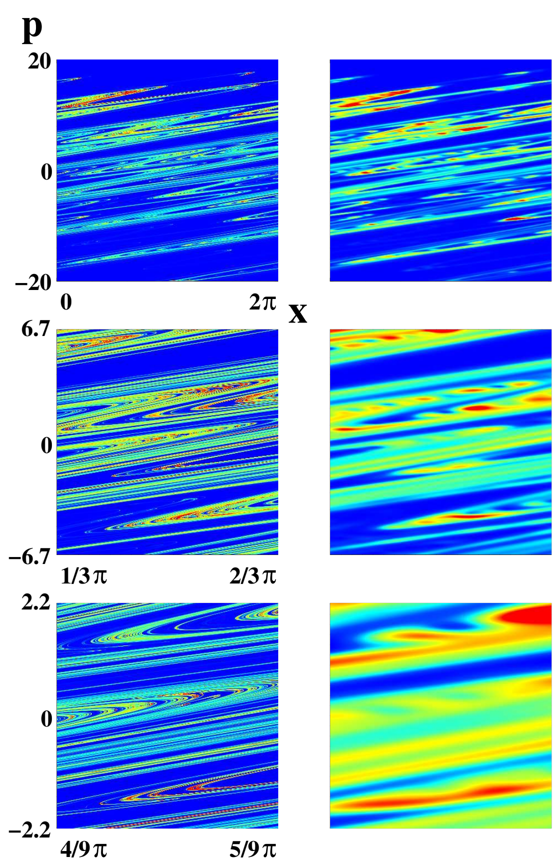
Lindblad operators:

$$\hat{L}_1 = g \sum_n \sqrt{n+1}\, |n\rangle \langle n+1|,$$
$$\hat{L}_2 = g \sum_n \sqrt{n+1}\, |-n\rangle \langle -n-1|,$$

with $n = 0, 1, ...$ Ehrenfest theorem leads to $g = \sqrt{-\ln\gamma}$.

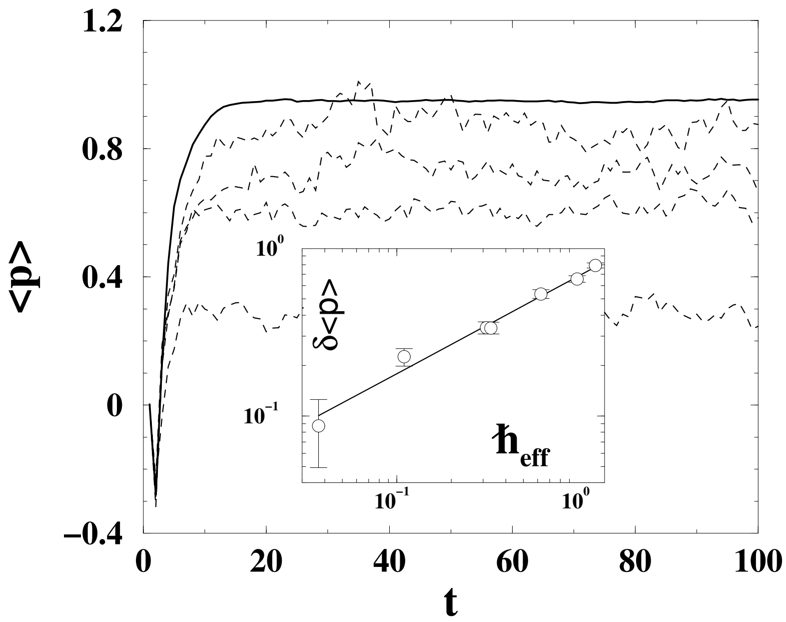
A model for quantum ratchets

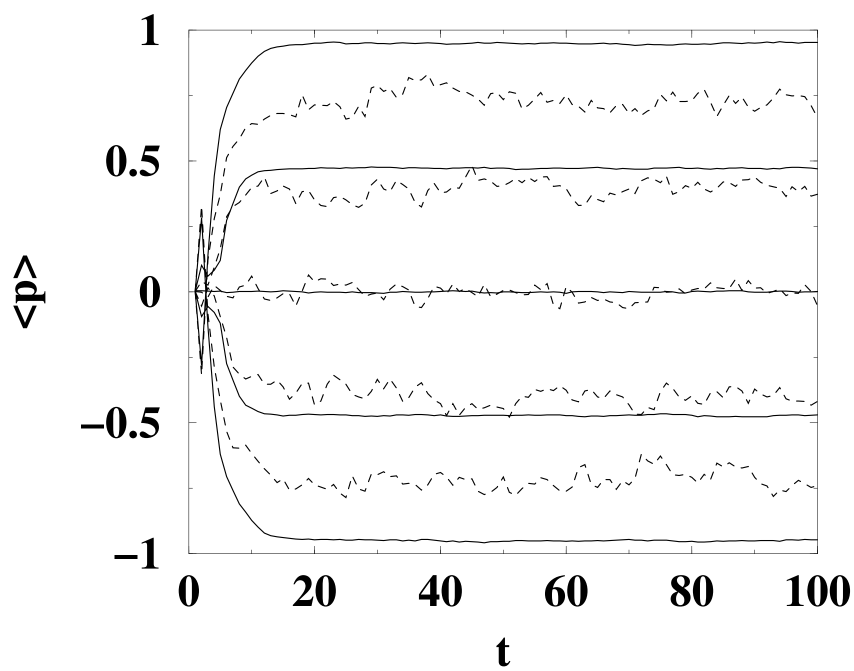
Phase space for $K = 7$, $\gamma = 0.7$, $\phi = \pi/2$, $a = 0.7$, after 100 kicks. Central region zoom; Poincaré (left) and Husimi (right).



A model for quantum ratchets

Average momentum $\hbar_{\text{eff}} = 0.99, 0.33, 0.11, 0.037$ (left) and $\phi = \pi/2, 2\pi/5, 0, -2\pi/5, -\pi/2$ (right).





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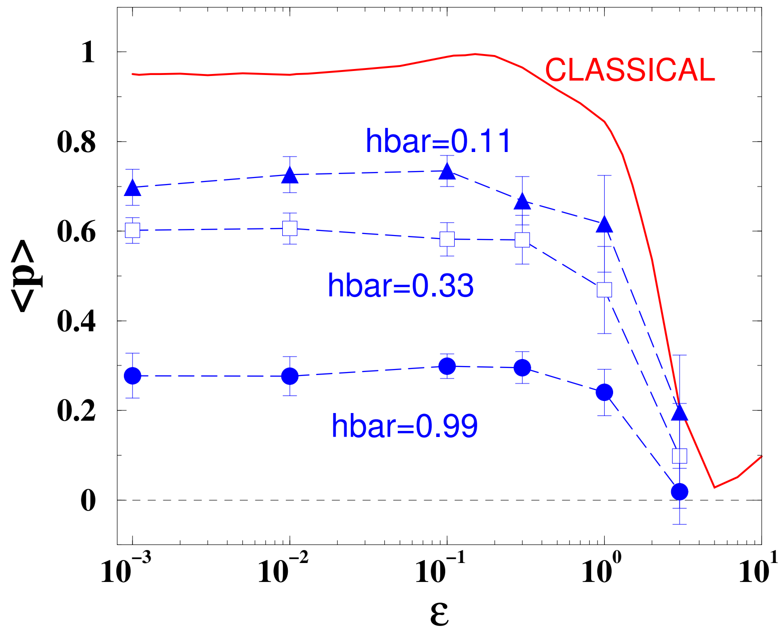


Memoryless fluctuations in the kicking strength: $K \to K_\epsilon(t) = K + \epsilon(t)$, $\epsilon(t) \in [-\epsilon, +\epsilon]$
The ratchet effect survives up to a noise strength ϵ of the order of the kicking strength K

Experimental realization

There is growing interest in using this phenomenon to transport Bose-Einstein condensates in optical lattices. For that purposes it is convenient to use

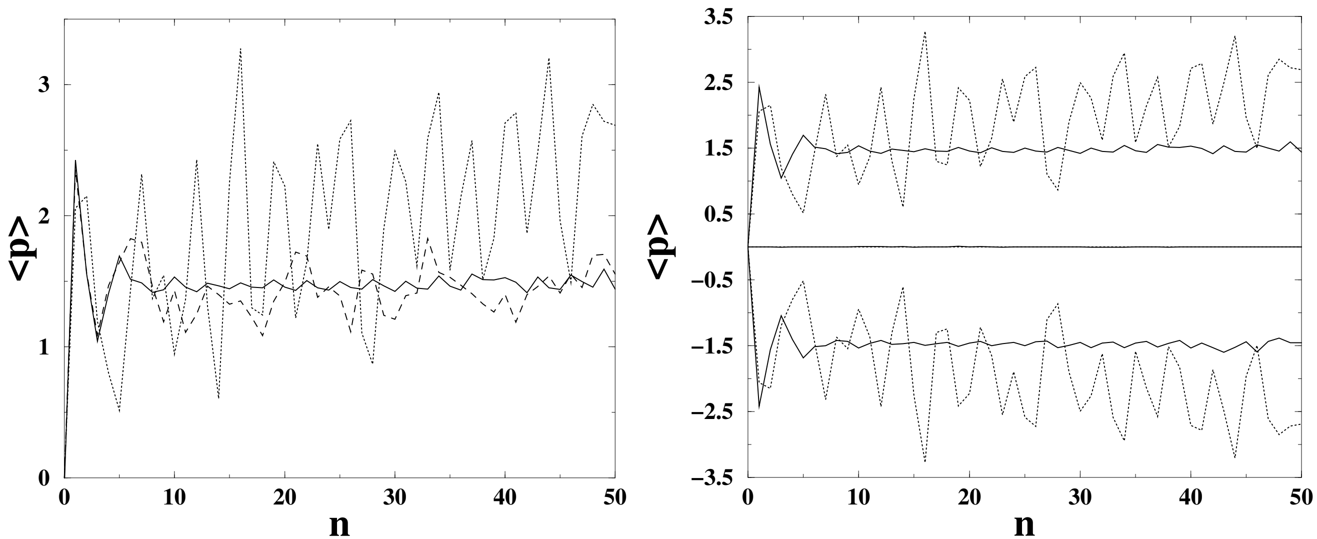
$$V_\phi(x,\tau) = k\times$$

$$\sum_{n=1}^{+\infty} \left[\delta(\tau - nT)\cos(x) + \delta(\tau - nT + 2/3T)\sin(x+\phi)\right],$$

in this case dissipation is given by the projection over a subspace of

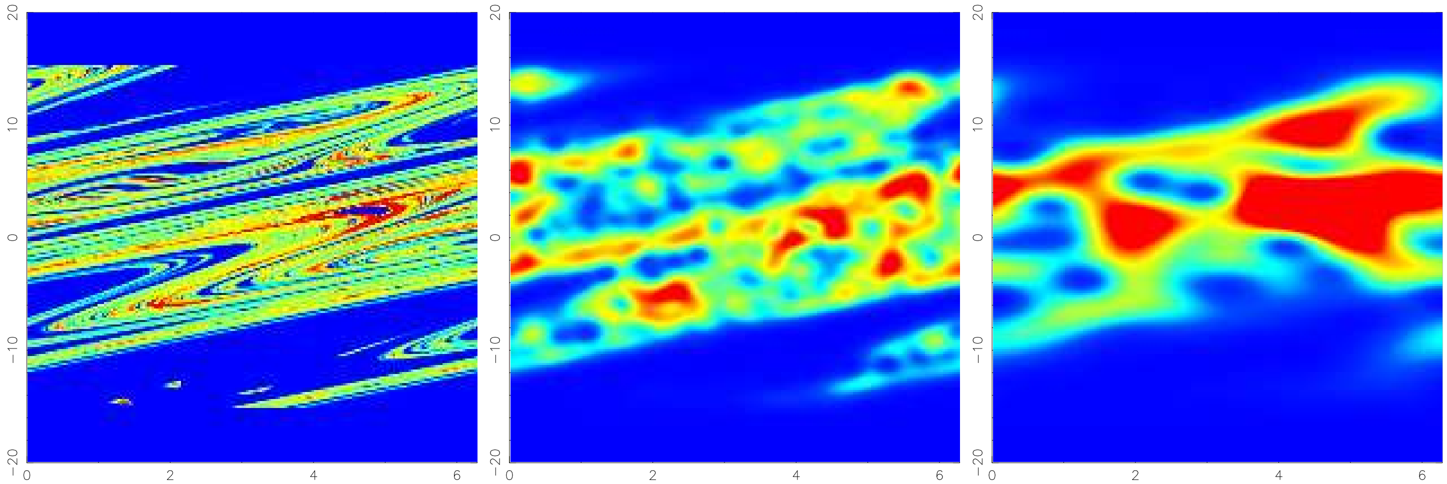
the original Hilbert space.

Experimental realization



- Average momentum (left panel) $\langle p \rangle$ as a function of time n (measured in units of T). Solid curve is classical, dashed line is quantum for $\hbar_{\rm eff} \simeq 0.16$ and the dotted one for $\hbar_{\rm eff} \simeq 1$. Initial conditions are inside the band $p \in [-1; 1]$. Average momentum (right panel) $\langle p \rangle$, for the case $\phi = 0$ (positive values), $\phi = \pi/2$ (zero value) and $\phi = \pi$ (negative values).

Experimental realization



- Phase space pictures for $k = 7$ and $\phi = 0$, at $n = 20$ kicks: classical Poincaré sections (left panel), and quantum Husimi functions at $\hbar_{\rm eff} \simeq 0.16$ (middle panel). Finally $\hbar_{\rm eff} \simeq 1$ (right panel). The displayed region is given by $p \in [-20, 20]$ and $x \in [0, 2\pi)$ (x is taken modulus 2π). The color is proportional to the density: blue for zero and red for maximal density.

Ehrenfest explosions

The instability of classical dynamics leads to exponentially fast spreading of the quantum wave packet on the logarithmically short Ehrenfest time scale

$$t_E \sim \frac{|\ln \hbar|}{\lambda}$$

λ Lyapunov exponent, $\hbar$ effective Planck constant

After the logarithmically short Ehrenfest time a description based on classical trajectories is meaningless for a closed quantum system

What is the interplay between wave packet explosion (delocalization) induced by chaotic dynamics and wave packet collapse (localization) caused by dissipation?

Dissipative chaotic dynamics model

Markovian master equation $\dot{\hat{\rho}} = -i[\hat{H}, \hat{\rho}] - \frac{1}{2}\sum_{\mu}\{\hat{L}_{\mu}^{\dagger}\hat{L}_{\mu}, \hat{\rho}\} + \sum_{\mu}\hat{L}_{\mu}\hat{\rho}\hat{L}_{\mu}^{\dagger}$

Kicked rotator Hamiltonian $\hat{H} = \frac{\hat{n}^2}{2} + k\cos(\hat{x})\sum_{m=-\infty}^{+\infty}\delta(\tau - mT)$

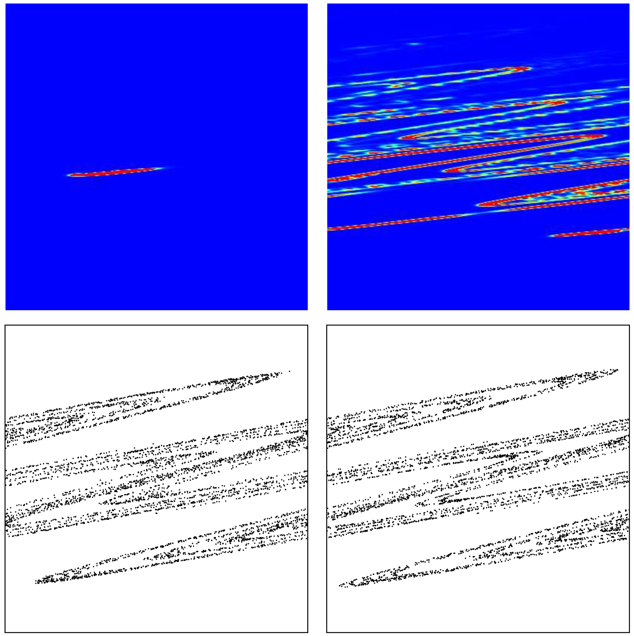
Dissipation described by the Lindblad operators

$$\hat{L}_1 = g\sum_{n}\sqrt{n+1}\,|n\rangle\,\langle n+1|,\ \hat{L}_2 = g\sum_{n}\sqrt{n+1}\,|-n\rangle\,\langle -n-1|$$

At the classical limit, the evolution of the system in one period is described by the Zaslavsky map

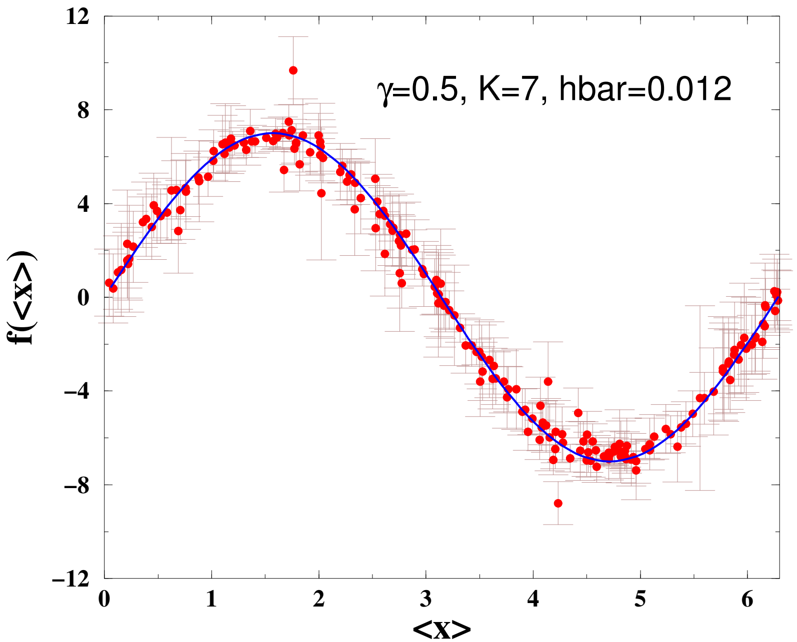
$$\begin{cases} n_{t+1} = (1-\gamma)n_t + k\sin x_t, \\ x_{t+1} = x_t + Tn_{t+1}, \end{cases}$$

Collapse to explosion transition



$K = 7$, $\hbar = 0.012$, $\gamma = 0.5$ and $\gamma = 0.01$

Classical-like q-trajectories

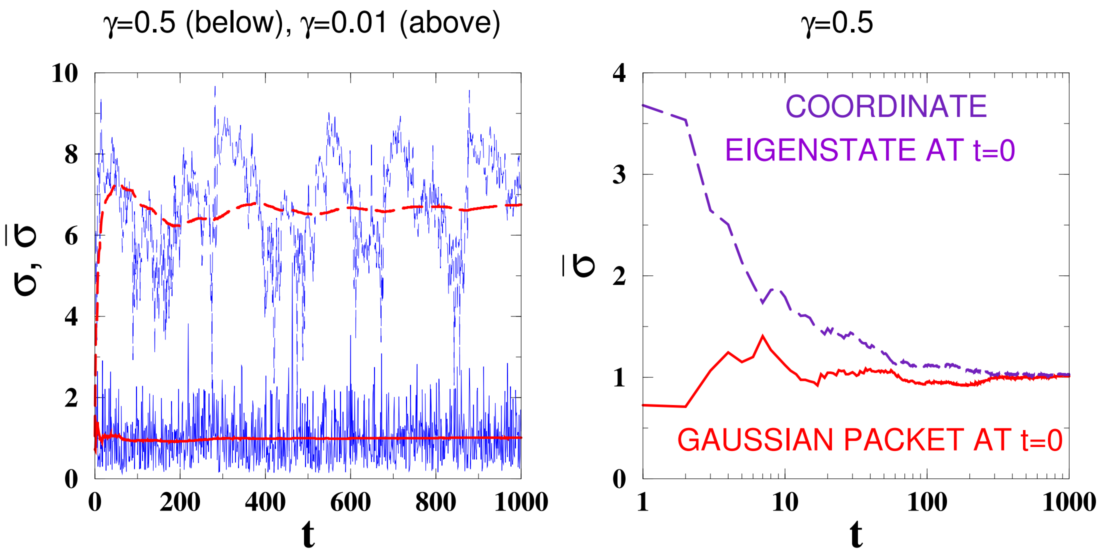


$$f \equiv \langle p \rangle_{t+1} - (1-\gamma)\langle p \rangle_t, \quad \langle p \rangle_t = \langle x \rangle_t - \langle x \rangle_{t-1}$$

From classical dynamics we expect $f(x) = K \sin x$ - Quantum fluctuations $\propto \sqrt{\hbar}$

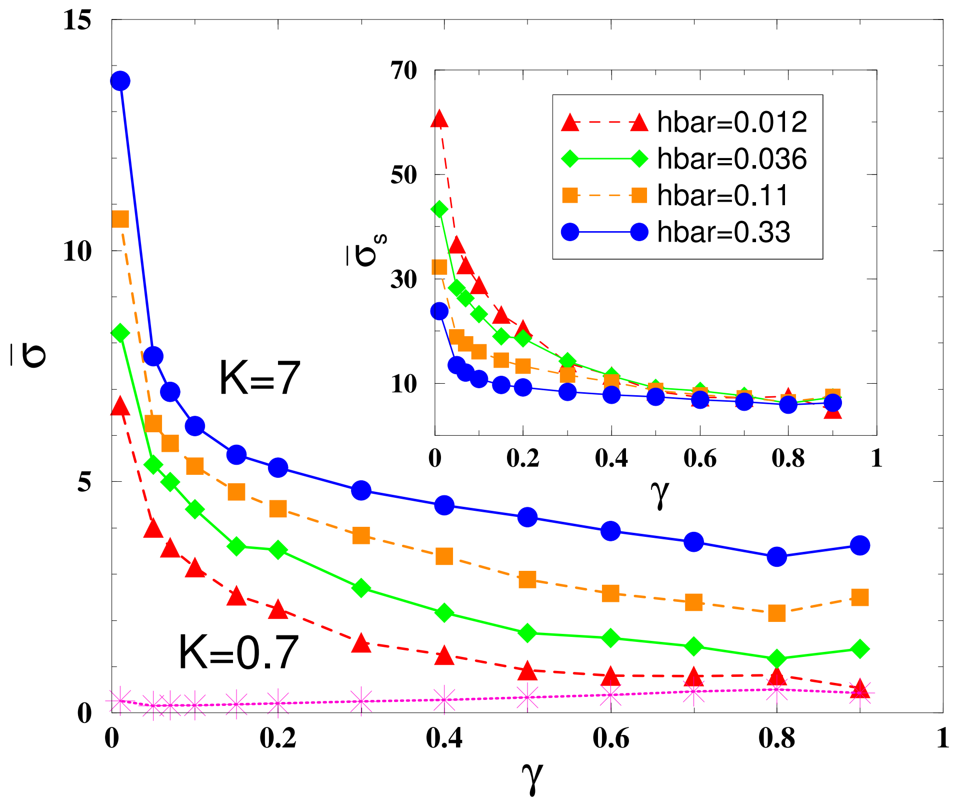
Wave packet dispersion

$$\sigma_t = \sqrt{(\Delta x)_t^2 + (\Delta p)_t^2}, \quad \text{cumulative average } \overline{\sigma}_t \equiv \frac{1}{t}\sum_{j=1}^{t} \sigma_j$$



$(K = 7,\, \hbar = 0.012)$

Localization-delocalization crossover



$\overline{\sigma}_s \equiv \overline{\sigma}/\sqrt{\hbar}$ scaled dispersion

Ehrenfest explosion

Due to the exponential instability of chaotic dynamics the wave packet spreads exponentially and for times shorter than the Ehrenfest time we have $\sigma_t \sim \sqrt{\hbar}\exp(\lambda t)$

The dissipation localizes the wave packet on a time scale of the order of $1/\gamma$

Therefore, for $1/\gamma \ll t_E \sim |\ln \hbar|/\lambda$, we obtain $\overline{\sigma} \sim \sqrt{\hbar}\exp(\lambda/\gamma) \ll 1$

In contrast, for $1/\gamma > t_E$ the chaotic wave packet explosion dominates over dissipation and we have complete delocalization over the angle variable

In this case, the wave packet spreads algebraically due to diffusion for $t > t_E$: for $t \gg t_E$ we have $\sigma_t \sim \sqrt{D(K)t}$, $D(K) \approx K^2/2$ being the diffusion coefficient; this regime continues up to the dissipation time $1/\gamma$, so that $\overline{\sigma} \sim \sqrt{D(K)/\gamma}$

Ehrenfest explosion

The transition from collapse to explosion (Ehrenfest explosion) takes place at

$$t_E \sim \frac{|\ln \hbar|}{\lambda} \sim \frac{1}{\gamma}$$

Therefore, even for infinitesimal dissipation strengths the quantum wave packet is eventually localized when $\hbar \to 0$: we have $\lim_{\hbar \to 0} \overline{\sigma} = 0$; in contrast, in the Hamiltonian case ($\gamma = 0$) $\lim_{\hbar \to 0} \overline{\sigma} = \infty$

Only for open quantum systems the classical concept of trajectory is meaningful for arbitrarily long times; on the contrary, for Hamiltonian systems a description based on wave packet trajectories is possible only up to the Ehrenfest time scale

Future plans

- Understanding the dynamical aspects of the ratchet model at zero temperature (linear stability study). Currently under way.

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- Effects of these models on quantum algorithms and maps.

Future plans

- Understanding the dynamical aspects of the ratchet model at zero temperature (linear stability study). Currently under way.
- Classical and quantum (semiclassical) mean current prediction.
- Experimental ralization of dissipative ratchets with Bose-Einstein condensates.
- Molecular transport applications, finite temperature models.
- General relation between noise models and branching processes. Applications.
- Effects of these models on quantum algorithms and maps.
- Bibliography:**(quant-ph/0503081) accepted in Phys. Rev. Lett** ; **Phys. Rev. Lett (164101, vol. 94,(2005))**;**Phys. Rev. A (052317, vol. 69, (2004))**; **Phys. Rev. Lett. (257903, vol. 91, (2003)).**