Effects of Decoherence and Imperfections for Quantum Information Processing (EDIQIP)

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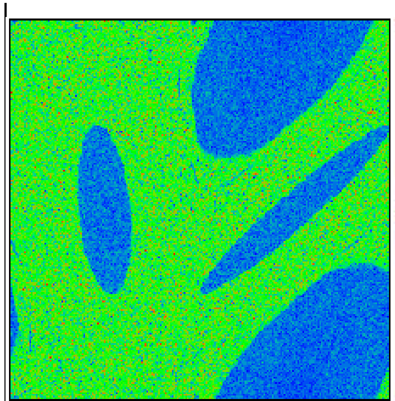
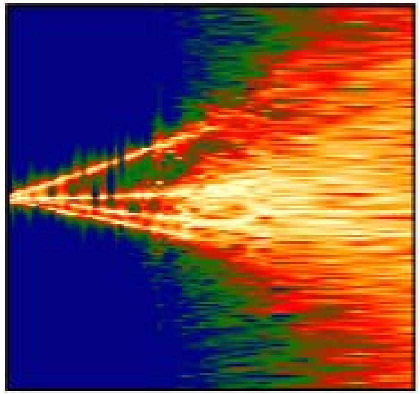
Objective

- Effects of realistic imperfections on quantum computer operability and accuracy
- Decoherence and quantum chaos induced by inter-qubit couplings
- New efficient algorithms for simulation of quantum and classical physical systems
- Numerical codes with up to 30 qubits
- Development and test of error-correcting codes for quantum chaos and noisy gates





Objective Approach

- Analytical methods developed for many-body systems (nuclei, atoms, quantum dots)
- Random matrix theory and quantum chaos
- Large-scale numerical simulations of many qubits on modern supercomputers
- Stability of algorithms to quantum errors

Status

- New quantum algorithms and imperfection effects for tent map, Harper map, Grover algorithm; numerics with 7-28 qubits
- Dissipative decoherence, quantum trajectories
- Quantum algorithms for state preparation
- Pauli random error correction method

Effects of Decoherence and Imperfections for Quantum Information Processing (EDIQIP)

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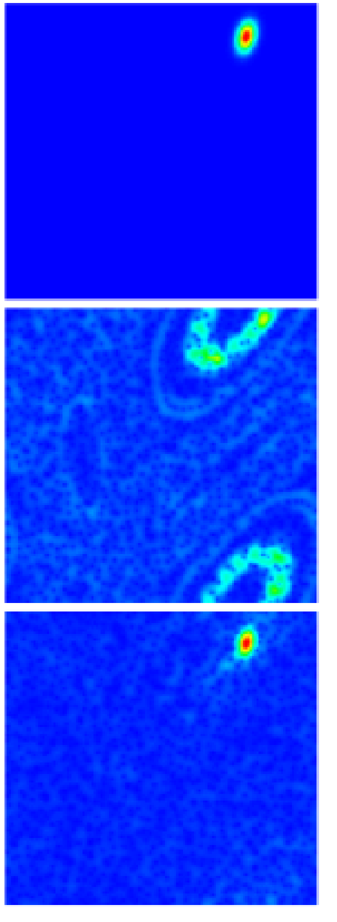
(collaboration with ARO/NSA/ARDA QC program)

- Report results 2004

- Quantum chaos algorithms: tent map, Harper map, electrons in a magnetic field, quantum images => polynomial number of gates but also only polynomial speed up for information extraction
- Universal law for fidelity decay induced by static imperfections: random matrix theory works for 10 orders of magnitude variation [first highlight paper of Eur. Phys. J. D], how to correct these errors?
- Phase diagram for the Grover algorithm with static imperfections
- Pauli random error correction for static imperfections: generic method to eliminate coherent errors and increase fidelity (2 orders for 10 qubits)
- Quantum algorithm for arbitrary pure state preparation with fidelity arbitrary close to unity
- Dissipative decoherence with quantum trajectories for the quantum baker map, a law for fidelity decay, universality?
- Effects of dissipative enviroment on cold atoms transport in laser fields, emergence of directed transport induced by dissipation (ratchet)
-EVENTS: E.Fermi summer school, Varenna, Italy, 5-15 July 2005; Institut Henri Poincaré, Paris, 4 Jan – 7 April, 2006 => QIPC review there?
-Publications: 33 papers published and submitted in 2004
- 2 PhD QIPC these in Toulouse with EDIQIP members participation



Dissemination of results

All information is at **www.quantware.ups-tlse.fr/EDIQIP**

During second year 2004:

- 33 papers published and submitted including:

$\longrightarrow$ first highlight paper of Eur. Phys. J. D

$\longrightarrow$ 1 book on QIPC (published)

$\longrightarrow$ 2 PhD these in QIPC field with participation of EDIQIP members

- 33 talks and posters on international conferences in EU, USA, Japan, Korea, Mexico and Belarus

Organization of conferences:

- Enrico Fermi summer school on QIPC, Varenna, 5 - 15 July, 2005
(directors: G.Casati, D.Shepelyansky, P.Zoller)
- Institut Henri Poincare, QIPC trimestre, Paris, 4 Jan - 7 April 2006
(directors: Ph.Grangier, M.Santha, D.Shepelyansky), www.quantware.ups-tlse.fr/IHP2006/

$\longrightarrow$ QIPC Review Feb 2006 at IHP ?

EDIQIP research group at Toulouse

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A.Chepelianskii (undergraduate)

16 papers in 2004, 2 PhD these

Fidelity decay due to errors

Accuracy measure of quantum computation is fidelity: $f(t) = |<\psi(t)|\psi_\varepsilon(t)>|^2$.

Quantum algorithm: $|\psi(t)> = U^t \, |\psi(0)>$, $U = \underbrace{U_{N_g} \cdot \ldots \cdot U_1}_{\text{elementary gates}}$.

Errors: $U_j \;\rightarrow\; U_j \, e^{i\delta H}$, $\delta H \sim \varepsilon$.

(i) Decoherence due to residual couplings of quantum computer to external bath:

δH random and different at each j and t,

e.g.: random phase fluctuations: $\delta\phi \in [-\varepsilon, \varepsilon]$ in phase-shift gates.

(ii) Static imperfections in the quantum computer itself:

δH (random but) constant at each j and t,

e.g.: $$\delta H = \sum_{j=0}^{n_q-1} \delta_j \, \sigma_j^{(z)} + 2 \sum_{j=0}^{n_q-2} J_j \, \sigma_j^{(x)} \, \sigma_{j+1}^{(x)} \quad , \quad J_j, \delta_j \in [-\varepsilon, \varepsilon] \; .$$

(iii) Non-unitary errors in quantum computation:

$e^{i\delta H}$ is non-unitary ($\delta H \neq \delta H^\dagger$, density matrix and quantum trajectories approach)

Quantum Hardware Melting Induced by Quantum Chaos

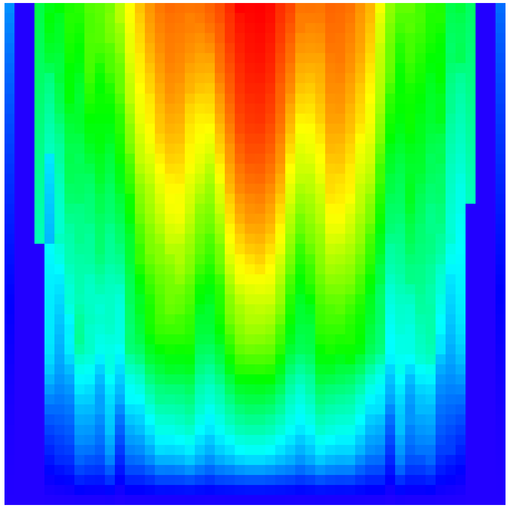
The quantum computer hardware is modeled as a (one)two-dimensional lattice of qubits (spin halves) with static fluctuations/imperfections in the individual qubit energies and residual short-range inter-qubit couplings. The model is described by the many-body Hamiltonian (B.Georgeot, D.S. PRE (2000)):

$$H_{\mathsf{S}} = \sum_i (\Delta_0 + \delta_i)\sigma_i^z + \sum_{i<j} J_{ij}\sigma_i^x \sigma_j^x,$$

where the σ_i are the Pauli matrices for the qubit i, and Δ_0 is the average level spacing for one qubit. The second sum runs over nearest-neighbor qubit pairs, and δ_i, J_{ij} are randomly and uniformly distributed in the intervals $[-\delta/2, \delta/2]$ and $[-J, J]$, respectively. Quantum chaos border for quantum hardware:

$$J > J_c \approx \Delta_c \approx 3\delta/n_q \gg \Delta_n \sim \delta 2^{-n_q}$$

Emergency rate of quantum chaos: $\Gamma \sim J^2/\Delta_c$.

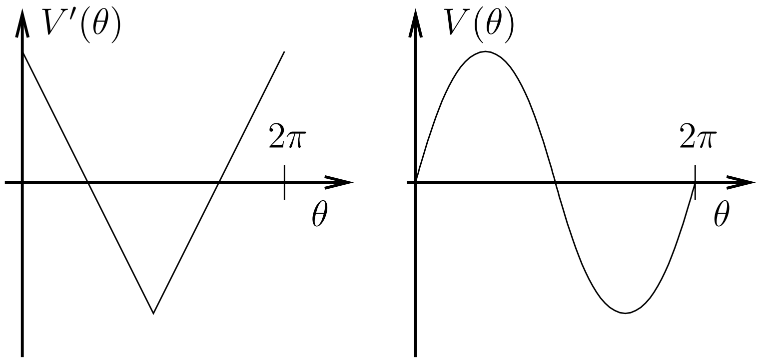


Quantum computer melting induced by inter-qubit couplings. Color represents the level of quantum eigenstate entropy S_q (red for maximum $S_q \approx 11$, blue for minimum $S_q = 0$). Horizontal axis is the energy of the computer eigenstates counted from the ground state to the maximal energy ($\approx 2n_q\Delta_0$). Vertical axis gives the value of J/Δ_0 (from 0 to 0.5). Here $n_q = 12$, $J_c/\Delta_0 = 0.273$, and one random realization of couplings is chosen.

What are effects of quantum many-body chaos on the accuracy of quantum computations?
Static imperfections vs. random errors in quantum gates of a quantum algorithm.

Example: Quantum algorithm for quantum tent map

$$H(t) = \frac{T\,p^2}{2} + V(\theta) \sum_{n=-\infty}^{\infty} \delta(t-n)$$



Classical map :

$$p_{n+1} = p_n - kV'(\theta_n)$$
$$\theta_{n+1} = \theta_n + T\,p_{n+1}$$

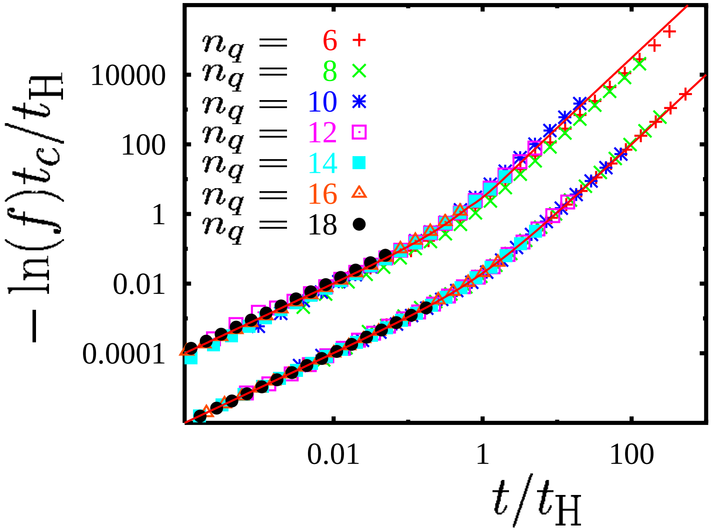
Quantum map : $p = -i\partial/\partial\theta$

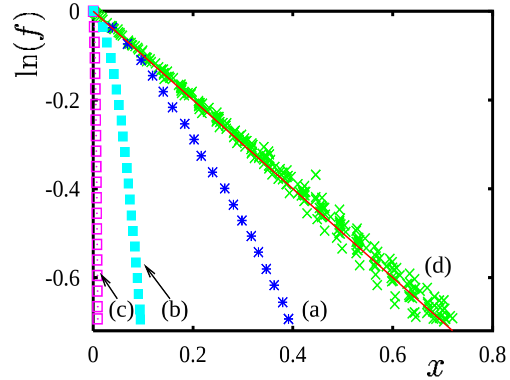
$$|\psi(t+1)>= U\,|\psi(t)>$$
$$U = e^{-iTp^2/2}\,e^{-ikV(\theta)}$$

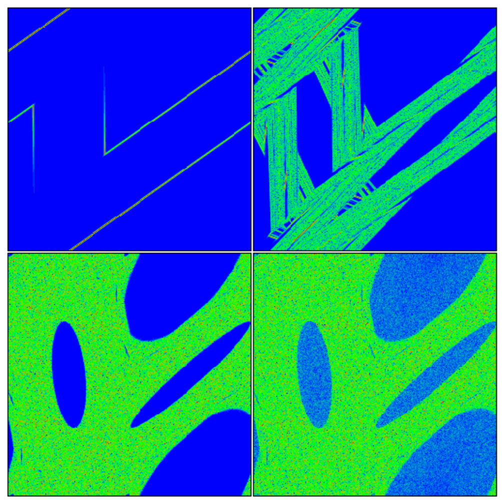
Quantum register with $N = 2^{n_q}$ states is used to store ψ

Quantum algorithm: map iteration is performed in $n_g \approx 9n_q^2/2$ elementary quantum gates

Universal fidelity decay law in quantum chaos algorithms







Upper curve: with theoretical values:
$t_{\rm H} = 2^{n_q}$ and $t_c = 1/(\varepsilon^2\, n_q\, n_g^2)$; $(\tilde t_{\rm H} \approx t_{\rm H}/3; \tilde t_c \approx t_c)$

Lower curve: $-\ln(f(t)) = \dfrac{t}{\tilde t_c} + \dfrac{t^2}{\tilde t_c \tilde t_{\rm H}}$ (fit values $\tilde t_c$ and $\tilde t_{\rm H}$)

Phase diagram for the Grover algorithm with static imperfections

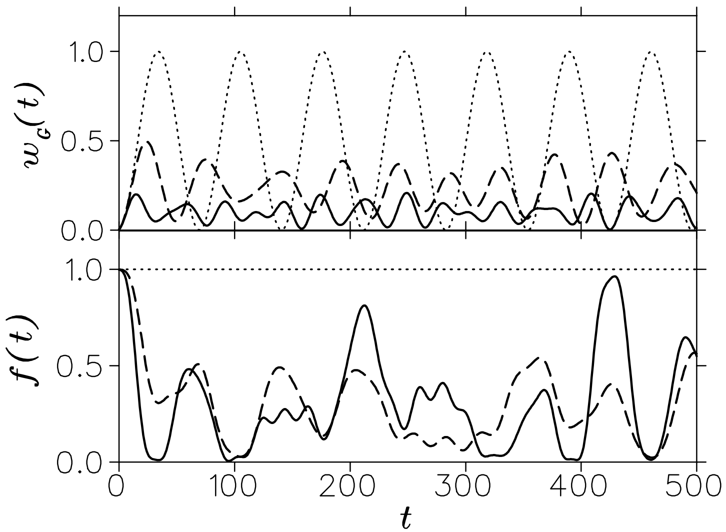
An unstructured database is presented by $N = 2^{n_q}$ states of quantum register with n_q qubits: $\{|x\rangle\}$, $x = 0, \ldots, N-1$. The searched state $|\tau\rangle$ can be identified by $oracle$ function $g(x)$, defined as $g(x) = 1$ if $x = \tau$ and $g(x) = 0$ otherwise. The Grover iteration operator $\hat{G}$ is a product of two operators: $\hat{G} = \hat{D}\hat{O}$. Here the oracle operator $\hat{O} = (-1)^{g(\hat{x})}$ is specific to the searched state $|\tau\rangle$, while the diffusion operator $\hat{D}$ is independent of $|\tau\rangle$: $D_{ii} = -1 + \frac{2}{N}$ and $D_{ij} = \frac{2}{N}$ $(i \neq j)$. For the initial state $|\psi_0\rangle = \sum_{x=0}^{N-1} |x\rangle/\sqrt{N}$, t applications of the Grover operator $\hat{G}$ give:

$$|\psi(t)\rangle = \hat{G}^t|\psi_0\rangle = \sin\left((t+1/2)\omega_G\right)|\tau\rangle + \cos\left((t+1/2)\omega_G\right)|\eta\rangle$$

where the Grover frequency $\omega_G = 2\arcsin(\sqrt{1/N})$ and $|\eta\rangle = \sum_{x\neq\tau}^{(0\leq x<N)} |x\rangle/\sqrt{N-1}$. Hence, the ideal algorithm gives a rotation in the 2D plane $(|\tau\rangle, |\eta\rangle)$.

The implementation of the operator D through the elementary gates requires an ancilla qubit. As a result the Hilbert space becomes a sum of two subspaces $\{|x\rangle\}$ and $\{|x+N\rangle\}$, which differ only by a value of (n_q+1)-th qubit. These subspaces are invariant with respect to operators O and D: $O = 1 - 2|\tau\rangle\langle\tau| - 2|\tau+N\rangle\langle\tau+N|$, $D = 1 - 2|\psi_0\rangle\langle\psi_0| - 2|\psi_1\rangle\langle\psi_1|$, where $|\psi_1\rangle = \sum_{x=0}^{N-1}|x+N\rangle/\sqrt{N}$ and $|\psi_{0,1}\rangle$ correspond to up/down ancilla states. Then D can be represented as $D = WRW$ (Grover (1997)), where the transformation $W = W_{n_q}\dots W_k\dots W_1$ is composed from n_q one-qubit Hadamard gates W_k, and R is the n_q-controlled phase shift defined as $R_{ij} = 0$ if $i \neq j$, $R_{00} = 1$ and $R_{ii} = -1$ if $i \neq 0$ $(i, j = 0, \dots, N-1)$. In turn, this operator can be represented as $R = W_{n_q}\sigma^x_{n_q-1}\dots\sigma^x_1 \wedge_{n_q} \sigma^x_{n_q-1}\dots\sigma^x_1 W_{n_q}$, where $\wedge_{n_q}$ is generalized n_q-qubit Toffolli gate, which inverts the n_q-th qubit if the first n_q-1 qubits are in the state $|1\rangle$. The construction of $\wedge_{n_q}$ from 3-qubit Toffolli gates with the help of only one auxillary qubit is described by A.Barenco *et al.* (1995). As a result the Grover operator G is implemented through $n_g = 12n_{tot} - 42$ elementary gates including one-qubit rotations, control-NOT and Toffolli gates. Here $n_{tot} = n_q + 1$ is the total number of qubits.

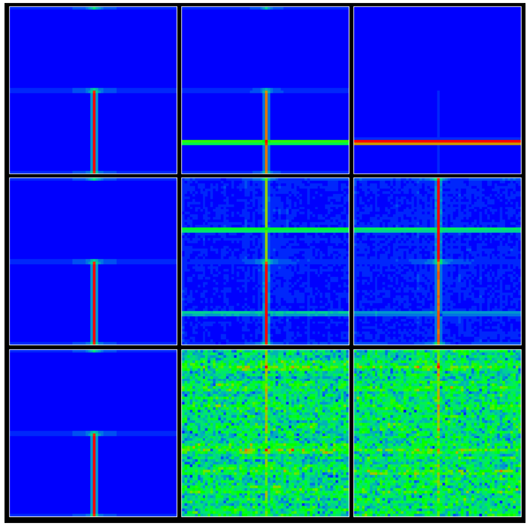
Oscillations of the Grover search probability



Probability of searched state $w_G(t)$ (top) and fidelity $f(t)$ (bottom) as a function of the iteration step t in the Grover algorithm for $n_{tot} = 12$ qubits. Dotted curves show results for the ideal algorithm ($\varepsilon = 0$), dashed and solid curves correspond to imperfection strength $\varepsilon = 4 \cdot 10^{-4}$ and 10^{-3}, respectively.

A typical example of imperfection effects on the accuracy of the Grover algorithm for a fixed disorder realization of H_S on 3×4 qubit lattice.

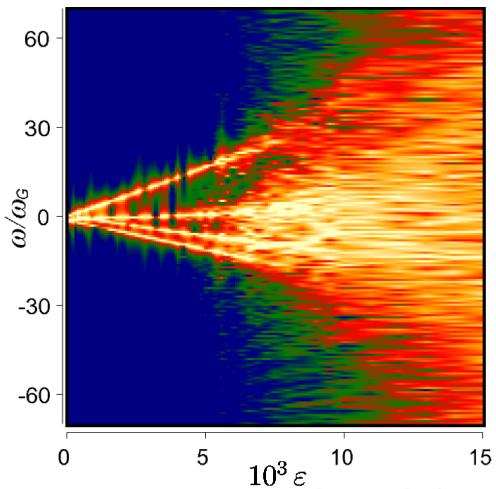
Husimi function in the Grover algorithm



Evolution of the Husimi function in the Grover algorithm at times $t = 0$, 17, and 34 (from left to right), and for $\varepsilon = 0$, 0.001, and 0.008 (from top to bottom). The qubit lattice and disorder realization are the same as in previous Fig. The vertical axis shows the computational basis $x = 0, \ldots, 2N-1$, while the horizontal axis represents the conjugated momentum basis. Density is proportional to color changing from maximum (red) to zero (blue).

the probability is mainly distributed over four states corresponding to four straight lines in phase space: $|\tau_0\rangle = |\tau\rangle$; $|\tau_1\rangle = |\tau + N\rangle$; $|\eta_0\rangle = |\eta\rangle$; $|\eta_1\rangle = \sum_{x\neq\tau}^{(0\leq x<N)} |x+N\rangle/\sqrt{N-1}$

Phase diagram for spectral density



Phase diagram for the spectral density $S(\omega)$ as a function of imperfection strength ε, $n_{tot} = 12$, same disorder realization as in previous Fig. Color is proportional to density $S(\omega)$ (yellow for maximum and blue for zero).

The transition rate induced by imperfections after one Grover iteration is given by the Fermi golden rule: $\Gamma \sim \varepsilon^2 n_g^2 n_{tot}$, where n_{tot} appears due to random contribution of qubit couplings ε while n_g^2 factor takes into account coherent accumulation of perturbation on n_g gates used in one iteration. In the Grover algorithm the four states are separated from all other states by energy gap $\Delta E \sim 1$ (sign change introduced by operators O and D). Thus these four states become mixed with all others for $\varepsilon > \varepsilon_c \approx 1.7/(n_g\sqrt{n_{tot}})$, when $\Gamma > \Delta E$.

Theoretical estimates for the Grover algorithm (GA)

In the regime where the dynamics of Grover algorithm is dominated by four states subspace the single-kick model can be treated analytically. The matrix elements of the effective Hamiltonian in this space are

$$H_{eff} = \begin{pmatrix} A+a & 0 & -i\omega_G & 0 \\ 0 & A-a & 0 & -i\omega_G \\ i\omega_G & 0 & B & b \\ 0 & i\omega_G & b & B \end{pmatrix}, \quad (1)$$

where $A = -Rn_g \sum_{i=1}^{n_q} a_i \langle\tau|\sigma_i^{(z)}|\tau\rangle$, $B = Rn_g \sum_{i<j}^{n_q} b_{i,j} - b$, $a = -Rn_g a_{n_q+1}$ and $b = Rn_g(b_{n_q+1,n_q+2-L_x} + b_{n_q+1,L_x} + b_{n_q,n_q+1} + b_{n_q+1-L_x,n_q+1})$ and qubits are arranged on $L_x \times L_y$ lattice, and numerated as $i = x + L_x(y-1)$, with $x = 1, \ldots, L_x$, $y = 1, \ldots, L_y$. In the limit of large n_q the terms a, b are small compared to A, B by a factor $1/\sqrt{n_q}$ and H_{eff} is reduced to 2×2 matrix, which gives $w_G = 2\omega_G^2/[(A-B)^2 + 4\omega_G^2]$.

For large n_q the difference $A - B$ has a Gaussian distribution with width $\sigma = Rn_g\sqrt{n_q/3}\sqrt{\alpha^2 + 2\beta^2} = \varepsilon R n_g \sqrt{n_q}$. The convolution of w_G with this distribution gives

$$\bar{w}_G = \sqrt{\pi/2}(1 - erf(\sqrt{2}\omega_G/\sigma)) \exp\left(2\omega_G^2/\sigma^2\right) \omega_G/\sigma \qquad (2)$$

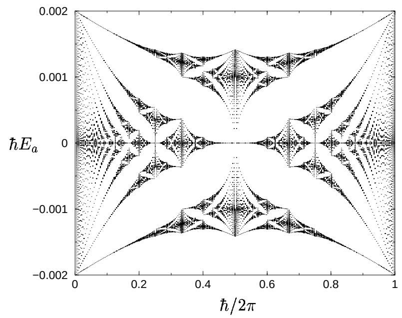
This formula gives a good description of numerical data in Fig. c that confirms the validity of single-kick model. For $\sigma \gg \omega_G$ and a typical disorder realization with $(A-B) \sim \sigma$ the actual frequency of Grover oscillations is strongly renormalized: $\omega \approx (A - B) \sim \sigma \gg \omega_G$, and in agreement with previous Fig. $\omega \sim \varepsilon/\varepsilon_c$. In this typical case $w_G \sim \omega_G^2/\sigma^2 \ll 1$ (almost total probability is in the states $|\eta_0\rangle$,$|\eta_1\rangle$). Hence, the total number of quantum operations N_{op}, required for detection of searched state $|\tau\rangle$, can be estimated as $N_{op} \sim N_M/\omega \sim \sigma/\omega_G^2 \sim \varepsilon N/\varepsilon_c$, where $N_M \sim 1/w_G \sim \sigma^2/\omega_G^2$ is a number of measurements required for detection of searched state. Thus, in presence of strong static imperfections the parametric efficiency gain of the Grover algorithm compared to classical one is of the order $\varepsilon_c/\varepsilon$. For $\varepsilon \sim \omega_G$ the efficiency is comparable with that of the ideal Grover algorithm while for $\varepsilon \sim \varepsilon_c$ there is no gain compared to the classical case.

Kicked Harper model

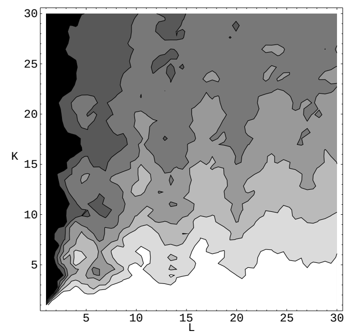
classical map: $\bar{n} = n + K \sin\theta \;,\; \bar{\theta} = \theta - L \sin\bar{n}$
quantization: $\bar{\psi} = \hat{U}\psi = e^{-iL\cos(\hbar\hat{n})/\hbar} e^{-iK\cos(\hat{\theta})/\hbar}\psi$
$\Rightarrow$ electrons in EM fields, stochastic heating of plasma

fractal spectrum "Hofstadter butterfly" for K,L small
transition to chaos as K,L increases
dynamical localization, similar to Anderson localization of electrons in solids
transition to a partially delocalized regime, with coexistence of localized and delocalized states

$\Rightarrow$ Economical quantum algorithms? Total complexity (including measurements)? Effects of static imperfections?



fractal spectrum



localization in (K,L) space

Three possible algorithms

Exact algorithm: cosine built up on extra registers

On N_H dimensional space: Several workspace registers and $O(\log N_H)^3$ gates

Time-slice algorithm:

Evolution operator is decomposed into succession of operators easy to implement. Approximate algorithm; for kicked Harper model on N_H dimensional space: Only one ancilla qubit and $O(\log N_H)^2$ quantum gates

Chebychev polynomials algorithm:

Replace functions in the exponential by polynomial approximations. Numerical simulations $\longrightarrow$ Chebyshev polynomial approximation of degree $d = 6$ gives very good approximation of the wave function. No ancilla qubit and $O(\log N_H)^d$ quantum gates

Quantum stochastic web

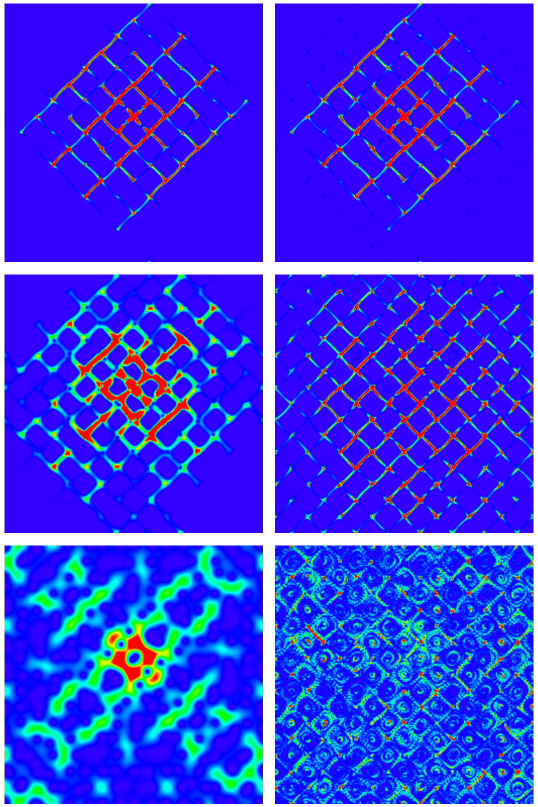
K, L very small $\Rightarrow$ small chaotic layer surrounding large integrable islands **"stochastic web"**

$\Rightarrow$ quantum transport=diffusion through layer+tunneling (much faster than classical)

Measuring diffusion constant:
$\Rightarrow$ Quantum gain (polynomial)

Effect of static errors:
$t_h \approx C_h/(\varepsilon n_q^{1.23})$

Fig: $K = L = 0.5$; Left: exact, $n_q = 15, 12, 9$; Right: $n_q = 15$, $\epsilon = 10^{-6}$, 10^{-5}, 10^{-4} (top/botom)



Localization properties

Measurable quantities:

In localized regime, localization length

In partially delocalized regime, localization length, relative amplitude of plateau, quantum diffusion constant

polynomial improvement for the quantum algorithm.

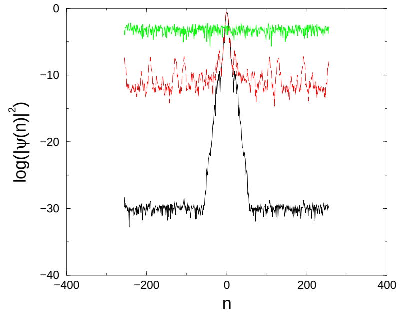
Effect of static imperfections:

In localized regime, $\varepsilon_c \approx C_1/(n_g\sqrt{n_q}\sqrt{l})$

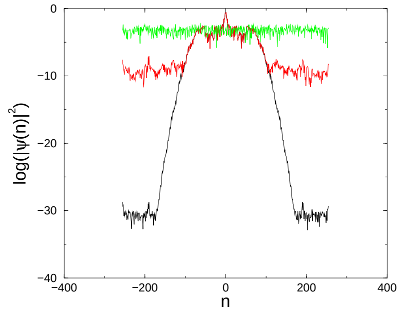
In partially delocalized regime, $\varepsilon_c \approx C_2/(n_g\sqrt{n_q}\sqrt{N})$

exponentially small: $N = 2^{n_q}$!

transition point $\sim \varepsilon n_g \sqrt{n_q} N$ ($\neq$ Anderson transition)



localized wave function



partial delocalization

Quantum phase space distribution functions

Wigner function:

Real but can take negative values

Two strategies: measurement of ancilla qubit (Miquel et al, $Nature$ 2002), direct construction of $W(p,q)$ on quantum registers (new)

Result of numerical simulations for kicked rotator quantum map:

$\longrightarrow$ **Small polynomial gain** for direct measurements and amplitude amplification

$\longrightarrow$ **Larger polynomial gain** using quantum wavelet transform

Gain is larger in chaotic regime

Husimi function:

Smoothing of Wigner function over cells of size $\hbar \Rightarrow$ real nonnegative function

Smoothing by a box (in p): Husimi-like distribution, easy to implement from $|\psi>$ by partial quantum Fourier transform

Result of numerical simulations for kicked rotator:

$\longrightarrow$ **Small polynomial gain** for direct measurements

$\longrightarrow$ At least **quadratic gain** with amplitude amplification

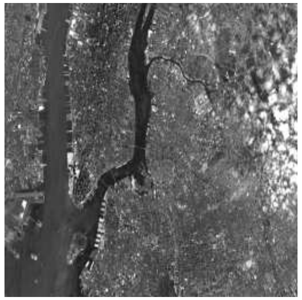
$\longrightarrow$ **Quadratic gain** using quantum wavelet transform

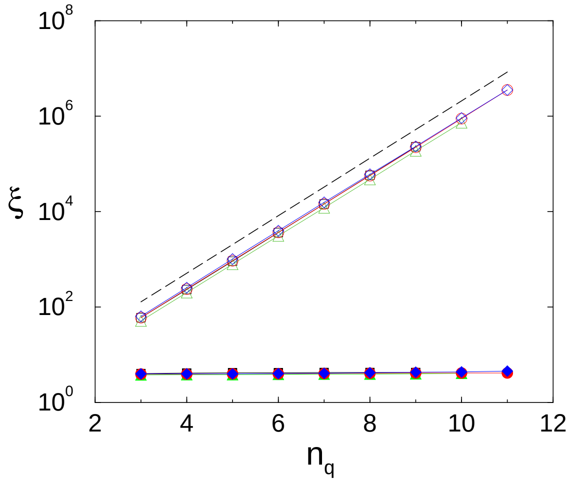
Standard images

Numerical simulations $\longrightarrow$ wavelet transform is **very efficient** at compressing information for standard images (Figure: number of significant components for image and wavelet-transformed image)

Largest wavelet coefficients can be obtained in **polynomial time** for **exponentially** large images. **Total gain** depends on efficiency of encoding the image

Reconstruction of image from such largest wavelet coefficients leads to large loss of information





Publications of EDIQIP in 2004

Scientific deliverables are marked by D4,D7,D8,D11,D12.

[1] A.A.Pomeransky and D.L.Shepelyansky, *Quantum computation of the Anderson transition in the presence of imperfections*, Phys. Rev. A **69**, 014302 (2004) [quant-ph/0306203] (D11,D7).

[2] B.Georgeot and D.L.Shepelyansky, *Les ordinateurs quantiques affrontent le chaos*, (in French, *Images de la Physique 2003-2004*, CNRS Edition, pp. 17-23) [quant-ph/0307103] (D11).

[3] B.Georgeot, *Quantum computing of Poincare recurrences and periodic orbits*, Phys. Rev. A **69**, 032301 (2004) [quant-ph/0307233] (D11).

[4] J.W.Lee, A.D.Chepelianskii and D.L.Shepelyansky, *Treatment of sound on quantum computers*, Proceedings of ERATO Conference on Quantum Information Science 2004, Tokyo, pp. 91-92 (2004); and *Applications of quantum chaos to realistic quantum computations and sound treatment on quantum computers*, in *Noise and information in nanoelectronics, sensors, and standards II* Proceedings of SPIE Eds. J.M.Smulko, Y.Blanter, M.I.Dykman, L.B.Kish, v.5472, pp.246-251 (2004) [quant-ph/0309018] (D11,D12).

[5] M.Terraneo and D.L.Shepelyansky, *Dynamical localization and repeated measurements in a quantum computation process*, Phys. Rev. Lett. **92**, 037902 (2004) [quant-ph/0309192] (D4).

[6] S.Bettelli, *A quantitative model for the effective decoherence of a quantum computer with imperfect unitary operations*, Phys. Rev. A **69**, 042310 (2004) [quant-ph/0310152] (D4,D8).

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Publications [1-7], [12], [14] and [22] were included in the EDIQIP publication list of the 2003 report as preprints.