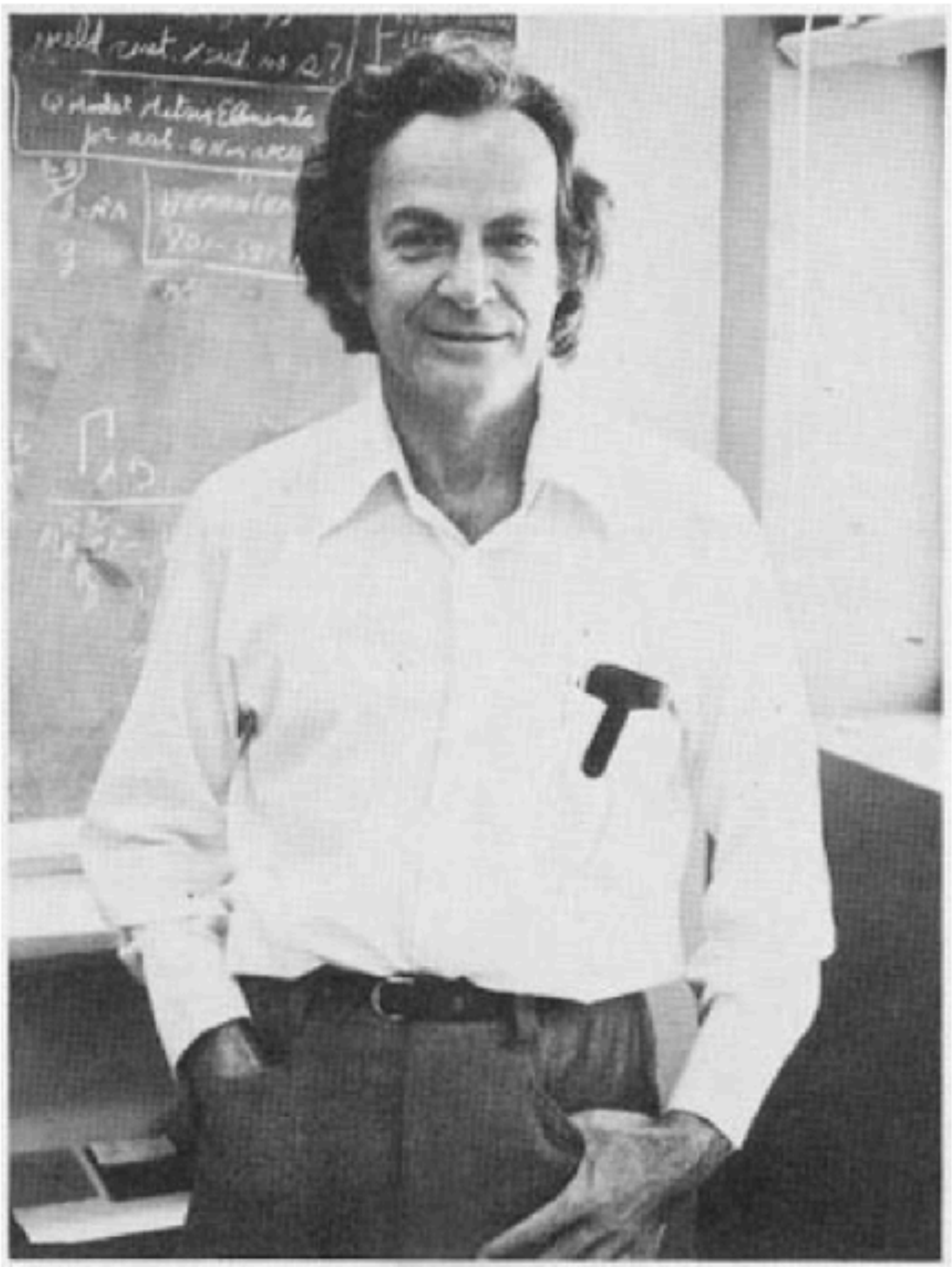
qubits superconductores

no linealidad y caos



International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman

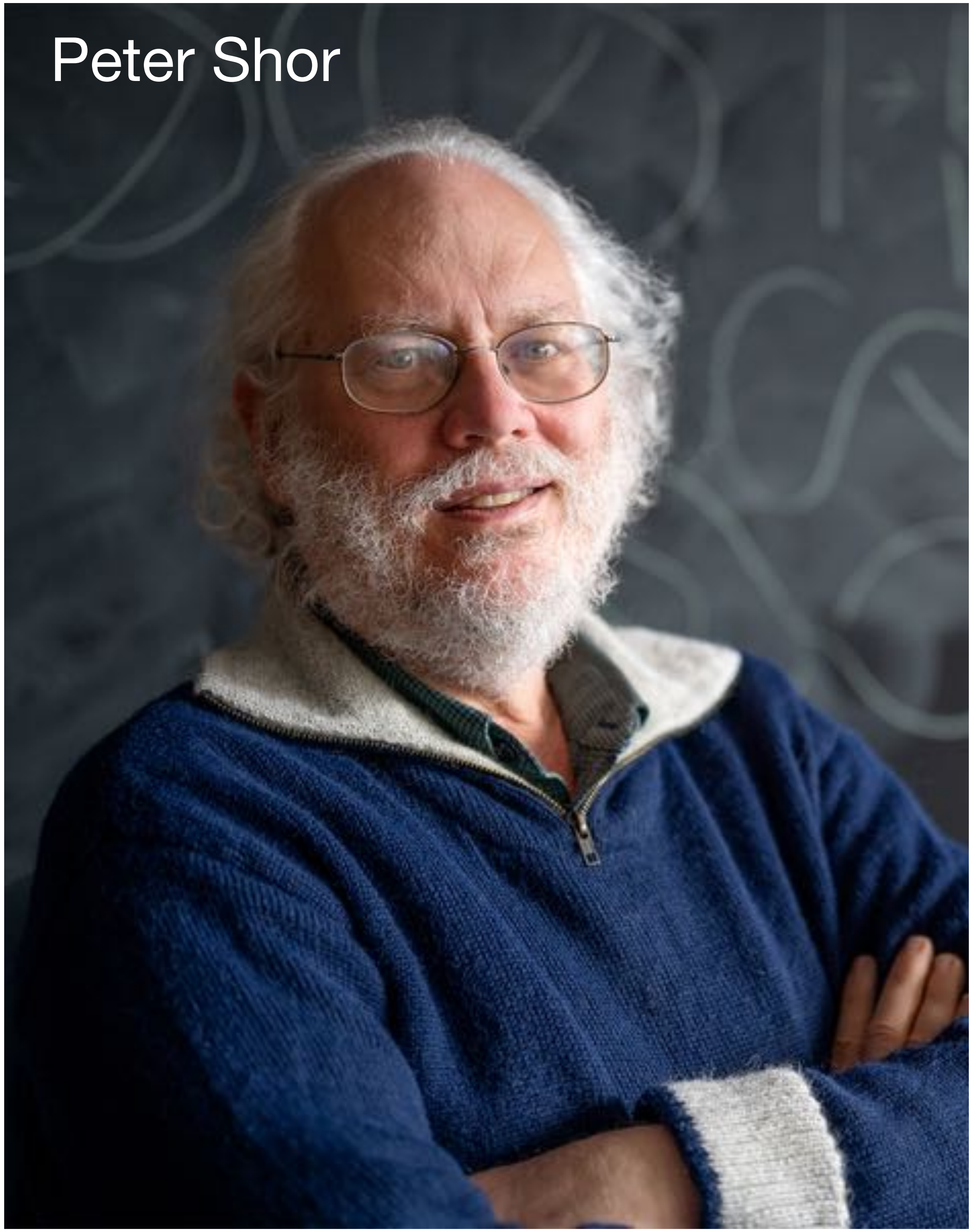
Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

Quantum Mechanical Computers

By Richard P. Feynman

Optics News 1986 & Foundations of Physics, Vol. 16, No. 6, 1986



Shor, P.W. (1994). "Algorithms for quantum computation: Discrete logarithms and factoring". Proceedings 35th Annual Symposium on Foundations of Computer Science. pp. 124–134.

Factorización de un entero grande N en factores primos

Algoritmo de Shor

$$O\left((\log N)^2(\log\log N)\right)$$

Mejor clásico

$$O\left(e^{1.9(\log N)^{1/3}(\log\log N)^{2/3}}\right)$$

1 qubit: $\alpha|0\rangle + \beta|1\rangle$

2 qubit: $\alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle$

$|0\rangle$ $|1\rangle$ $|2\rangle$ $|3\rangle$

n qubits: $\sum_{i=0}^{n-1} \alpha_i|i\rangle$

$|i=0\rangle = |00\ldots0\rangle$
$|i=2\rangle = |00\ldots10\rangle$
$\vdots$

+ coherencia + entrelazamiento

Criterios

qubits escalables

inicializción

coherencia

compuertas universales

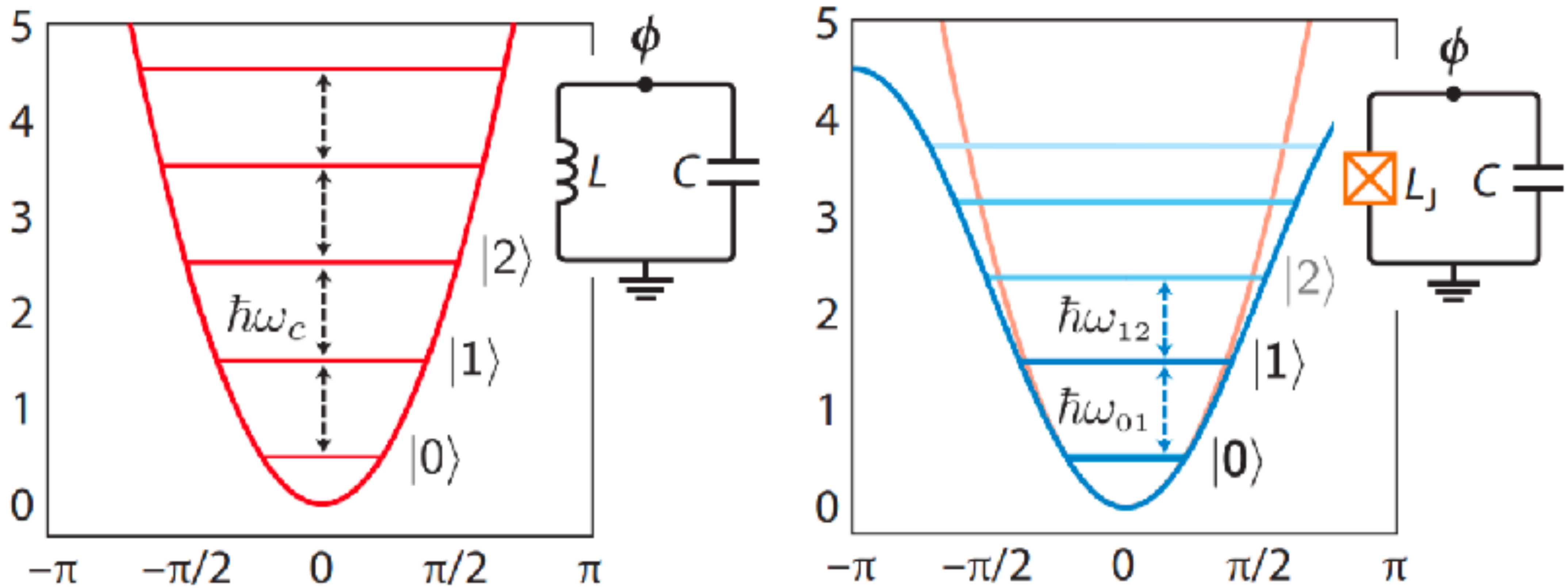
medición

conversión estacionario-volador

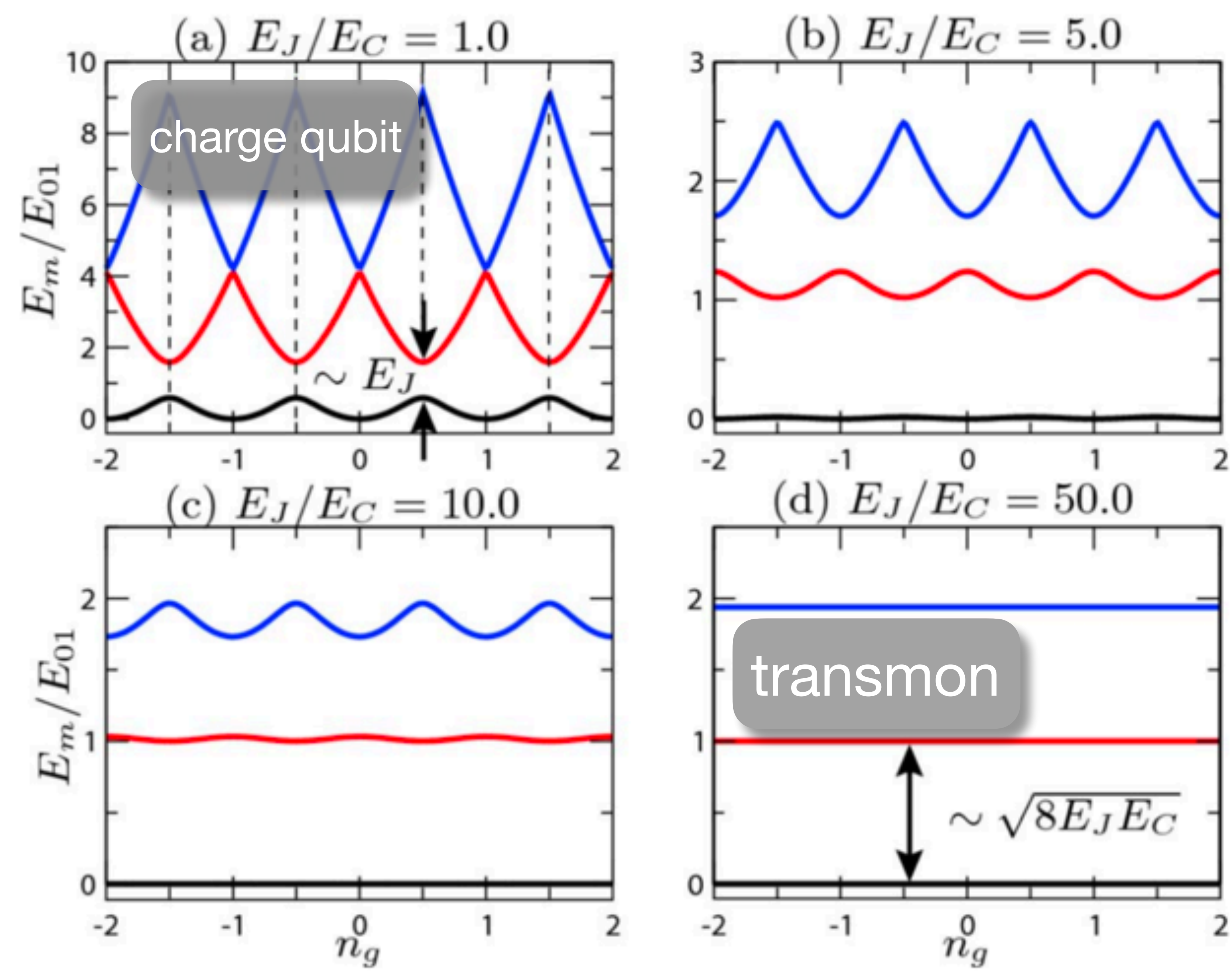
transmisión de qubits voladores

Criterio	Superconductores	Iones atrapados	Fotónicos	Espín en puntos cuánticos	Topológicos
1. qubits escalables	✓	∼	∼	∼	✗
2. Inicialización	✓	✓	∼	✓	∼
3. coherencia	∼	✓	✓	∼	✓
4. compuertas universales	✓	✓	∼	∼	✗
5. Medición	✓	✓	∼	∼	✗
6. Conversión estacionario-volador	∼	∼	✓	∼	✗
7. Transmisión de qubits voladores	∼	∼	✓	∼	✗
	IBM | Google | Rigetti	IonQ I Quantinuum	PsiQuantum I Xanadu	Intel I Delft	Microsoft

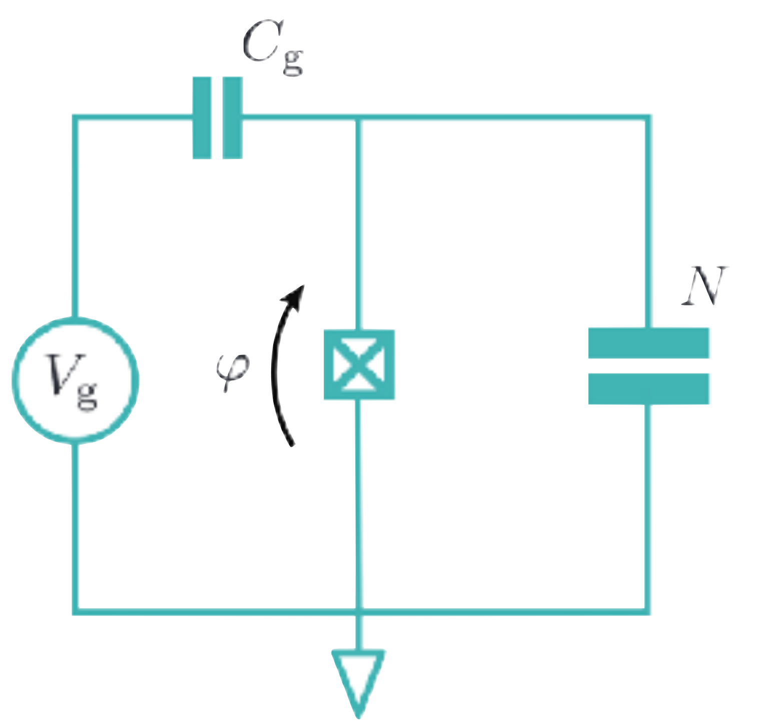
Criterio	Superconductores	Iones atrapados	Fotónicos	Espín en puntos cuánticos	Topológicos
1. qubits escalables	✓	∼	∼	∼	✗
2. Inicialización	✓	✓	∼	✓	∼
3. coherencia	∼ $100\mu s$ y mejorando	✓	✓	∼	✓
4. compuertas universales	✓	✓	∼	∼	✗
5. Medición	✓	✓	∼	∼	✗
6. Conversión estacionario-volador	∼ en desarrollo	∼	✓	∼	✗
7. Transmisión de qubits voladores	∼ cortas distancias	∼	✓	∼	✗
	IBM | Google | Rigetti	IonQ I Quantinuum	PsiQuantum I Xanadu	Intel I Delft	Microsoft



5
4
3
2
1
0
−π
−π/2
0
π/2
π
$|0\rangle$
$|1\rangle$
$|2\rangle$
$\hbar\omega_c$
ϕ
L
C
$\hbar\omega_{12}$
$\hbar\omega_{01}$
L_J

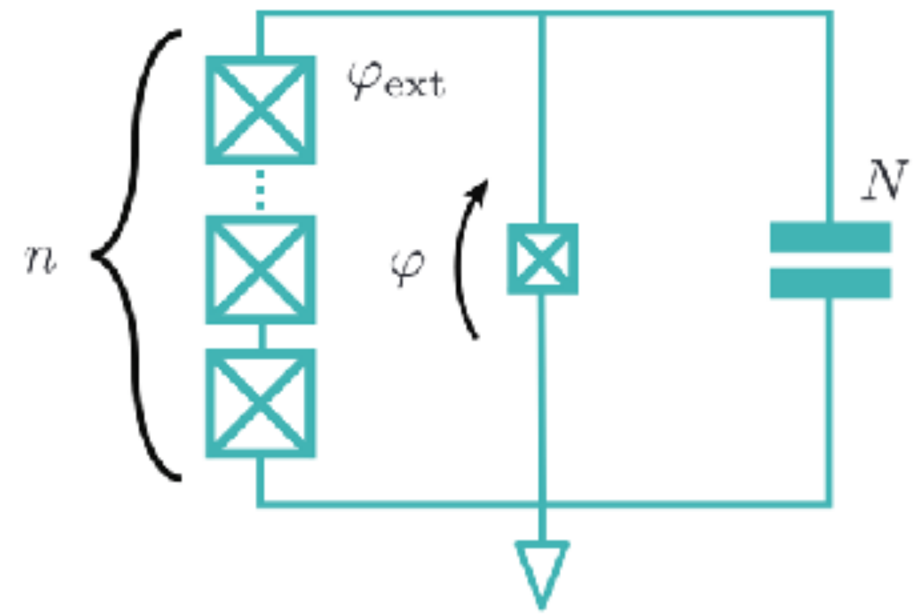

(a) $E_J/E_C = 1.0$
charge qubit
$\sim E_J$
(b) $E_J/E_C = 5.0$
(c) $E_J/E_C = 10.0$
(d) $E_J/E_C = 50.0$
transmon
$\sim \sqrt{8E_JE_C}$
E_m/E_{01}
n_g

Transmon

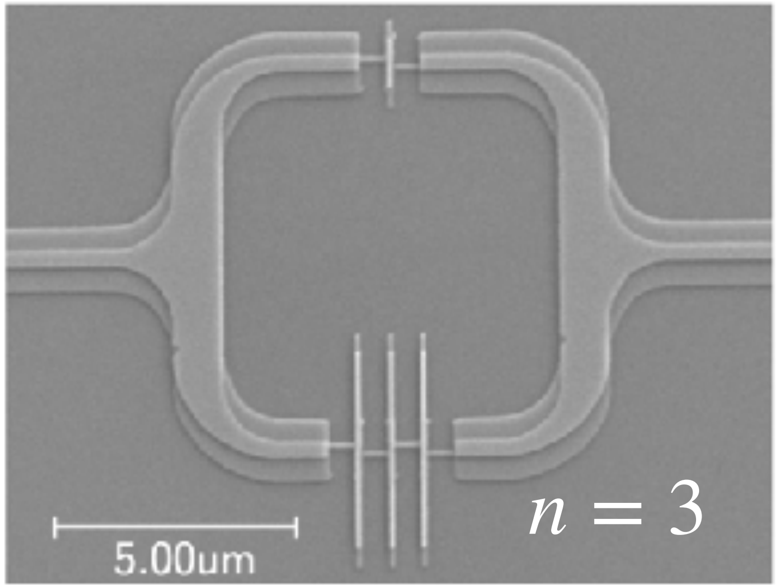


$$\hat{H}_0 = 4E_C\left(\hat{N} - N_g\right)^2 - E_J \cos\hat{\varphi}$$

SNAIL Transmon

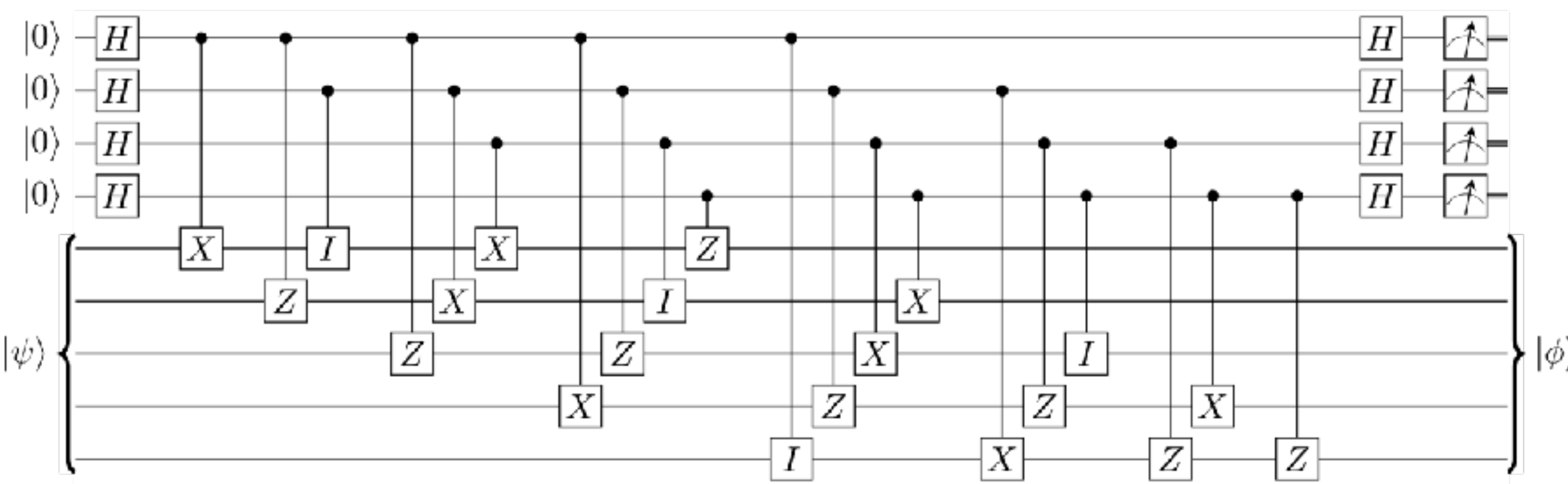


$$\hat{H}_0 = 4E_C\hat{N}^2 - \alpha E_J \cos\left(\hat{\varphi} - \varphi_{ext}\right) - nE_J \cos(\hat{\varphi}/n)$$



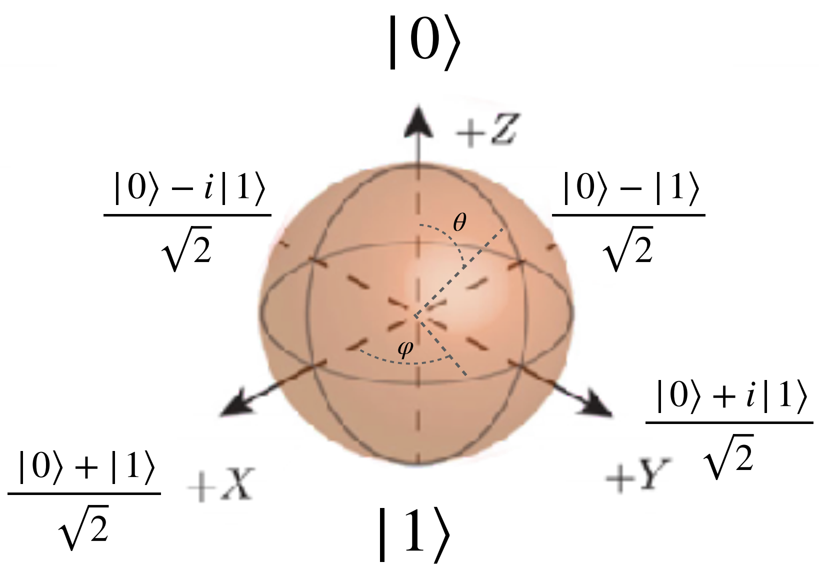
corrección de errores

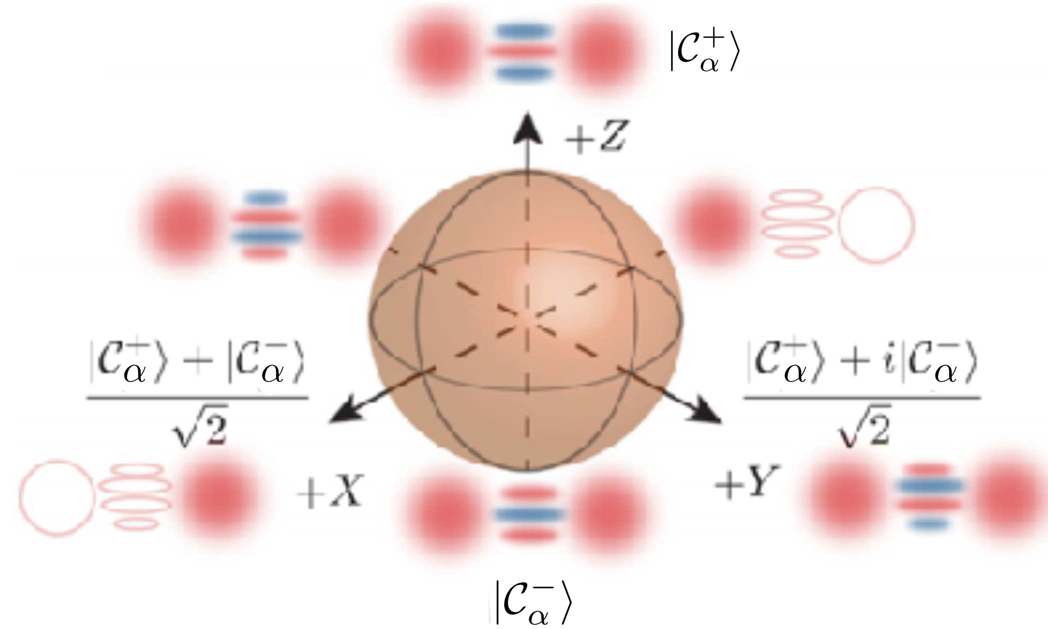
$$|0_L\rangle = \frac{1}{4}[|00000\rangle + |10010\rangle + |01001\rangle + |10100\rangle + |01010\rangle - |11011\rangle - |00110\rangle - |11000\rangle$$
$$-|11101\rangle - |00011\rangle - |11110\rangle - |01111\rangle - |10001\rangle - |01100\rangle - |10111\rangle + |00101\rangle],$$
$$|1_L\rangle = \frac{1}{4}[|11111\rangle + |01101\rangle + |10110\rangle + |01011\rangle + |10101\rangle - |00100\rangle - |11001\rangle - |00111\rangle$$
$$-|00010\rangle - |11100\rangle - |00001\rangle - |10000\rangle - |01110\rangle - |10011\rangle - |01000\rangle + |11010\rangle].$$



Laflame, Miquel, Paz & Zurek, Phys. Rev. Lett. **77**, 198 (1996) protección eficiente desde el hardware

Esfera de Bloch





$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle$$

$$|\mathcal{C}_\alpha^\pm\rangle = \mathcal{N}(|\alpha\rangle \pm |\alpha\rangle)$$

$$\rho = \frac{1}{2}(I + \vec{a}\cdot\vec{\sigma})$$

estado gato

Stabilization and operation of a Kerr-cat qubit

https://doi.org/10.1038/s41586-020-2587-z

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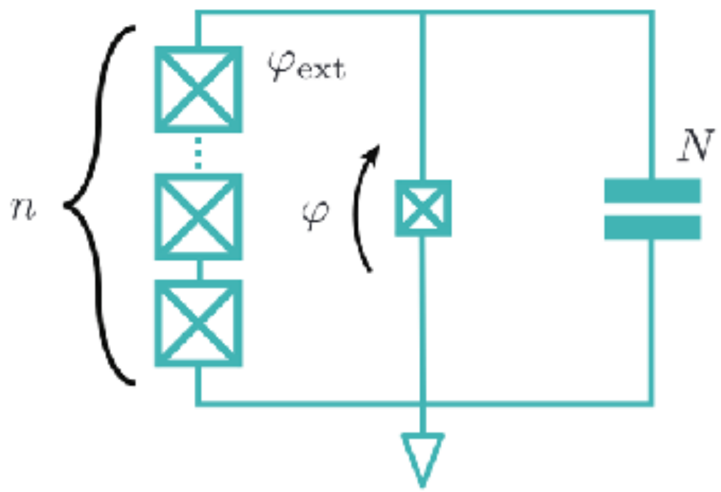
Check for updates

A. Grimm[1,4,6]✉, N. E. Frattini[1,6], S. Puri[2], S. O. Mundhada[1], S. Touzard[1], M. Mirrahimi[3], S. M. Girvin[2], S. Shankar[1,5] & M. H. Devoret[1]✉

Quantum superpositions of macroscopically distinct classical states—so-called Schrödinger cat states—are a resource for quantum metrology, quantum communication and quantum computation. In particular, the superpositions of two opposite-phase coherent states in an oscillator encode a qubit protected against phase-flip errors[1,2]. However, several challenges have to be overcome for this concept to become a practical way to encode and manipulate error-protected quantum information. The protection must be maintained by stabilizing these highly excited states and, at the same time, the system has to be compatible with fast gates on the encoded qubit and a quantum non-demolition readout of the encoded information. Here we experimentally demonstrate a method for the generation and stabilization of Schrödinger cat states based on the interplay between Kerr nonlinearity and single-mode squeezing[1,3] in a superconducting microwave resonator[4]. We show an increase in the transverse relaxation time of the stabilized, error-protected qubit of more than one order of magnitude compared with the single-photon Fock-state encoding. We perform all single-qubit gate operations on timescales more than sixty times faster than the shortest coherence time and demonstrate single-shot readout of the protected qubit under stabilization. Our results showcase the combination of fast quantum control and robustness against errors, which is intrinsic to stabilized macroscopic states, as well as the potential of these states as resources in quantum information processing[5–8].

Stabilization

SNAIL Transmon+forzado (squeezing) periódico



$$\hat{H}_0 = 4E_C\hat{N}^2 - \alpha E_J \cos\left(\hat{\varphi} - \varphi_{\text{ext}}\right) - nE_J\cos(\hat{\varphi}/n)$$

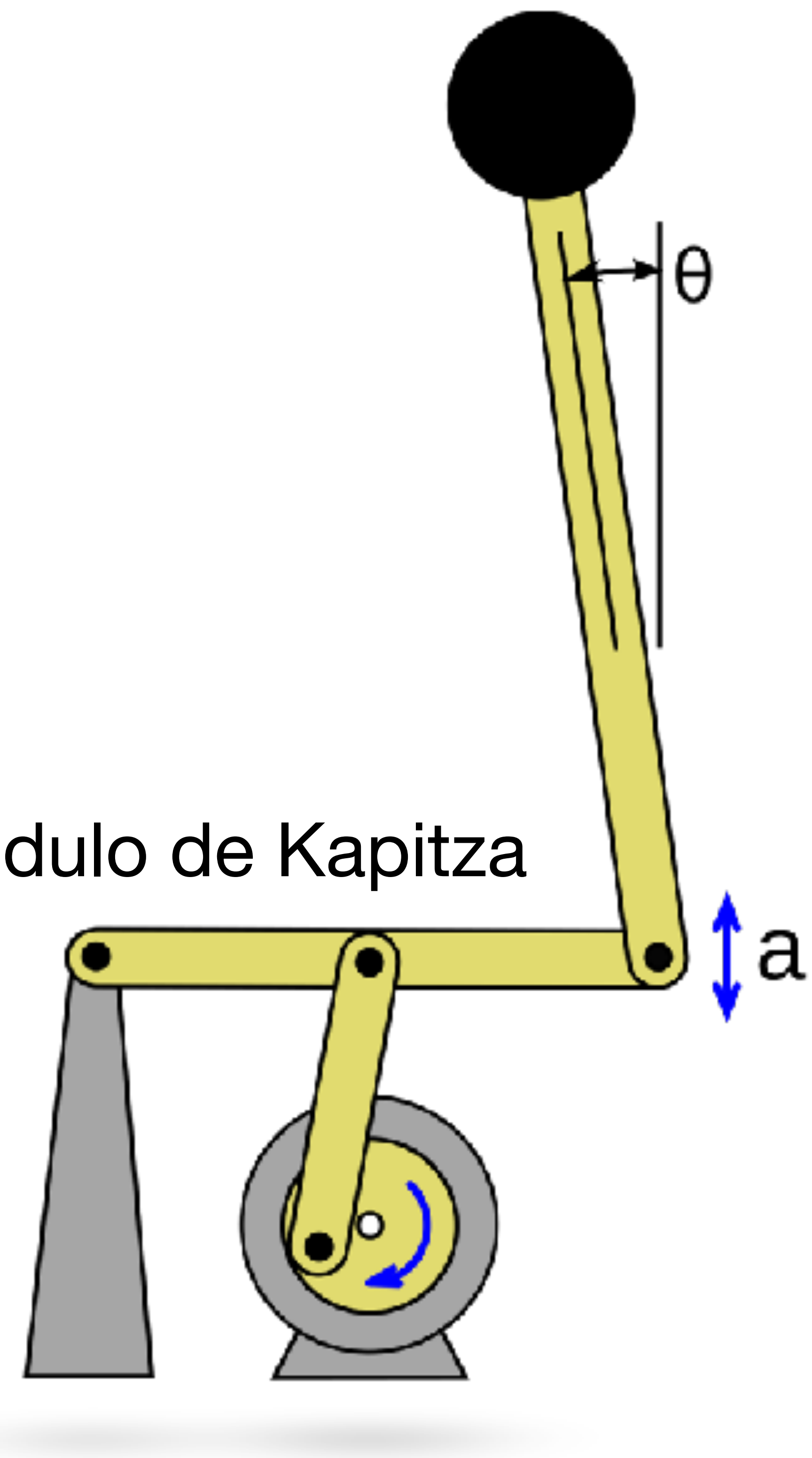
Taylor… $\hat{a} = \frac{1}{2}\left(\frac{\hat{\phi}}{\phi_{zps}} + i\frac{\hat{N}}{N_{zps}}\right), \quad \hat{a}^\dagger = \frac{1}{2}\left(\frac{\hat{\phi}}{\phi_{zps}} - i\frac{\hat{N}}{N_{zps}}\right).$

$$\hat{H}_0 = \omega_0\hat{a}^\dagger\hat{a} + \sum_{m>3} g_m\left(\hat{a} + \hat{a}^\dagger\right)^m$$

$$\hat{H} = \omega_0\hat{a}^\dagger\hat{a} + g_3\left(\hat{a} + \hat{a}^\dagger\right)^3 + g_4\left(\hat{a} + \hat{a}^\dagger\right)^4 - i\Omega_d\left(\hat{a} - \hat{a}^\dagger\right)\cos\left(\omega_d t\right)$$

Stabilization

péndulo de Kapitza



Hamiltoniano efectivo

traslación   cambio al sistema rotante   T. Canonica

$$\hat{\mathscr{H}}(t) = -\delta \hat{a}^\dagger \hat{a} + \sum_{m=3}^{4} \frac{g_m}{m} \left(\hat{a} e^{-i\omega_d t/2} + \hat{a}^\dagger e^{i\omega_d t/2} + \Pi e^{-i\omega_d t} + \Pi^* e^{i\omega_d t} \right)^m$$

$$\delta = \omega_d/2 - \omega_o \ll \omega_o \qquad \Pi \approx \frac{2\Omega_d}{3\omega_d}$$

bifurcación para $\omega_d = 2\omega_o$

kerr cat

"Kerr parametric oscillator"

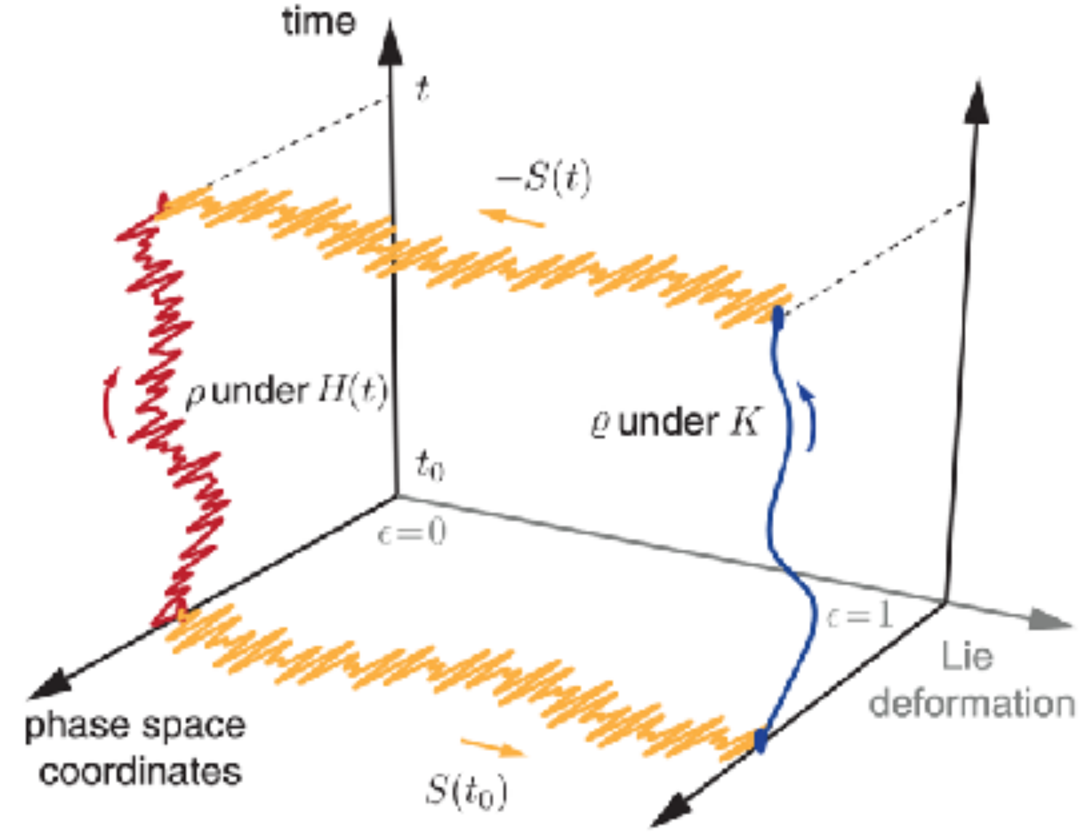
$$H_{\text{eff}} = \epsilon_2(\hat{a} + \hat{a}^\dagger) - K\hat{a}^{\dagger 2}\hat{a}^2$$

$[H_{\text{eff}}, e^{i\pi\hat{a}^\dagger\hat{a}}]$ preserva paridad

$$\omega_d = 2\omega_a$$

$$K \approx -\frac{3g_4}{2} + \frac{10g_3^2}{3\omega_o} \qquad \epsilon_2 \approx g_3 \frac{\Omega_d}{3\omega_o}$$

$$\omega_a \approx \omega_o + 3g_4 - 20g_3^2/3\omega_o + (6g_4 + 9g_3^2/\omega_o)(2\Omega_d/3\omega_o)^2$$



$$\hat{U}(T) = \mathcal{T} \exp\left(-\frac{i}{\hbar}\int_0^T \hat{\mathcal{H}}(t)\,dt\right) = e^{\frac{i}{\hbar}\hat{S}(T)} e^{-\frac{i}{\hbar}\hat{H}_{\text{eff}}T} e^{-\frac{i}{\hbar}\hat{S}(0)}$$

cálculo perturbativo hasta orden arbitrario

J. Venkatraman, X. Xiao, R. G. Cortiñas, A. Eickbusch, & M. H. Devoret, Phys. Rev. Lett. 129, 100601 (2022).

ARTICLE OPEN

Engineering the quantum states of light in a Kerr-nonlinear resonator by two-photon driving

Shruti Puri[1], Samuel Boutin[1] and Alexandre Blais[1,2]

RESULTS

Our starting point is the two-photon driven KNR Hamiltonian in a frame rotating at the resonator frequency

$$\hat{H}_0 = -K\hat{a}^\dagger\hat{a}^\dagger\hat{a}\hat{a} + (\mathcal{E}_p\hat{a}^{\dagger 2} + \mathcal{E}_p^*\hat{a}^2). \tag{1}$$

Article

Stabilization and operation of a Kerr-cat qubit

https://doi.org/10.1038/s41586-020-2587-z

Received: 28 July 2019

A. Grimm[1,4,6], N. E. Frattini[1,5], S. Puri[2], S. O. Mundhada[1], S. Touzard[1], M. Mirrahimi[3], S. M. Girvin[2], S. Shankar[1,5] & M. H. Devoret[1]

Our approach is based on the application of a resonant single-mode squeezing drive to a Kerr-nonlinear resonator[4]. In the frame rotating at the resonator frequency ω_a, the system is described by the Hamiltonian

$$\hat{H}_{\mathrm{cat}}/\hbar = -K\hat{a}^{\dagger 2}\hat{a}^2 + \epsilon_2(\hat{a}^{\dagger 2} + \hat{a}^2), \tag{1}$$

SCIENCE ADVANCES | RESEARCH ARTICLE

APPLIED PHYSICS

Bias-preserving gates with stabilized cat qubits

Shruti Puri[1,2]*, Lucas St-Jean[3], Jonathan A. Gross[3], Alexander Grimm[2,4], Nicholas E. Frattini[2,4], Pavithran S. Iyer[5], Anirudh Krishna[3], Steven Touzard[2,4], Liang Jiang[2,4,6], Alexandre Blais[3,7], Steven T. Flammia[2,8], S. M. Girvin[1,2]

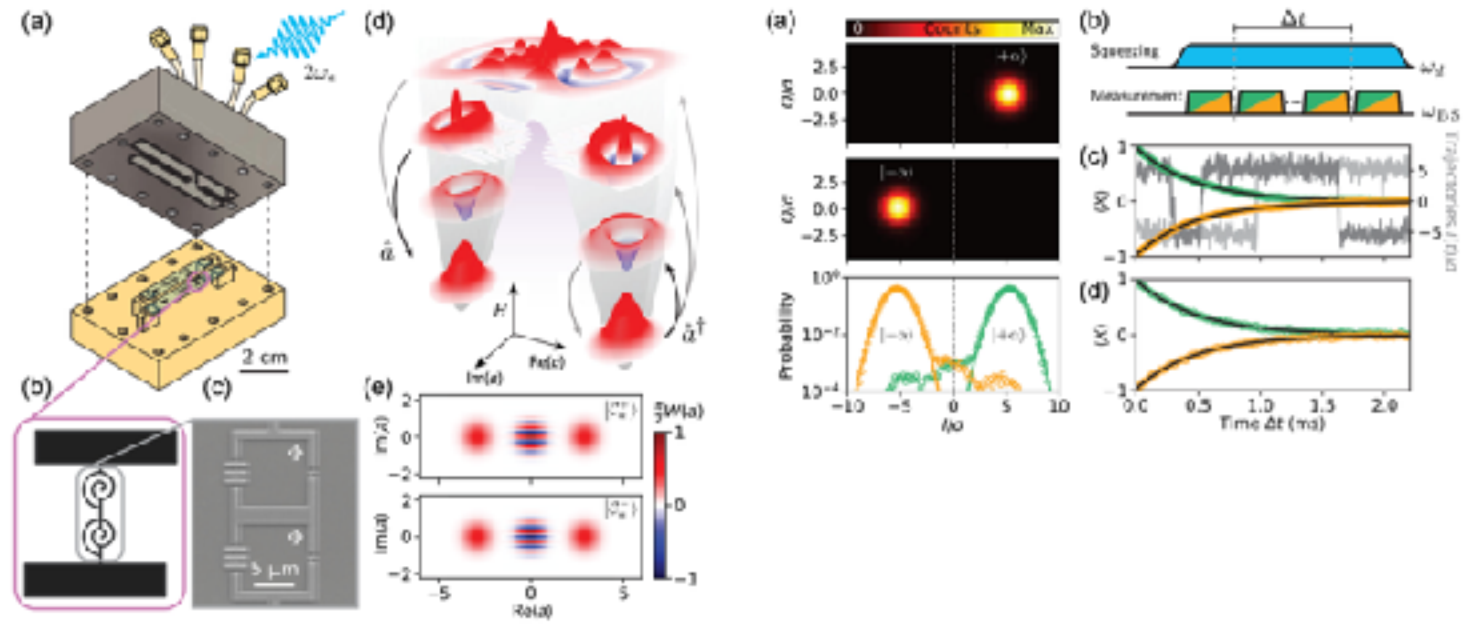
RESULTS

Two-photon driven nonlinear oscillator

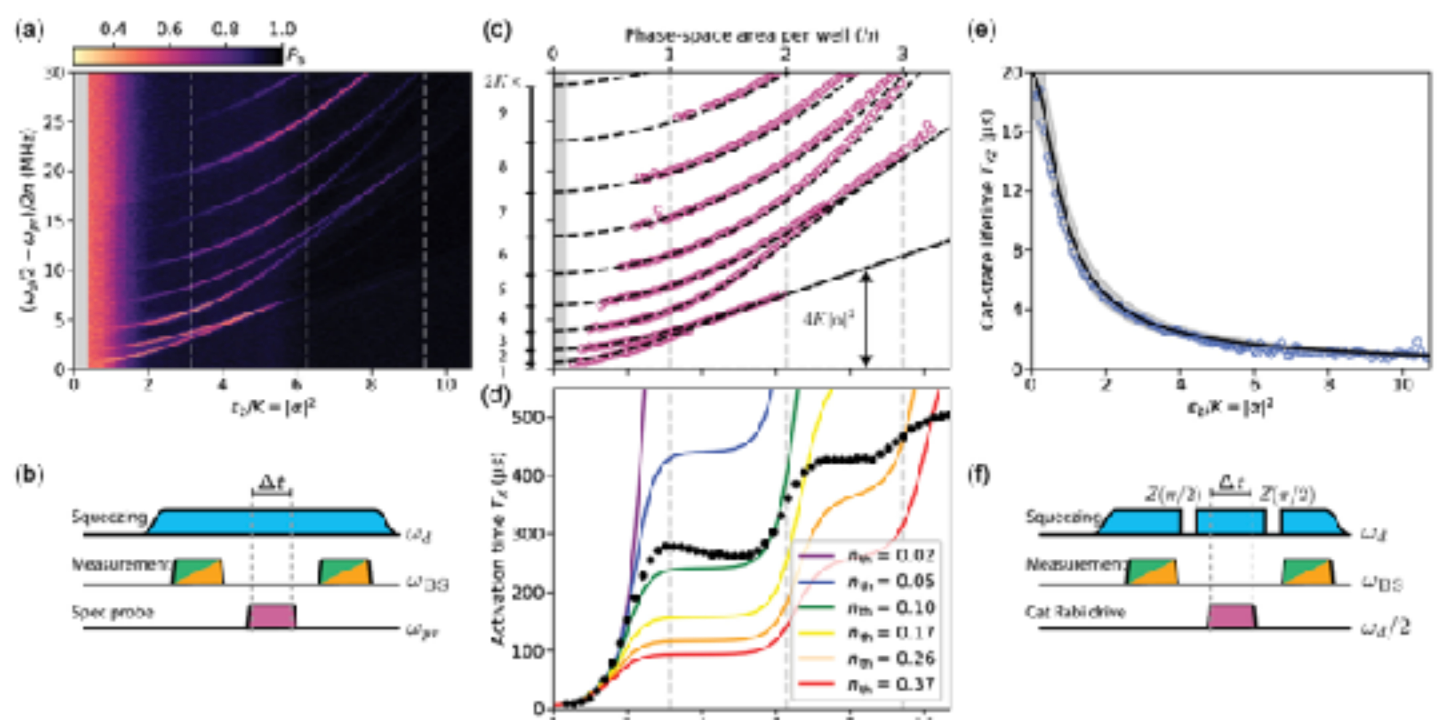
The Hamiltonian of a two-photon driven Kerr nonlinear oscillator in a frame rotating at the oscillator frequency ω_r is given by

$$\hat{H}_0(\phi) = -K\hat{a}^{\dagger 2}\hat{a}^2 + P(\hat{a}^{\dagger 2}e^{2i\phi} + \hat{a}^2e^{-2i\phi}) \tag{4}$$

$$= -K(\hat{a}^{\dagger 2} - \alpha^2e^{-2i\phi})(\hat{a}^2 - \alpha^2e^{2i\phi}) + \frac{P^2}{K} \tag{5}$$


(a)
(d)
2 cm
(b)
(c)
5 μm
(e)
Squeezing
Measurement
Probability
Time Δt (ms)

da bien


(a)
(b)
Squeezing
Measurement
Spec probe
(c)
Phase-space area per well
(d)
Activation time
(e)
Cat-state lifetime
(f)
Squeezing
Measurement
Cat Rabi drive

hasta cierto punto

comparamos $\mathscr{H}(t)$ con H_{eff}

H_{eff}	estados	$\lvert\psi_k\rangle$
	energías	E_k
$\mathscr{H}(t)$	estados de Floquet	$\lvert\Psi_k(t)\rangle = e^{-i\varepsilon_k t}\lvert\phi_k(t)\rangle$
	modos de Floquet	$\lvert\phi_k(t)\rangle = \lvert\phi_k(t+T)\rangle$
	mapa de Floquet	$U(T)\lvert\phi_k\rangle = e^{i\varepsilon_k T}\lvert\phi_k\rangle$
	cuasienergías	$\varepsilon_k \in [0,\hbar\omega_d/2]$

QuTiP

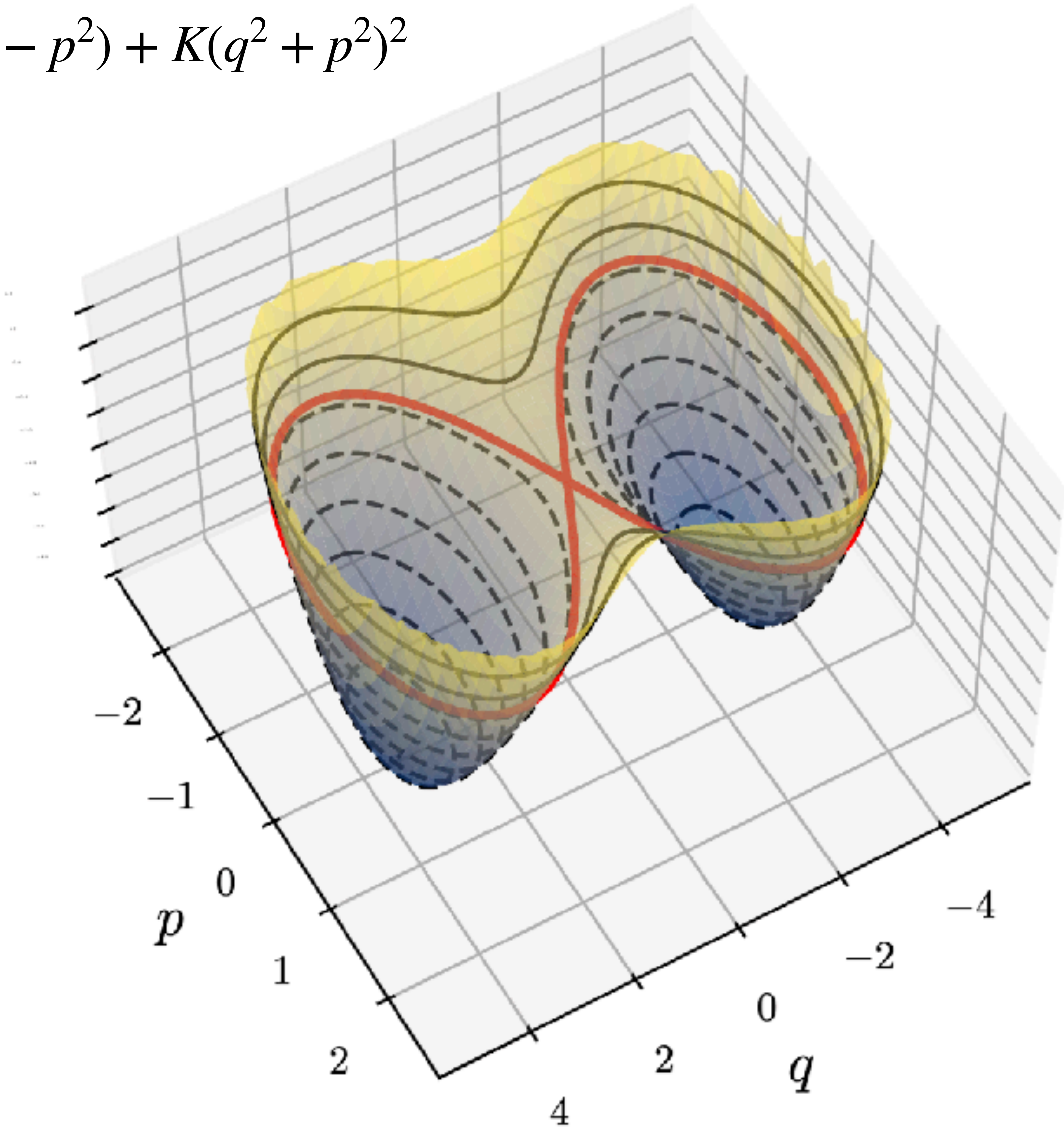
Quantum Toolbox in Python

Get Started with QuTiP v5 | Try QuTiP from your Browser!

We hope you enjoy using QuTiP. Please help us make QuTiP better by citing it in your publications.

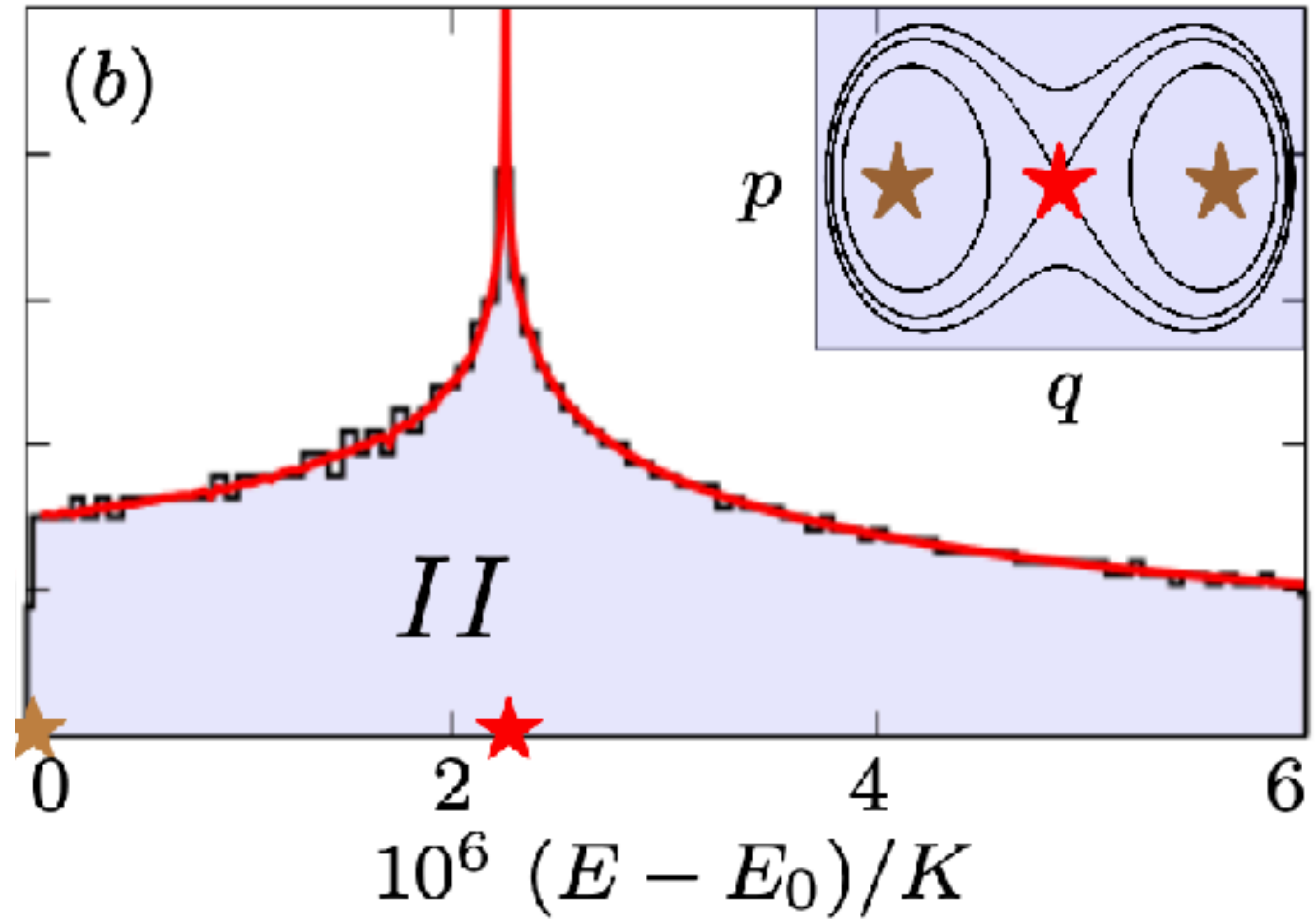
QuTiP is open-source software for simulating the dynamics of open quantum systems. The QuTiP library depends on the excellent Numpy, Scipy, and Cython numerical packages. In addition, graphical output is provided by Matplotlib. QuTiP aims to provide user-friendly and efficient numerical simulations of a wide variety of Hamiltonians, including those with arbitrary time-dependence, commonly found in a wide range of physics applications such as quantum optics, trapped ions, superconducting circuits, and quantum nanomechanical resonators. QuTiP is freely available for use and/or modification on all major platforms such as Linux, Mac OSX, and Windows. Being free of any licensing fees, QuTiP is ideal for exploring quantum mechanics and dynamics in the classroom.

$$H_{\mathrm{cl}} = \epsilon_2(q^2 - p^2) + K(q^2 + p^2)^2$$



ESQPT

$\rho =$ densidad de estados

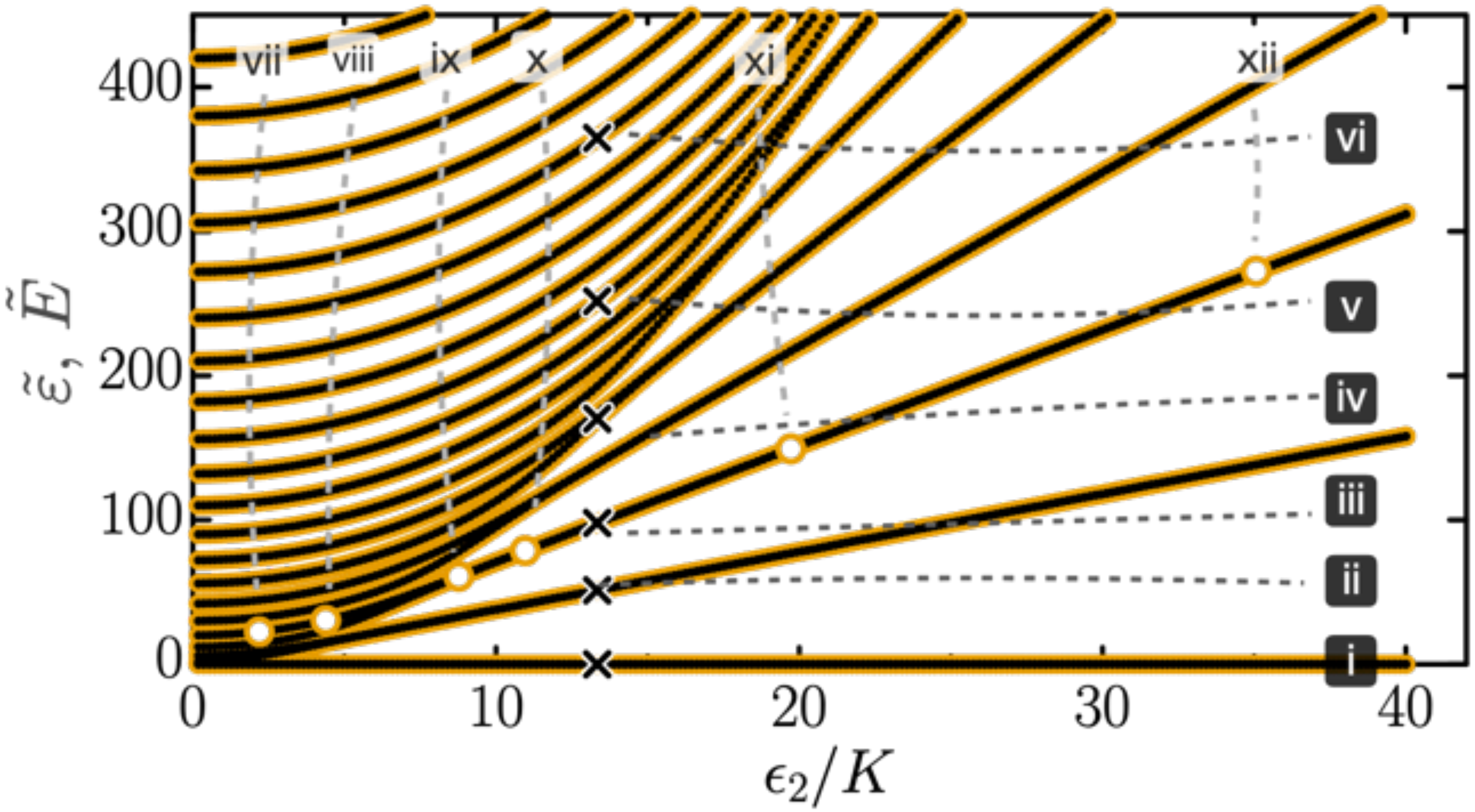


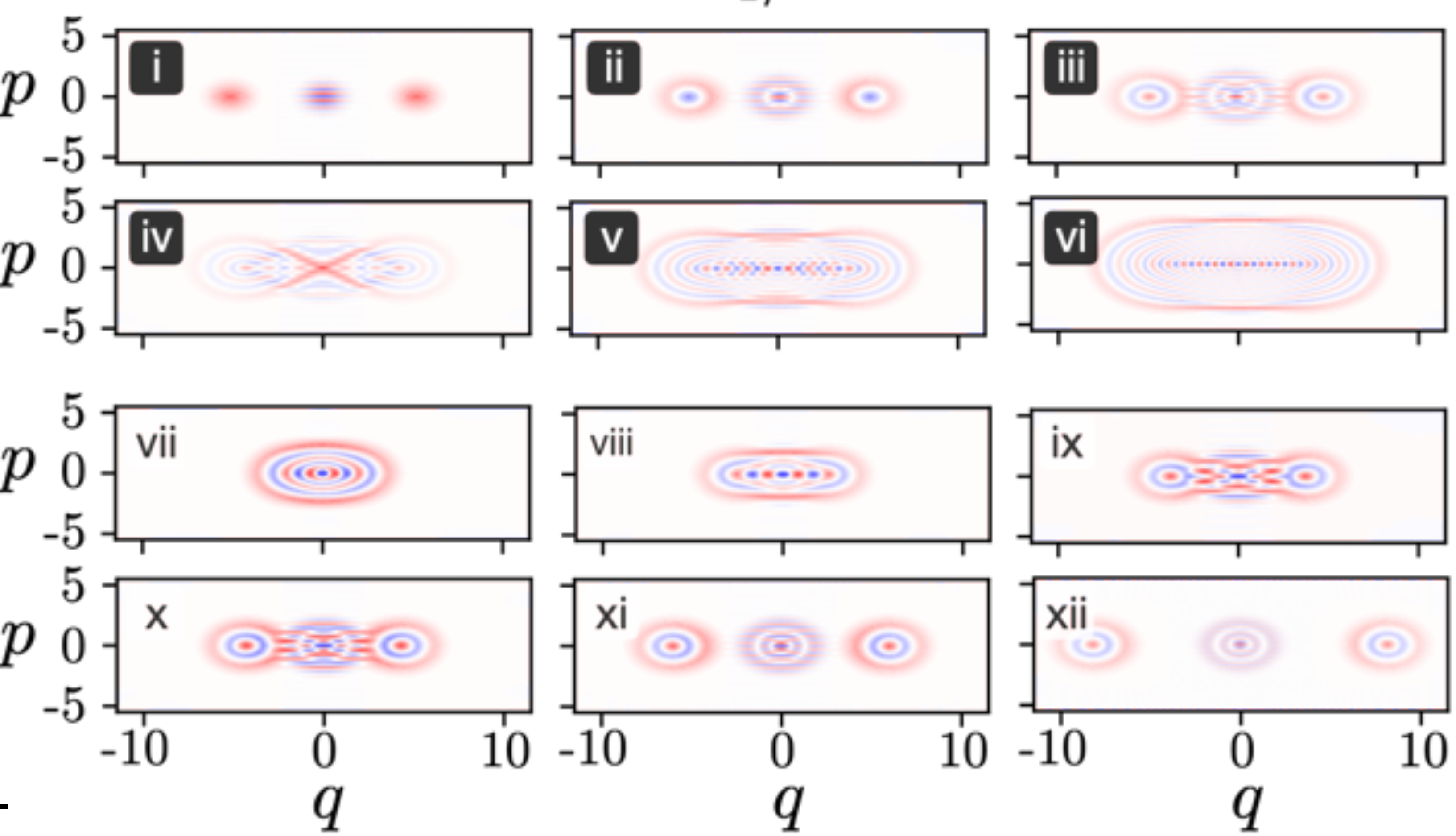
Phys. Rev. A **108**, 033709 (2023)

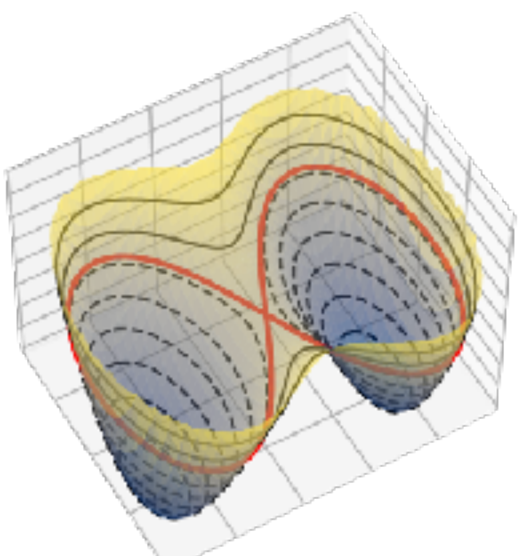
comparamos $\mathscr{H}(t)$ con H_{eff}

$$\tilde{E} = (E - E_0)/K$$

$$\tilde{\varepsilon} = [(\varepsilon - \varepsilon_0) \mod (\omega_d/2)]$$





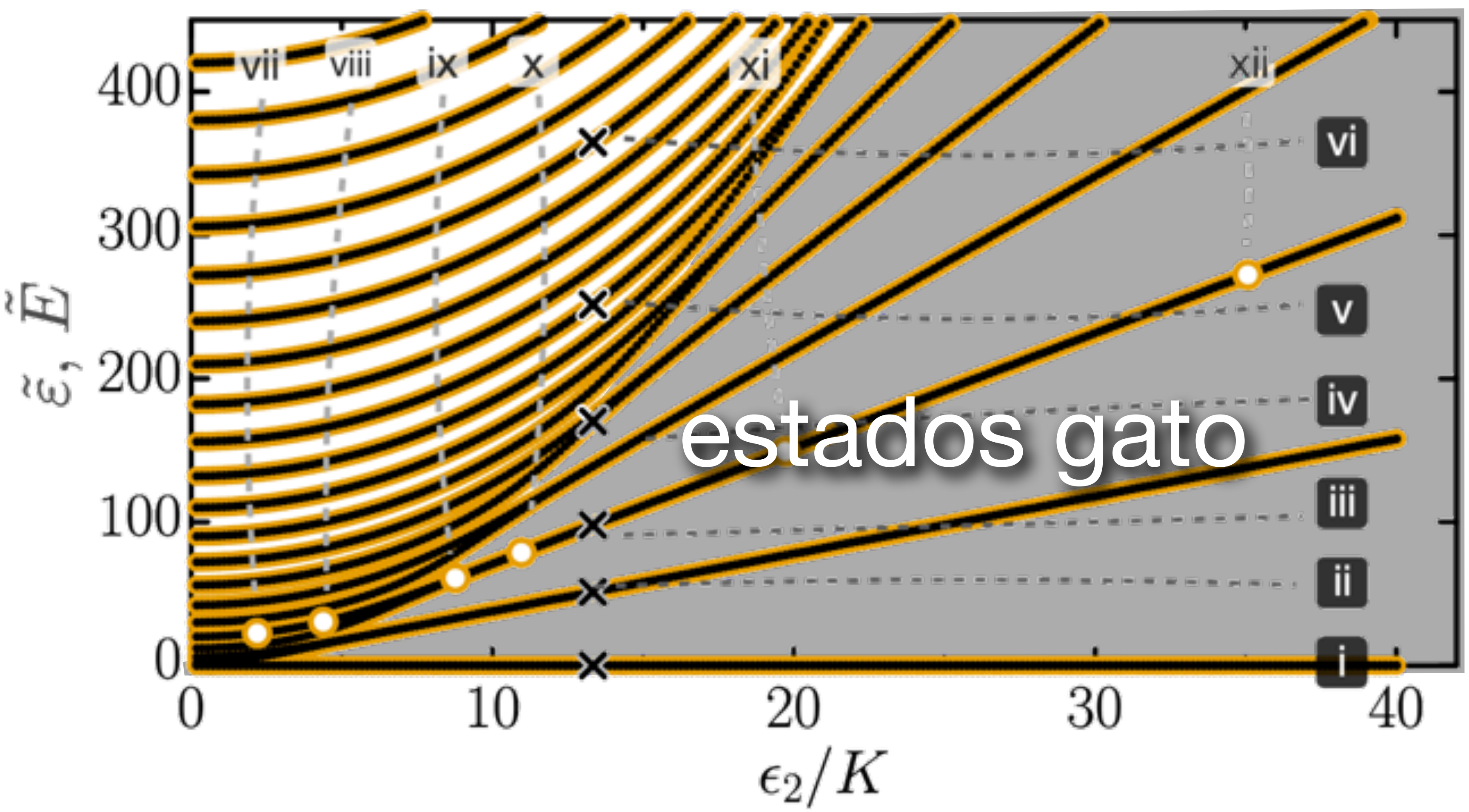


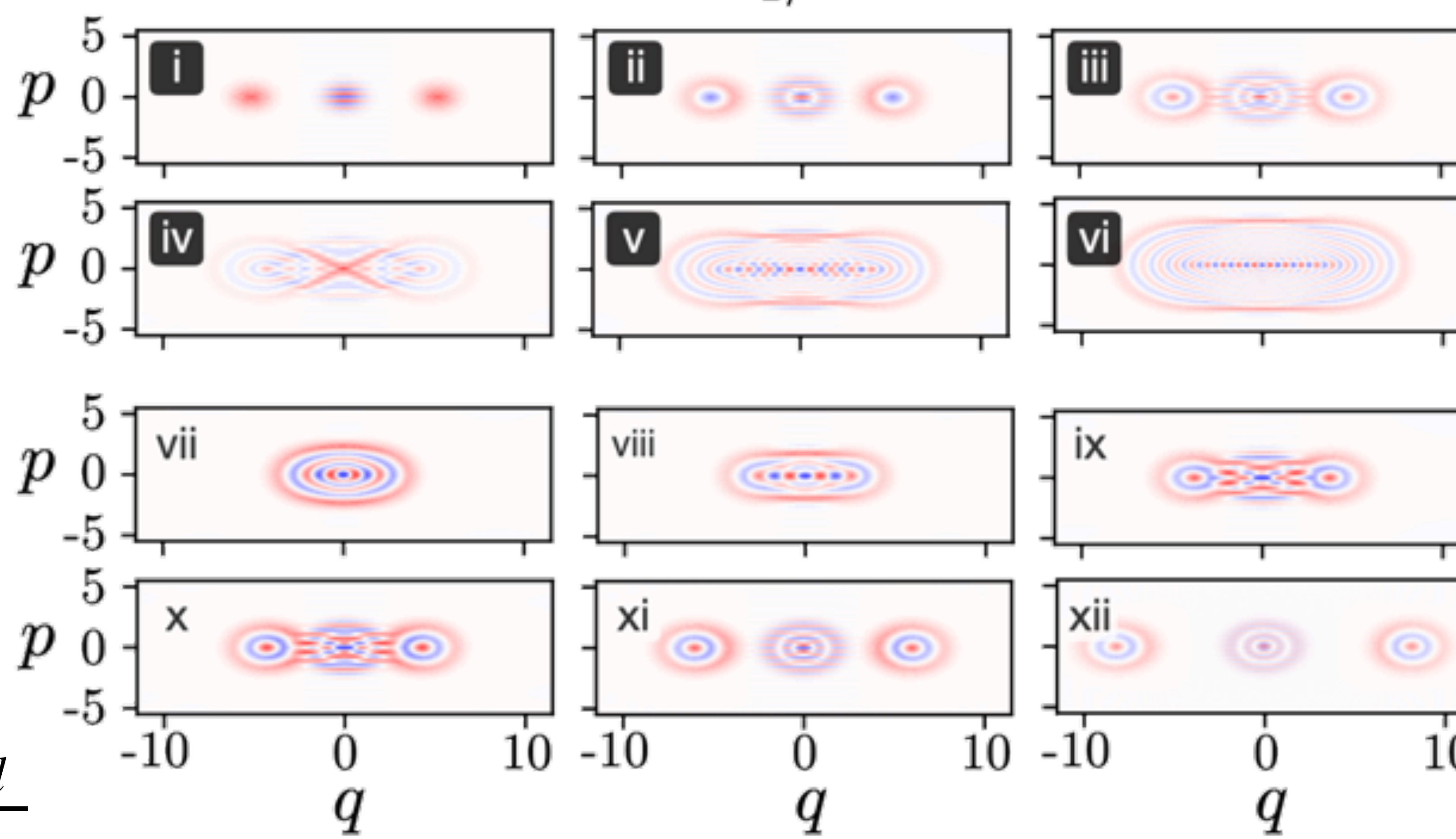
$$K \approx -\frac{3g_4}{2} + \frac{10g_3^2}{3\omega_o} \qquad \epsilon_2 \approx g_3\frac{\Omega_d}{3\omega_o}$$

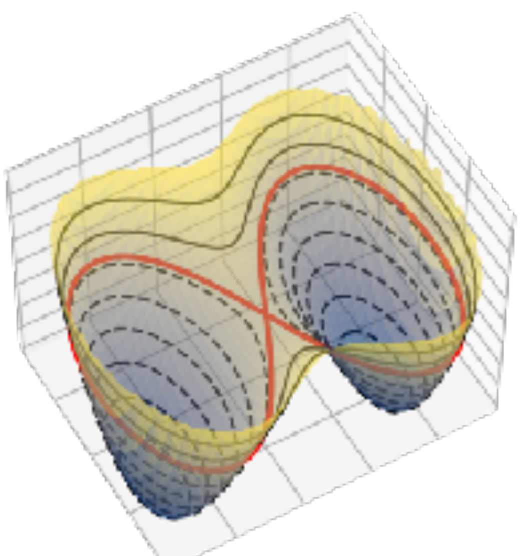
comparamos $\mathscr{H}(t)$ con H_{eff}

$$\tilde{E} = (E - E_0)/K$$

$$\tilde{\varepsilon} = [(\varepsilon - \varepsilon_0) \mod (\omega_d/2)]$$



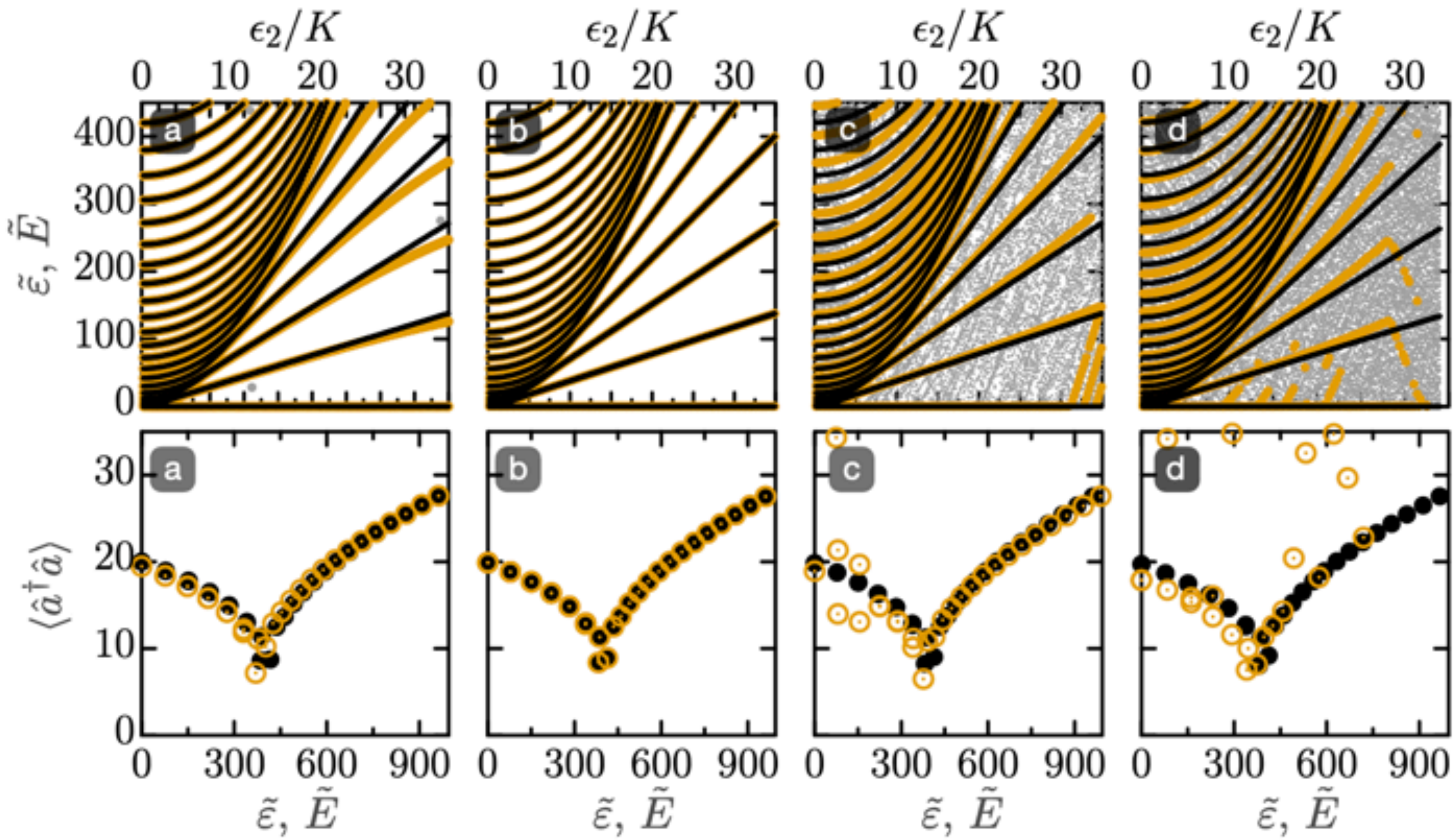




$K \approx -\frac{3g_4}{2} + \frac{10g_3^2}{3\omega_o}$

$$\epsilon_2 \approx g_3 \frac{\Omega_d}{3\omega_o}$$

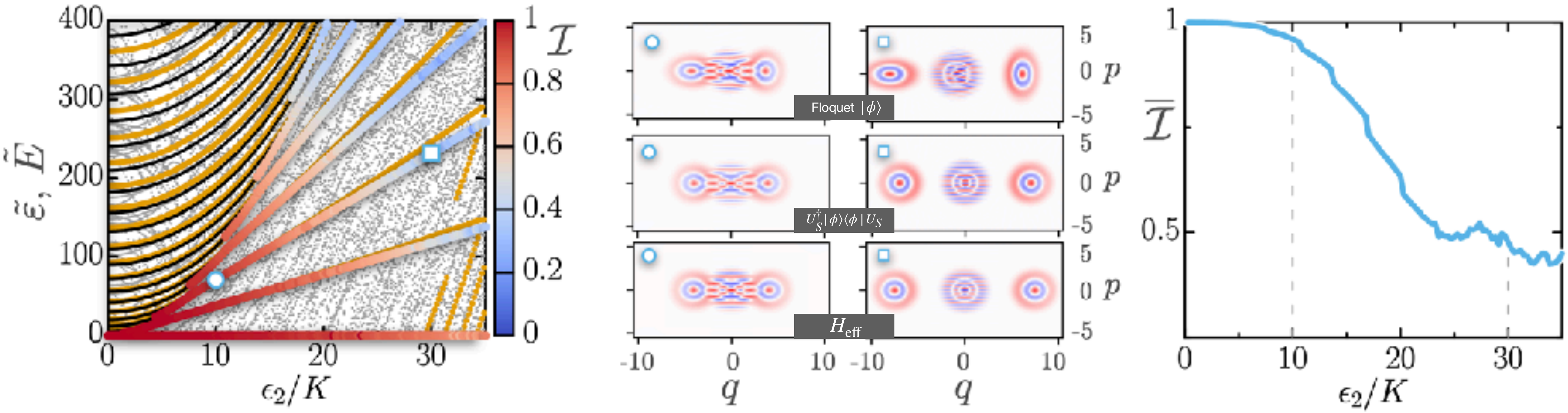
comparamos $\mathscr{H}(t)$ con H_{eff}



(g_3, g_4) are $(2\times10^{-5}, 8\times10^{-6})$ for (a); $(0.00075, 1.27\times10^{-7})$ for (b); $(0.015, 10^{-7})$ for (c); and $(0.02, 10^{-7})$ for (d). Basis size is $N = 200$

$\varepsilon_2/K = 20$

comparamos $\mathscr{H}(t)$ con H_{eff}



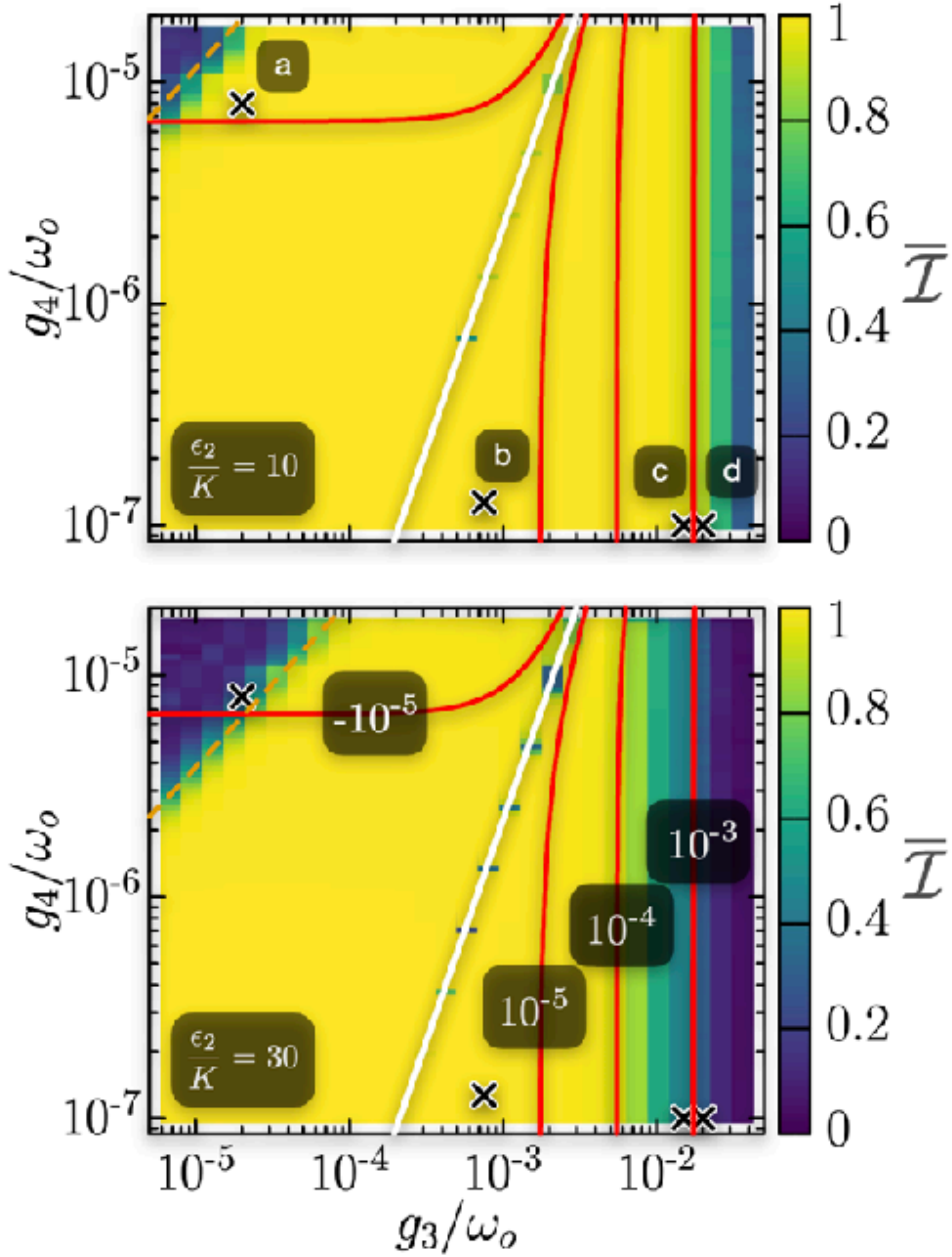
$$\mathcal{I}_k = \sum_j |\langle\phi_j|\hat{U}_S|E_k\rangle|^4.$$

IPR en la base de Floquet

$$\overline{\mathcal{I}} = \frac{1}{n_b}\sum_{k=1}^{n_b}\mathcal{I}_k,$$

$$n_b \approx 2\frac{\epsilon_2}{\pi K}$$

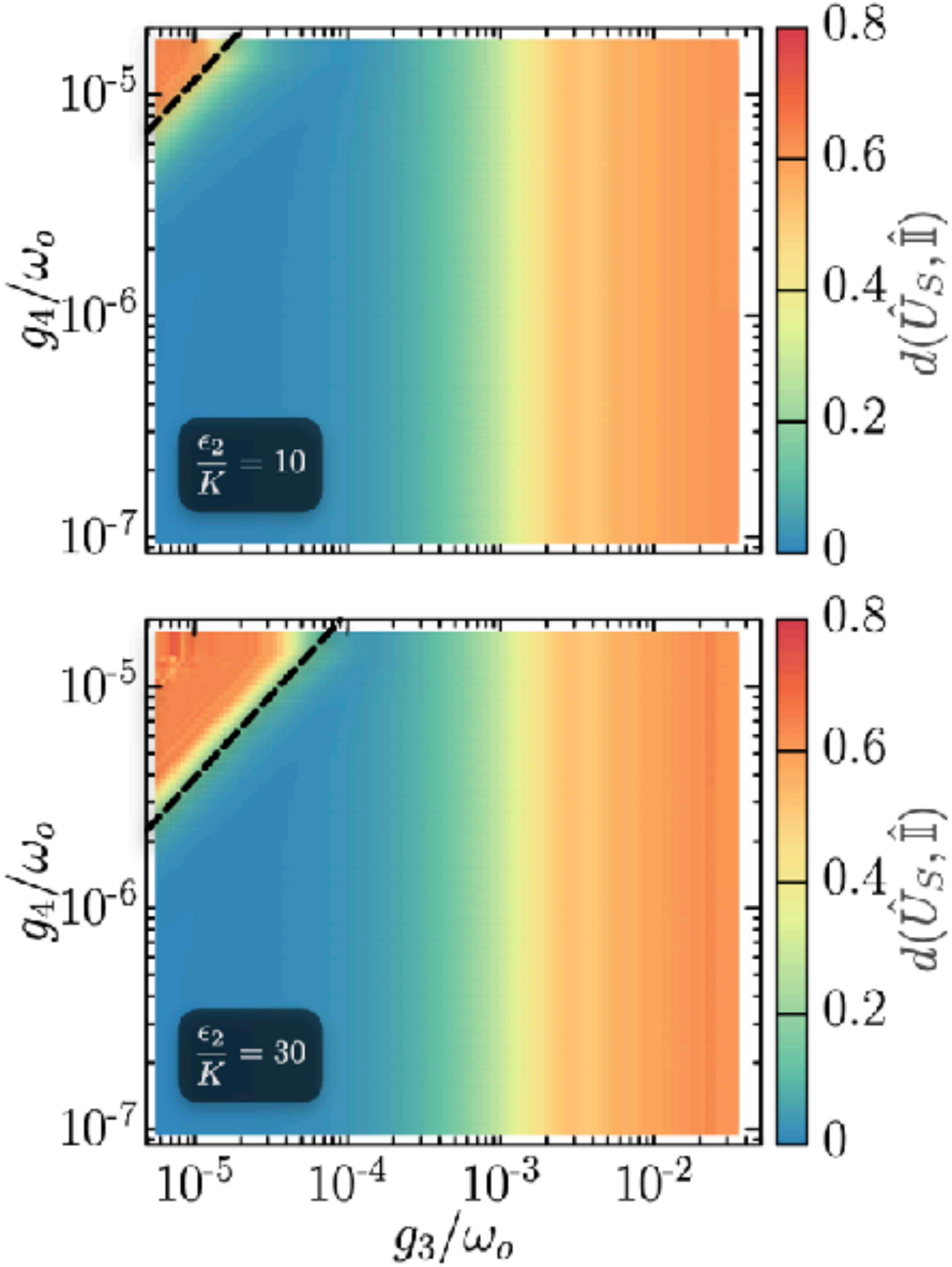
comparamos $\mathscr{H}(t)$ con H_{eff}



comparamos $\mathscr{H}(t)$ con H_{eff}

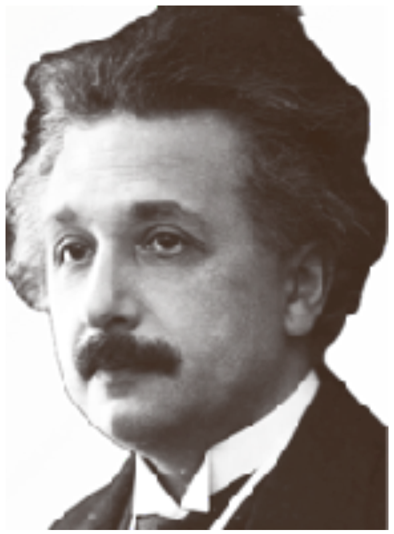
$$\hat{U}(T) = e^{i\hat{S}(T)}e^{-i\hat{H}_{\text{eff}}T}\underbrace{e^{-i\hat{S}(0)}}_{}.$$

$\hat{U}_S$



"If there exist fewer than d [constants of motion], as is the case, for example, according to Poincaré in the three-body problem, then the p_i are not expressible by the q_i and the quantum condition of Sommerfeld–Epstein fails also in the slightly generalized form that has been given here."

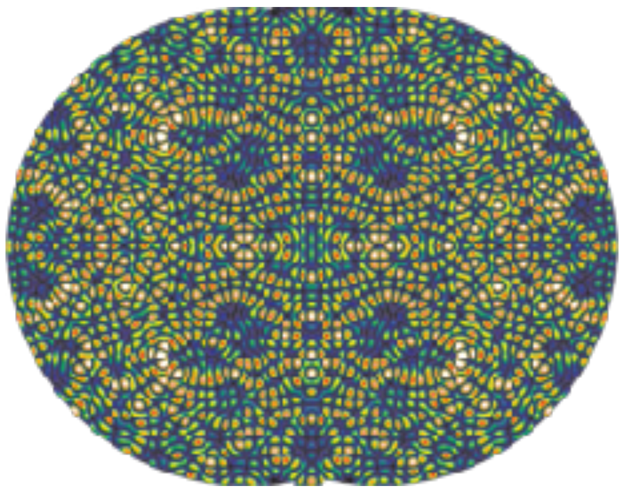
— Einstein, DPG meeting 1917



"Einstein's Unknown Insight and the Problem of Quantizing Chaos" D. Stone, Physics Today (2005)

caos clásico

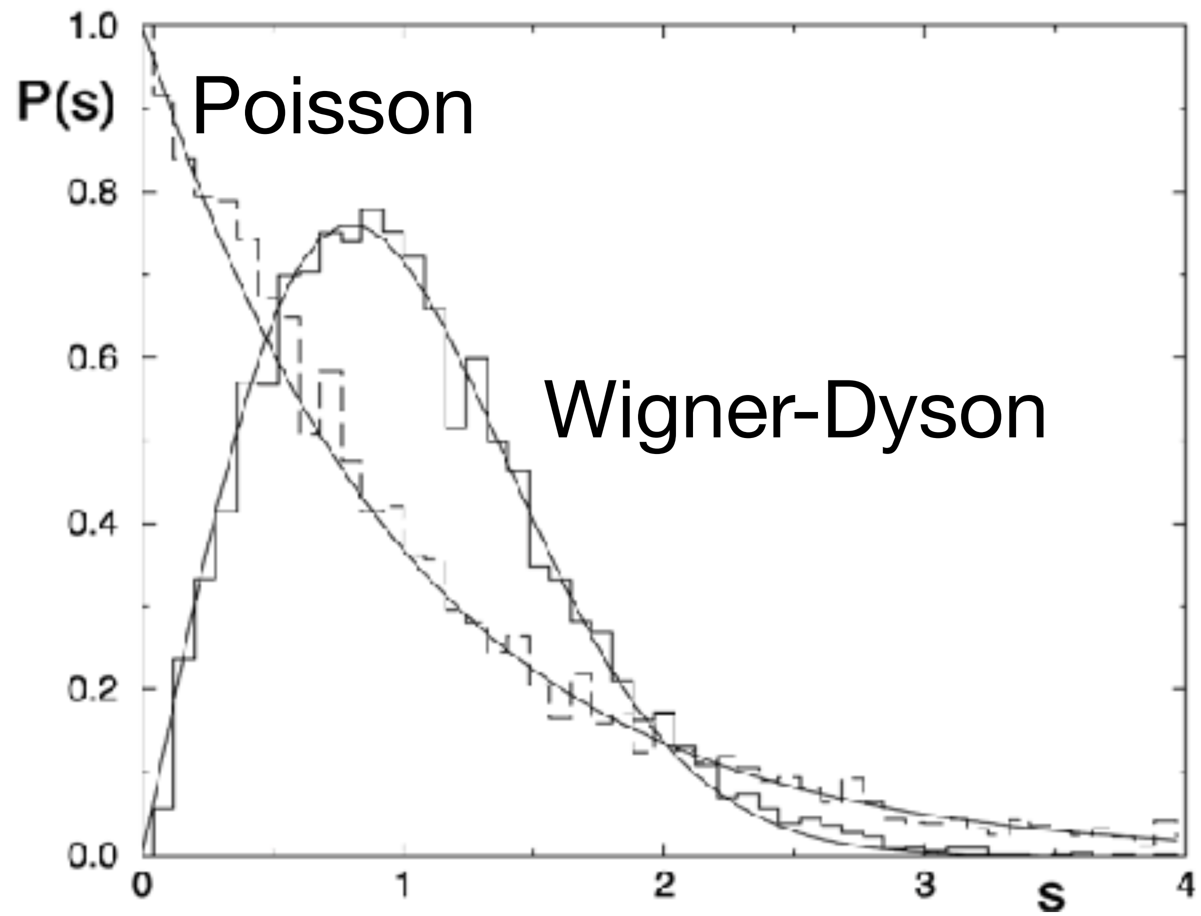
"caos cuántico"
quantized, classically chaotic



Caos cuántico

estadística
espectral

Bohigas, Gianoni, Schmit(1984)



Physical Review E

Quantum chaos border for quantum computing

B. Georgeot and D. L. Shepelyansky

Phys. Rev. E **62**, 3504 – **Published 1 September, 2000**

DOI: https://doi.org/10.1103/PhysRevE.62.3504

Abstract

We study a generic model of quantum computer, composed of many qubits coupled by short-range interaction. Above a critical interqubit coupling strength, quantum chaos sets in, leading to quantum ergodicity of the computer eigenstates. In this regime the noninteracting qubit structure disappears, the eigenstates become complex, and the operability of the computer is destroyed. Despite the fact that the spacing between multiqubit states drops exponentially with the number of qubits *n*, we show that the quantum chaos border decreases only linearly with *n*. This opens a broad parameter region where the efficient operation of a quantum computer remains possible.

Caos cuántico

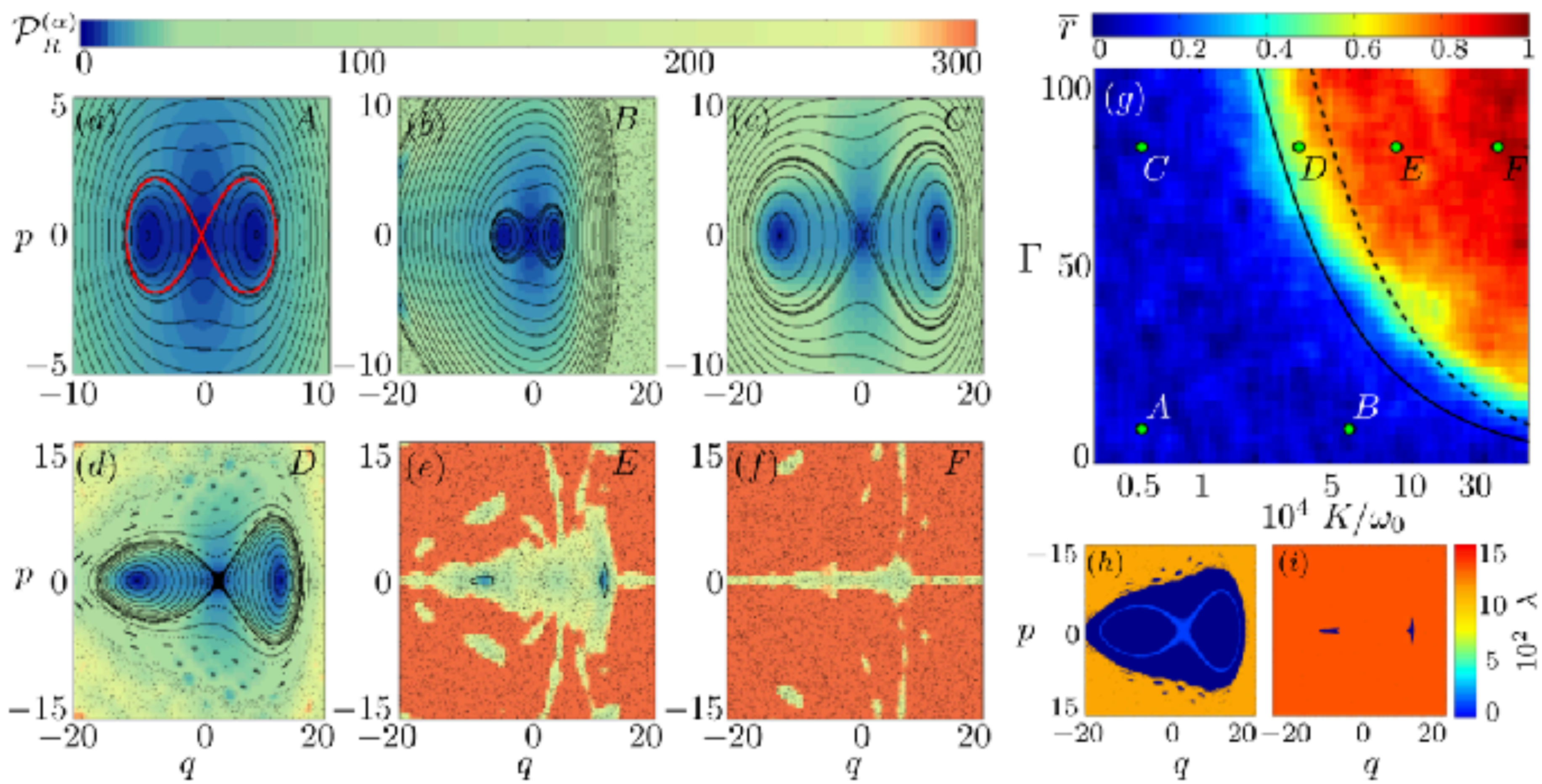
spacing ratios $r_n = \frac{s_n}{s_{n-1}}.$ $\tilde{r}_n = \frac{\min(s_n, s_{n-1})}{\max(s_n, s_{n-1})} = \min\left(r_n, \frac{1}{r_n}\right),$

Atas, Bogomolny, Giraud, & Roux
PRL 110, 084101 (2013)

$$< r >_P \approx 0.38$$

$$< r >_W D \approx 0.53$$

$$\bar{r} = \frac{< r > - < r >_P}{< r >_{WD} - < r >_P}$$



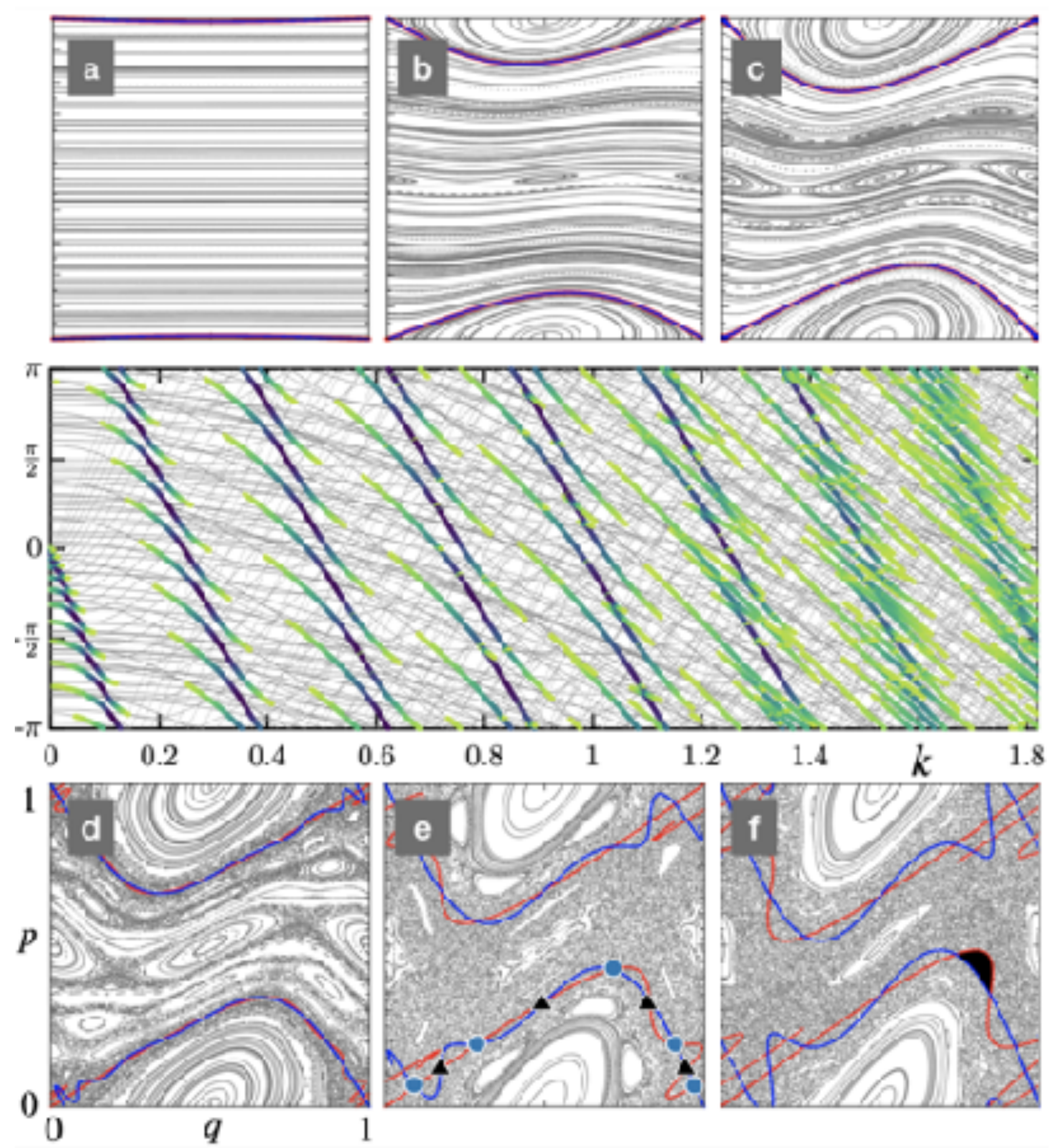
Quantum Sci. Technol. **10** (2025) 015039

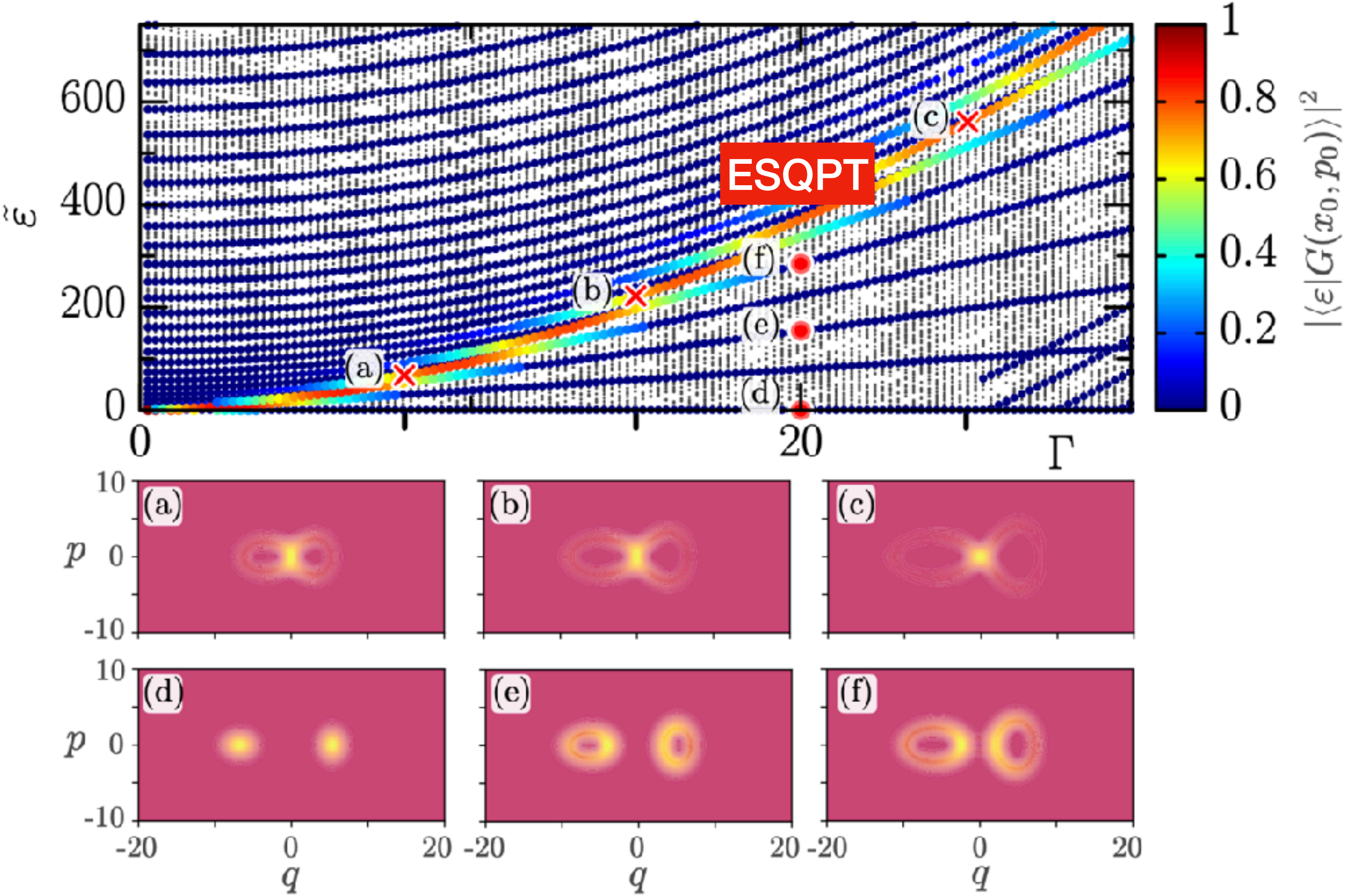
PHYSICAL REVIEW E **104**, L062202 (2021)

Letter

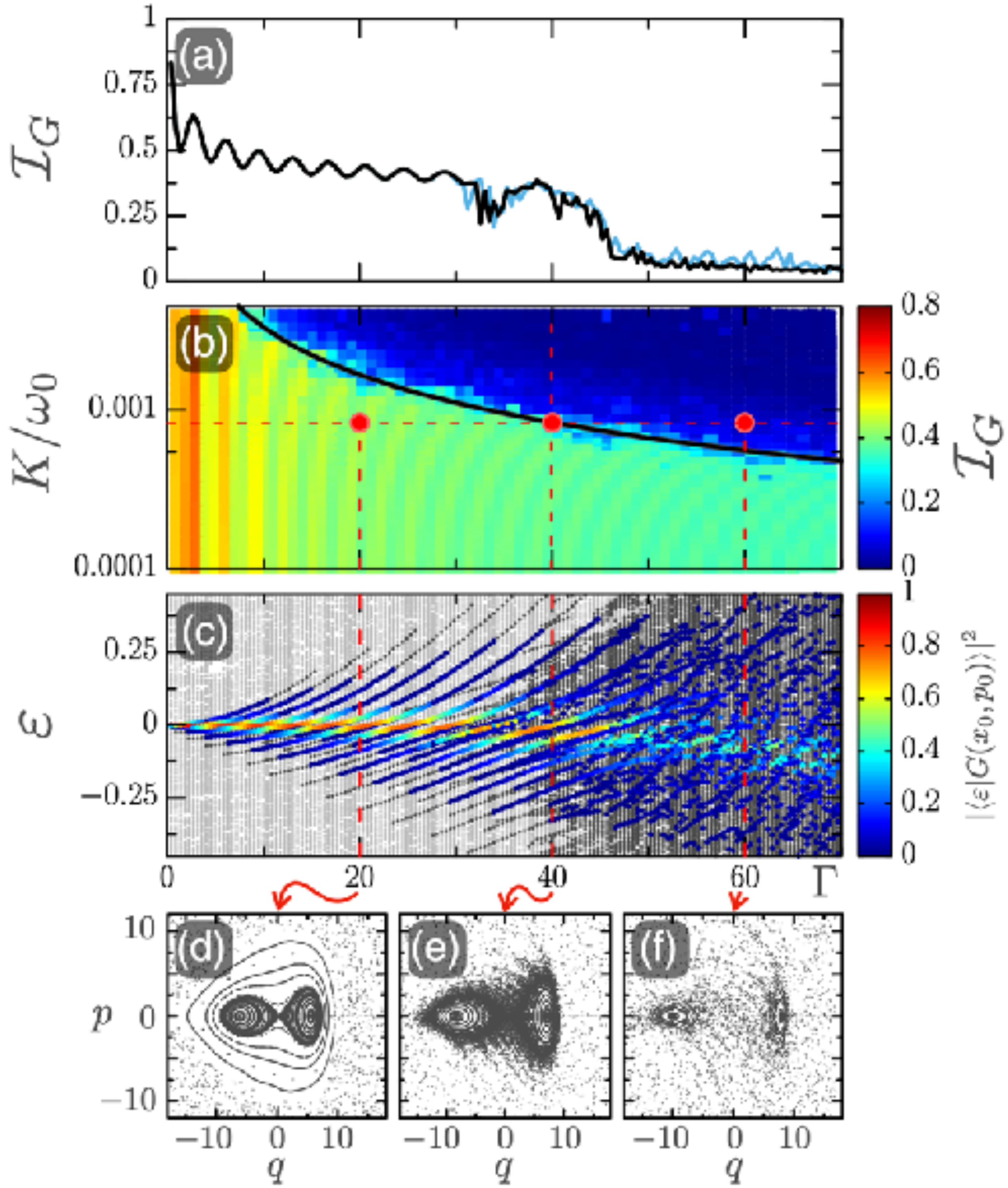
Impact of chaos on precursors of quantum criticality

Ignacio García-Mata,[1] Eduardo Vergini,[2,3] and Diego A. Wisniacki[4]





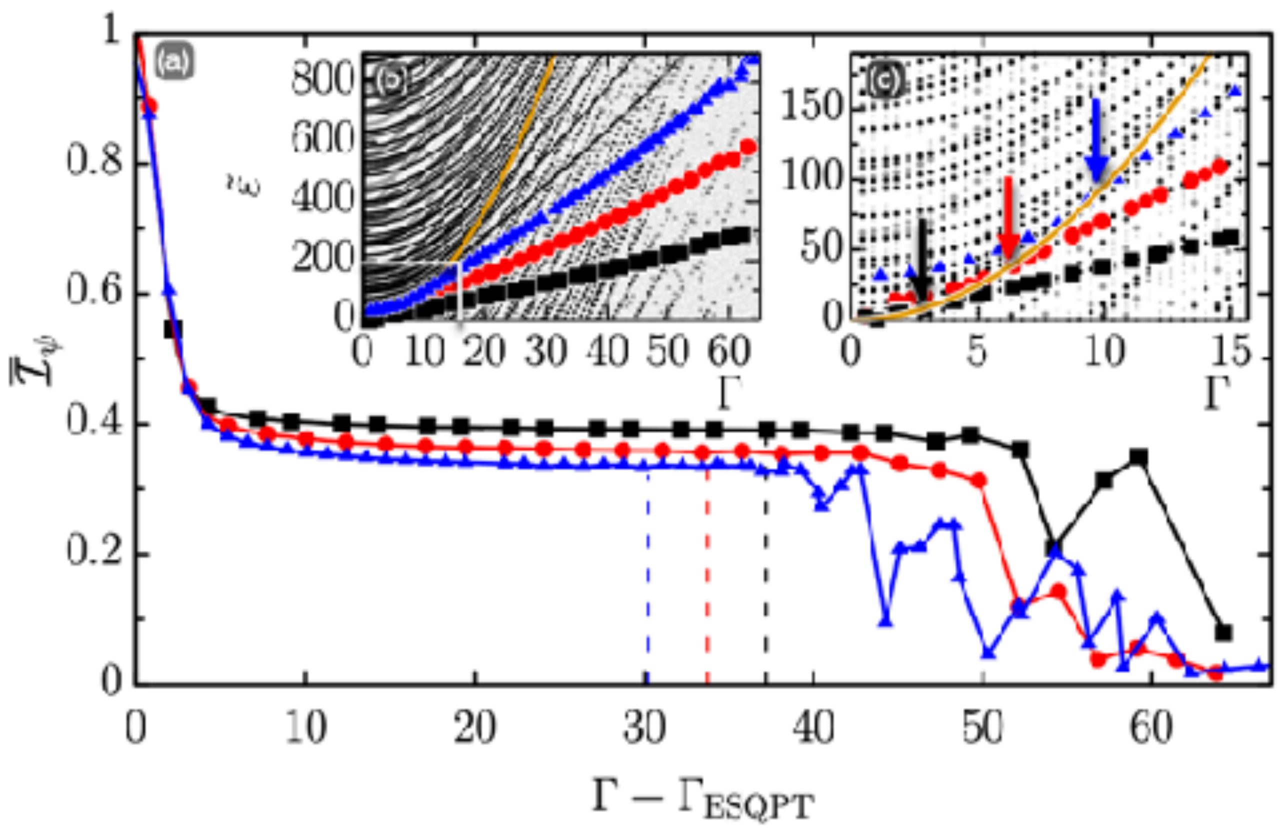
ESQPT
600
400
200
0
$\tilde{\varepsilon}$
0
20
Γ
1
0.8
0.6
0.4
0.2
0
$|\langle\varepsilon|G(x_0,p_0)\rangle|^2$
(a)
(b)
(c)
(d)
(e)
(f)
10
0
-10
p
-20
0
20
q

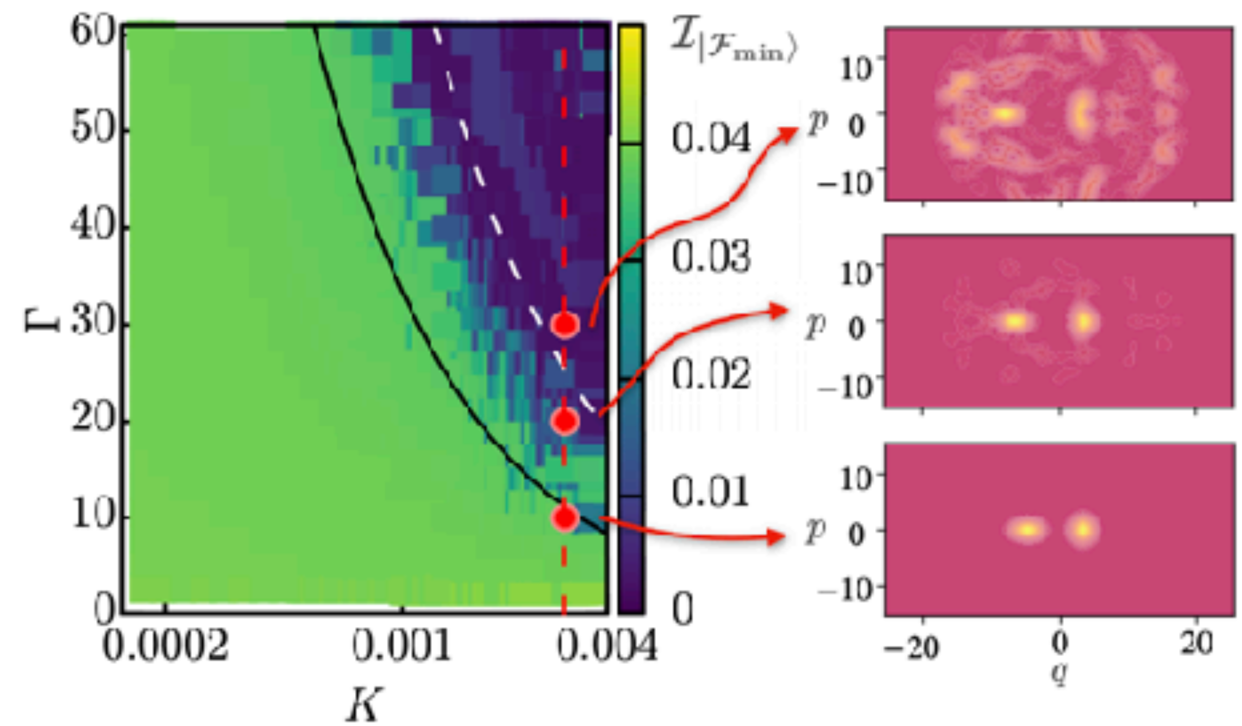


(a)
(b)
(c)
(d)
(e)
(f)
$\mathcal{I}_G$
K/ω_0
ε
Γ
$|\langle\varepsilon|G(x_0,p_0)\rangle|^2$
p
q

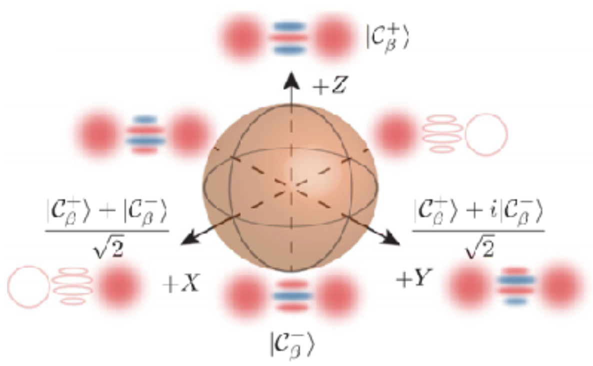
$$\mathcal{I}_\psi = \int Q^2(q,p)dq, dp$$

$$Q_\psi(q,p) = \frac{|\langle \alpha|\psi\rangle|^2}{\pi}$$ Husimi

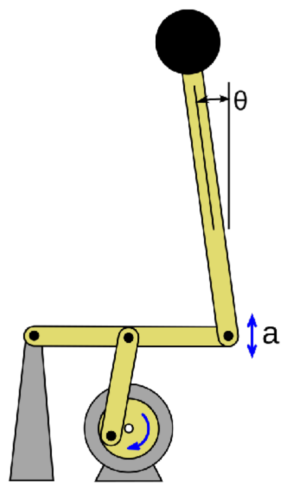




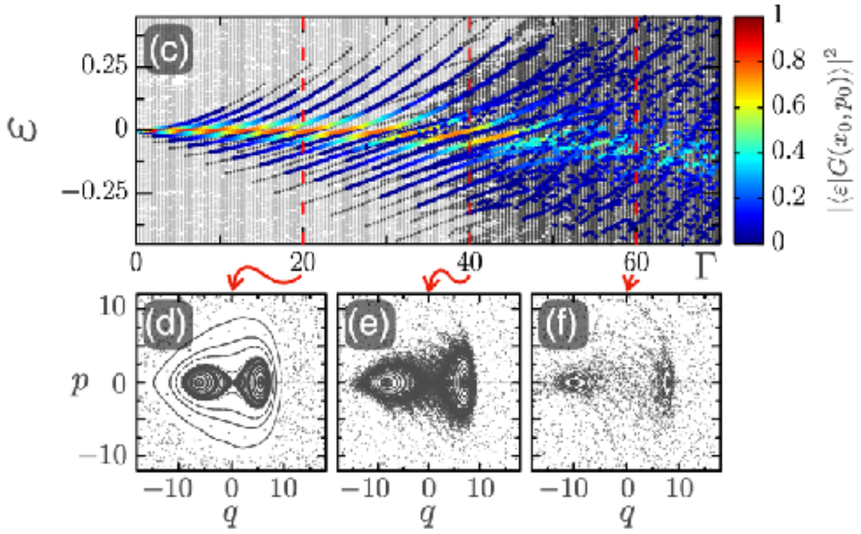
Cat qubit



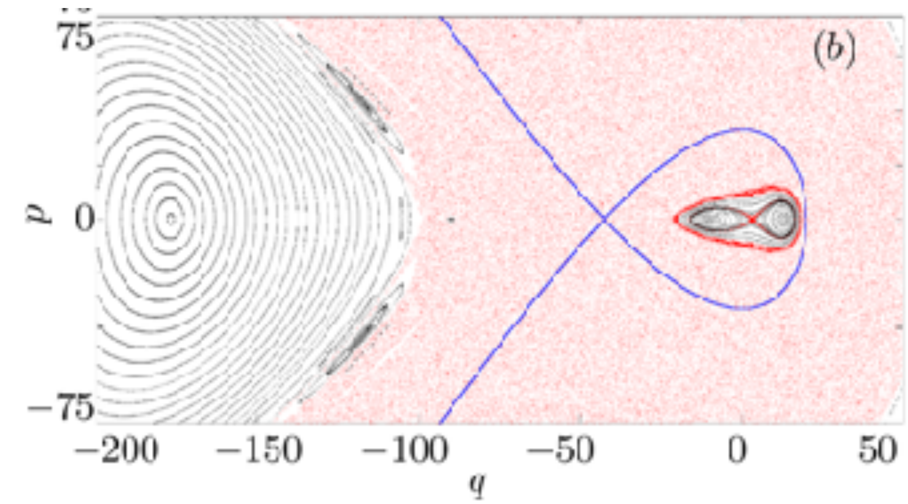
Hamiltoniano efectivo



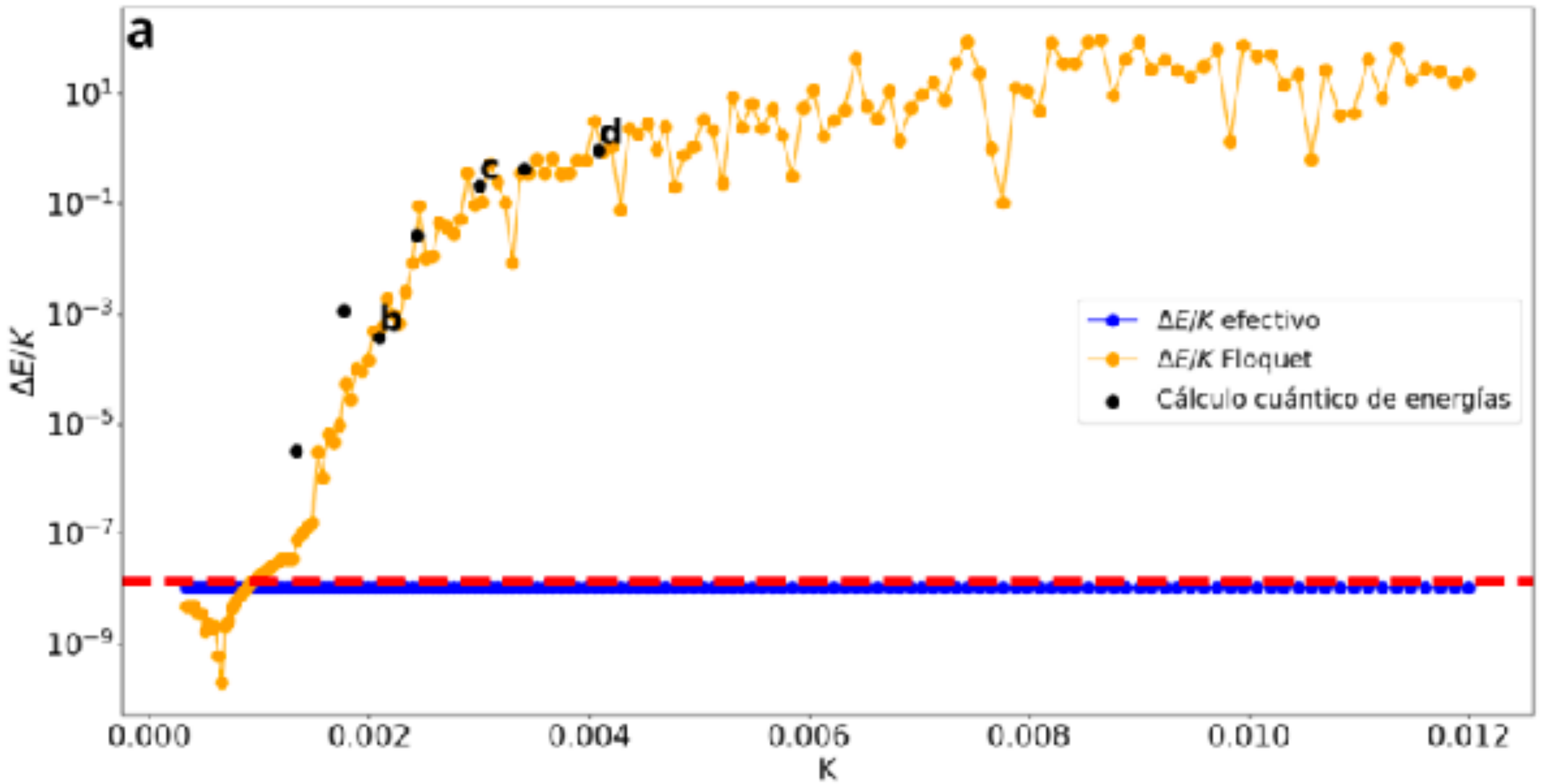
Caos

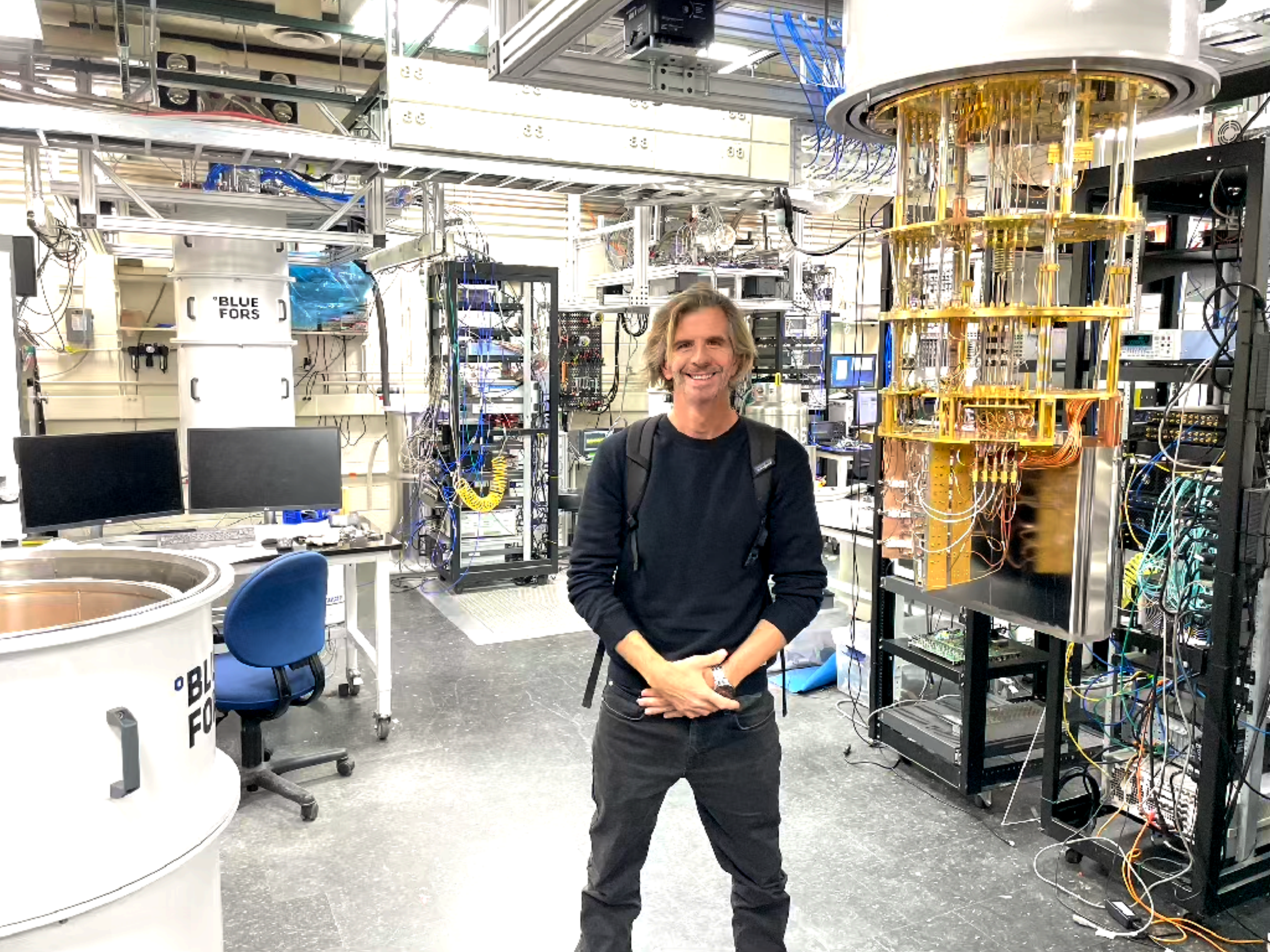


próximo



evidencia de chaos assisted tunneling





BLUE
FORS

Effective versus Floquet theory for the Kerr parametric oscillator

https://doi.org/10.22331/q-2024-03-25-1298

Quantum 8, 1298 (2024).

Ignacio García-Mata[1], Rodrigo G. Cortiñas[2,3], Xu Xiao[2], Jorge Chávez-Carlos[4], Victor S. Batista[5,3], Lea F. Santos[4], and Diego A. Wisniacki[6]

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Quantum Science and Technology

Driving superconducting qubits into chaos

Jorge Chávez-Carlos[1,*], Miguel A Prado Reynoso[1], Rodrigo G Cortiñas[2], Ignacio García-Mata[3], Victor S Batista[4], Francisco Pérez-Bernal[5,6], Diego A Wisniacki[7] and Lea F Santos[1]

PHYSICAL REVIEW A **111**, L031502 (2025)

Letter

Impact of chaos on the excited-state quantum phase transition of the Kerr parametric oscillator

Ignacio García-Mata,[1] Miguel A. Prado Reynoso,[2] Rodrigo G. Cortiñas,[3,4] Jorge Chávez-Carlos,[2] Victor S. Batista,[4,5] Lea F. Santos,[2] and Diego A. Wisniacki[6]