Quantum thermodynamics: 1

Mauro Paternostro
Queen's University Belfast

Advanced School on Quantum Science and Quantum Technologies
(ICTP, Trieste, 4 September 2017)

Non-equilibrium thermodynamics of quantum processes: 1

or an invitation to study stochastic thermodynamics of quantum processes

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Queen's University Belfast

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Queen's University Belfast

Joseph Larmor

John Stuart Bell

David Bates, FRS

Harrie Massey

On the shoulders of Belfast's giants

John Stewart Bell in Erice

"There is no new Physics without new projects"

4 November:

John Bell day

On the shoulders of Belfast's giants

Lord Kelvin

Born in Belfast in 1824

Belfast, Botanic Gardens

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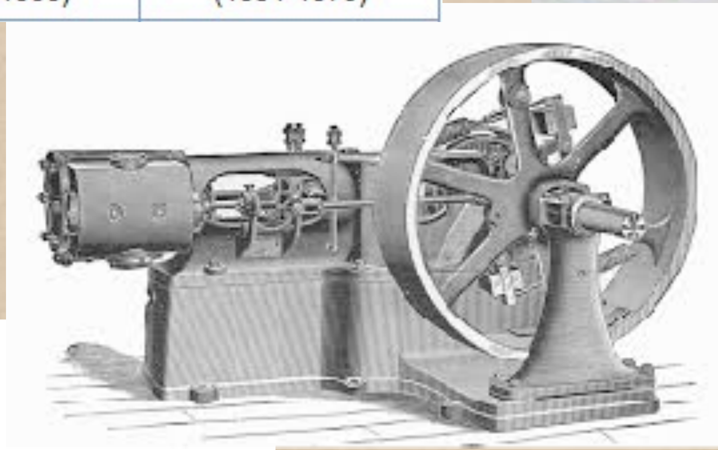
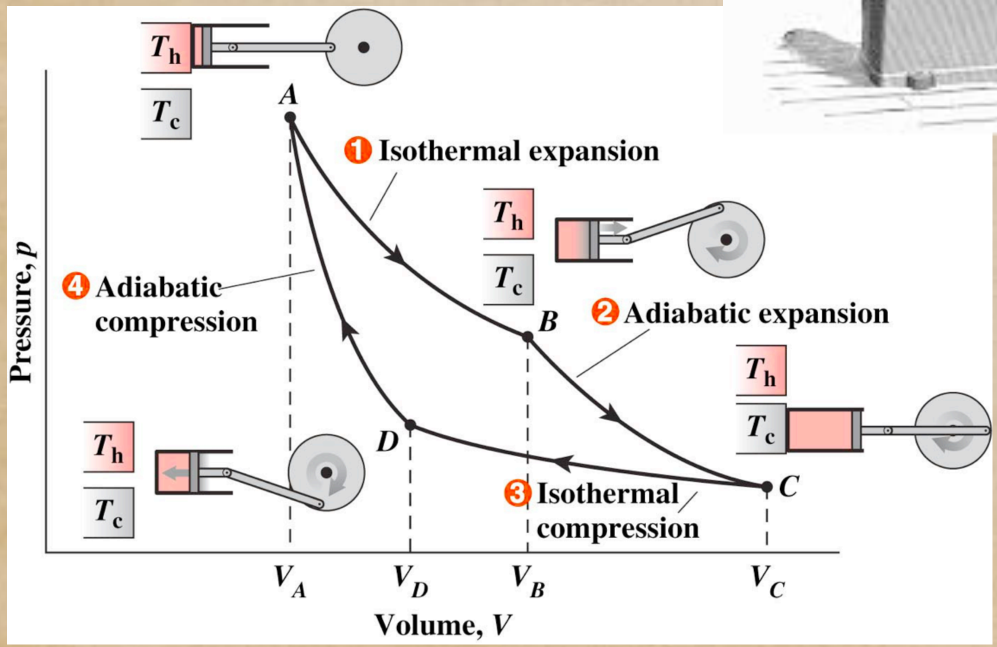
Thermodynamics...

École Polytechnique	Glasgow school	Berlin school	Edinburgh school
			
Sadi Carnot (1796-1832)	William Thomson (1824-1907)	Rudolf Clausius (1822-1888)	James Maxwell (1831-1879)





Vienna school	Gibbsian school	Dresden school	Dutch school
			
Ludwig Boltzmann (1844-1906)	Willard Gibbs (1839-1903)	Gustav Zeuner (1828-1907)	Johannes der Waals (1837-1923)

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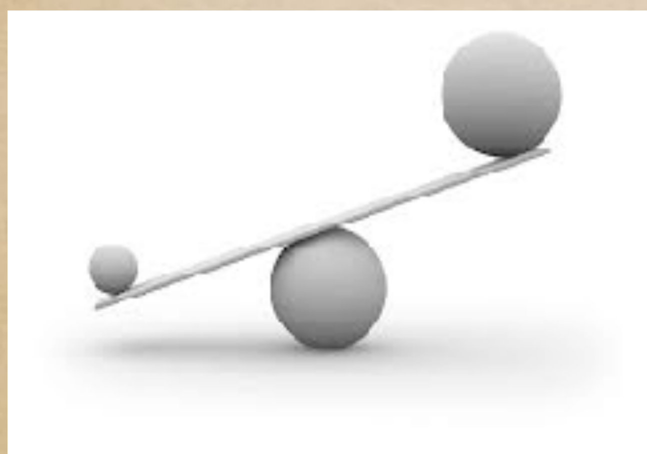
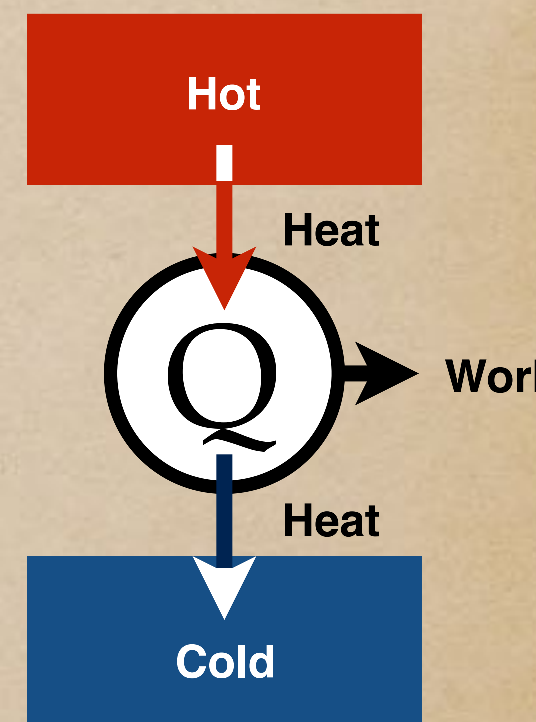
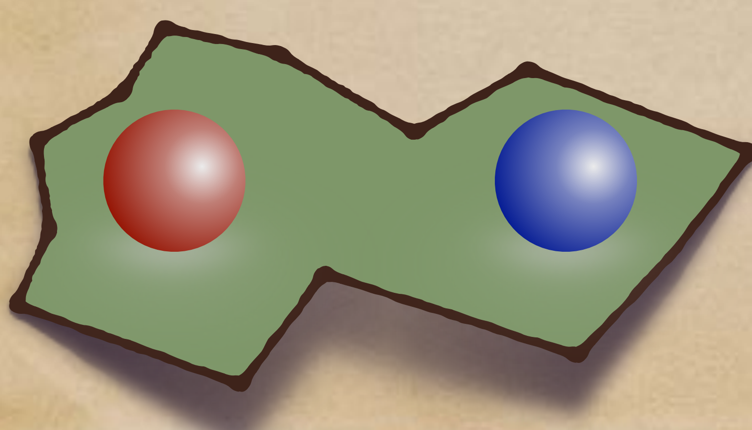
...and (one of) its evolution(s)



Framework for non-equilibrium quantum processes



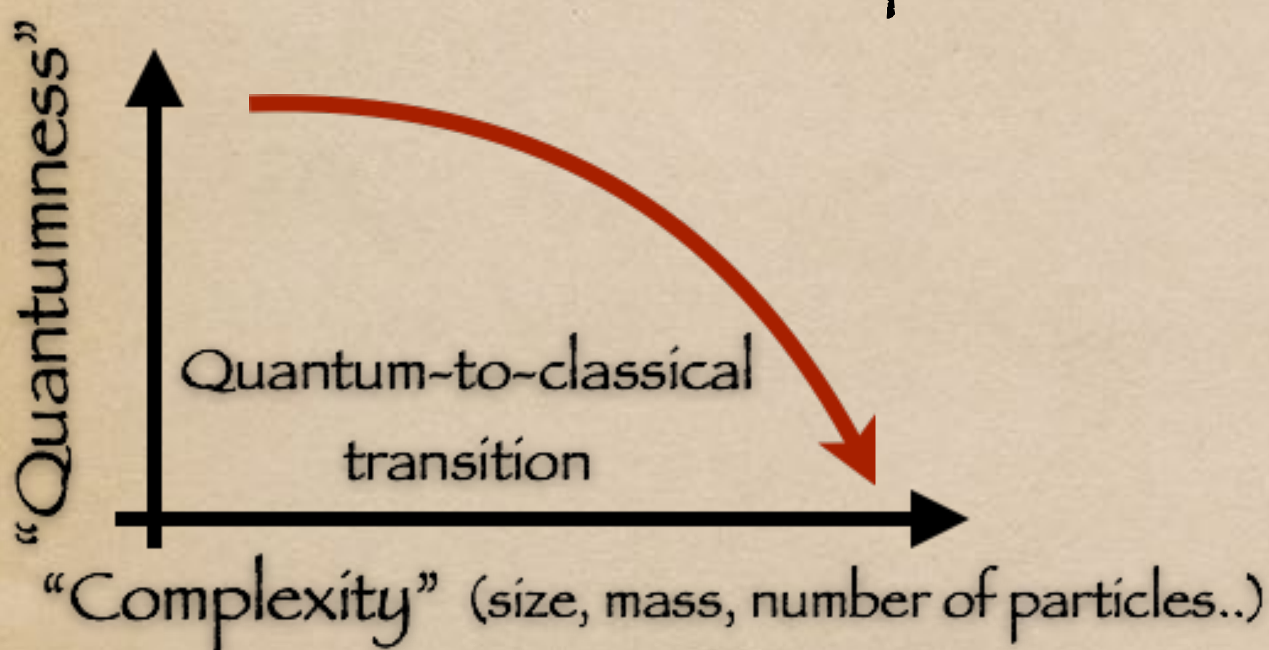
Re-definition of work, heat, entropy... in non-equilibrium quantum contexts



Thermodynamics-inspired arena for the study/use of quantum resources

My take of it

Fundamental viewpoint



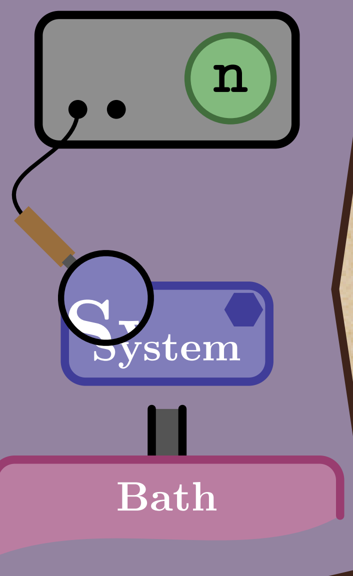
Thermodynamics is a theory of inherently complex systems

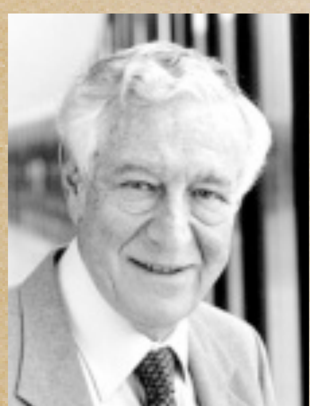
Technological viewpoint

Using quantumness to optimise machine performance

Content & structure

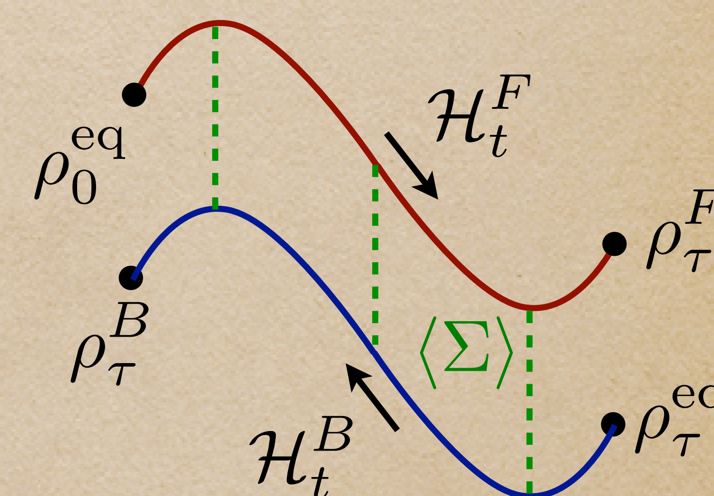
Non-equilibrium definition of thermodynamic work: fluctuation theorems





Landauer principle & quantum (open-system) dynamics

Irreversibility & entropy production in closed q-systems



Quantum correlations, coherences and thermodynamics

Work and quantum

Fluctuation theorems: Work is not an observable

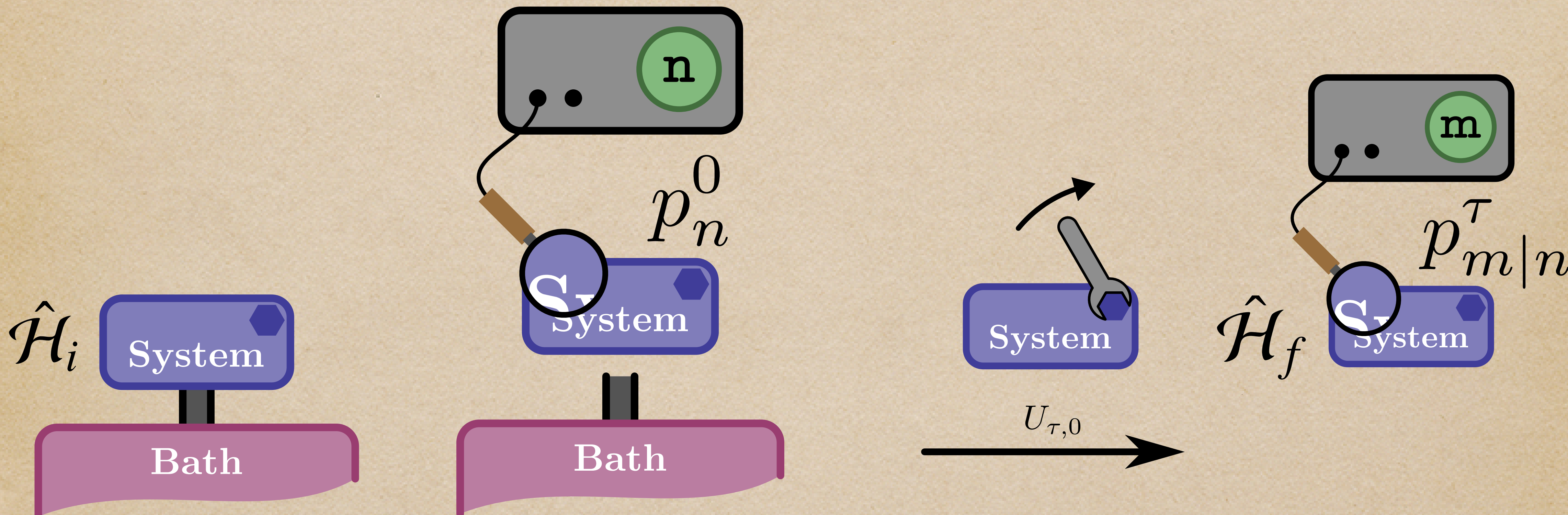
Peter Talkner, Eric Lutz, Peter Hänggi
Institute of Physics, University of Augsburg, D-86135 Augsburg, Germany
(Dated: February 6, 2008)

The characteristic function of the work performed by an external time-dependent force on a Hamiltonian quantum system is identified with the *time-ordered correlation function* of the exponentiated system's Hamiltonian. A similar expression is obtained for the averaged exponential work which is related to the free energy difference of equilibrium systems by the Jarzynski work theorem.

Talkner, Lutz, and Haenggi, Phys. Rev. E 75, 050102 (2007)

Setting the context

In quantum contexts: work is not an observable



(a) $t < 0$ (b) $t = 0^+$ (c) $0 < t < \tau$ (d) $t = \tau$

Work Distribution
$$P_F(W) = \sum_{n,m} p_n^0 p^\tau_{m|n} \delta\left(W - (E'_m - E_n)\right)$$

P. Talkner, E. Lutz, and P. Haenggi, Phys. Rev. E 75, 050102 (2007)

Fluctuation theorems

Work Distribution

$$P_F(W) = \sum_{n,m} p_n^0 p_{m|n}^\tau \delta\left(W - (E'_m - E_n)\right)$$

Characteristic function of Work Distribution

$$\chi_F(u) = \int dW e^{\imath u W} P_F(W)$$

$$\chi_F(u) = \mathrm{Tr}\left[U^\dagger(\tau,0) e^{\imath u H(\lambda_\tau)} U(\tau,0) e^{-\imath u H(\lambda_0)} \rho_G(\lambda_0)\right]$$

$$\rho_G(\lambda_0) = \frac{e^{-\beta H(\lambda_0)}}{Z(\lambda_0)}$$

Fluctuation theorems

Work Distribution

$$P_F(W) = \sum_{n,m} p_n^0 p^\tau_{m|n} \delta\left(W - (E'_m - E_n)\right)$$

Characteristic function of Work Distribution

$$\chi_F(u) = \int dW \, e^{\imath u W} P_F(W)$$

Jarzynski equality $$\langle e^{-\beta W} \rangle = e^{-\beta \Delta F}$$

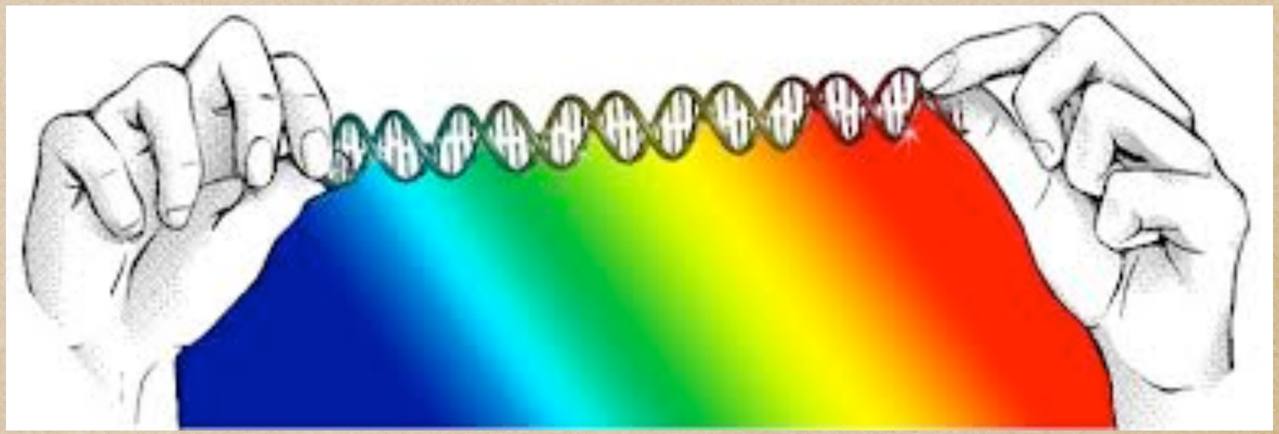
free-energy change

Jarzynski, PRL *78* 2690 (1997)

Tasaki-Crooks relation $$\frac{P_F(W)}{P_B(-W)} = e^{\beta(W - \Delta F)}$$

G. E. Crooks, PRE 60, 2721 (1999)
H. Tasaki, cond-mat/0009244 (2000)

Classical fluctuation relations



J. Liphardt, S. Dumont, S. B. Smith, I. Jr Tinoco, and C. Bustamante, Science, 296, 1832 (2002)

D. Collin, F. Ritort, C. Jarzynski, S. B. Smith, I. Tinoco Jr, and C. Bustamante, Nature 437, 231 (2005)

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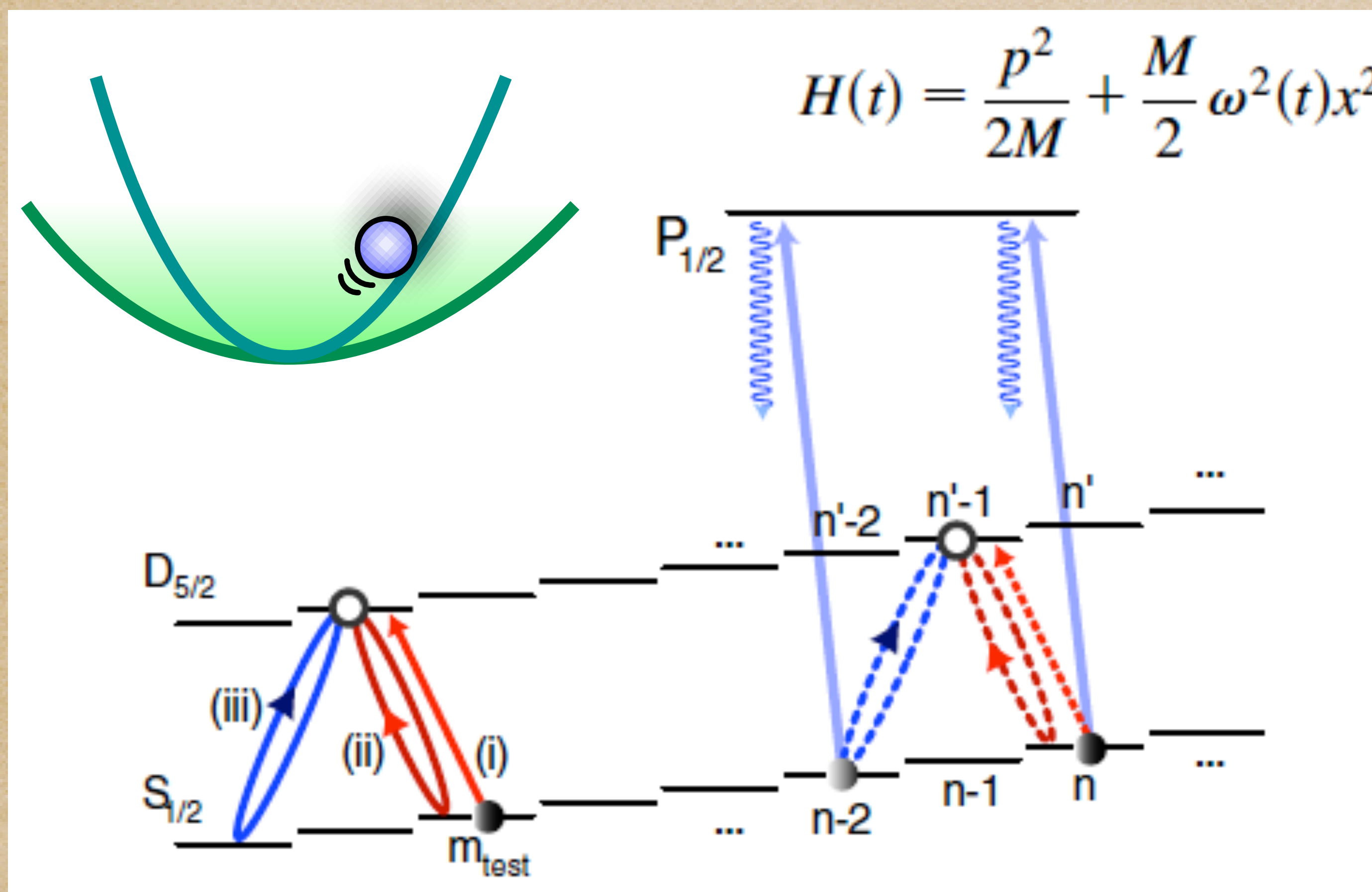
First proposal
(as far as I know)



Ingenious filtering scheme for energy measurements

PRL 101, 070403 (2008) PHYSICAL REVIEW LETTERS week ending 15 AUGUST 2008

Employing Trapped Cold Ions to Verify the Quantum Jarzynski Equality

Gerhard Huber and Ferdinand Schmidt-Kaler
Institut für Quanten-Informationsverarbeitung, Universität Ulm, Albert-Einstein-Allee 11, D-89069 Ulm, Germany

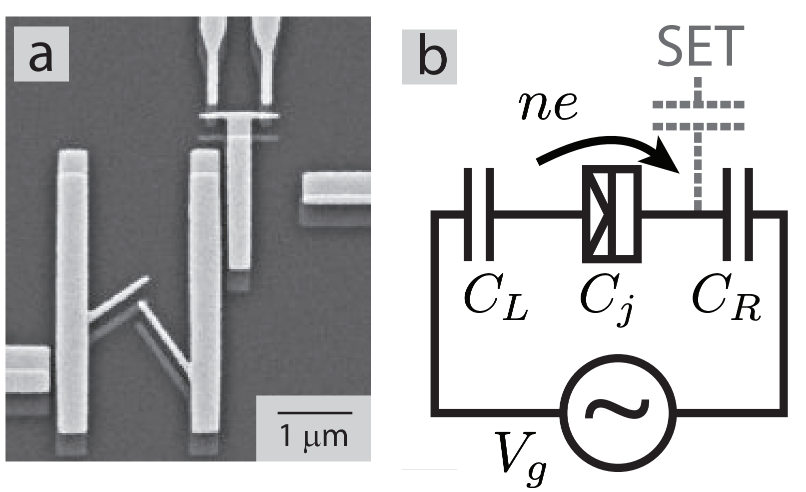
Sebastian Deffner and Eric Lutz
Department of Physics, University of Augsburg, D-86135 Augsburg, Germany
(Received 11 April 2008; revised manuscript received 28 May 2008; published 14 August 2008)

Other proposals and implementations

Crooks Relation in Optical Spectra: Universality in Work Distributions for Weak Local Quenches

M. Heyl
Department of Physics, Arnold Sommerfeld Center for Theoretical Physics, and Center for NanoScience, Ludwig-Maximilians-Universität München, Theresienstrasse 37, 80333 Munich, Germany

S. Kehrein
Department of Physics, Arnold Sommerfeld Center for Theoretical Physics, and Center for NanoScience, Ludwig-Maximilians-Universität München, Theresienstrasse 37, 80333 Munich, Germany and Georg-August-Universität Göttingen, Friedrich-Hund-Platz 1, 37077 Göttingen
(Received 28 June 2010; revised manuscript received 9 March 2012; published 7 May 2012)



PRL 109, 180601 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

Test of the Jarzynski and Crooks Fluctuation Relations in an Electronic System

O.-P. Saira,[1,2] Y. Yoon,[1] T. Tanttu,[2] M. Möttönen,[1,2] D. V. Averin,[3] and J. P. Pekola[1]
[1]*Low Temperature Laboratory (OVLL), Aalto University, P.O. Box 15100, FI-00076 Aalto, Finland*
[2]*Department of Applied Physics/COMP, Aalto University, P.O. Box 14100, FI-00076 Aalto, Finland*
Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, New York 11794-3800, USA
(Received 26 July 2012; published 31 October 2012)

Recent progress on micro- and nanometer-scale manipulation has opened the possibility to probe systems small enough that thermal fluctuations of energy and coordinate variables can be significant compared with their mean behavior. We present an experimental study of nonequilibrium thermodynamics in a classical two-state system, namely, a metallic single-electron box. We have measured with high statistical accuracy the distribution of dissipated energy as single electrons are transferred between the box electrodes. The obtained distributions obey Jarzynski and Crooks fluctuation relations. A comprehensive microscopic theory exists for the system, enabling the experimental distributions to be reproduced without fitting parameters.

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What's wrong with it

"The major obstacle for the experimental verification of the work fluctuation relation is posed by the necessity of performing quantum projective measurements of energy"

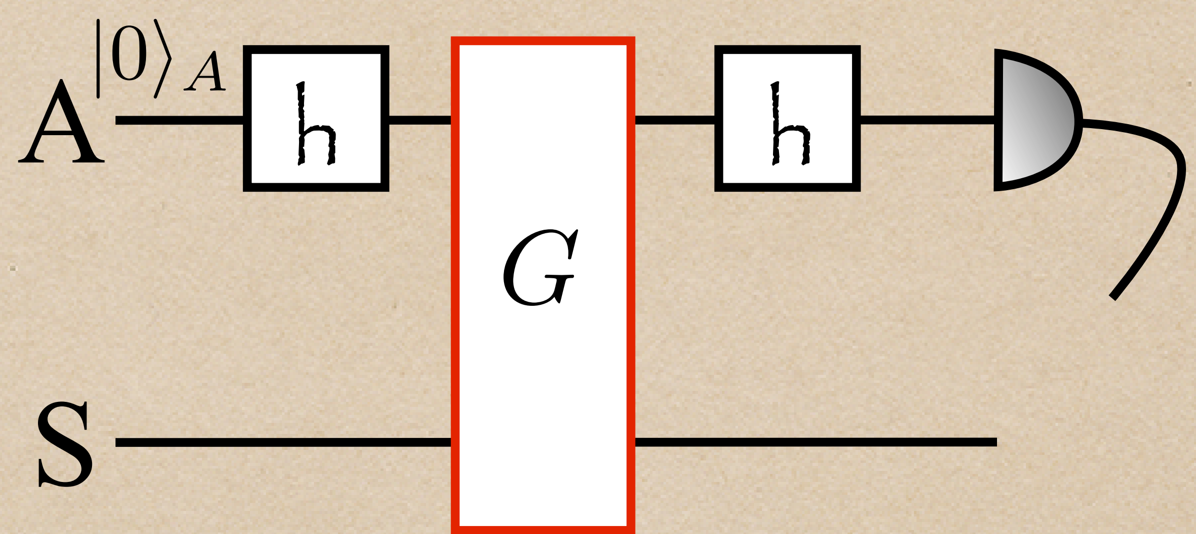
REVIEWS OF MODERN PHYSICS, VOLUME 83, JULY–SEPTEMBER 2011

Colloquium: Quantum fluctuation relations: Foundations and applications

Michele Campisi, Peter Hänggi, and Peter Talkner

Institute of Physics, University of Augsburg, Universitätsstrasse 1, D-86135 Augsburg, Germany

Measuring work



$$\hat{G}(u,\tau) = \hat{U}_\tau e^{-i\hat{\mathcal{H}}_i u} \otimes |0\rangle\langle 0|_A + e^{-i\hat{\mathcal{H}}_f u}\hat{U}_\tau \otimes |1\rangle\langle 1|_A$$

$$\rho_A = (I + \alpha\hat{\sigma}_z + \beta\sigma_y)/2$$

$\mathrm{Re}\chi(u,\tau)$ $\mathrm{Im}\chi(u,\tau)$

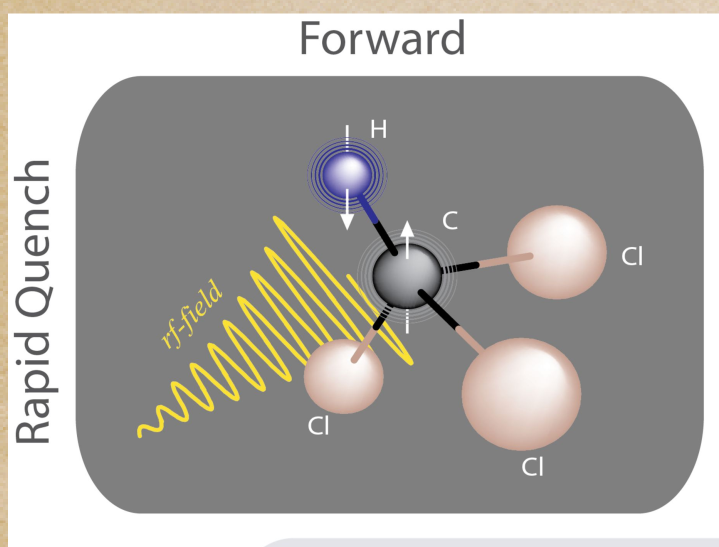
R. Dorner, et al., Phys. Rev.Lett. 110, 230601 (2013)
L. Mazzola, G. De Chiara, and MP, Phys. Rev. Lett. 110, 230602 (2013)
L. Mazzola, G. De Chiara, and MP, Int. J. Quant. Inf. (2014)

The experiment

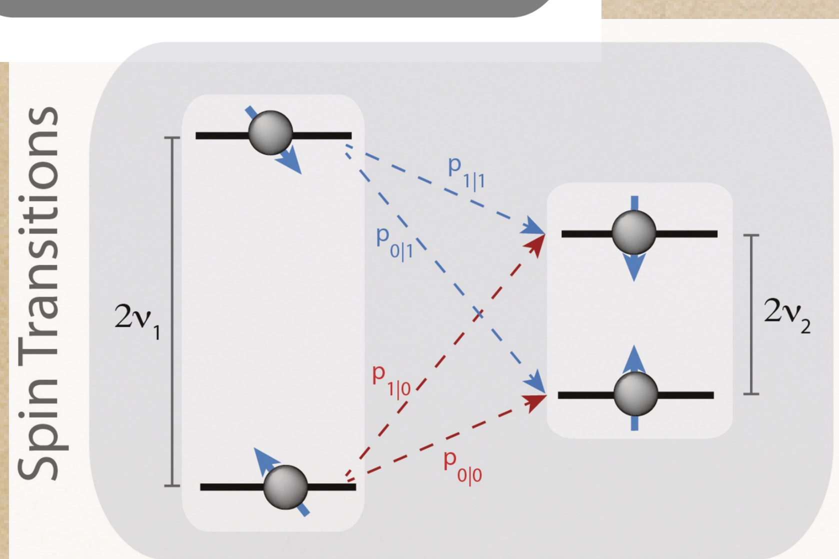
PRL **113,** 140601 (2014) PHYSICAL REVIEW LETTERS week ending 3 OCTOBER 2014

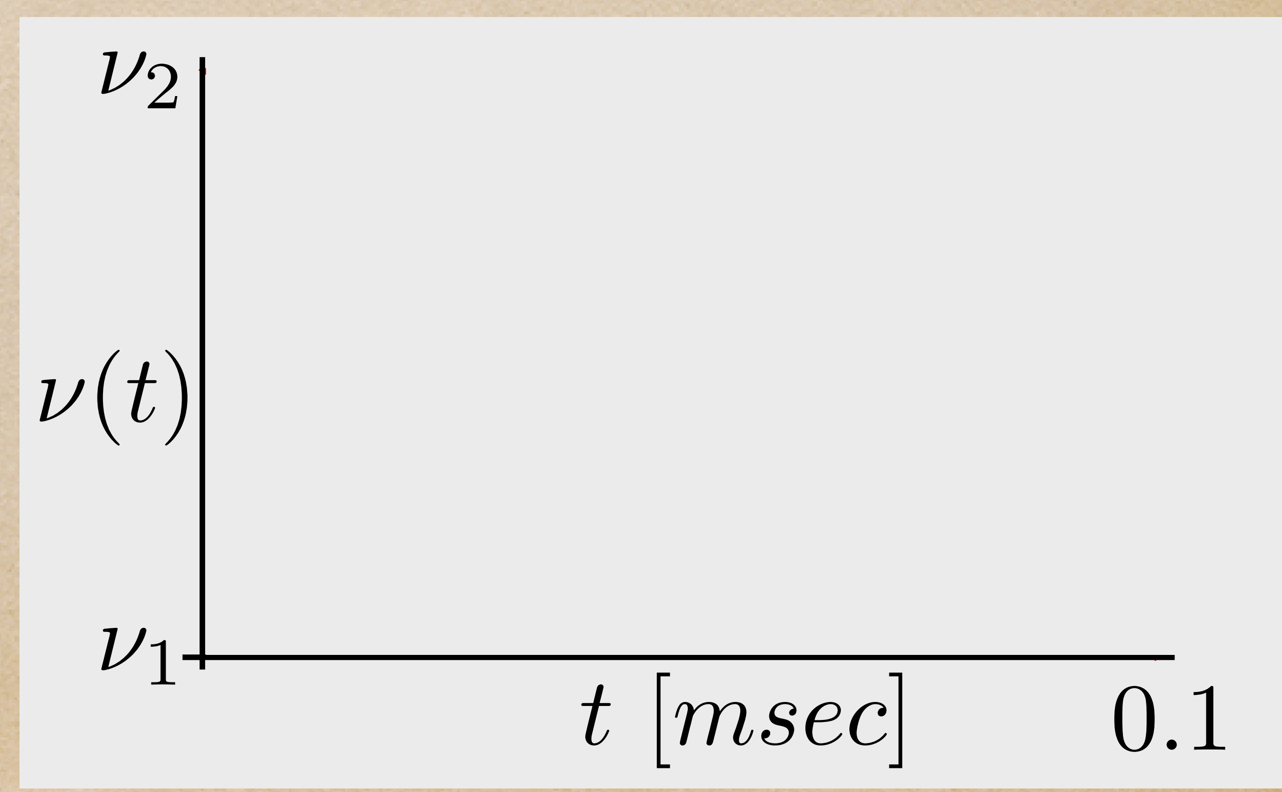
Experimental Reconstruction of Work Distribution and Study of Fluctuation Relations in a Closed Quantum System

Tiago B. Batalhão,[1] Alexandre M. Souza,[2] Laura Mazzola,[3] Ruben Auccaise,[2] Roberto S. Sarthour,[2] Ivan S. Oliveira,[2] John Goold,[4] Gabriele De Chiara,[3] Mauro Paternostro,[3,5] and Roberto M. Serra[1]

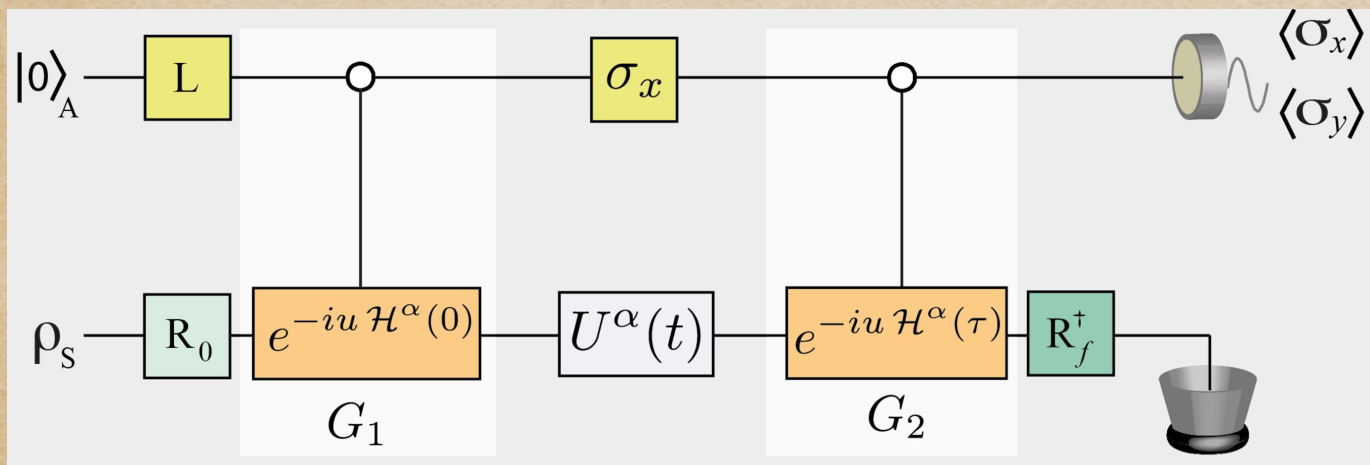


$$\hat{\mathcal{H}}^F(t) = 2\pi\hbar\nu(t)\left(\hat{\sigma}_x^C \sin\frac{\pi t}{2\tau} + \hat{\sigma}_y^C \cos\frac{\pi t}{2\tau}\right)$$





The experiment

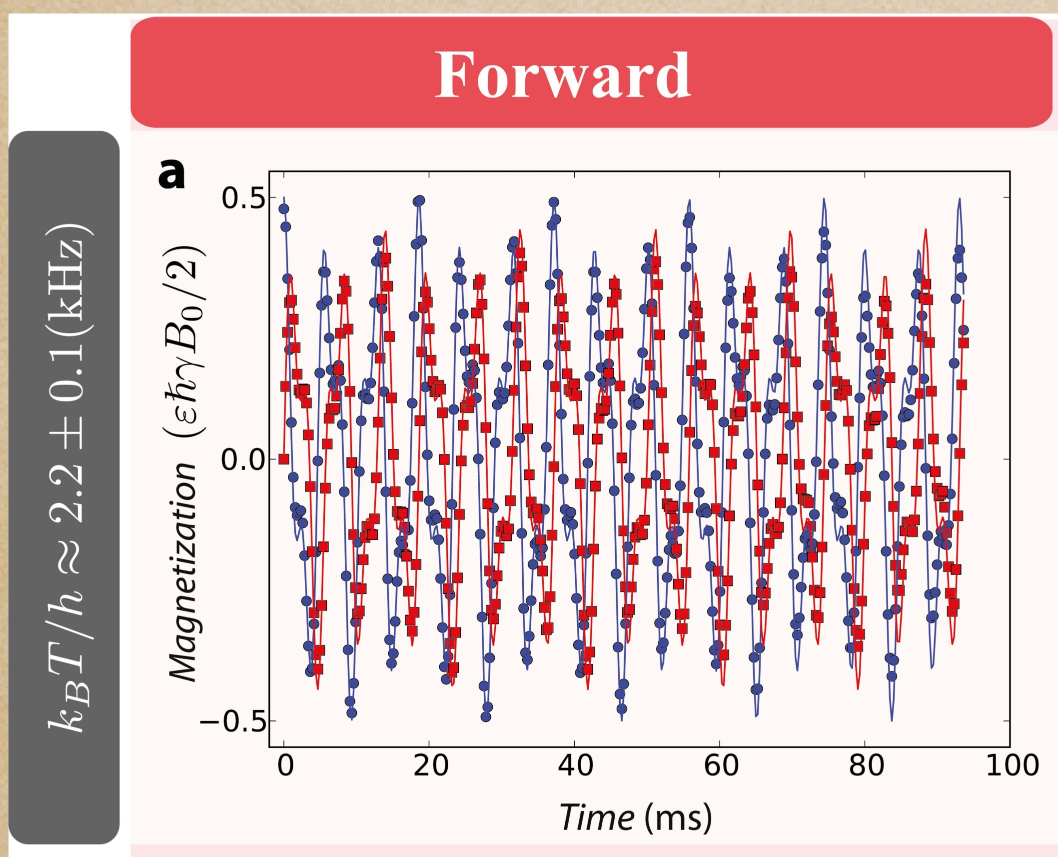


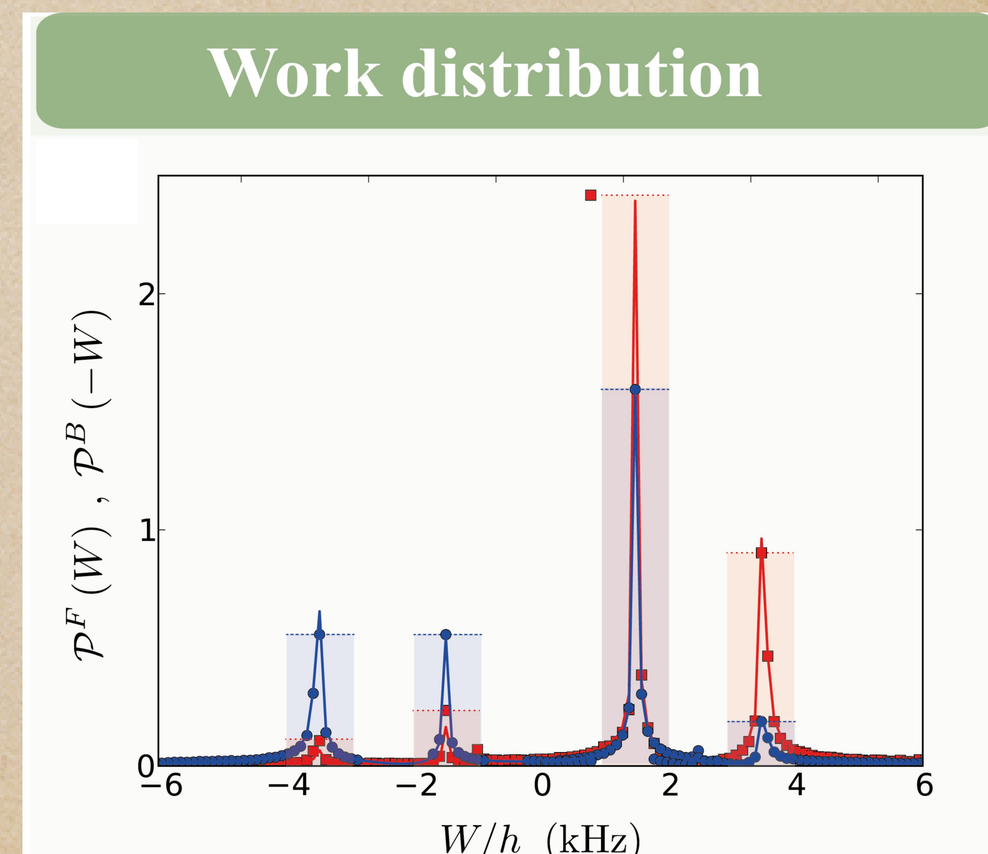
$$\hat{G}_1 \equiv |0\rangle\langle 0|_H \otimes e^{-iu\hat{\mathcal{H}}^\alpha(0)} + |1\rangle\langle 1|_H \otimes \hat{\mathbb{1}}^C$$

$$\hat{G}_2 \equiv |0\rangle\langle 0|_H \otimes \hat{\mathbb{1}}^C + |1\rangle\langle 1|_H \otimes e^{-iu\hat{\mathcal{H}}^\alpha(\tau)}$$

$$\hat{\mathcal{H}}_J = 2\pi J \hat{\sigma}_z^H \hat{\sigma}_z^C$$

$$\rho_{HC}^0 = |0\rangle\langle 0|_H \otimes e^{-\beta\hat{\mathcal{H}}^\alpha(0)}/Z_0$$





T. B. Batalhao, et al. Phys. Rev. Lett. 113, 140601 (2014)

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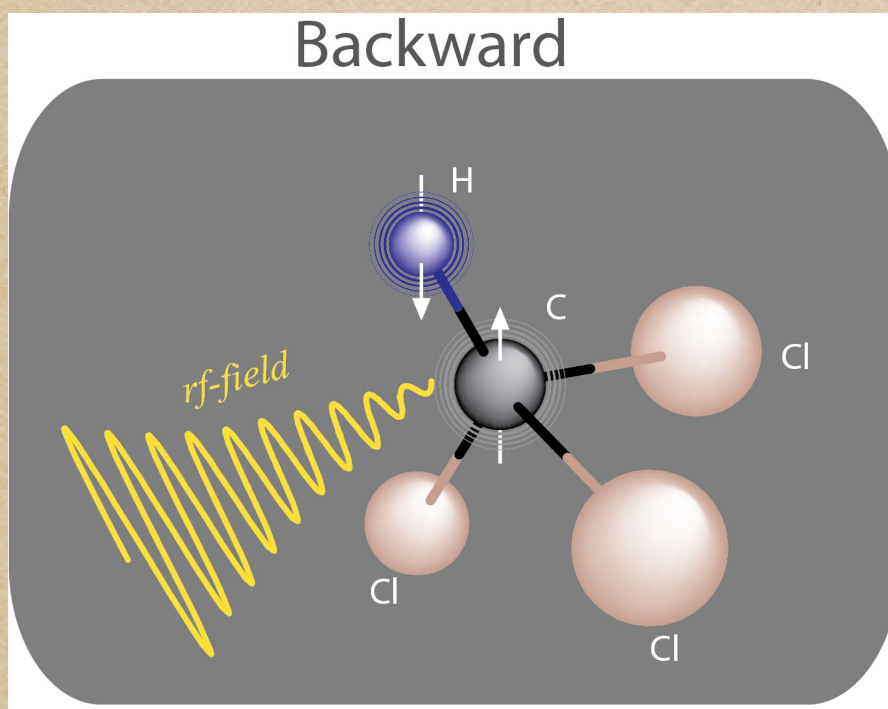
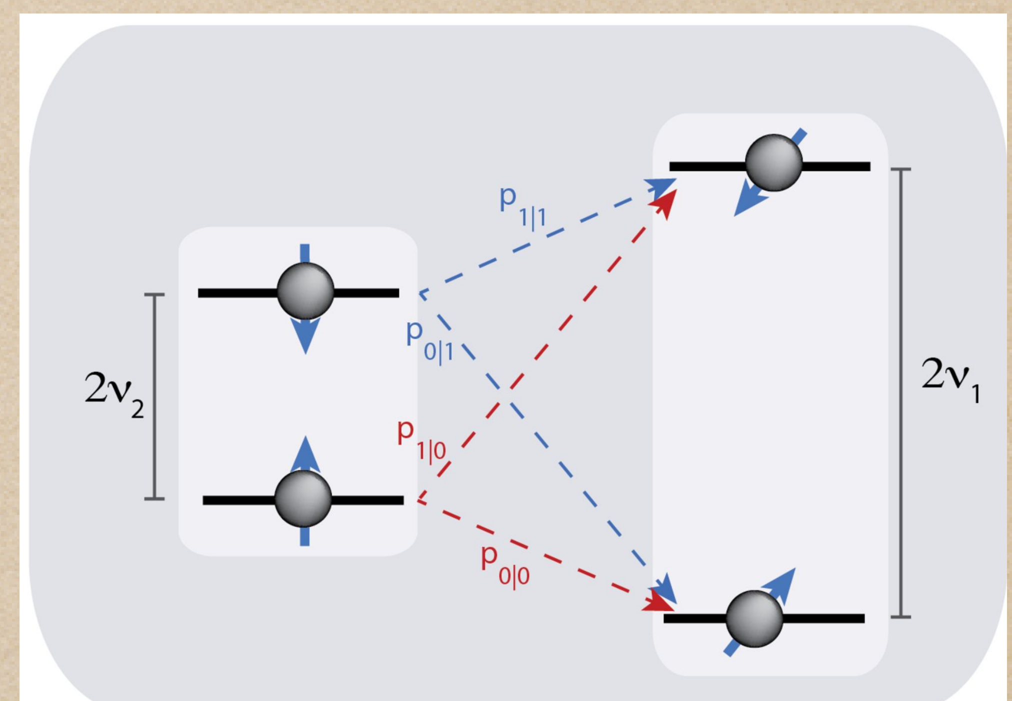
The experiment

Backward process



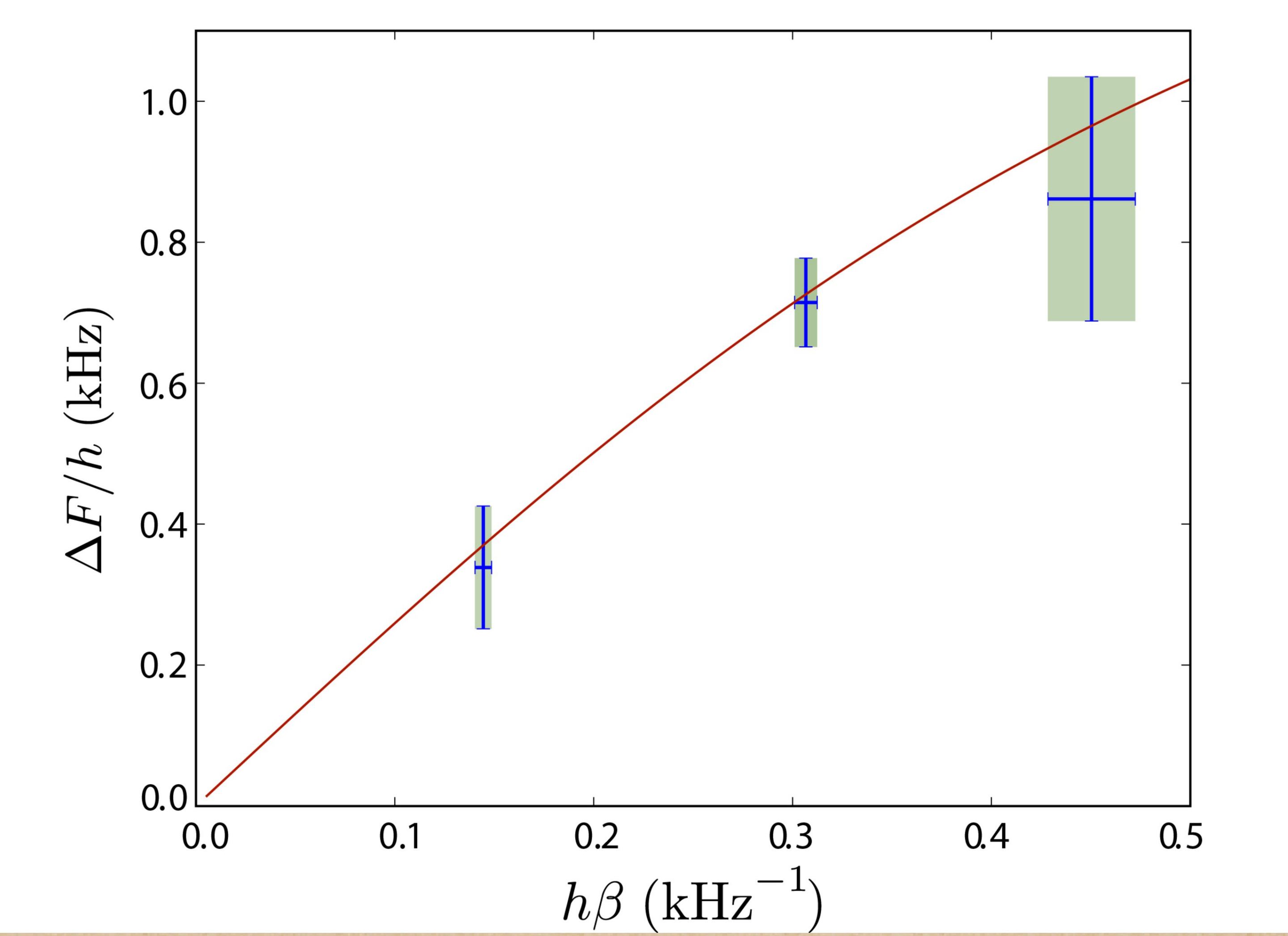


T. B. Batalhao, et al. Phys. Rev. Lett. 113, 140601 (2014)

The experiment

Tasaki-Crooks relation

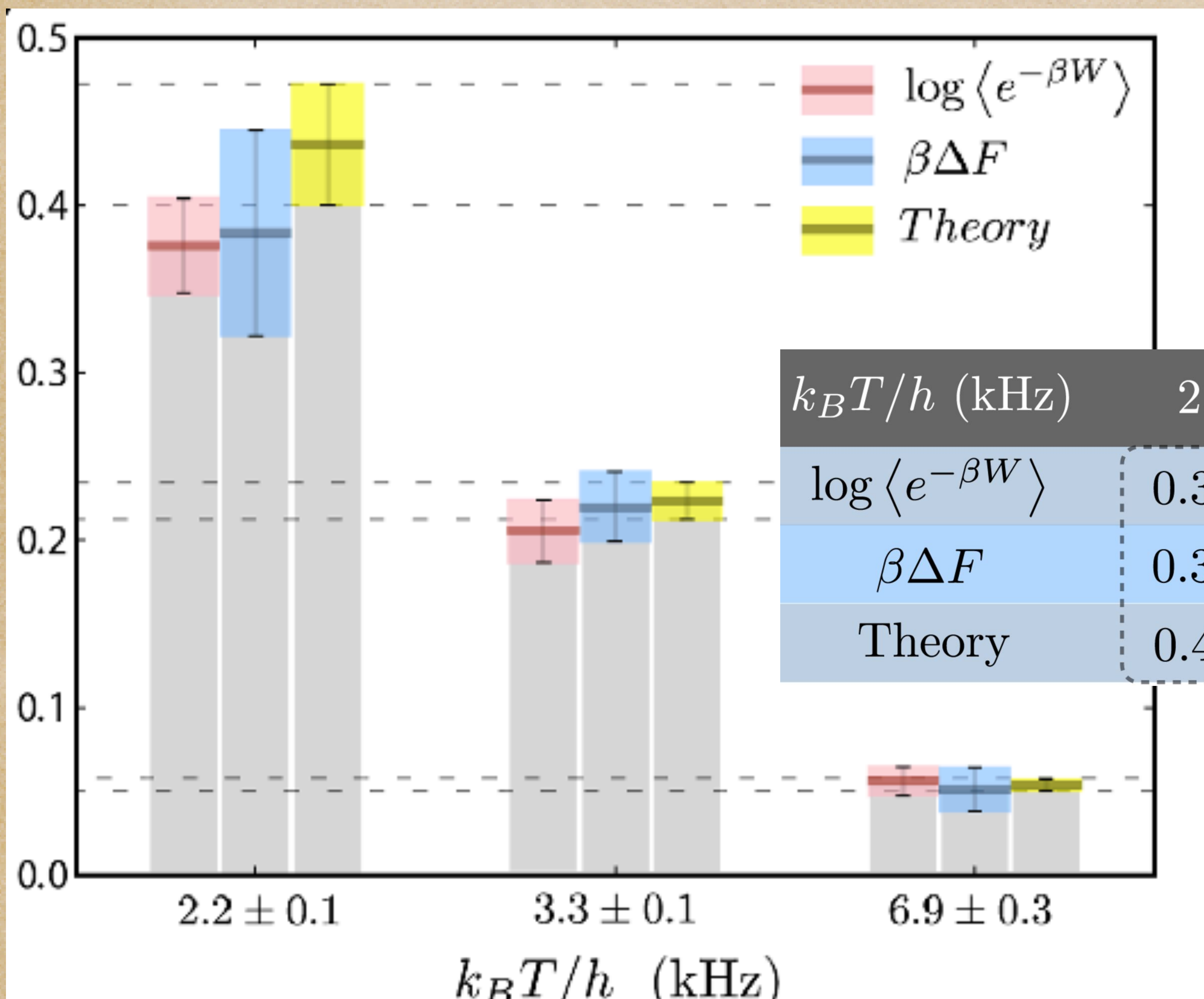
$$\ln[P_F(W)/P_B(-W)] = \beta(W - \Delta F)$$



T. B. Batalhao, et al. Phys. Rev. Lett. 113, 140601 (2014)

The experiment

Jarzynski equality



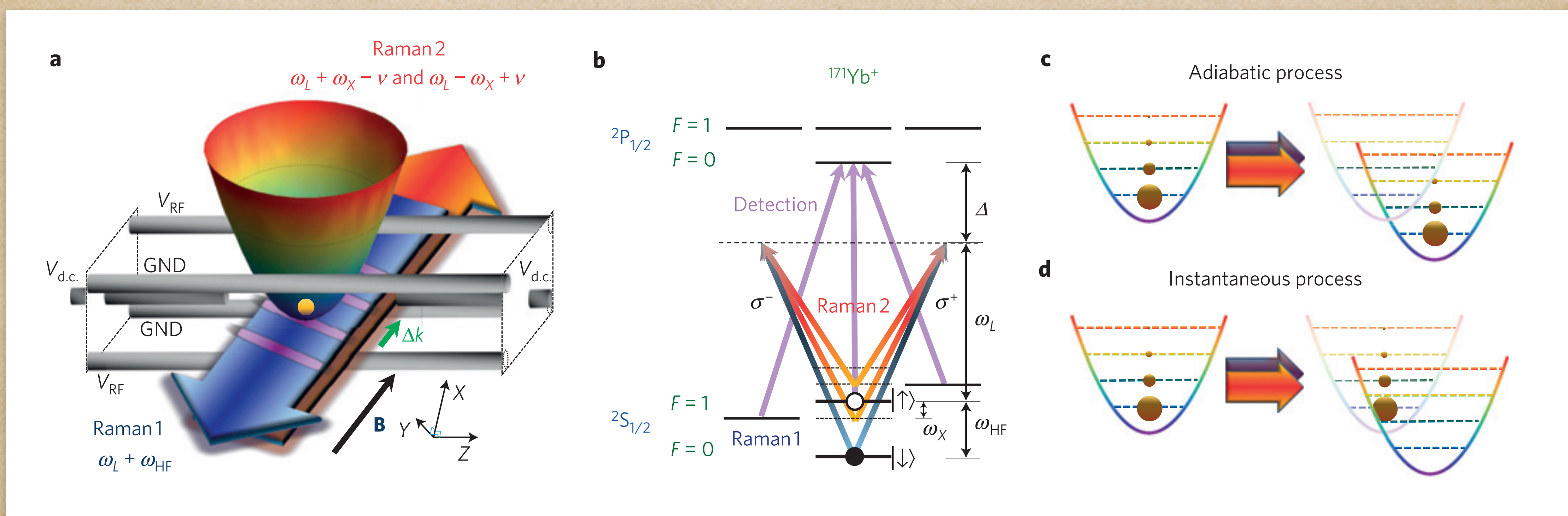
$k_B T/h$ (kHz)	2.2 ± 0.1	3.3 ± 0.1	6.9 ± 0.3
$\log\langle e^{-\beta W}\rangle$	0.38 ± 0.03	0.20 ± 0.02	0.06 ± 0.01
$\beta\Delta F$	0.39 ± 0.06	0.22 ± 0.02	0.05 ± 0.01
Theory	0.43 ± 0.03	0.22 ± 0.01	0.053 ± 0.003

T. B. Batalhao, et al. Phys. Rev. Lett. 113, 140601 (2014)

Other experimental studies

Experimental test of the quantum Jarzynski equality with a trapped-ion system

Shuoming An[1], Jing-Ning Zhang[1], Mark Um[1], Dingshun Lv[1], Yao Lu[1], Junhua Zhang[1], Zhang-Qi Yin[1], H. T. Quan[2,3]* and Kihwan Kim[1]*

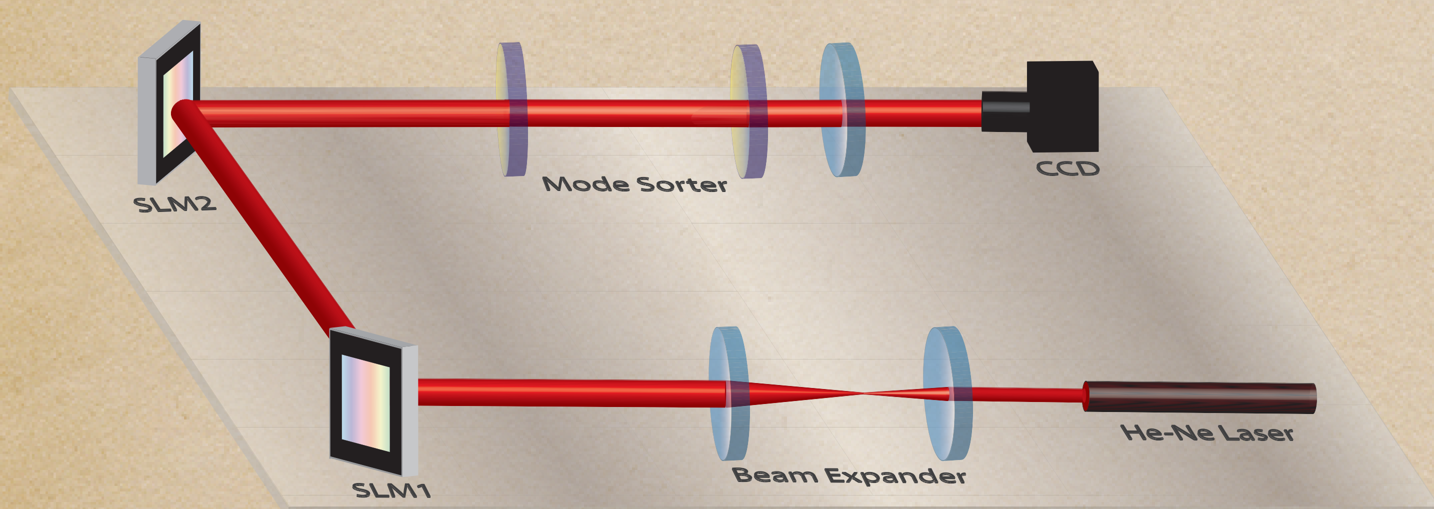


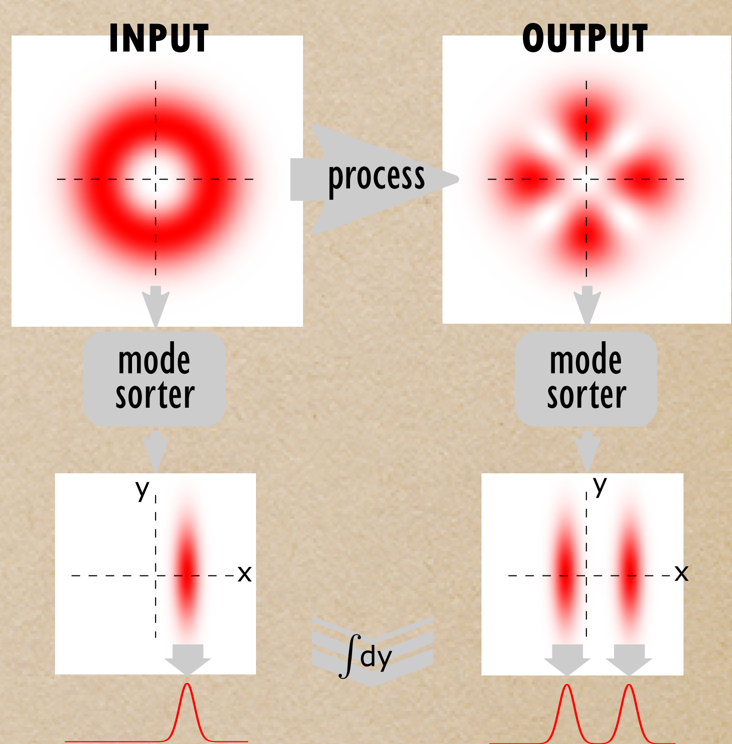
S. An, et al., Nature Phys. 11, 193 (2015)

Other experimental studies

Experimental study of quantum thermodynamics using optical vortices

R. Medeiros de Araújo,[1] T. Häffner,[1] R. Bernardi,[1] D. S. Tasca,[2] M. P. J. Lavery,[3] M. J. Padgett,[4] A. Kanaan,[1] L. C. Céleri,[5,*] and P. H. Souto Ribeiro[1,†]



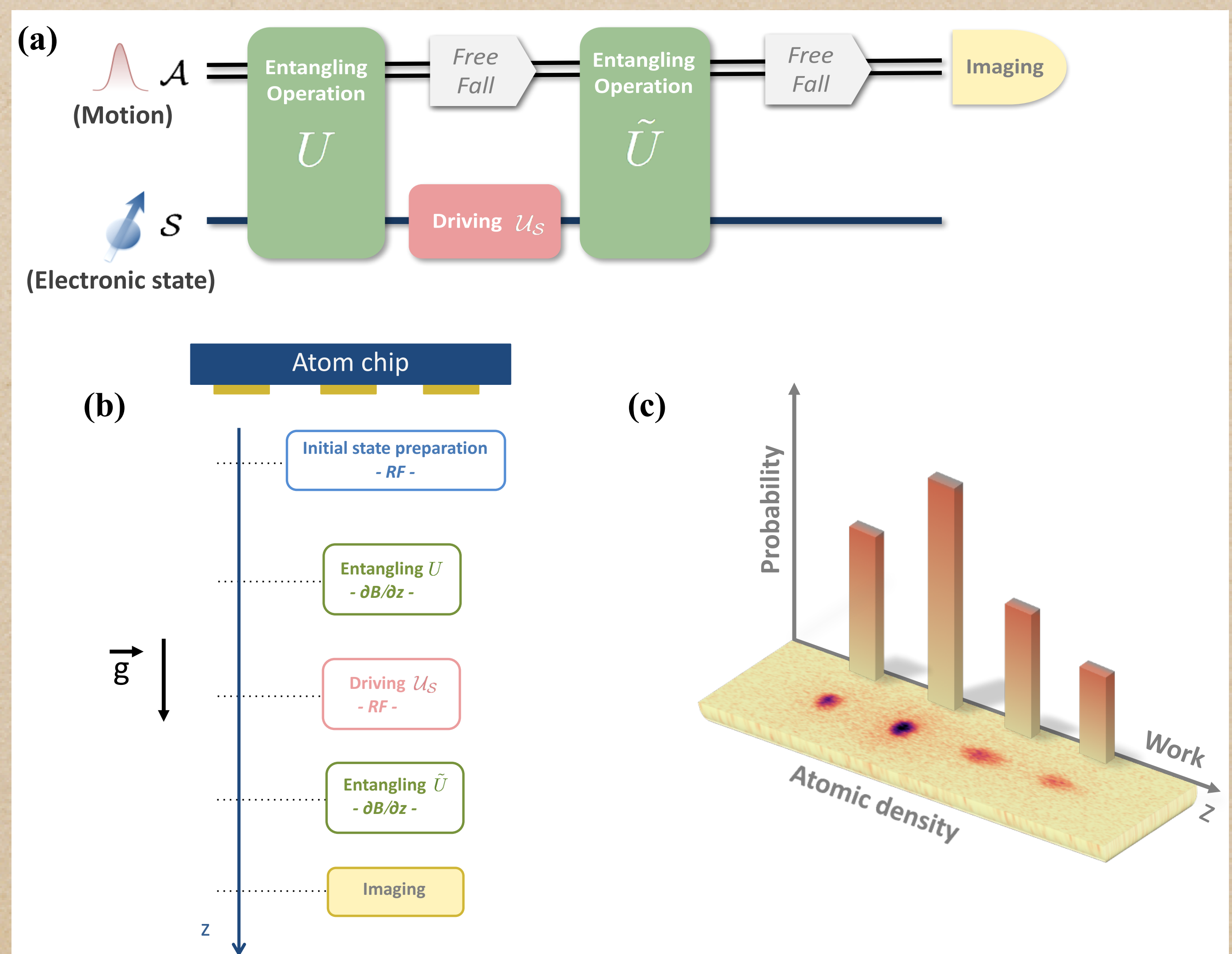


R. Medeiros de Araujo, et al. arXiv: 1705.02990

Other experimental studies

Using a *quantum work meter* to test non-equilibrium fluctuation theorems

Federico Cerisola,[1,2] Yair Margalit,[3] Shimon Machluf,[4] Augusto J. Roncaglia,[1,2] Juan Pablo Paz,[1,2] and Ron Folman[3]



F. Cerisola et al., arXiv:1706.07866

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The Belfast crew

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Go raibh maith agaibh

Department for the Economy

Science Foundation Ireland
SFI
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