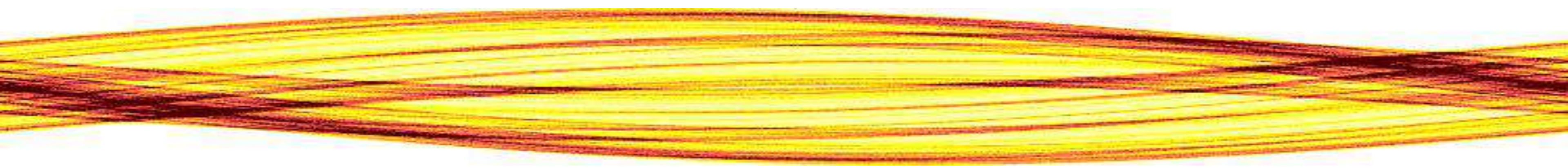
Quantum Thermodynamics of complex systems

Adolfo del Campo

Department of Physics
University of Massachusetts, Boston
Jun 25, 2018



KITP, Santa Barbara

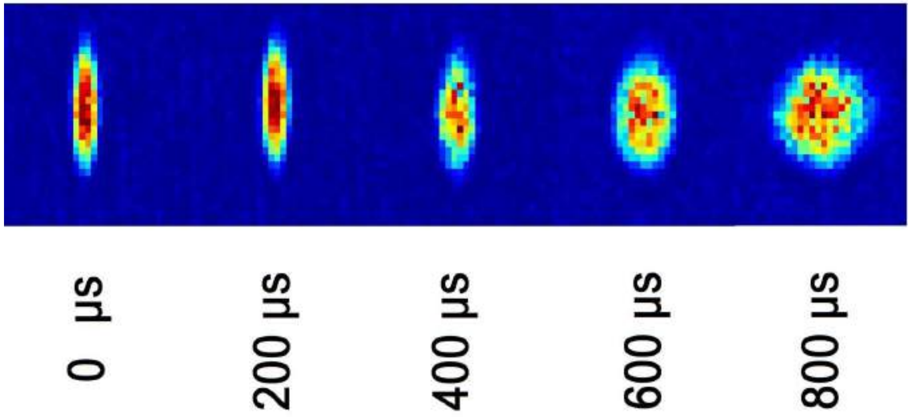
Outline

- Friction-free quantum machines
- Work statistics in Complex systems

Part I

Friction-free quantum machines

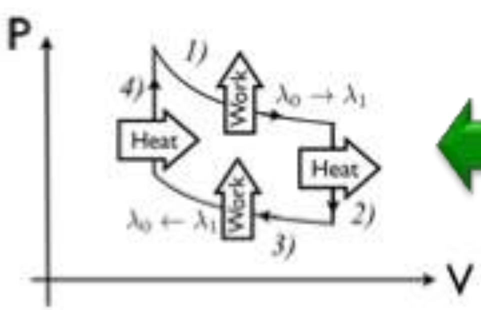
Progress with cold atoms

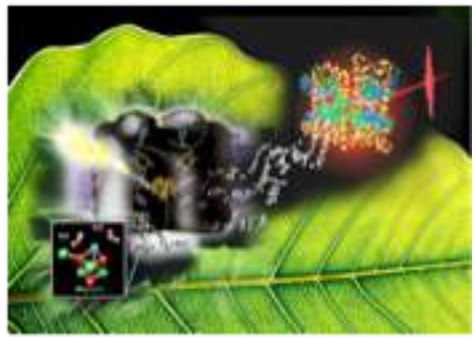


Quantum Heat Engines: Towards Green Quantum Energy

Optimal energy consumption and conversion

Equivalence Quantum engines & Photocells





PRL 104, 207701 (2010) PHYSICAL REVIEW LETTERS week ending 21 MAY 2010

Quantum Photocell: Using Quantum Coherence to Reduce Radiative Recombination and Increase Efficiency

Marlan O. Scully
Texas A&M University, College Station, Texas 77843, USA
Princeton University, Princeton, New Jersey 08544, USA

Photosynthetic reaction center as a quantum heat engine

Konstantin E. Dorfman, Dmitri V. Voronine, Shaul Mukamel, and Marlan O. Scully
Texas A&M University, College Station, TX 77843-4242; Princeton University, Princeton, NJ 08544; University of California, Irvine, CA 92697-2025, and Baylor University, Waco, TX 76798

PNAS

THE JOURNAL OF CHEMICAL PHYSICS 143, 155102 (2015)

CrossMark

Enhancing light-harvesting power with coherent vibrational interactions: A quantum heat engine picture

N. Killoran, S. F. Huelga, and M. B. Plenio
Institut für Theoretische Physik, Universität Ulm, Albert-Einstein-Allee 11, D-89069 Ulm, Germany

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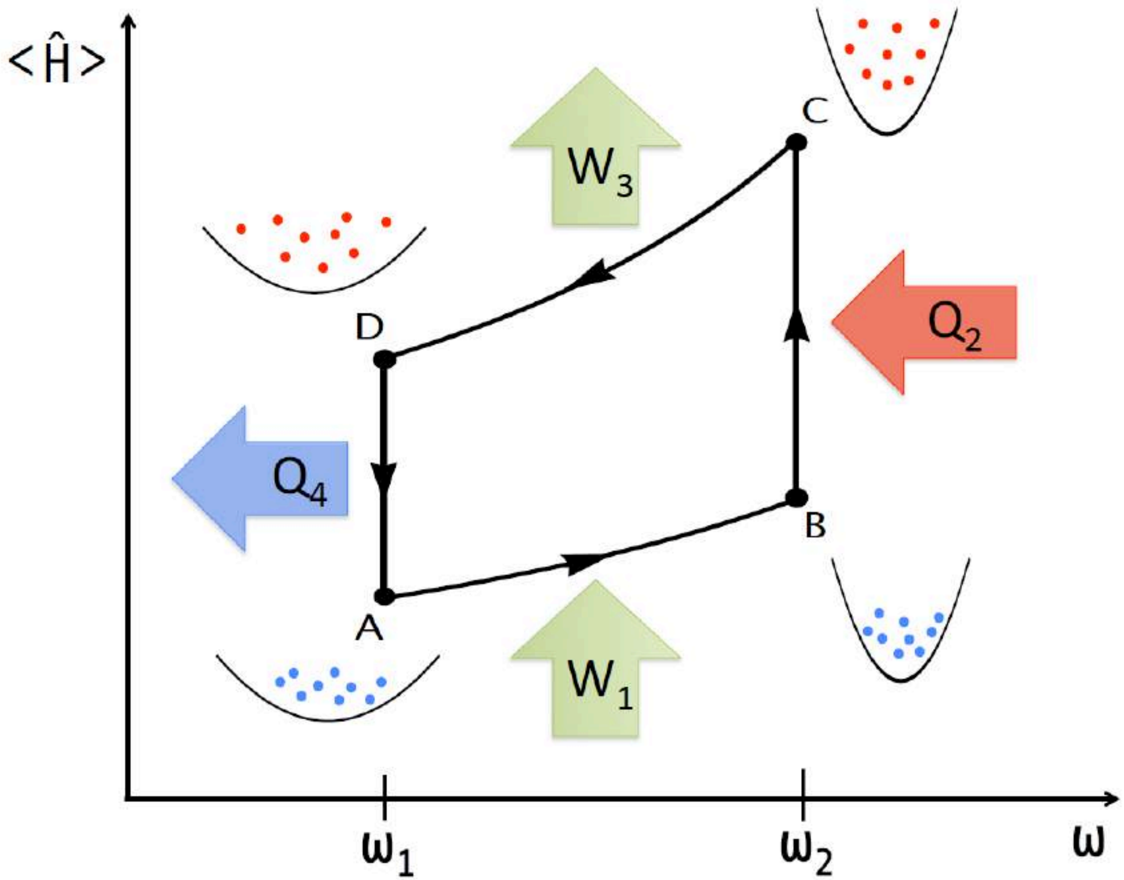
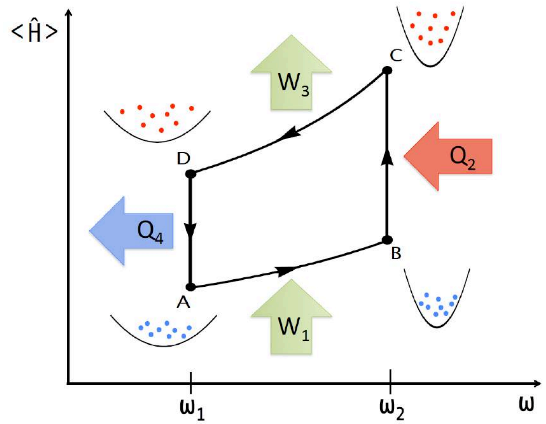
Many-particle QHE: Otto cycle



Performance of a QHE



$$\langle W \rangle = \langle H_f \rangle - \langle H_i \rangle$$

Efficiency: work done/heat absorbed

$$\eta = -\frac{\langle W_1 \rangle + \langle W_3 \rangle}{\langle Q_2 \rangle}$$

Power: work done per cycle time

$$\mathcal{P} = -\frac{\langle W \rangle_1 + \langle W \rangle_3}{\sum_{j=1}^{4} \tau_j}$$

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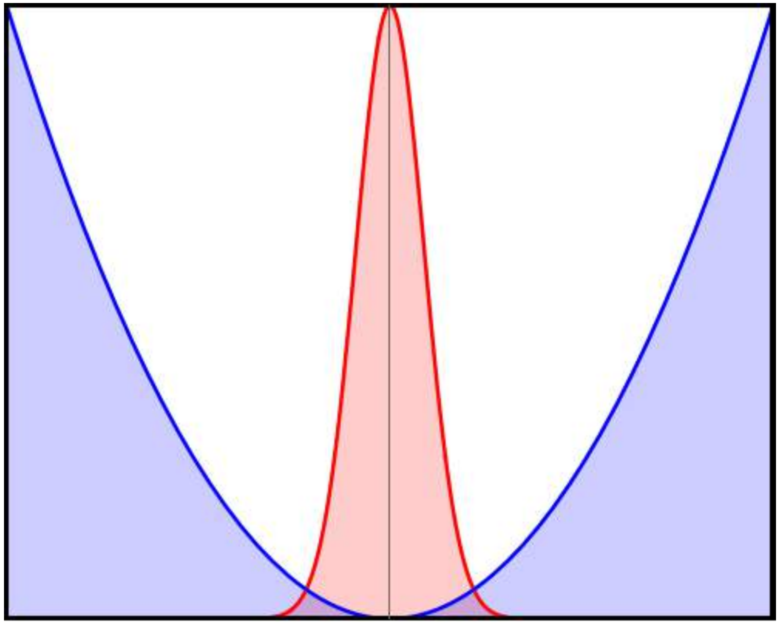
Many-particle working medium

Interacting quantum fluids

$$\hat{H}=\sum_{i=1}^{N}\left[-\frac{\hbar^2}{2m}\nabla^2+\frac{1}{2}m\omega(t)^2\mathbf{r}_i^2\right]+\sum_{i<j}V(\mathbf{r}_i-\mathbf{r}_j)$$

Scaling-invariant dynamics when $V(\gamma\mathbf{r})=\gamma^{-2}V(\mathbf{r})$



AdC, PRA 84, 031606 (2011); PRL **111**, 100502 (2013)

Exact Finite-time thermodynamics

Mean energy in scale-invariant dynamics

$$\langle H(t)\rangle = \frac{1}{b^2}\langle H(0)\rangle + \sum_{i=1}^{N}\frac{\dot{b}}{2b}\langle\{z_i,p_i\}(0)\rangle + \sum_{i=1}^{N}\frac{m}{2}(\dot{b}^2 - b\ddot{b})\langle z_i^2(0)\rangle$$

Scaling factor obeys Ermakov equation

$$\ddot{b} + \omega(t)^2 b = \omega_0^2/b^3$$

Jaramillo et al NJP 18, 075019 (2016); Beau et al Entropy 18, 168 (2016)

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Exact Finite-time thermodynamics

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Nonadiabatic factor

$$\langle H(t)\rangle = Q^*(t)\langle H(t)\rangle_{\rm adiab} \qquad Q^*(t) \geq 1$$

$$Q^*(t) = \frac{\omega_0}{\omega(t)}\left(\frac{1}{2b^2} + \frac{\omega(t)^2}{2\omega_0^2}b^2 + \frac{\dot{b}^2}{2\omega_0^2}\right)$$

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Jaramillo et al NJP 18, 075019 (2016); Beau et al Entropy 18, 168 (2016)

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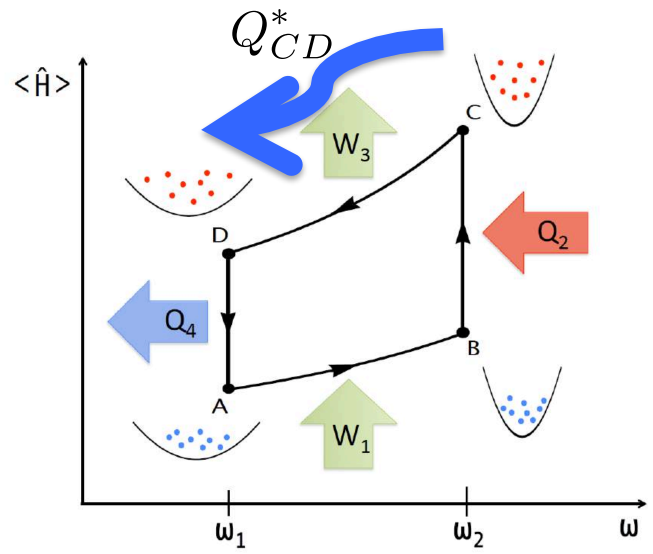
Universal Bound to Quantum Efficiency

Mean work $\langle W \rangle = \langle H_f \rangle - \langle H_i \rangle$

Quantum efficiency of many-particle QHE



$$\eta = -\frac{\langle W_1 \rangle + \langle W_3 \rangle}{\langle Q_2 \rangle}$$

$$\eta = 1 - \frac{\omega_1}{\omega_2}\left(\frac{Q^*_{CD}\langle H \rangle_C - \frac{\omega_2}{\omega_1}\langle H \rangle_A}{\langle H \rangle_C - Q^*_{AB}\frac{\omega_2}{\omega_1}\langle H \rangle_A}\right)$$

Upper bound to quantum efficiency via nonadiabatic compression factor

$$\eta \leq \eta_{\mathrm{nad},O} \equiv 1 - Q^*_{CD}\frac{\omega_1}{\omega_2}$$

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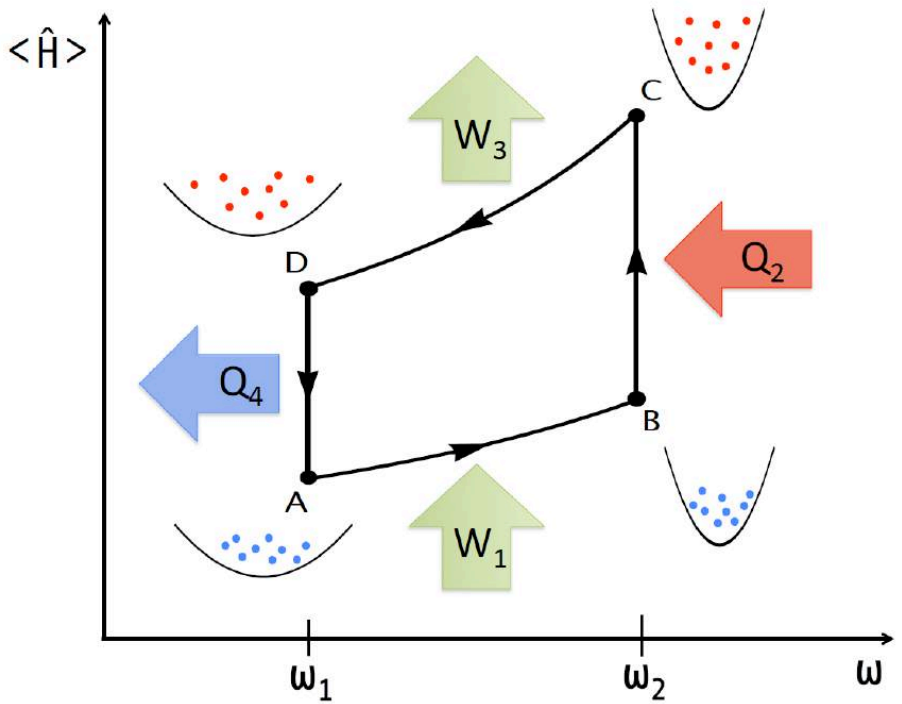
Jaramillo et al NJP 18, 075019 (2016); Beau et al Entropy 18, 168 (2016)

Quantum Heat Engines (e.g. Otto Cycle)



$$\eta \leq \eta_{\mathrm{nad},O} \equiv 1 - Q^{*}_{CD}\frac{\omega_1}{\omega_2}$$

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Alternative: Shortcuts to adiabaticity (STA)

Fast non-adiabatic process to prepare a state mimicking adiab. dynamics

Proposal: Phys. Rev. Lett. **104**, 063002 (2010)
Review: Adv. At. Mol. Opt. Phys. **62**, 117 (2013)

Processes: Expansion, transport, splitting, adiabatic passage, phase transitions, …

Systems: ultracold atoms, ions chains, quantum dots, spin systems, NVC, …

Experiments: Nice, NIST, Mainz, PTB, MPQ, Florence, Trento, Tsukuba, …

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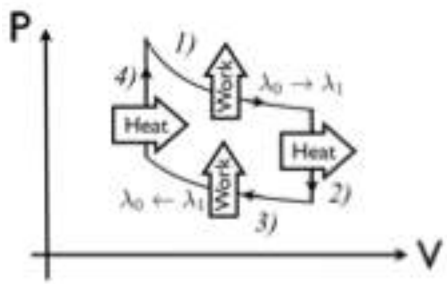
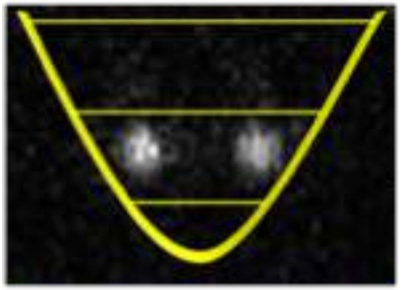
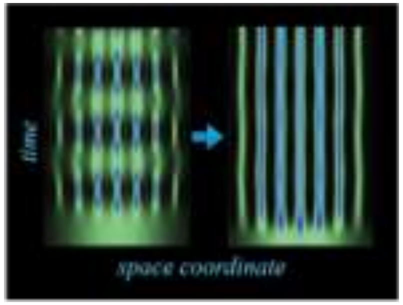
Some applications of STA



Quantum thermodynamics
Chen et al, PRL 104, 063002 (2010)
AdC & Boshier, Sci. Rep. 2, 648 (2012)
AdC, Goold, Paternostro Sci. Rep. 4, 6208 (2014)

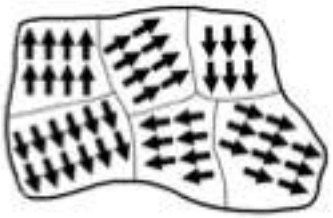


Ion transport
Deffner, Jarzynski, AdC PRX 4, 021013 (2014)

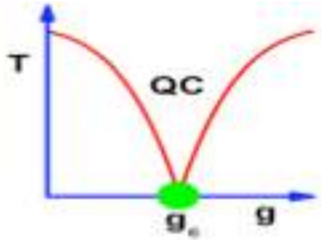


Ground state loading
In an optical lattice
Masuda, Nakamura, AdC PRL 113, 063003 (2014)

Ultracold Atom microscopy
AdC, EPL 96, 60005 (2011)
AdC, PRA 84, 031606(R) (2011)
AdC, PRL 111, 100502 (2013)



Topological Defect suppression
AdC et al. PRL105, 075701 (2010)
AdC et al. NJP 13, 083022 (2011)
Pyka et al. Nat. Commun. 4, 2291 (2013)
AdC, Kibble, Zurek, JPCM 25, 404210 (2013)
AdC & Zurek Int. J. Mod. Phys. A 29, 1430018 (2014)



Quantum Phase Transitions
& Quantum Annealing
AdC, Rams, Zurek PRL 109, 115703 (2012)
Saberi, Opatrný, Mølmer, AdC, PRA 90, 060301(R)
AdC & Sengupta, EPJ ST 224, 189 (2015)
Rams, Mohseni, AdC, NJP 18, 123034 (2016)
Gomez-Ruiz, AdC arXiv:1805.00525

And many other applications
(chemical rate processes, quantum logic gates, soliton dynamics, atom interferometry, ...)

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Deutsche Physikalische Gesellschaft DPG IOP Institute of Physics

Focus on Shortcuts to Adiabaticity

Prof. Adolfo del Campo, *Department of Physics, University of Massachusetts Boston, USA*
Prof. Kihwan Kim, *Institute for Interdisciplinary Information Sciences, Tsinghua University, China*

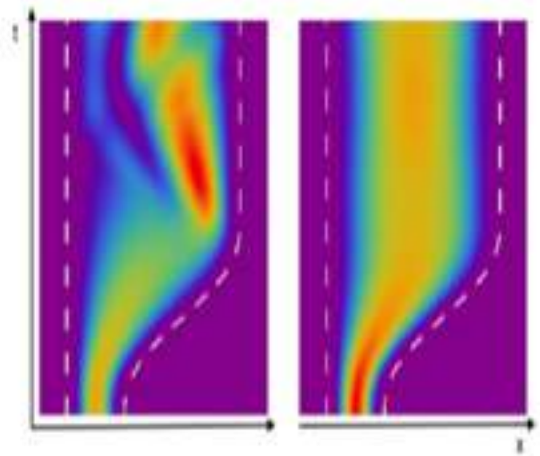


Image. Tailoring of excitations in a nonadiabatic expansion of matter-waves in a quantum piston (left) via shortcuts to adiabaticity (right).

Scope

Tailoring the far from equilibrium dynamics of quantum matter is an open problem at the frontiers of physics. Yet, it is also a necessity for the development of quantum science and technology.

Conventional adiabatic protocols are ubiquitously exploited for the manipulation and control of quantum matter in a wide variety of fields. They require however long evolution times and are thus prone to noise and decoherence errors.

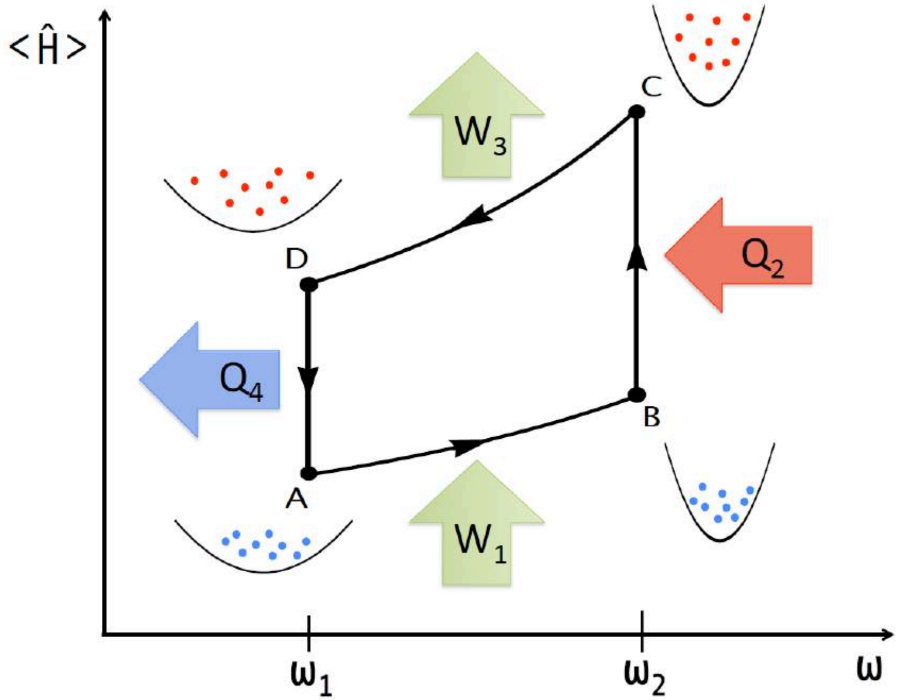
Shortcuts to adiabaticity provide an alternative control paradigm, free from the requirement of slow driving. They have been exploited in various quantum platforms with both discrete and continuous variables. Prominent examples include ultracold gases, trapped ions, nitrogen-vacancy centers and other realizations of few-level systems.

Shortcuts to adiabaticity have also important implications on the foundations and applications of quantum theory, quantum statistical mechanics and thermodynamics, quantum optics, quantum control, quantum information processing and quantum computation.

This special issue aims at spurring the development of shortcuts to adiabaticity, fostering experimental and theoretical progress at the frontiers of the field.

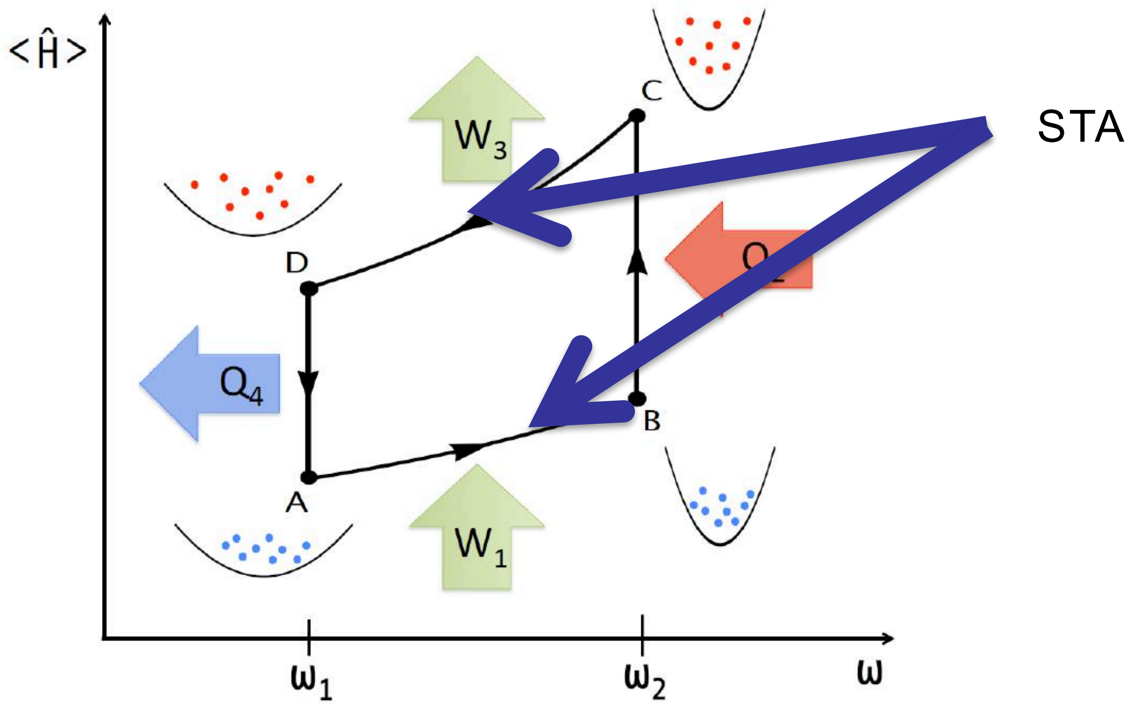
Adolfo del Campo: adolfo.delcampo@gmail.com

Quantum Heat Engines (e.g. Otto Cycle)



$$\eta \leq \eta_{\mathrm{nad},O} \equiv 1 - Q^{*}_{CD}\frac{\omega_1}{\omega_2}$$

Quantum Heat Engines (e.g. Otto Cycle)



$$\eta_{\rm STA} = \eta_{\max} = 1 - \frac{\omega_1}{\omega_2}$$

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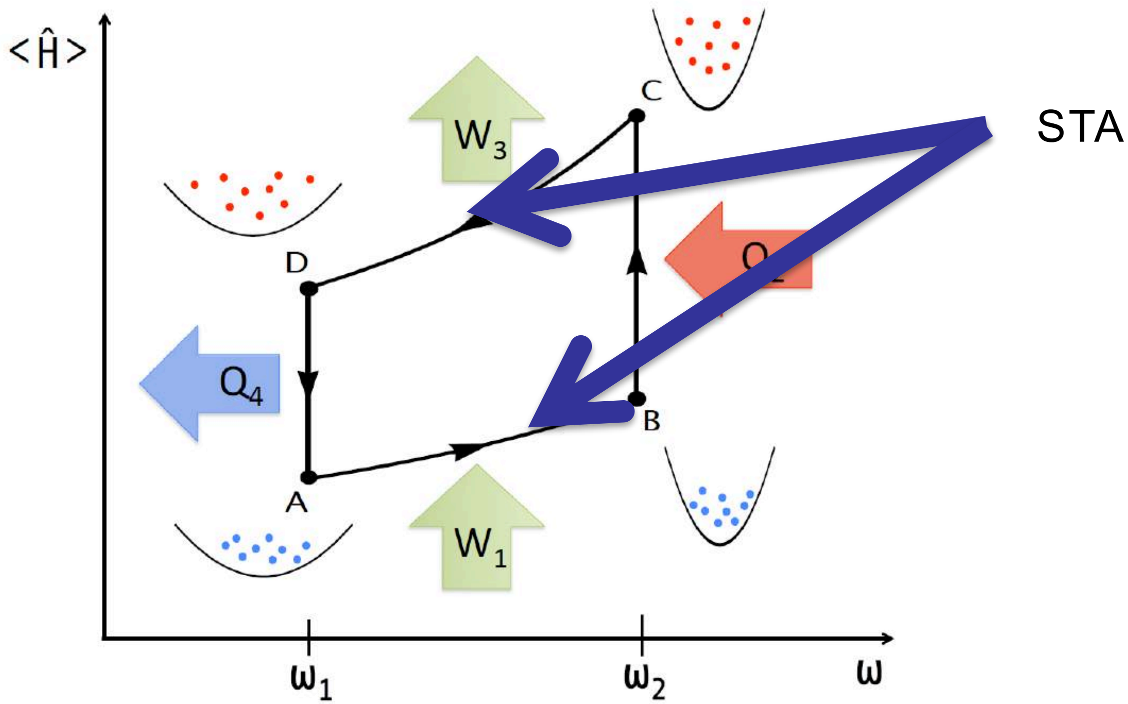
Quantum Heat Engines (e.g. Otto Cycle)



- AdC, J. Goold, M. Paternostro, Sci. Rep. **4**, 6208 (2014); arXiv:1305.3223
- J. Deng et al., Phys. Rev. E **88**, 062122 (2013); arXiv:1307.4182
- M. Beau, J. Jaramillo, AdC, Entropy **18**, 168 (2016) (many-particle QHE)

Adolfo del Campo: adolfo.delcampo@umb.edu

Superadiabatic strokes: Fermi gas at Unitarity

Superadiabatic quantum friction suppression in finite-time thermodynamics

Shujin Deng,[1] Aurélia Chenu,[2] Pengpeng Diao,[1] Fang Li,[1] Shi Yu,[1] Ivan Coulamy,[3,4] Adolfo del Campo,[3] and Haibin Wu[1,5]

[1] *State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai 200062, P. R. China*
[2] *Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA*
[3] *Department of Physics, University of Massachusetts, Boston, MA 02125, USA*
[4] *Departamento de Física, Universidade Federal Fluminense, Niterói, RJ, Brazil*
[5] *Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan 030006, China*

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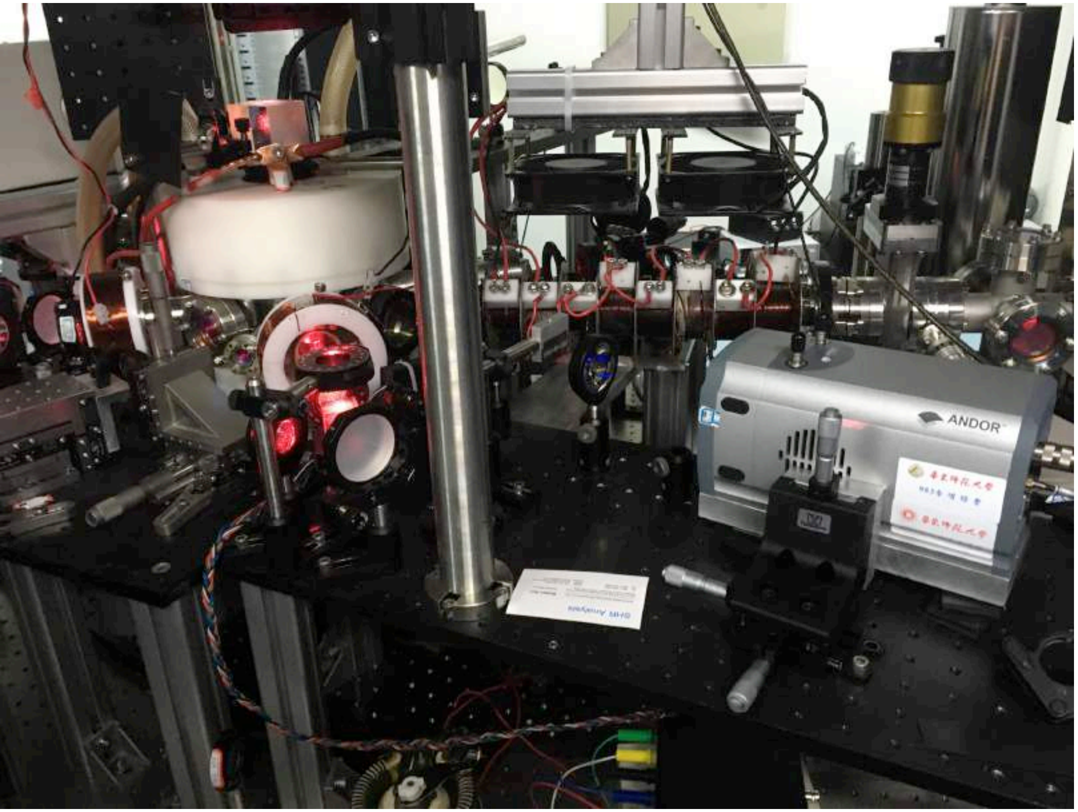
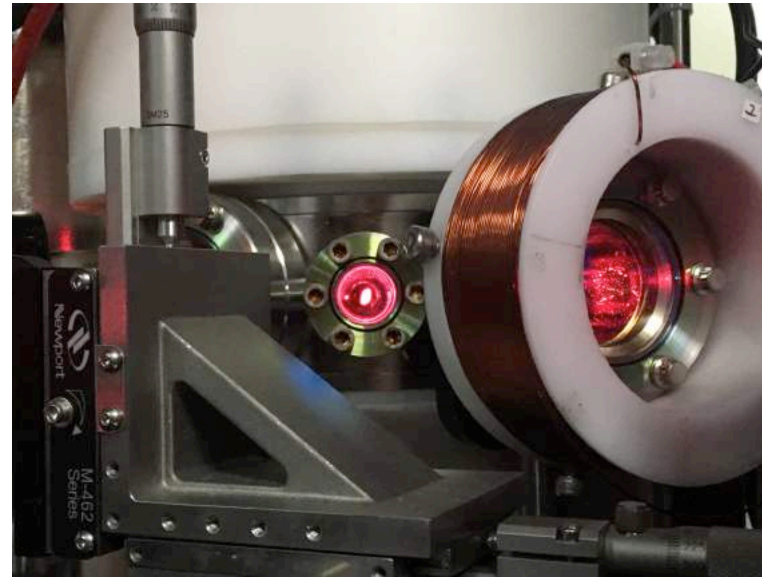
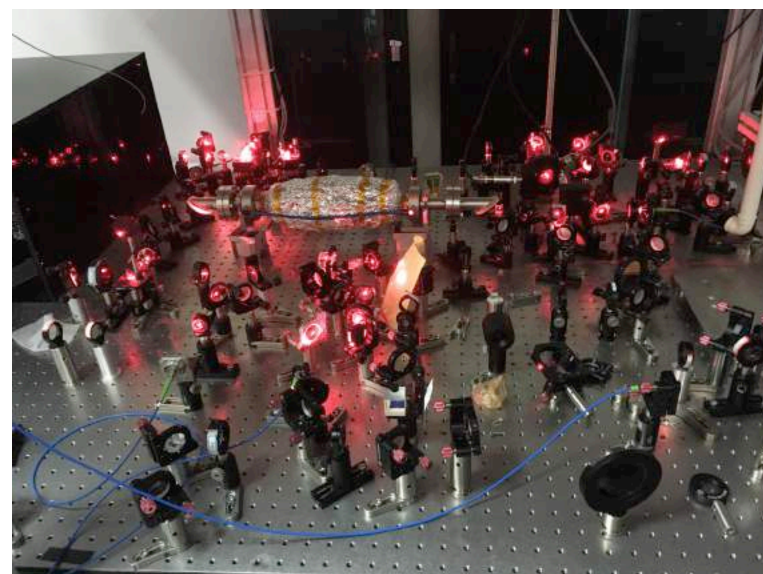
Deng et al. Sci. Adv. 4, eaar5909 (2018)

How it actually looks like …







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Superadiabatic quantum friction suppression in finite-time thermodynamics

Shujin Deng,[1] Aurélia Chenu,[2] Pengpeng Diao,[1] Fang Li,[1] Shi Yu,[1] Ivan Coulamy,[3,4] Adolfo del Campo,[3] Haibin Wu[1,5]*

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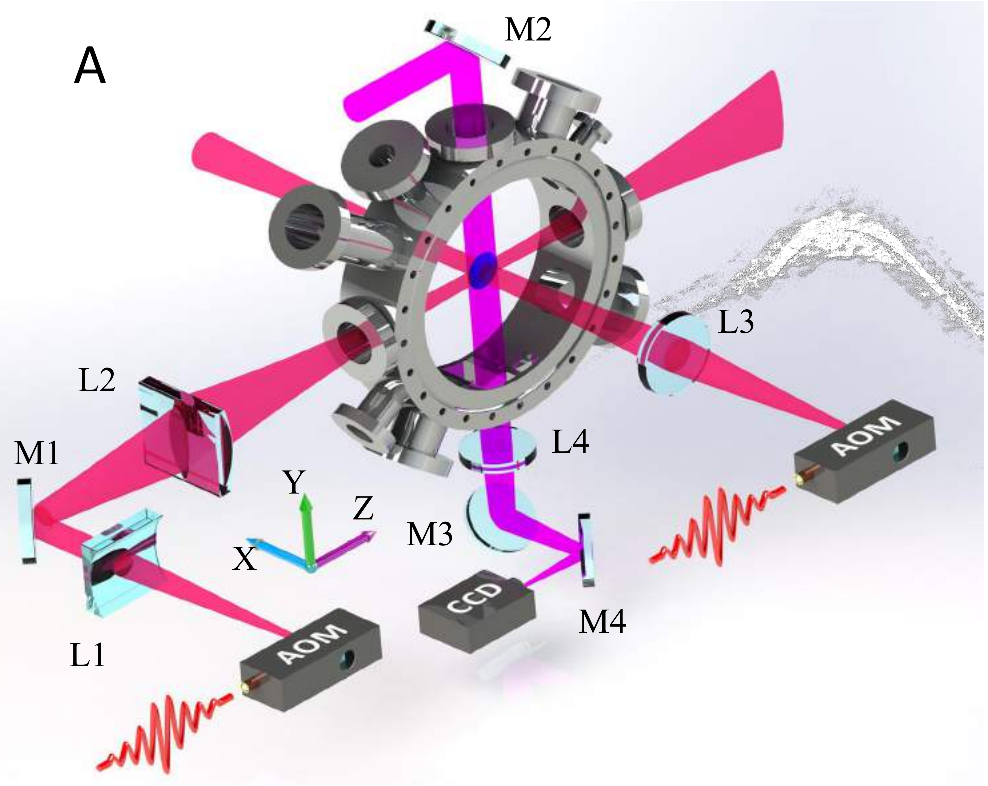
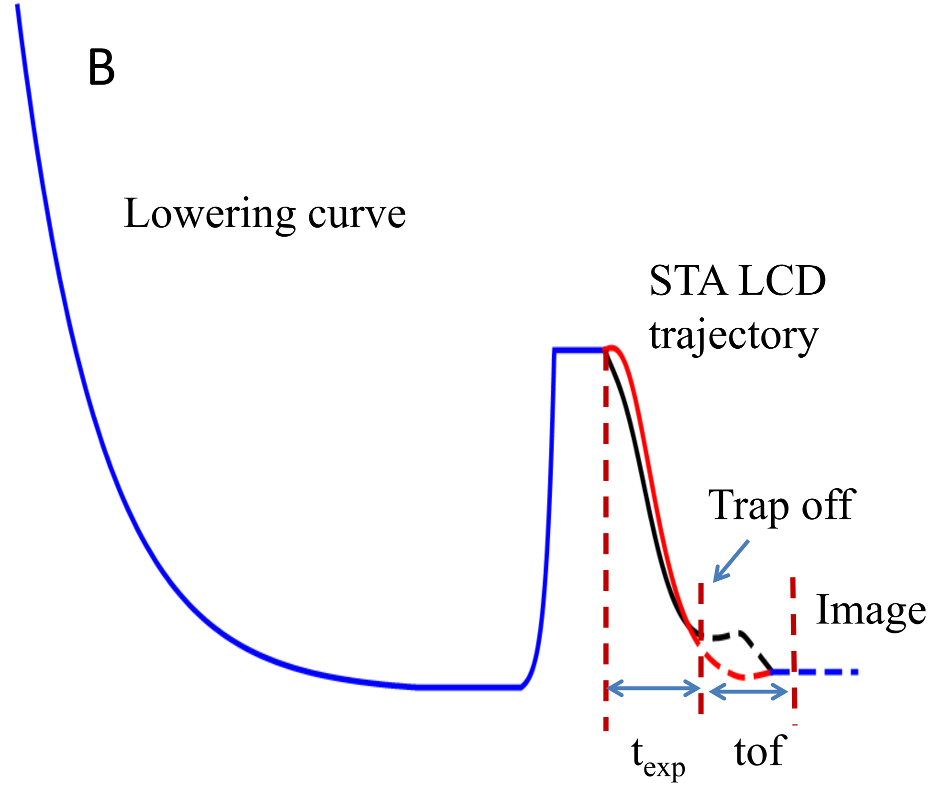




Adolfo del Campo: adolfo.delcampo@umb.edu

Fermi gas: noninteracting and at Unitarity

Balanced mixture of ^{6}Li in the two lowest hyperfine states

$$\hat{\mathcal{H}} = \sum_{\sigma=\uparrow,\downarrow} \int d^3\mathbf{r} \hat{\psi}^\dagger_\sigma(\mathbf{r}) \left[\frac{-\hbar^2\nabla^2}{2m} + \frac{1}{2} m\omega(t)^2 \mathbf{r}_i^2 \right] \hat{\psi}_\sigma(\mathbf{r}) + g\hat{\psi}^\dagger_\uparrow(\mathbf{r})\hat{\psi}^\dagger_\downarrow(\mathbf{r})\hat{\psi}_\downarrow(\mathbf{r})\hat{\psi}_\uparrow(\mathbf{r})$$

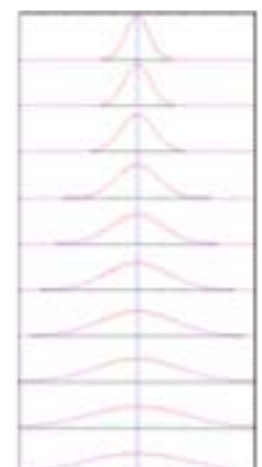
Feshbach resonance to tune interactions

Ideal Fermi gas B=528G $g \rightarrow 0$

Unitary Fermi gas B=832G $g \rightarrow \infty$

In both cases: Emergent conformal invariance at weak/strong coupling

$$V(\gamma\mathbf{r}) = \gamma^{-2} V(\mathbf{r})$$



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Quantum fluids: scaling laws & counterdiabatic driving

Family of interacting quantum fluids

$$\hat{H} = \sum_{i=1}^{N} \left[-\frac{\hbar^2}{2m} \nabla^2 + \frac{1}{2} m \omega(t)^2 \mathbf{r}_i^2 \right] + \sum_{i<j} V(\mathbf{r}_i - \mathbf{r}_j)$$

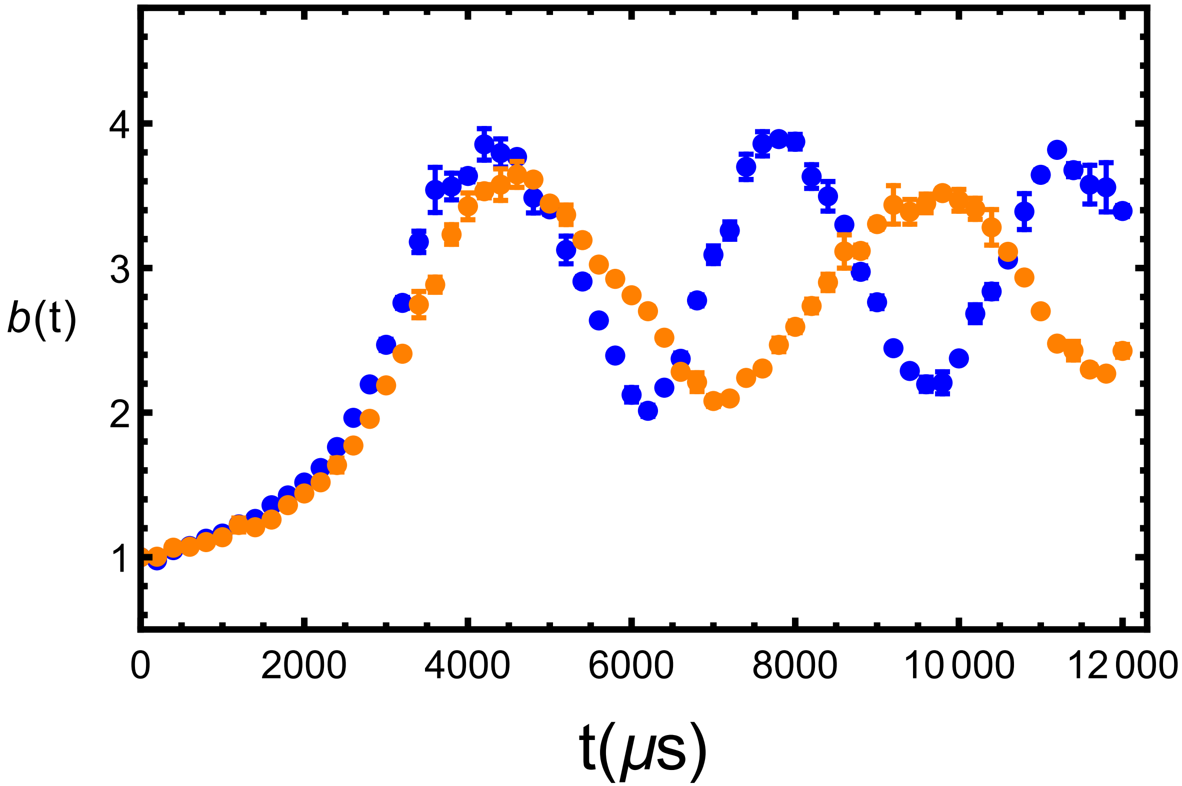
Scaling-invariant dynamics when $V(\gamma \mathbf{r}) = \gamma^{-2} V(\mathbf{r})$

Shortcut to adiabaticity = Fast motion video of adiabatic dynamics

$$\omega(t)^2 \rightarrow \Omega^2(t) = \omega^2(t) - \frac{3}{4}\frac{\dot{\omega}^2}{\omega^2} + \frac{1}{2}\frac{\ddot{\omega}}{\omega}.$$

A. del Campo, PRL **111**, 100502 (2013)

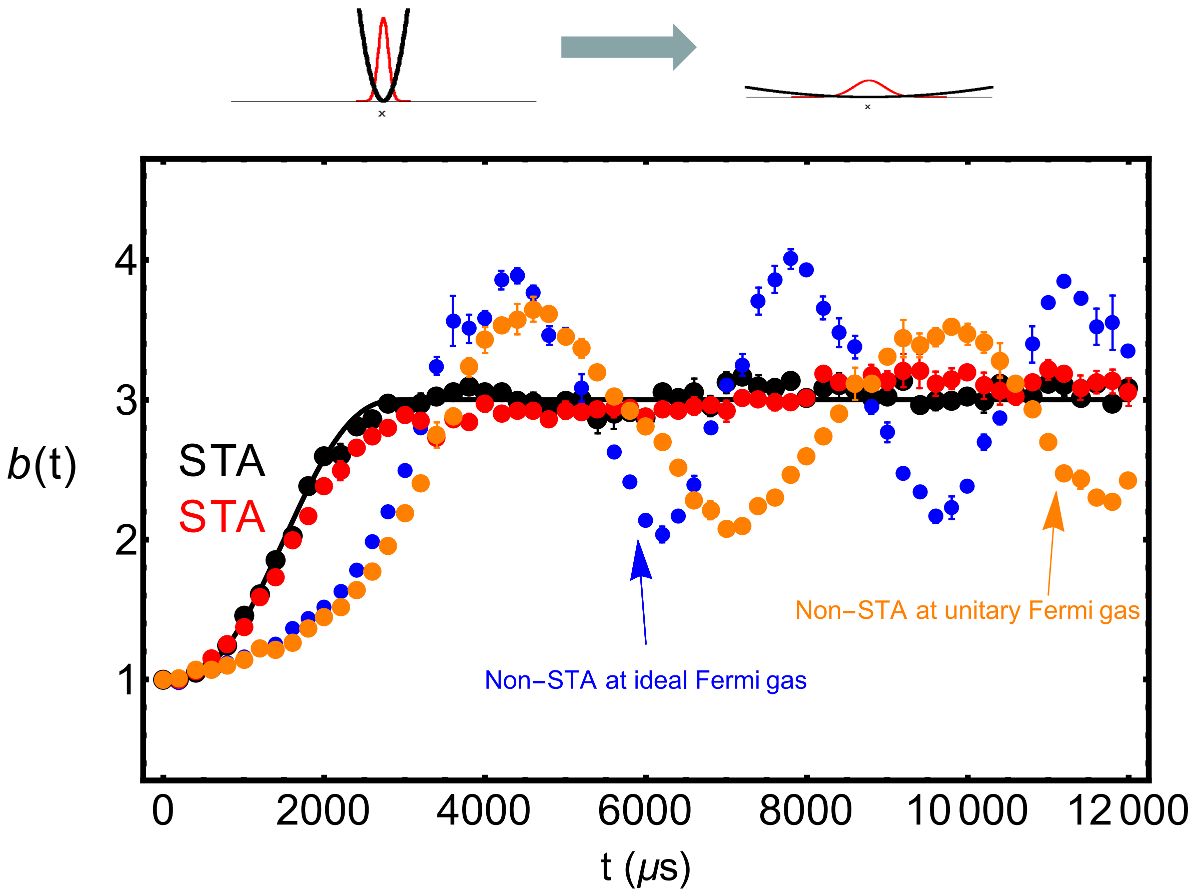
Evolution of cloud radius b(t) without STA



Theory
Quantum fluids
AdC PRA **84**, 031606(R) (2011)
AdC PRL **111**, 100502 (2013)

Experiment
STA in anisotropic unitary Fermi gas
Deng et al. PRA 97, 013628 (2018)
Deng et al. Sci. Adv. 4, eaar5909 (2018)

Evolution of cloud radius b(t) along a STA



Theory

Quantum fluids

AdC PRA **84**, 031606(R) (2011)

AdC PRL **111**, 100502 (2013)

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STA in anisotropic unitary Fermi gas

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Deng et al. Sci. Adv. 4, eaar5909 (2018)

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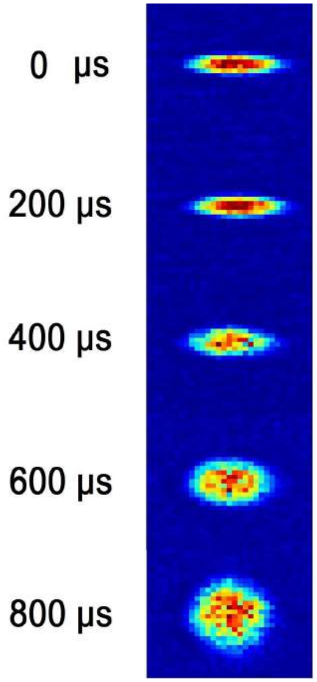
Shortcuts: Suppressing quantum friction

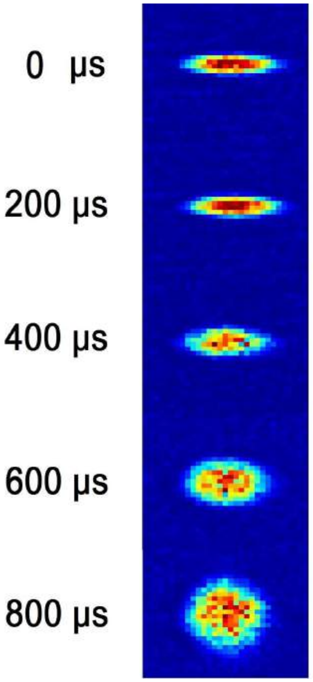
$$\langle H(t)\rangle = Q^*(t)\langle H(t)\rangle_{\mathrm{adiab}} \qquad Q^*(t)\geq 1$$

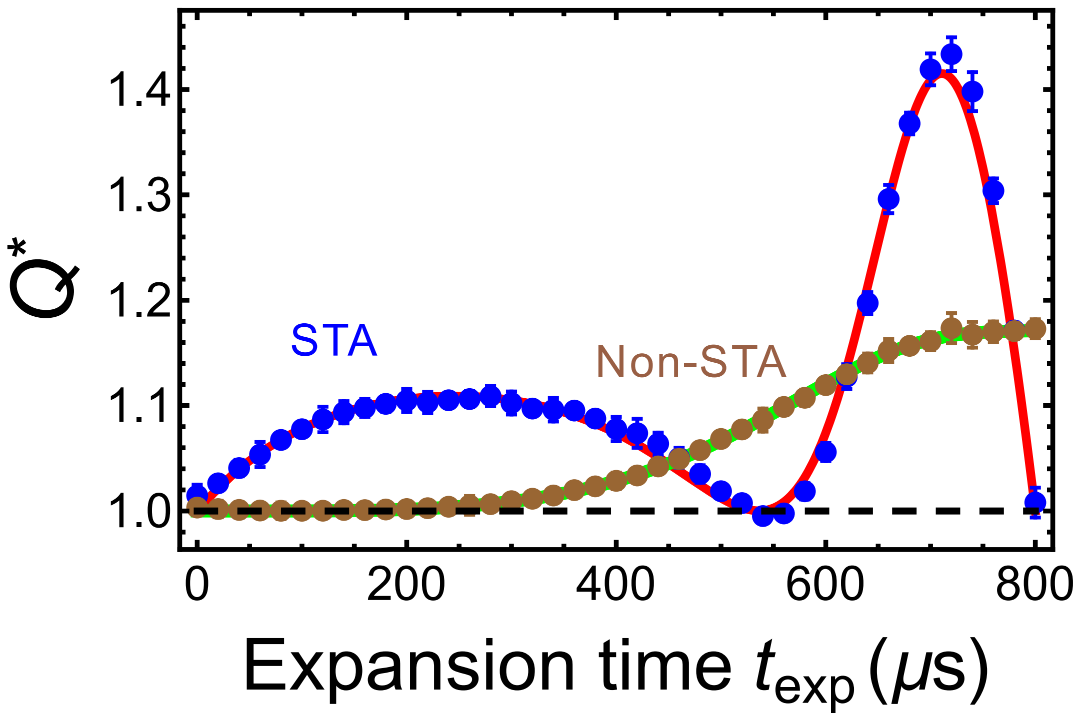


Deng et al. Sci. Adv. 4, eaar5909 (2018)

Shortcuts: Suppressing quantum friction

$$\langle H(t)\rangle = Q^*(t)\langle H(t)\rangle_{\rm adiab} \qquad Q^*(t)\geq 1$$





Deng et al. Sci. Adv. 4, eaar5909 (2018)

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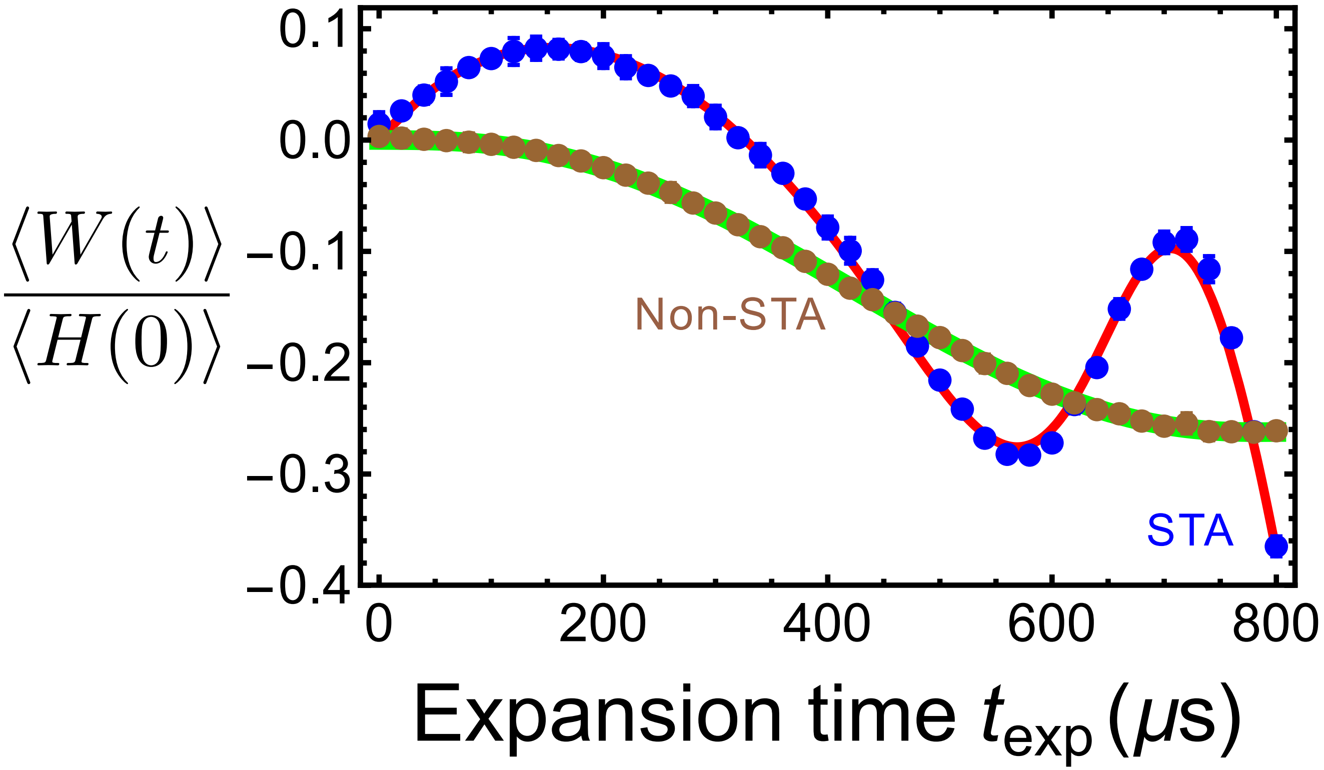
Work output with/without STA



Deng et al. Sci. Adv. 4, eaar5909 (2018)

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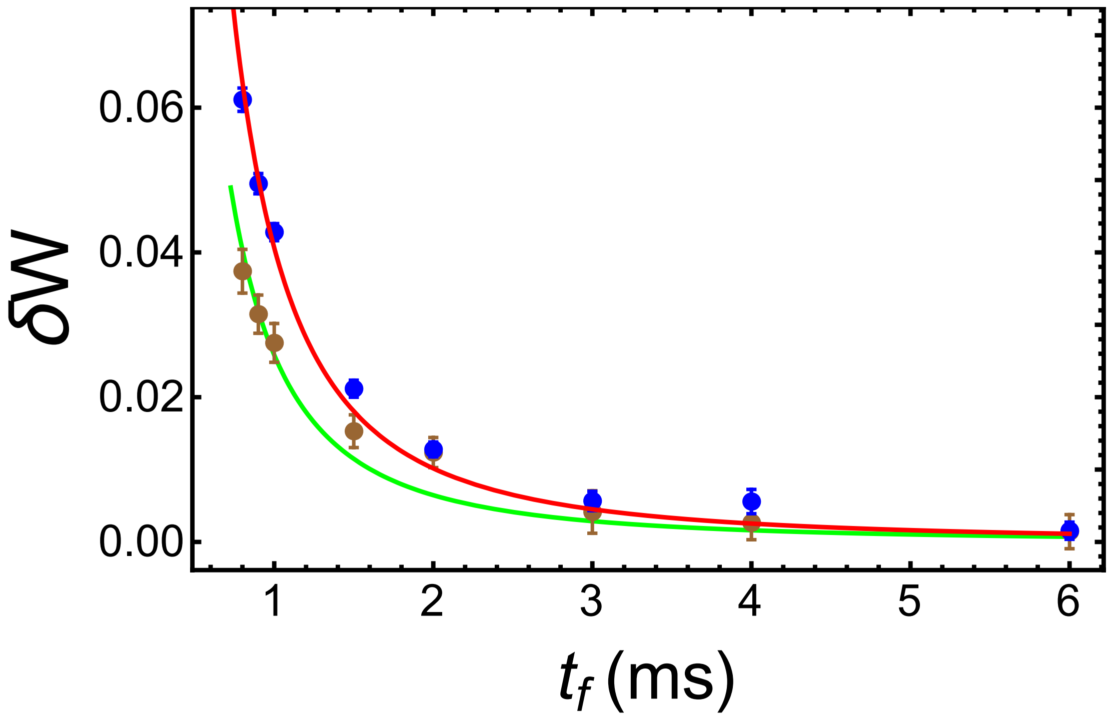
Integrated irreversible work along STA



$$\delta W = \frac{1}{t_f}\int_0^{t_f} dt \left[\langle W(t)\rangle - \langle W_{ad}(t)\rangle\right] \sim \frac{1}{t_f^2}$$

Deng et al. Sci. Adv. 4, eaar5909 (2018)

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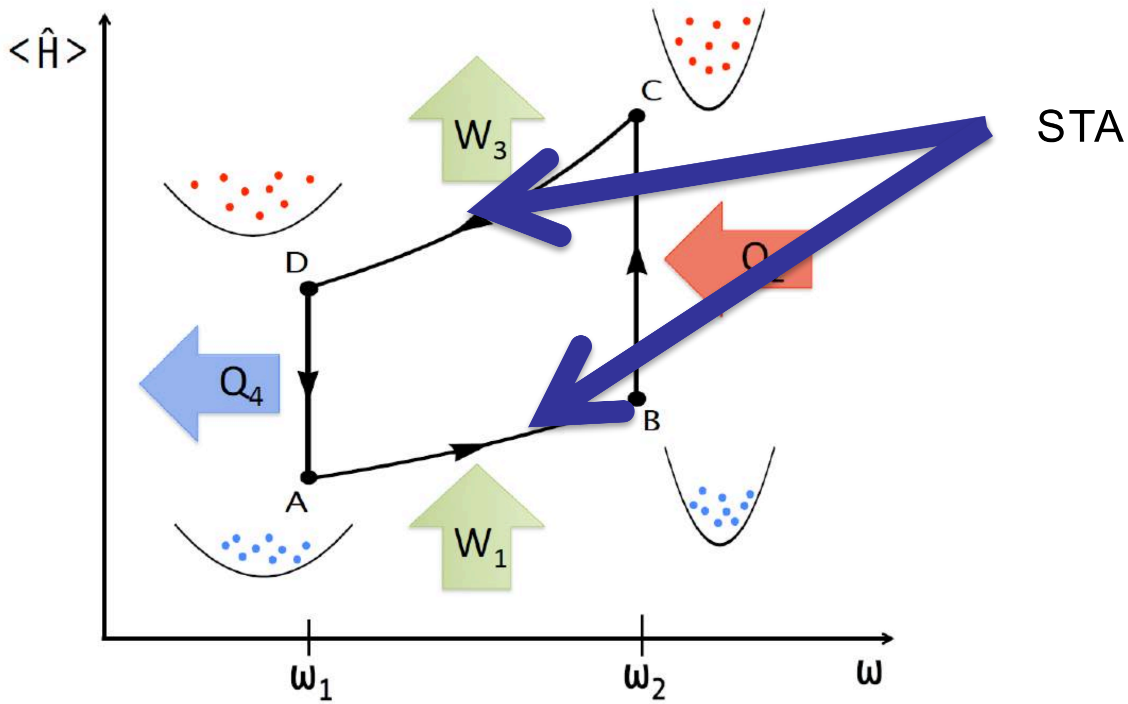
Quantum Heat Engines (e.g. Otto Cycle)



Superadiabatic heat engines

Fast and Frictionless

$$\eta_{\mathrm{STA}} = \eta_{\max} = 1 - \frac{\omega_1}{\omega_2}$$

- AdC, J. Goold, M. Paternostro, Sci. Rep. **4**, 6208 (2014) (single-particle)
- M. Beau, J. Jaramillo, AdC, Entropy **18**, 168 (2016) (many-particle)

See too: Abah-Lutz EPL 118, 40005 (2017)

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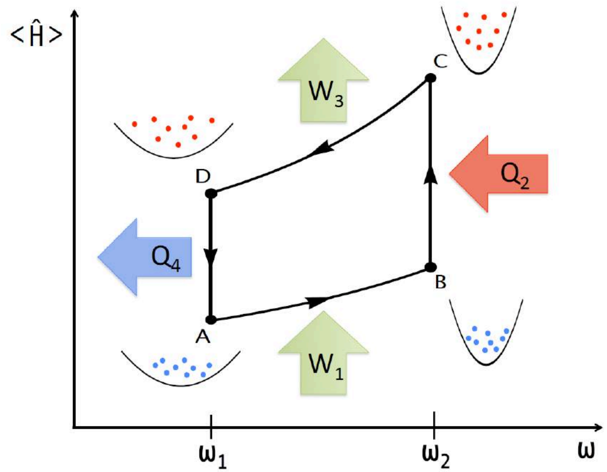
Full engine cycle?

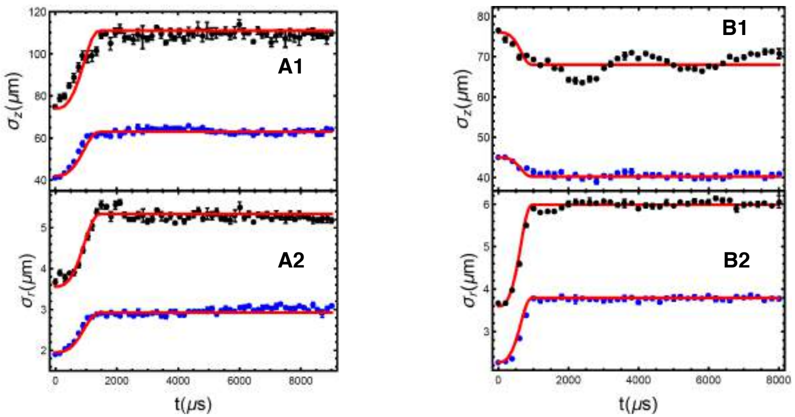
Missing strokes

Hot isochore: parametric heating

Cold isochore: ?



Hot isentropic stroke: viscous hydrodynamics can limit STA (Diao et al. NJP, TBS)



Talk by R. Serra
Thu 28

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Deng et al. Sci. Adv. 4, eaar5909 (2018), book chapter arXiv:1804.00604

Part II

Work statistics in complex systems

A. Chenu, I. L. Egusquiza, J. Molina-Vilaplana, AdC, arXiv:1711.01277
A. Chenu, J. Molina-Vilaplana, AdC, arXiv:1804.09188

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

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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

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

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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., arXiv:1711.01277; arXiv:1804.09188

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Characteristic function as a Loschmidt echo amplitude

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

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Loschmidt echo

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

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A. Chenu et al., arXiv:1711.01277; arXiv:1804.09188

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)

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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

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A. Chenu et al., arXiv:1711.01277; arXiv:1804.09188

AdC, J. Molina-Vilaplana, J. Sonner, PRD 95, 126008 (2017)

Work statistics and information scrambling

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A. Chenu et al., arXiv:1711.01277; arXiv:1804.09188

AdC, J. Molina-Vilaplana, J. Sonner, PRD 95, 126008 (2017)

See too connections P(W) & OTOC

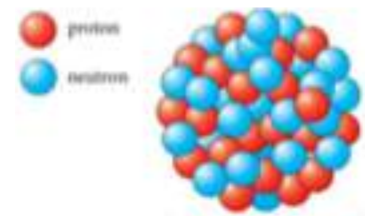
Goold Campisi PRE 95, 062127 (2017)

Yunger Halpern PRA 95, 012120 (2017)

Chaos & Complex systems

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

Described by Random Matrix Theory

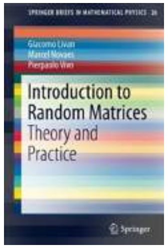


Heavy Nucleus Systems

Ensembles of random matrices

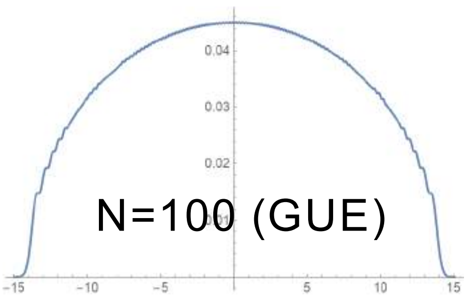
Gaussian Unitary Ensembles (GUE): Hermitian Hamiltonians

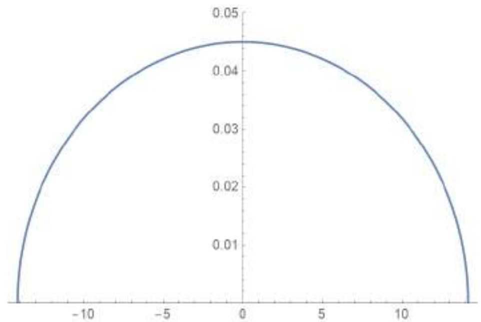
Gaussian Orthogonal Ensembles (GOE): Real Symmetric Hamiltonians with time-reversal symm



Chaos & Complex systems

Density of states: Universal for large Hilbert space dimension N





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

Eigenvalues spacing

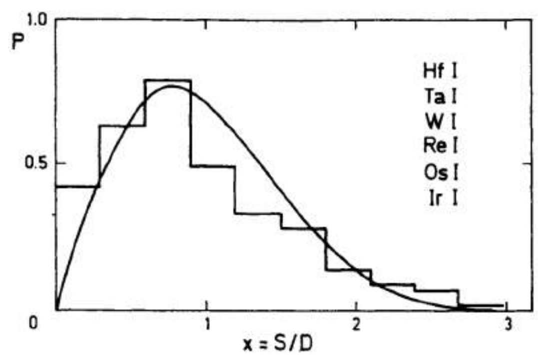


Figure 1.6. Plot of the density of nearest neighbor spacings between odd parity atomic levels of a group of elements in the region of osmium. The levels in each element were separated according to angular momentum, and separate histograms were constructed for each level series, and then combined. The 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).

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:

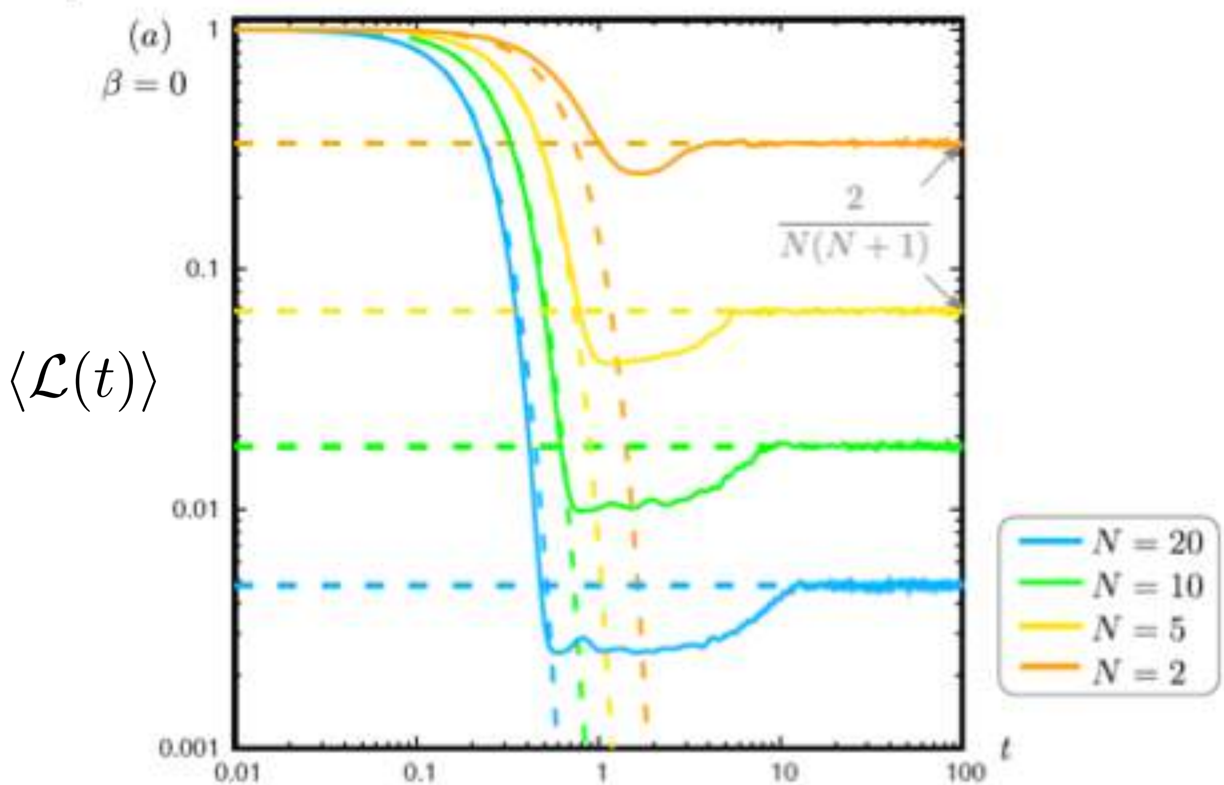
RMT large N asymptotics: M. Łobejko, J. Łuczka, P. Talkner PRE 95, 052137 (2017)

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

Chaos & Complex systems

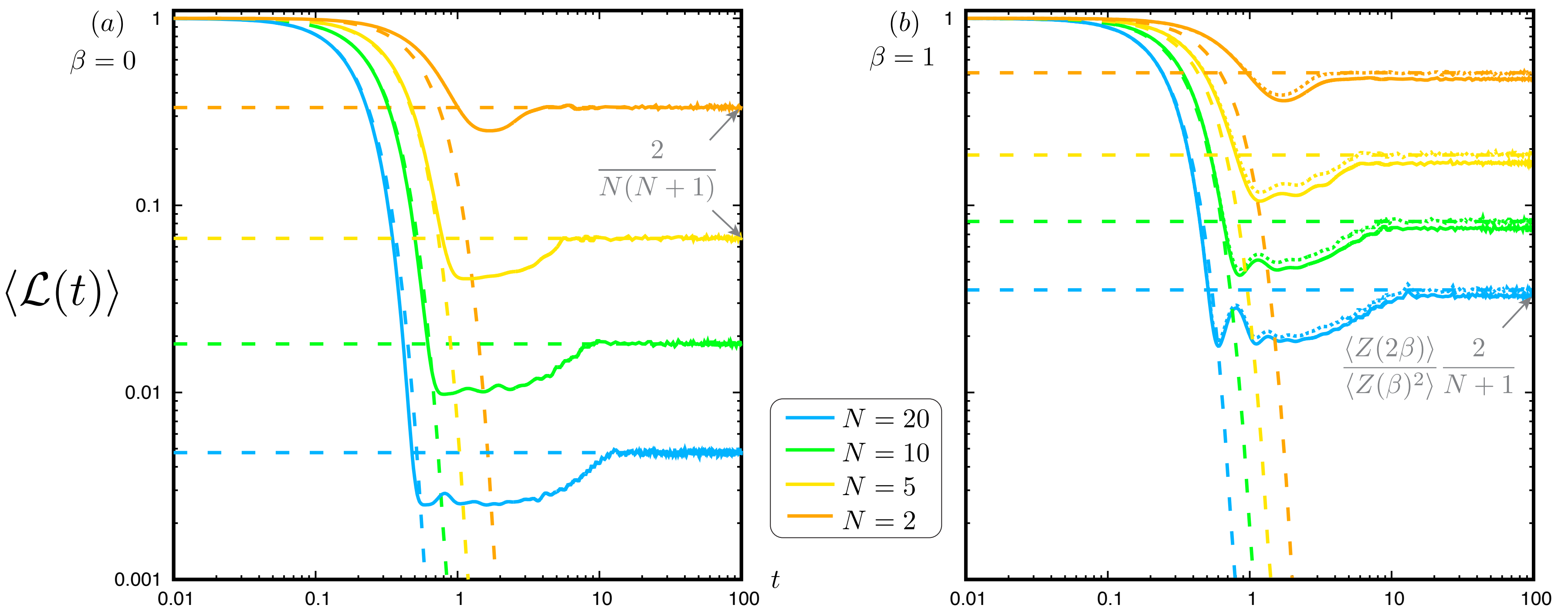
Initial thermal state $$|\Psi_0\rangle = \frac{1}{\sqrt{Z(\beta)}} \sum_n e^{-\frac{\beta}{2}\hat{H}_0 \otimes \mathbf{1}_R} |n_0\rangle_L \otimes |n_0\rangle_R$$

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



A. Chenu et al., arXiv:1804.09188

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 $\langle \mathcal{L}(t) \rangle_{\mathrm{GUE}} \rightarrow \frac{\langle Z(2\beta) \rangle}{\langle Z(\beta)^2 \rangle} \frac{2}{(N+1)}$

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A. Chenu et al., arXiv:1804.09188

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 partition function

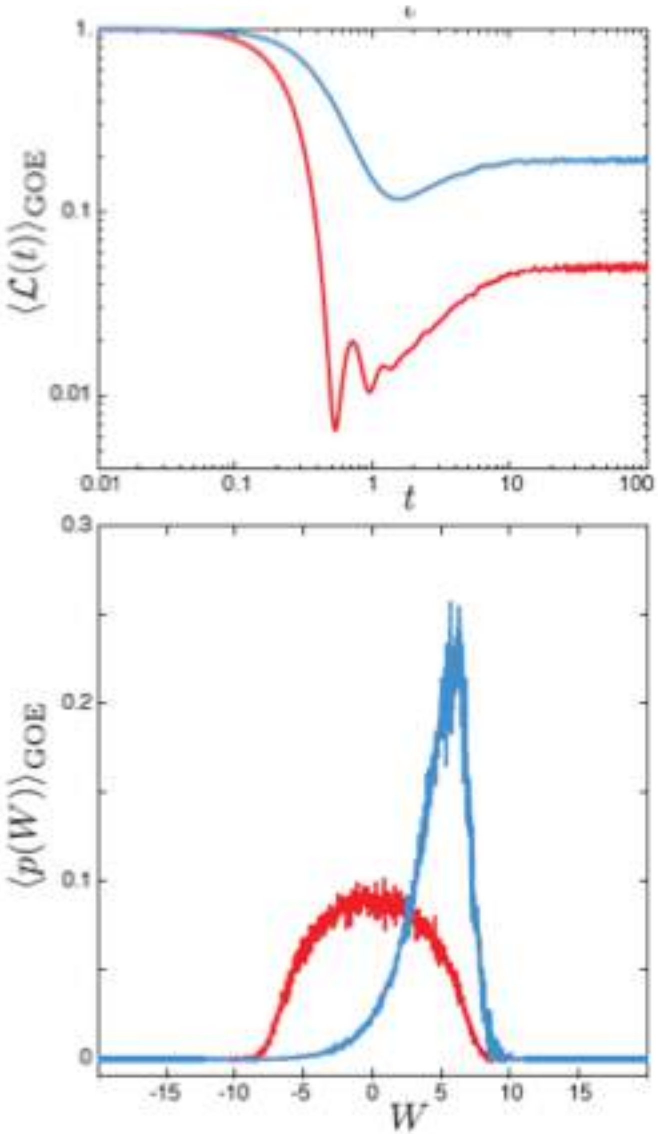
$$\mathcal{L}(t) = |\langle \Psi_0 | \Psi_0(t) \rangle|^2 = \left| \frac{Z(\beta + i2t)}{Z(\beta)} \right|^2$$

Work pdf

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

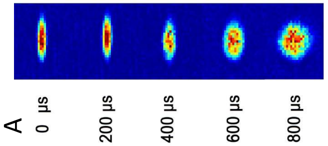
Mean work

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



A. Chenu et al., arXiv:1711.01277

Summary



- Friction-free quantum machines
  - via Shortcuts to Adiabaticity
  - Ideal and Unitary Fermi gas
  - Friction measurement & control of

- 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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Thanks
for your attention!!