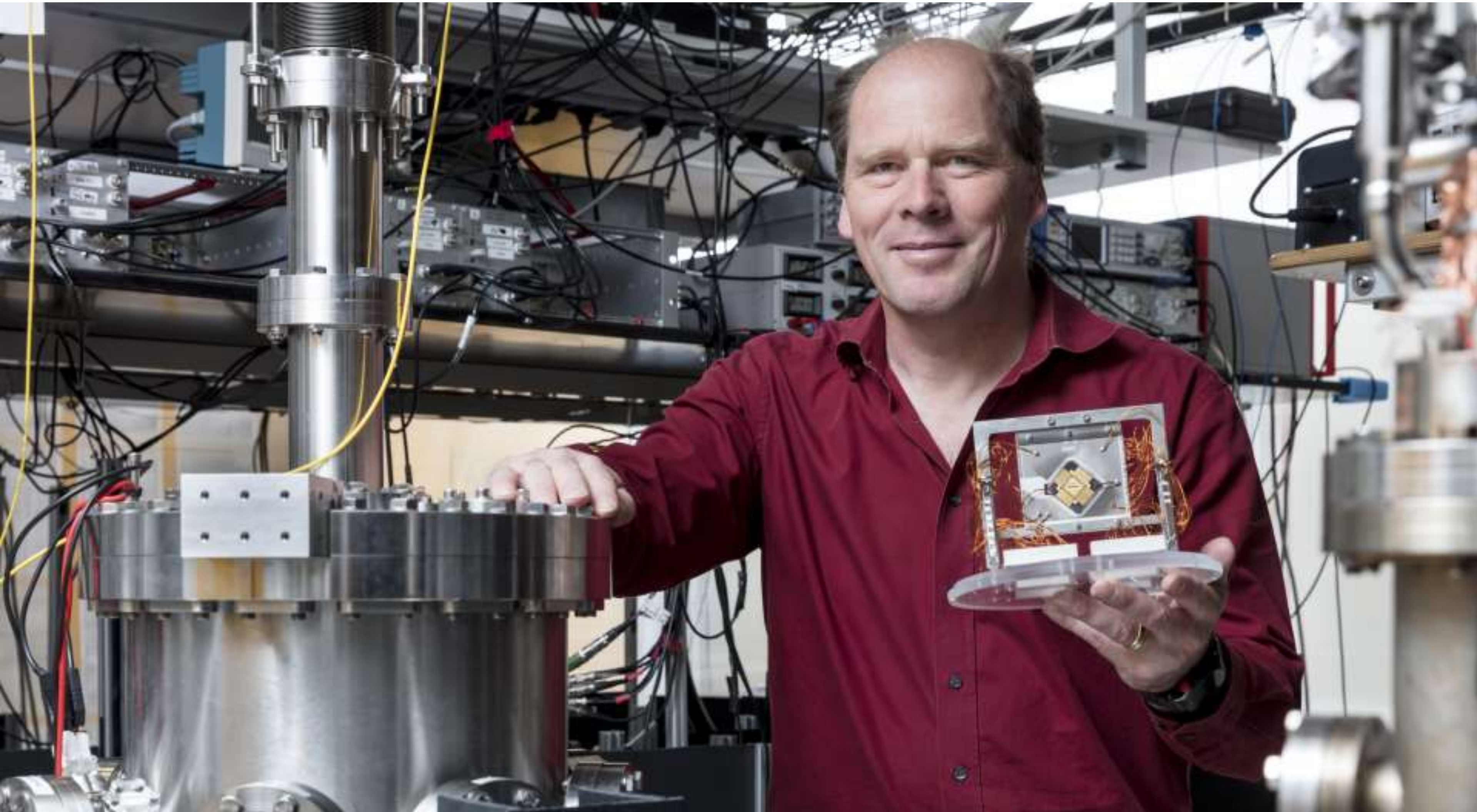
Quantum information with trapped ions

- Trapped ions as qubits for quantum computing and simulation
- Qubit architectures for scalable entanglement



Quantum thermodynamics with ions

- Quantum thermodynamics introduction
- Heat transport, Fluctuation theorems,
- Phase transitions, Heat engines
- Outlook

Hartmut
Häffner

Kihwan
Kim

Dzmitry
Matsukevich

清華大學 Tsinghua University 量子信息中心 Center for Quantum Information

Centre for Quantum Technologies

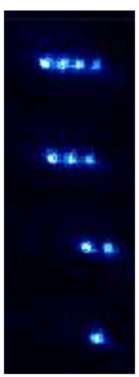
Overview

km

m

mm

µm



nm

Large system:
Many degrees of freedom
and many particles

Average values

In equilibrium, or very close to it

Fluctuations unimportant

Small system:
few degrees of freedom
and single particles

Work probability distribution

Thermal fluctuations

Brownian motion

Quantum system: Quantized
degrees of freedom,
superpositions and entanglement

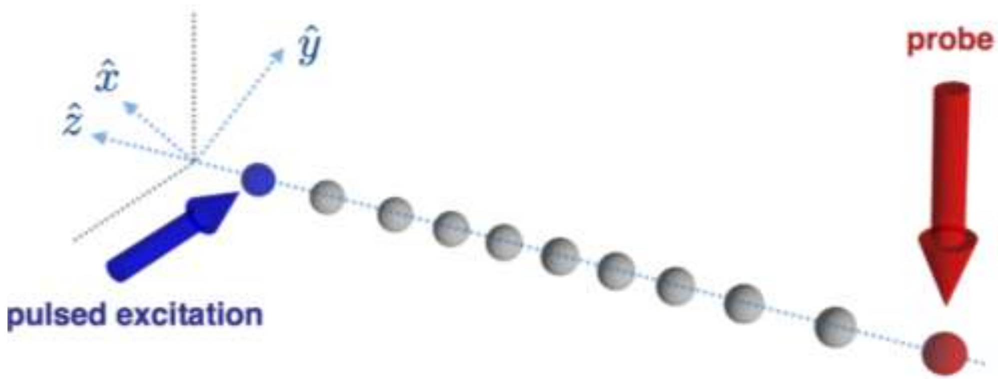
Probabilistic nature
of quantum processes

Observation of system matters

Correlations with
environment (bath) matter

New machines

Energy transport



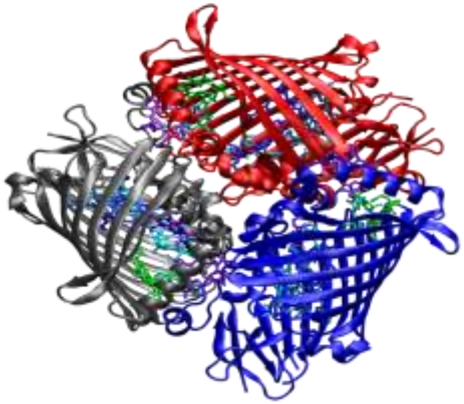
Hartmut Häffner

Transport of radial phonons via a linear ion crystal

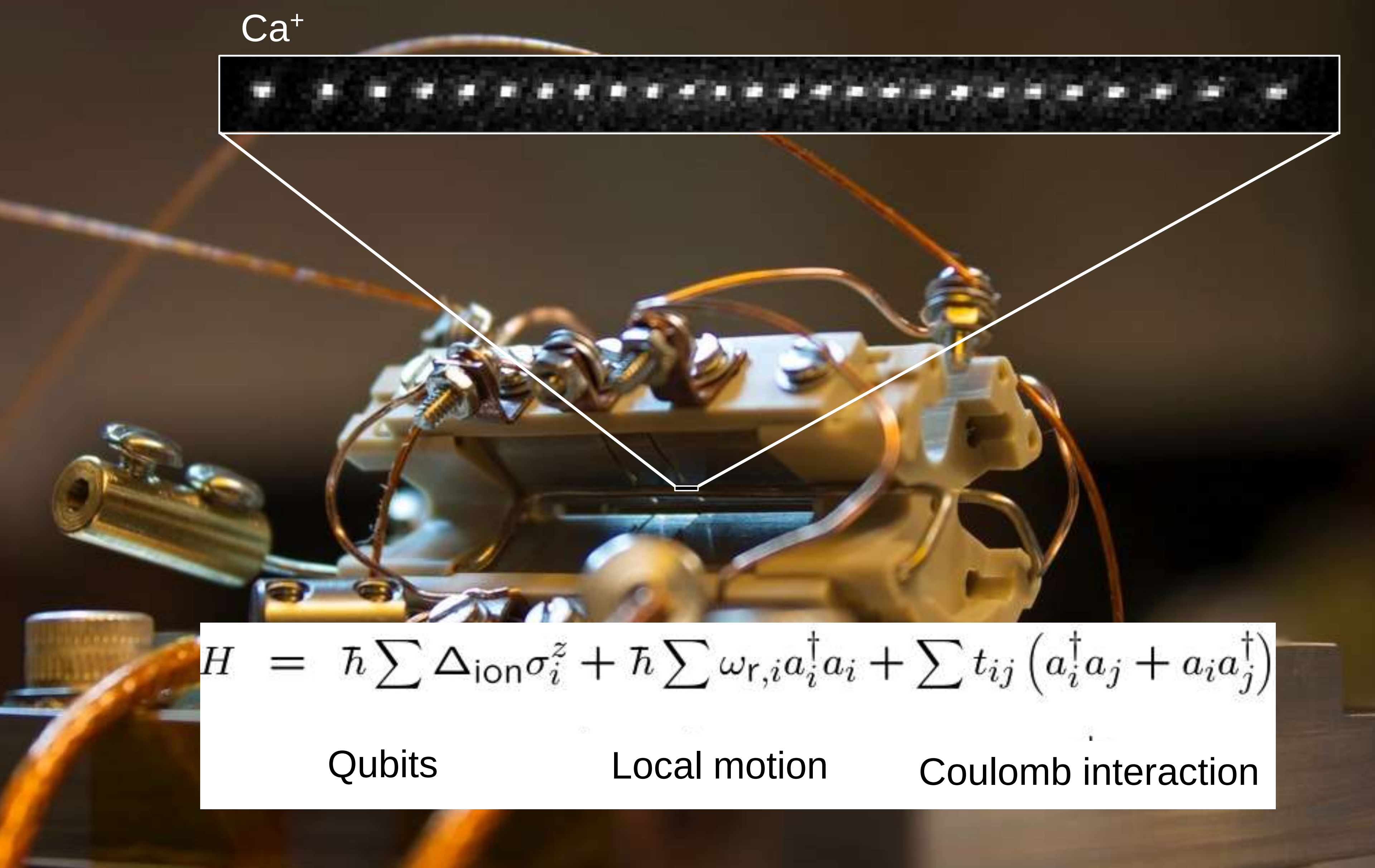
Energy propagation
Propagation of quantum correlations

Vibrationally assisted energy transport

Explores high dimensional Hilbert space
Transport involving nonlinear interactions
Understanding transport principles in light harvesting



The ion crystal

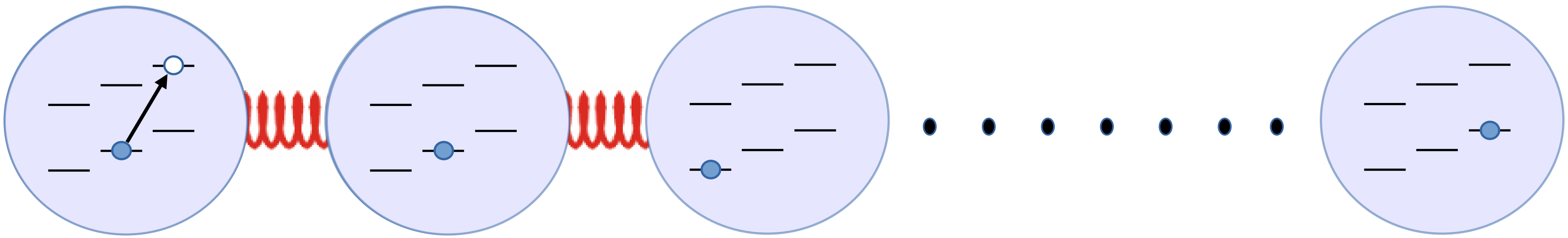


$$H = \hbar \sum \Delta_{\text{ion}} \sigma_i^z + \hbar \sum \omega_{\text{r},i} a_i^\dagger a_i + \sum t_{ij} \left(a_i^\dagger a_j + a_i a_j^\dagger \right)$$

Qubits | Local motion | Coulomb interaction

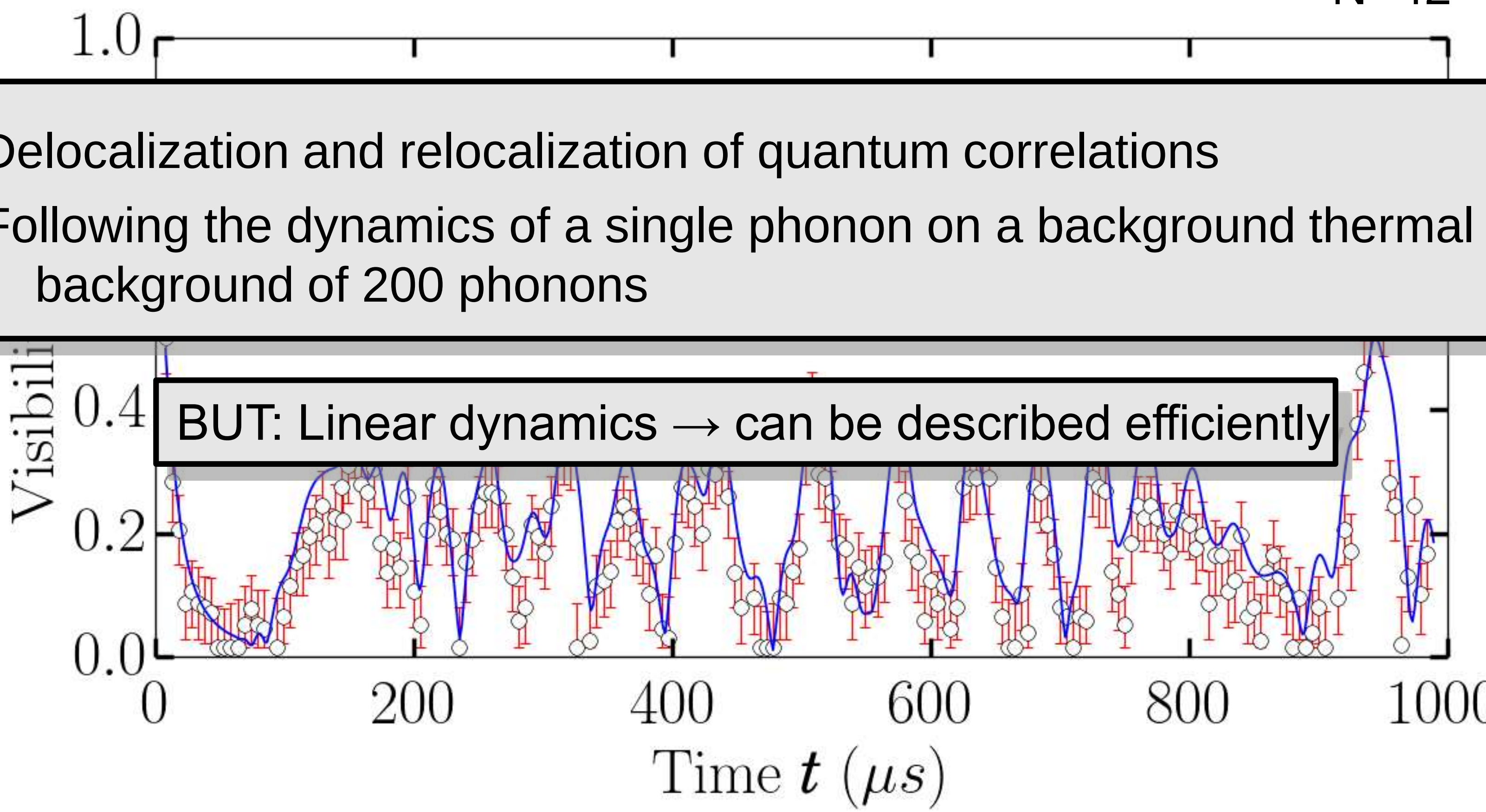
The scheme:

$$|S\rangle\,|n\rangle + |D\rangle\,|n+1\rangle \longrightarrow |S\rangle\,|\Psi(t)\rangle + |D\rangle\,|\Psi_\epsilon(t)\rangle$$



- Excite first ion on sideband, generates spin-motion entanglement
- Motion propagates throught the crystal
- Wait-time
- Analyse if motion returned back
- Contrast of Ramsey reveals delocalization of motional excitation

Result:



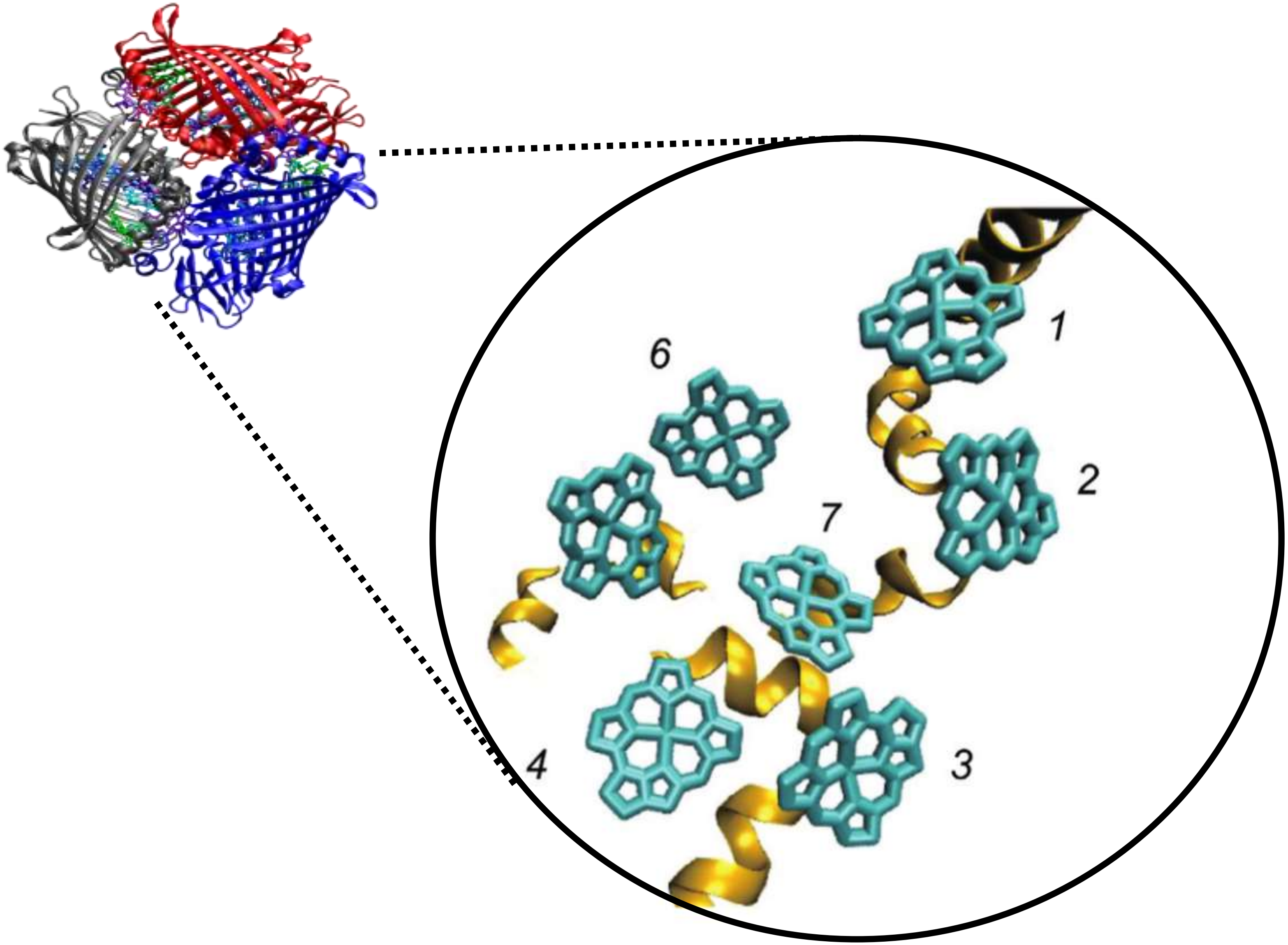
Delocalization and relocalization of quantum correlations

Following the dynamics of a single phonon on a background thermal background of 200 phonons

BUT: Linear dynamics → can be described efficiently

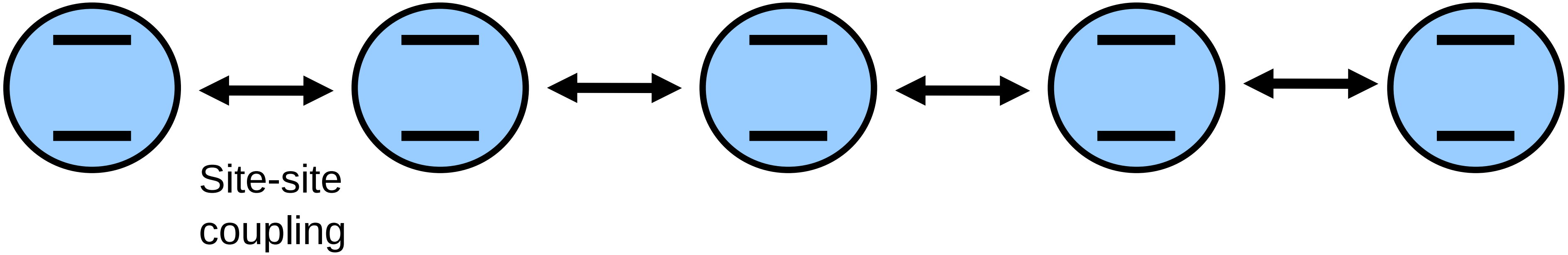
Ramm et al., NJP 16 063062 (2014)
Abdelrahman et al., Nat. Comm. 8 15712 (2017)

Light harvesting complex



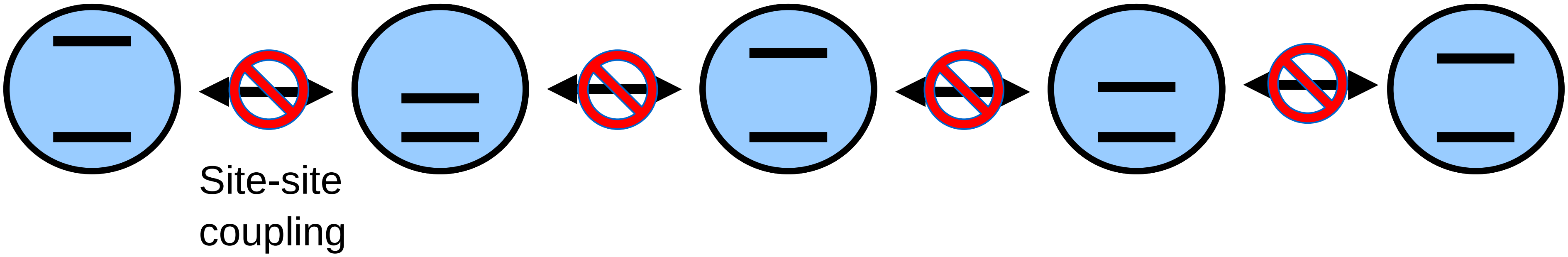
Ishizaki, Flemming, PNAS **106** 17255 (2009)

Light harvesting complex - model

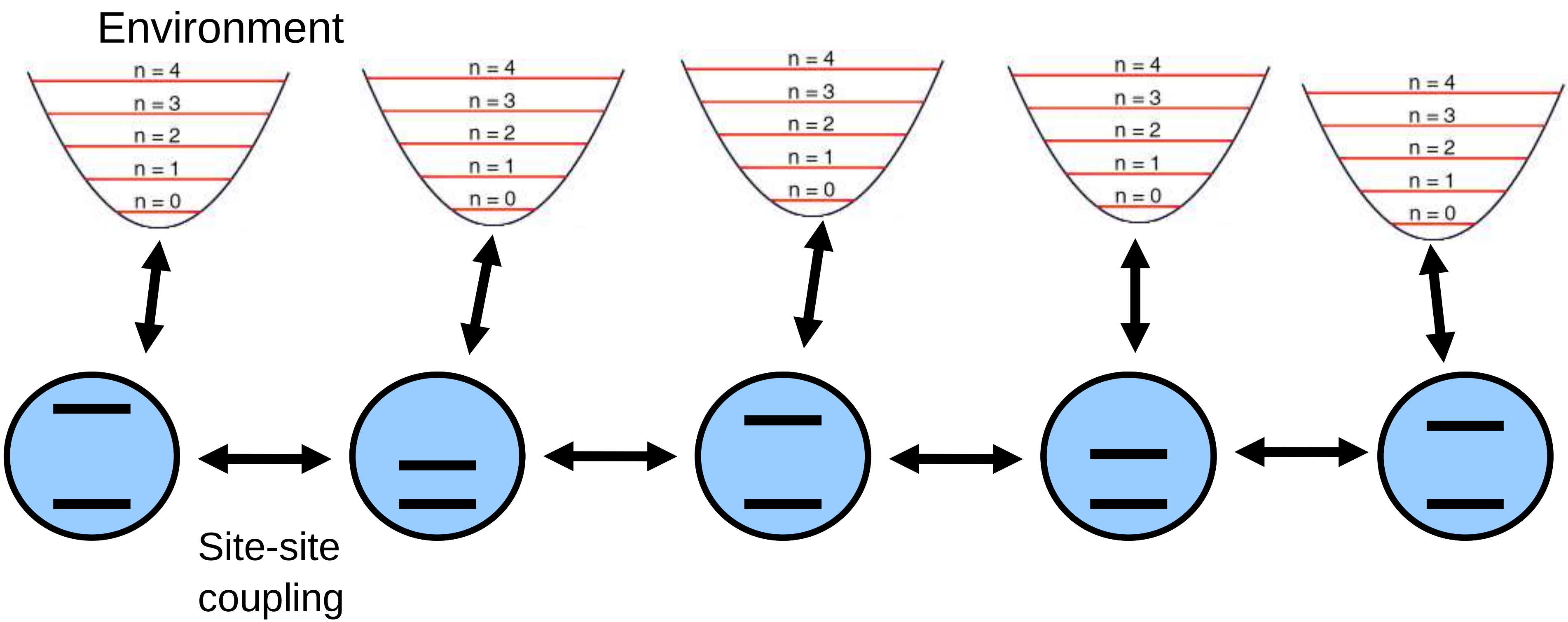


Light harvesting complex - model

Inhomogenity inhibits the energy transfer



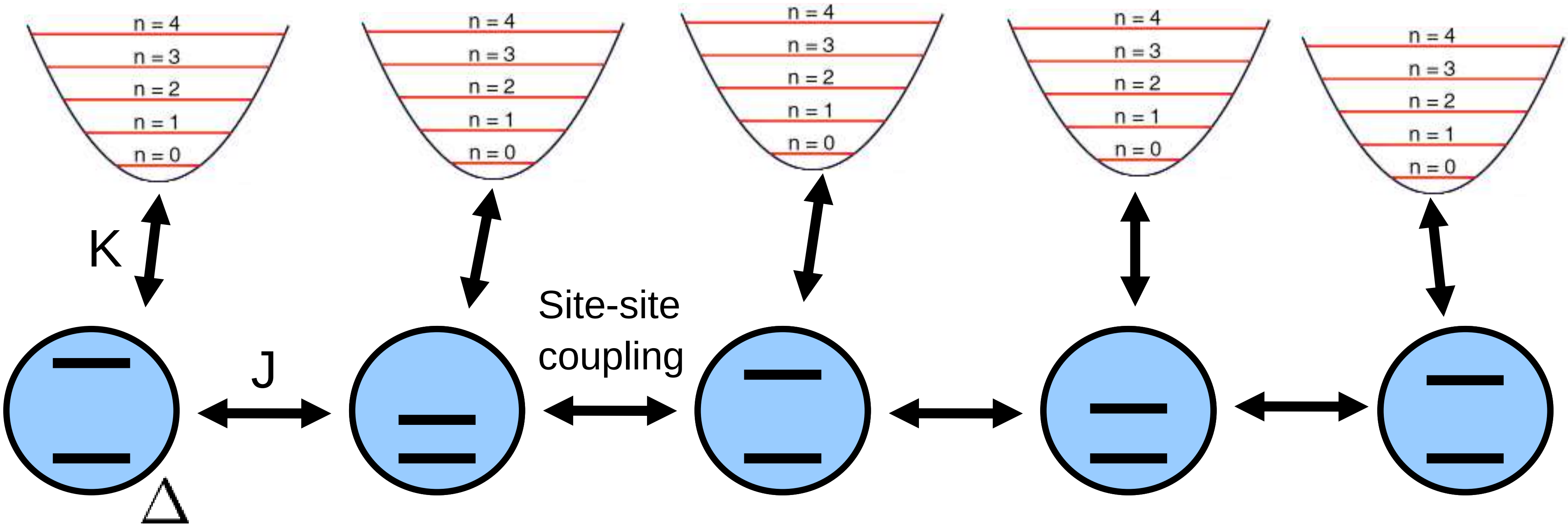
Light harvesting complex - model



Environment helps fulfilling resonance condition

Vibrationally assisted energy transport

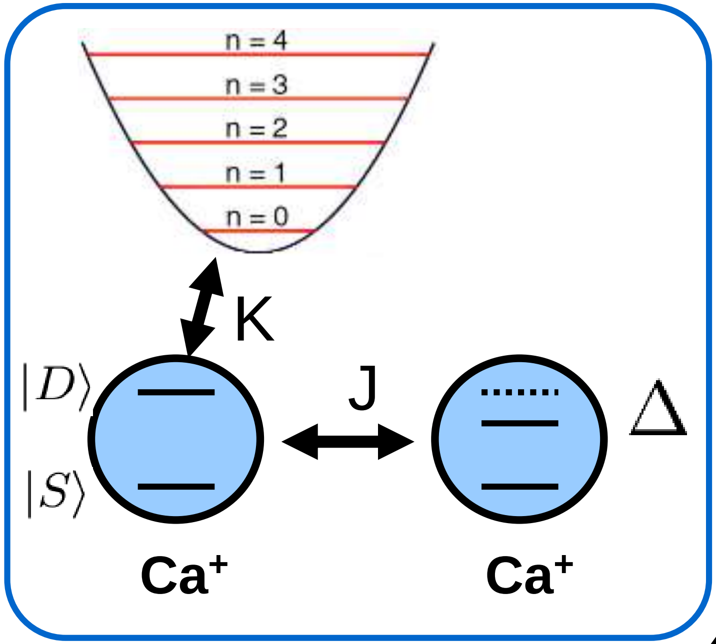
Full Hamiltonian



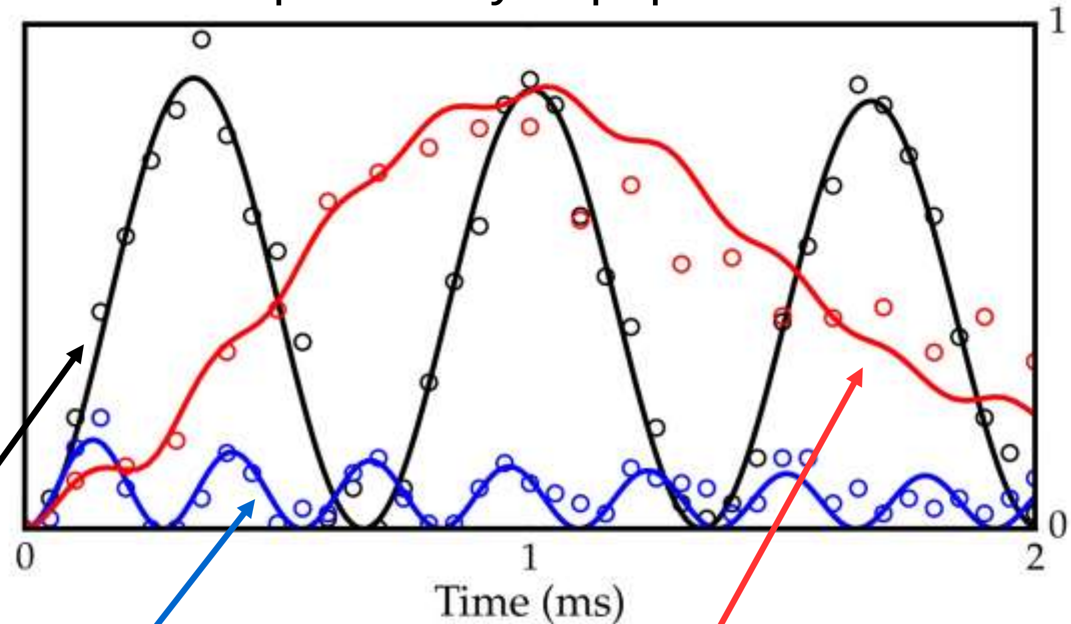
Even for small phonon excitation and few ions becomes high dimensional Hilbert space

$$H_{\text{eff}}/\hbar = \sum_{i,j} \frac{J_{ij}}{2}\left(\sigma_i^+\sigma_j^- + \sigma_i^-\sigma_j^+\right) + \sum_{i,j} \frac{K_{ij}}{2}\sigma_i^z\left(a_i + a_i^\dagger\right) + \sum_i \frac{\Delta_i}{2}\sigma_i^z + \sum_i \nu_i a_i^\dagger a_i$$

Minimal system – two ions



Measured probability of population transfer

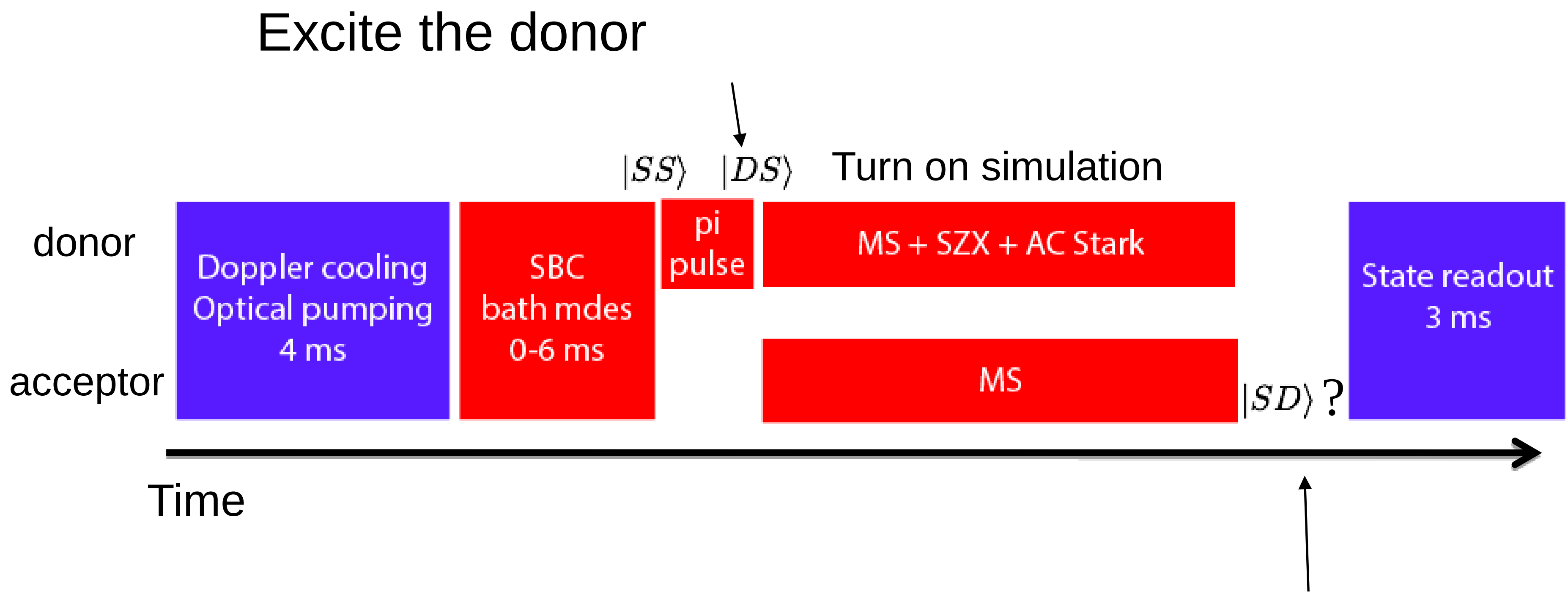


Vibrationally assisted energy transport

$$H = \frac{J}{2}\sigma_x^1\sigma_x^2 + \frac{\Delta}{2}\sigma_z^1 + \nu_{\text{eff}}a^\dagger a + \frac{K}{2}\sigma_z^1\left(a + a^\dagger\right)$$

Site-site coupling Detuning Spin-bath coupling

Measurement sequence



Measure population in acceptor state |SD>

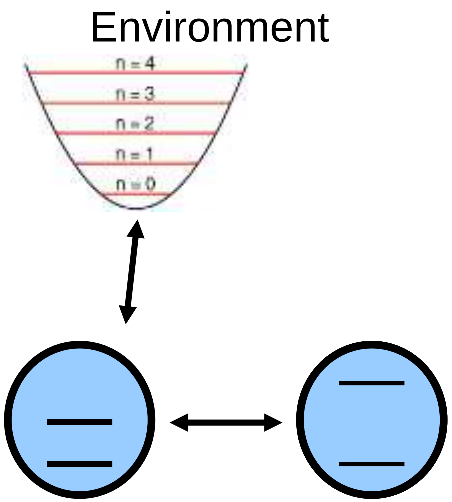
Parameter control

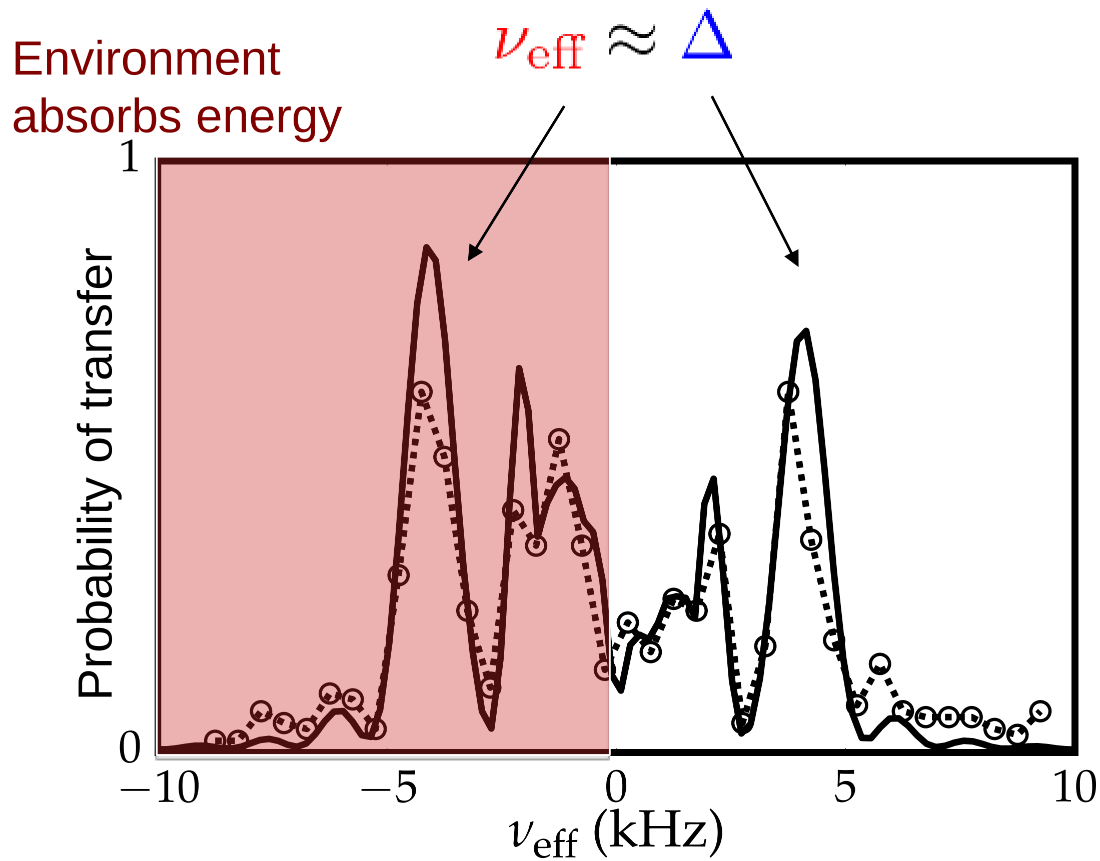
J = 1.3 kHz
K = 1.4 kHz
Δ = 4 kHz

$$H = \frac{J}{2}\sigma_x^1\sigma_x^2 + \frac{\Delta}{2}\sigma_z^1 + \frac{K}{2}\sigma_z^1(a + a^\dagger) + \nu a^\dagger a$$

Gorman *et al.*, PRX **8**, 011038 (2018)

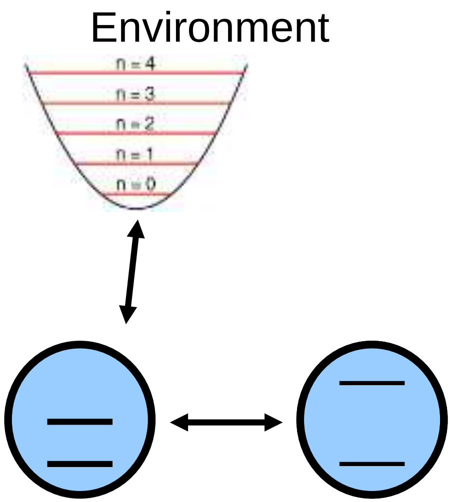
Result

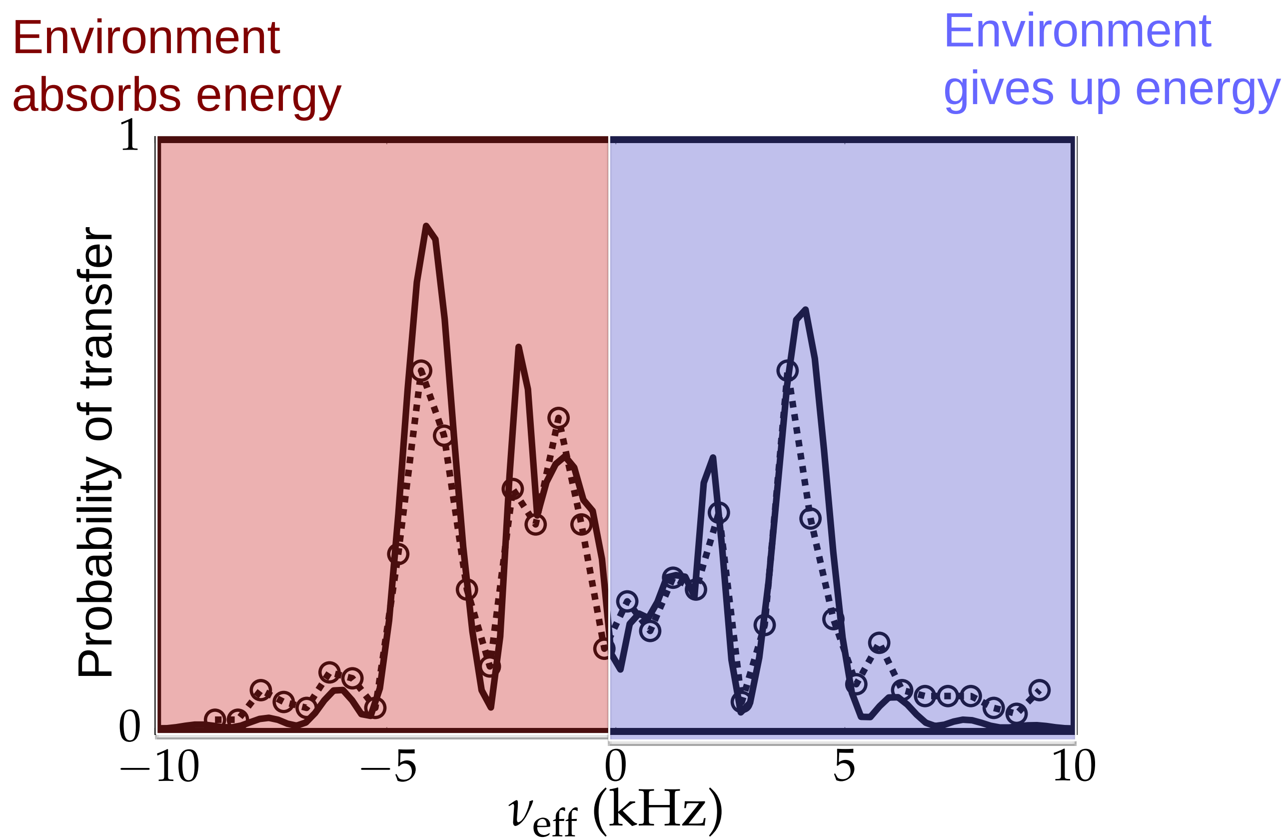




Gorman *et al.*, PRX**8**, 011038 (2018)

Result

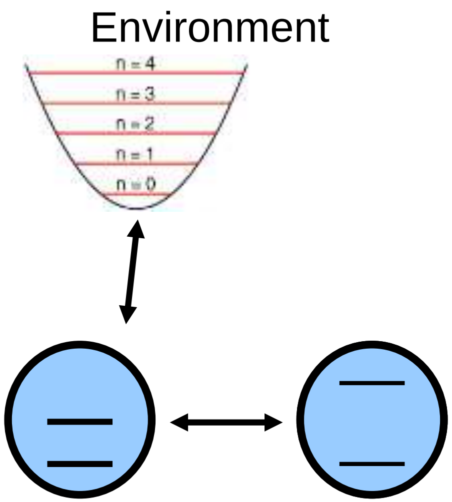


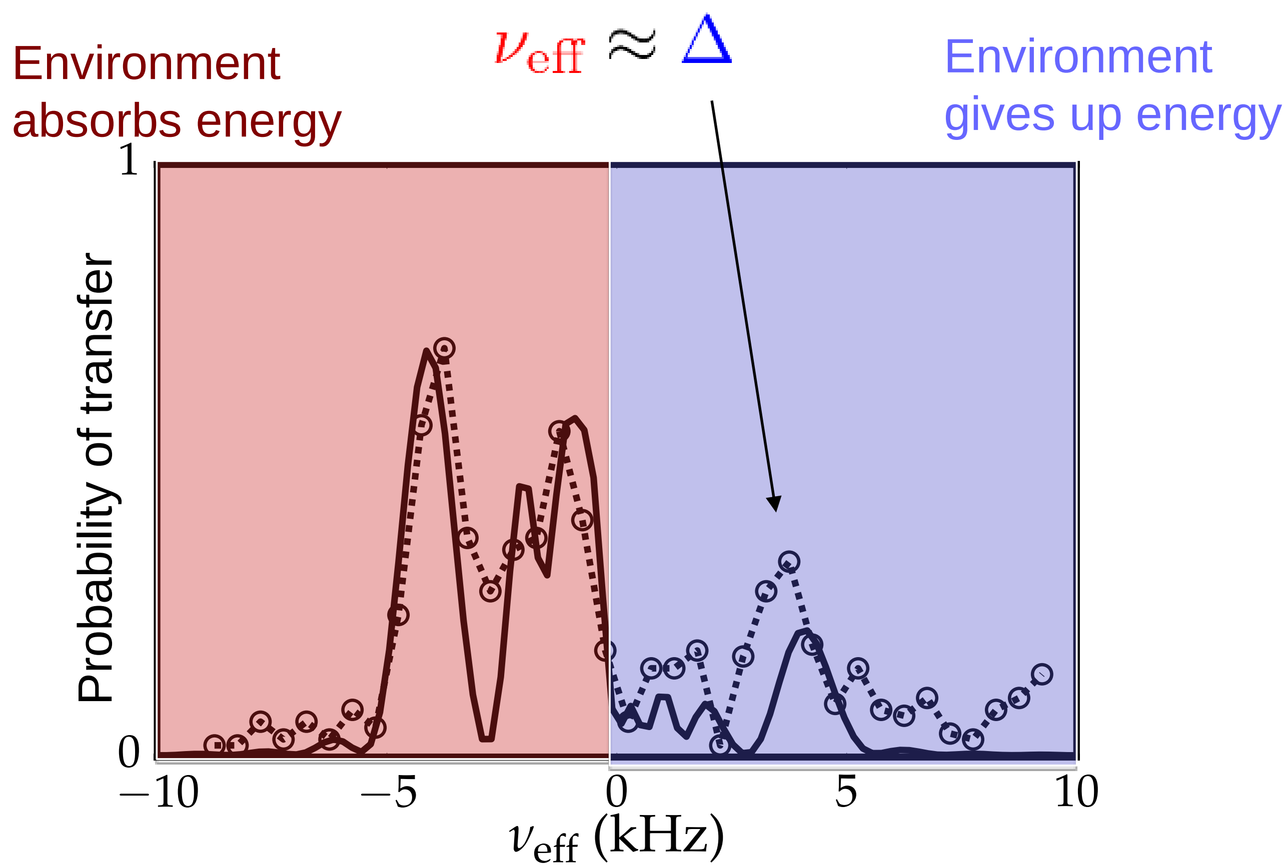


Gorman *et al.*, PRX **8**, 011038 (2018)

Result

Temperature reduced from <n>=5 to <n>=0.5





Related work with SC: Potočnik *et al.*, Nat. Comm **9**, 904 (2018)

Gorman *et al.*, PRX **8**, 011038 (2018)

Quantum thermodynamics with ions

- Quantum thermodynamics introduction
- Heat transport
- Phase transitions
- Fluctuation theorem
- Single ion refrigerator
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Hartmut Häffner

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清華大學 Tsinghua University

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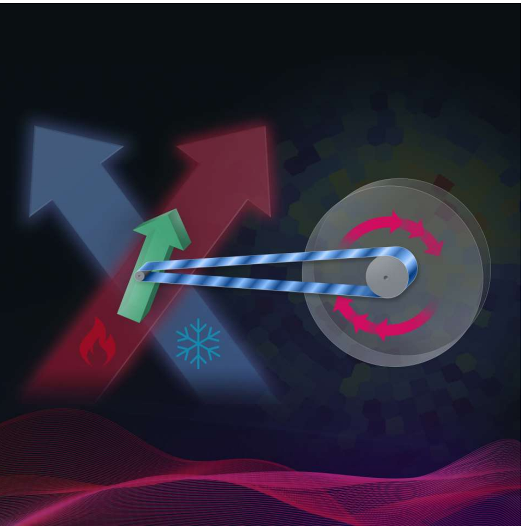
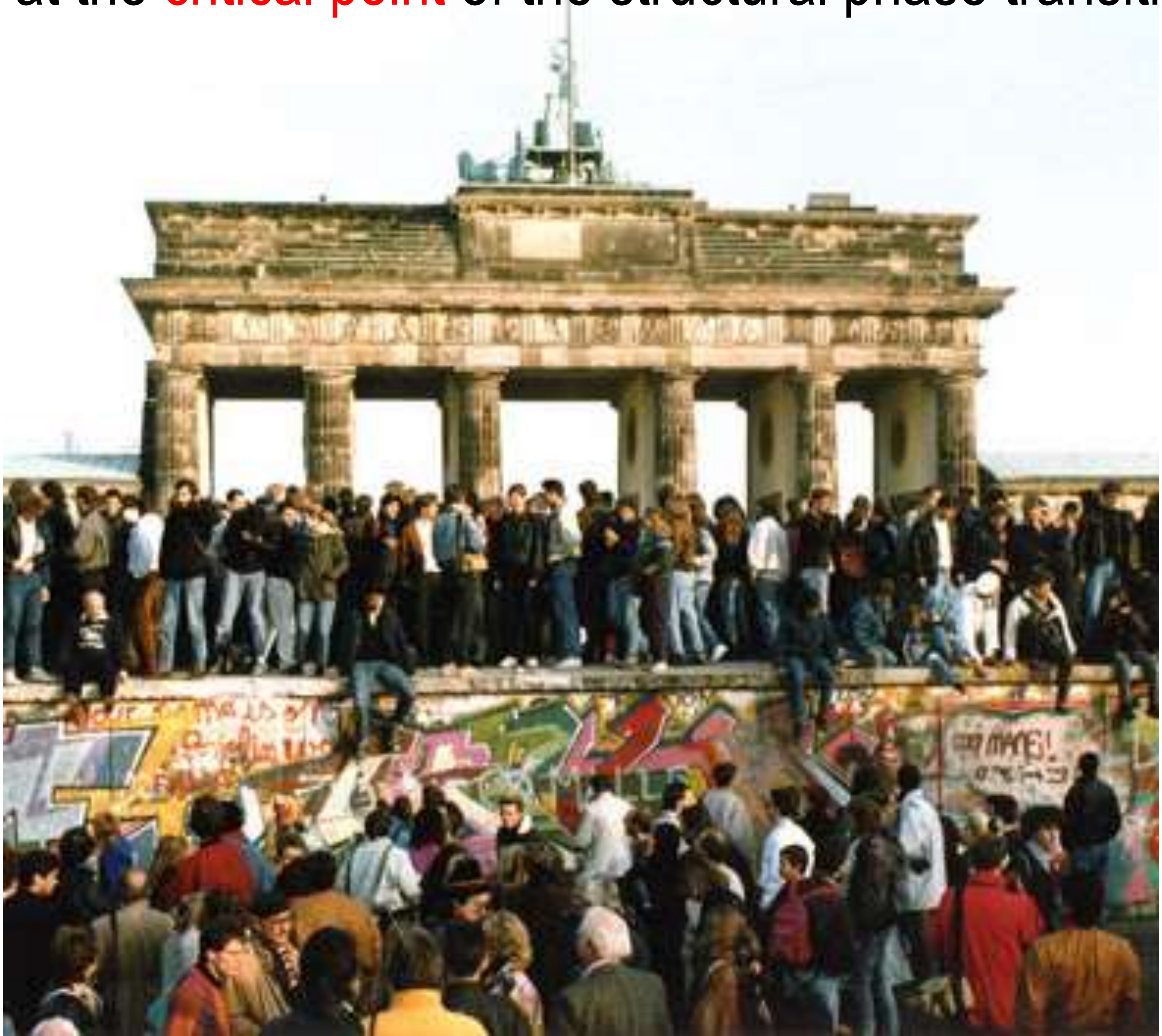
CQT Centre for Quantum Technologies



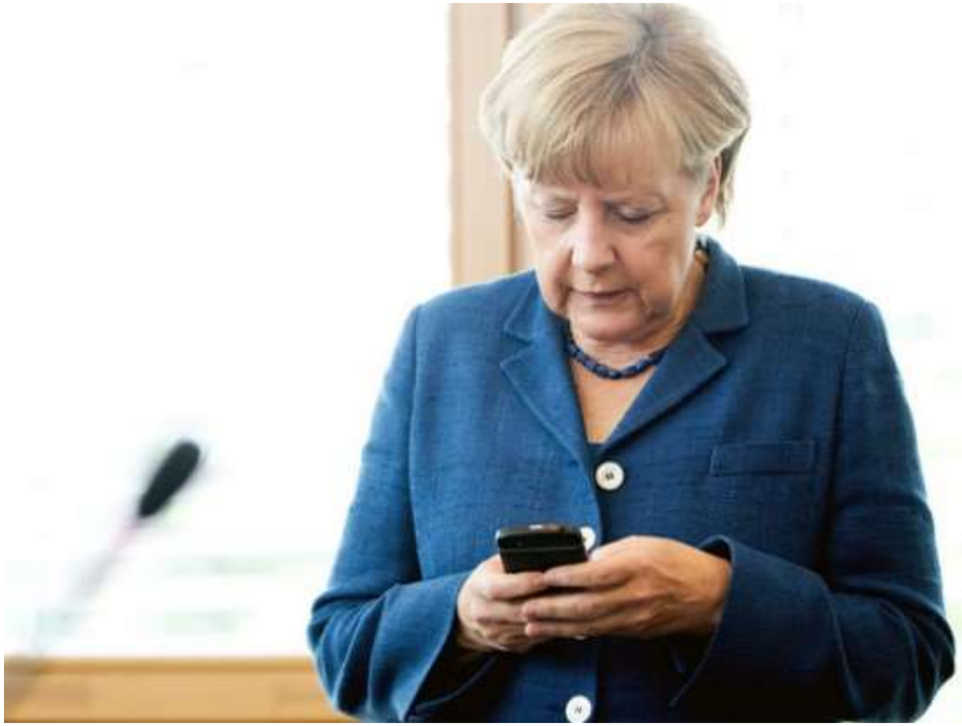
Structural phase transition & defect formation

Germany before phase transition

Berlin at the critical point of the structural phase transition



Germany after the structural phase transition



1D, 2D, 3D ion crystals

Wineland et al., J. Res. Natl. Inst. Stand. Technol. 103, 259 (1998)

Enzer et al., PRL85, 2466 (2000)

- Depends on $\alpha=(\omega_{ax}/\omega_{rad})^2$
- Depends on the number of ions $a_{crit}= cN^{\beta}$

1D

- Generate a planar Zig-Zag when $\nu_{ax} < \nu^{y}_{rad} << \nu^{x}_{rad}$
- Tune radial frequencies in y and x direction

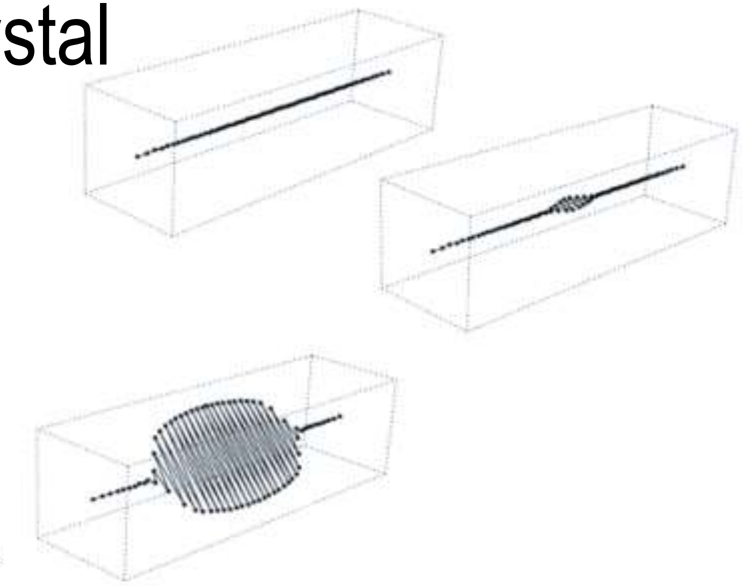
2D

Structural phase transition in ion crystal

$$H = \sum_{i,\mu} \left(\frac{p_{i\mu}^2}{2m} + \frac{1}{2} m \omega_\mu^2 r_{i\mu}^2 \right) + \frac{1}{2} \sum_{i \neq j} \frac{e^2}{4\pi\varepsilon_0} \frac{1}{|\mathbf{r}_i - \mathbf{r}_j|}$$

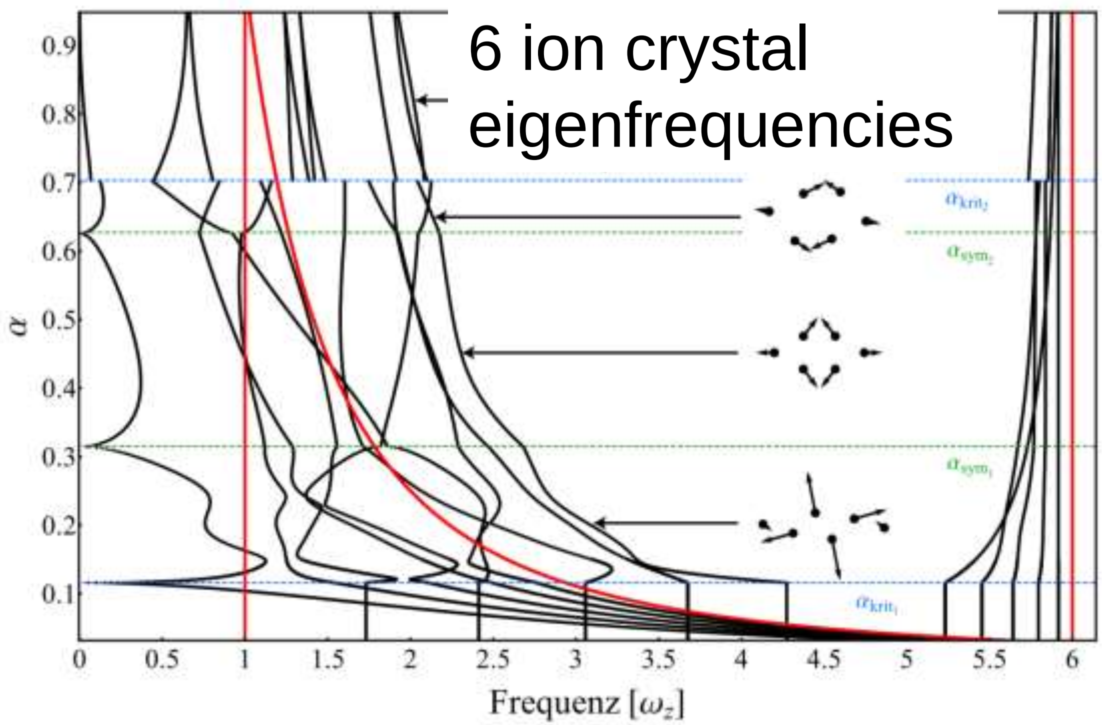
E_{kin} $U_{pot,harm.}$ $U_{Coulomb}$

$$H \approx H_0 = \hbar\omega_z \sum_n \sqrt{\gamma_n^x} a_n^\dagger a_n + \sqrt{\gamma_n^y} b_n^\dagger b_n + \sqrt{\lambda_n^z} c_n^\dagger c_n$$



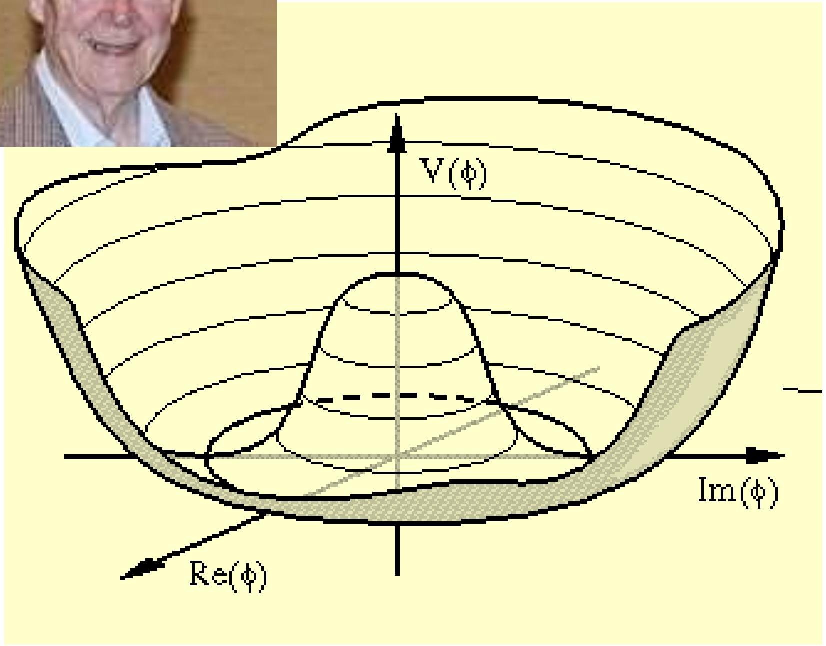
Phase transition @ CP:

- One mode frequency $\rightarrow 0$
- Large non-harmonic contributions
- coupled Eigen-functions
- Eigen-vectors reorder to generate new structures



Universal principles of defect formation

Kibble (1976)
- symmetry breaking at a second order phase transitions such that topological defects form
- may explain formation of cosmic strings or domain walls



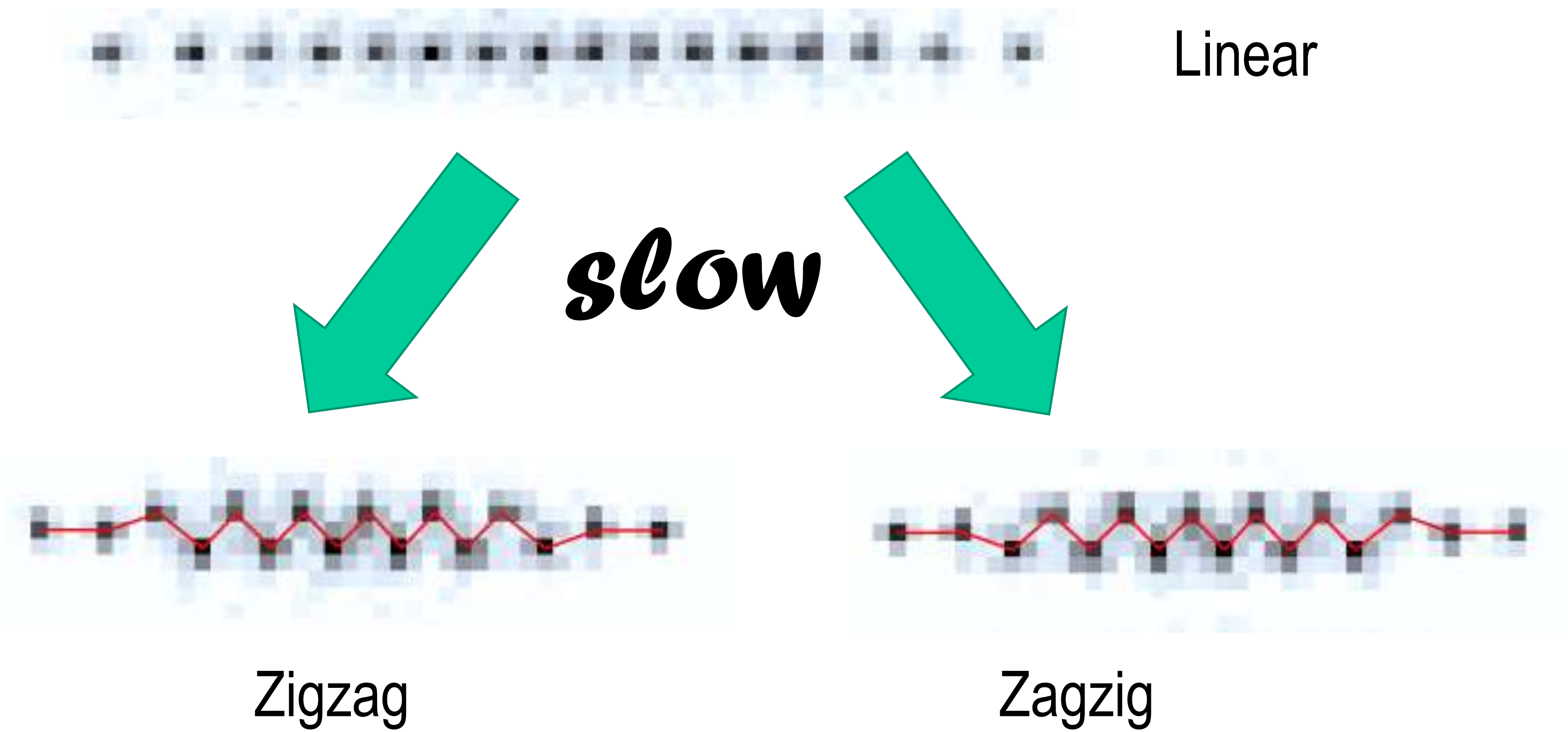
Zurek (1985)
- Sudden quench though the critical point leads to defect formation
- experiments in solid state phys. may test theory of universal scaling

Morigi, Retzger, Plenio (2010)
- Proposal for KZ study in trapped ions crystals

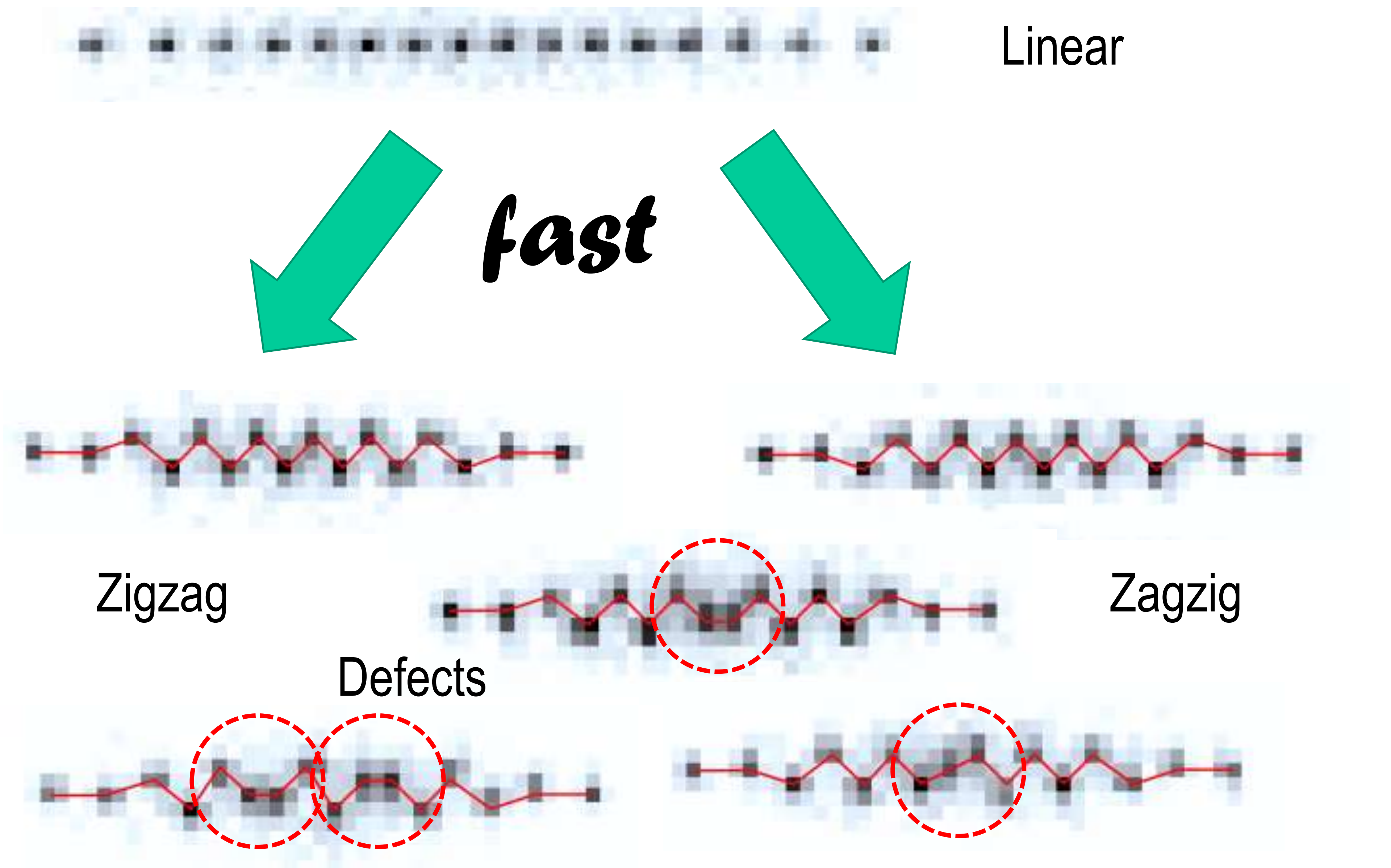
Kibble, Journal of Physics A 9, 1387 (1976)
Kibble, Physics Reports 67, 183 (1980)

Zurek, Nature 317, 505 (1985),
DelCampo, Zurek arXiv:1310.1600,
Nikoghosyan, Nigmatullin, Plenio, arXiv:1311.1543

Structural configuration change in ion crystals

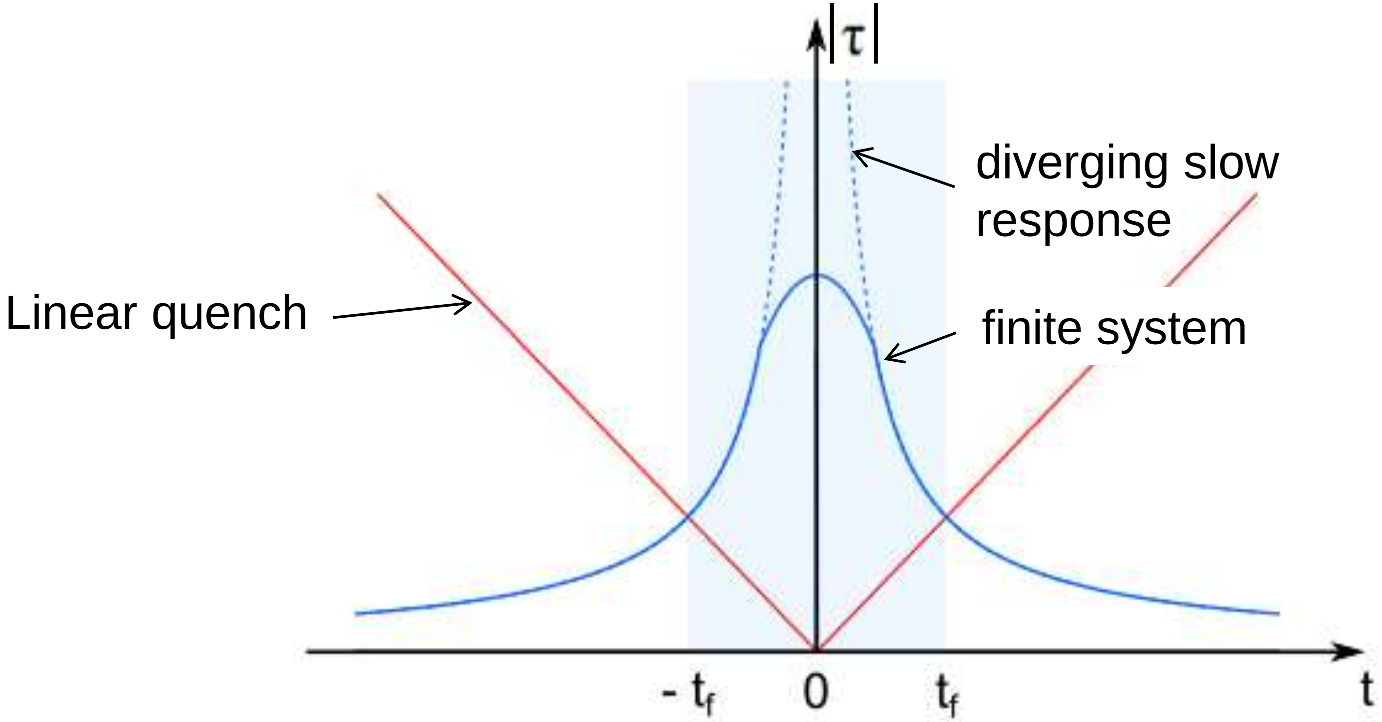


Structural configuration change in ion crystals



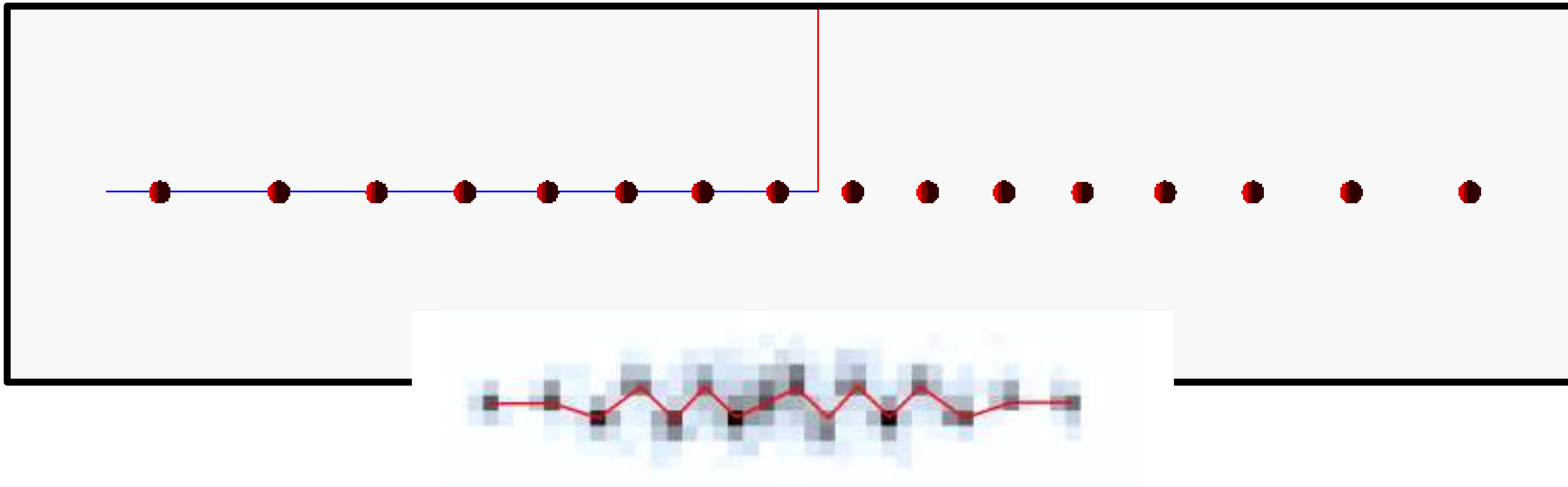
Universal principles of defect formation

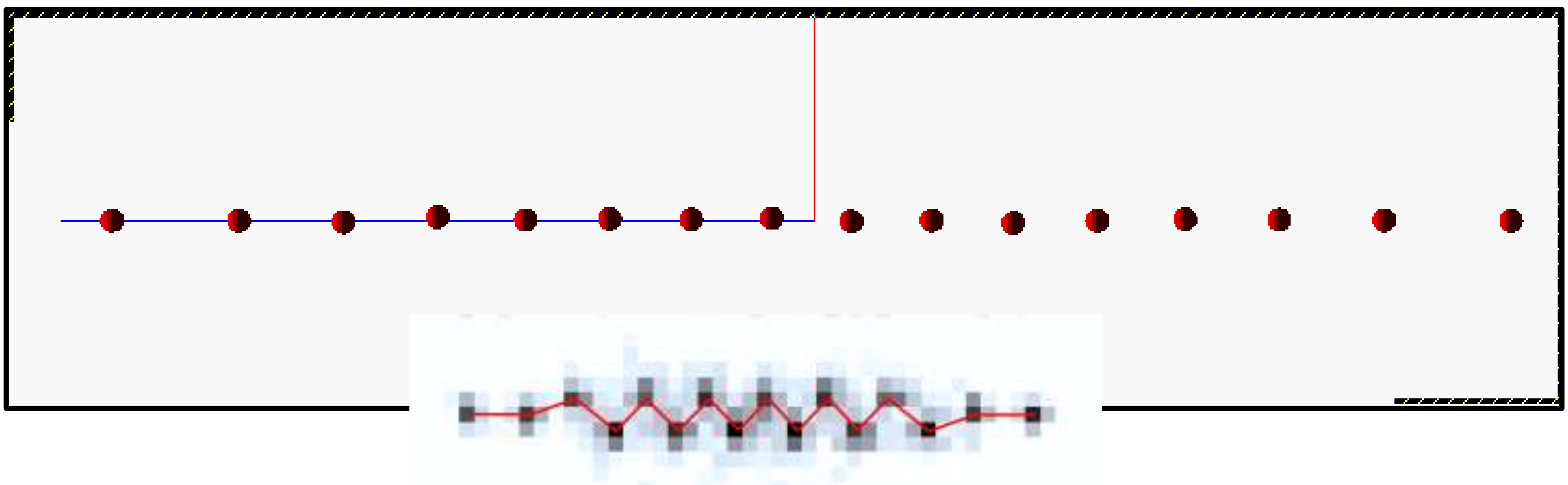
- System response time, thus information transfer, slows down
- At some moment, the system becomes non-adiabatic and freezes
- Relaxation time diverges / increases



Control of phase transition

Molecular dynamics simulations





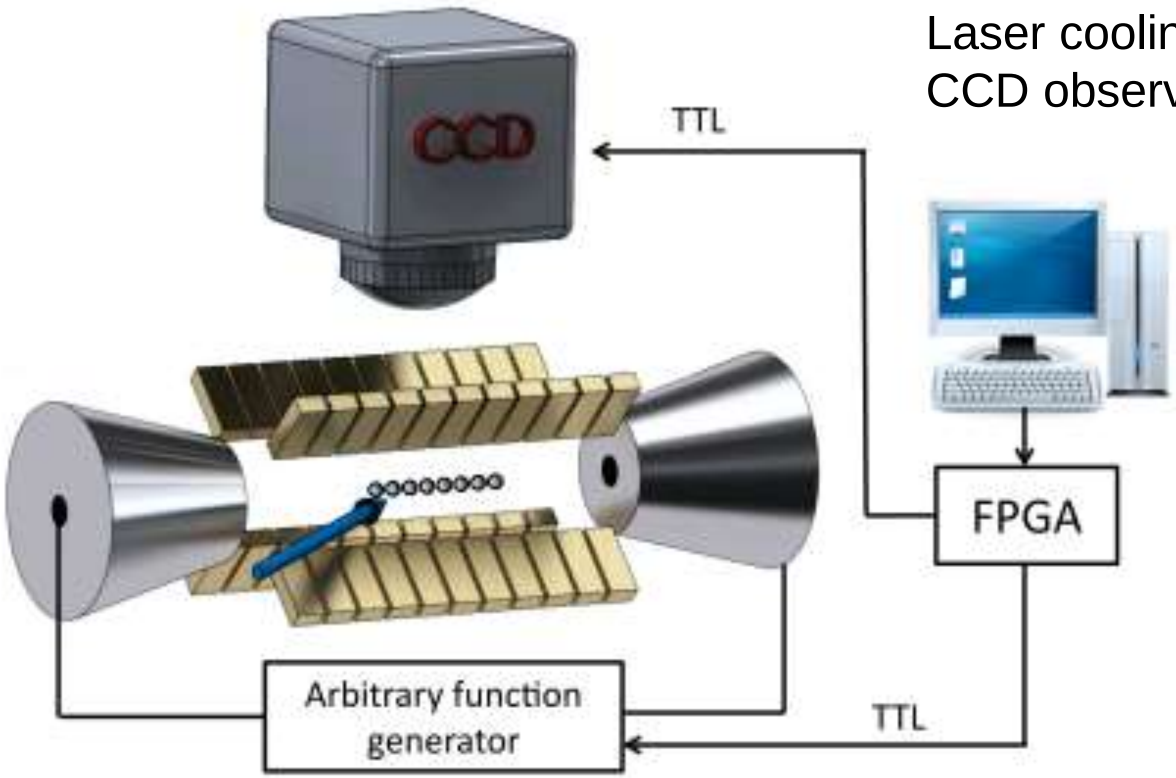
Experimental setup and parameters

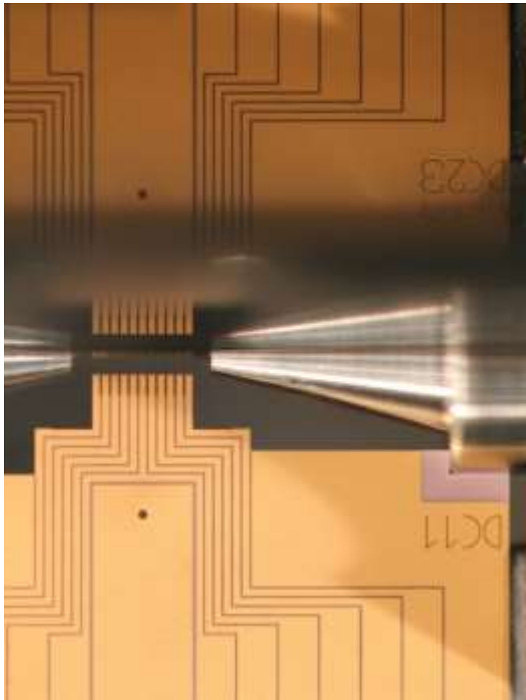
Trap with 11 segments

Controlled by FPGA and arbitray waveform gen.

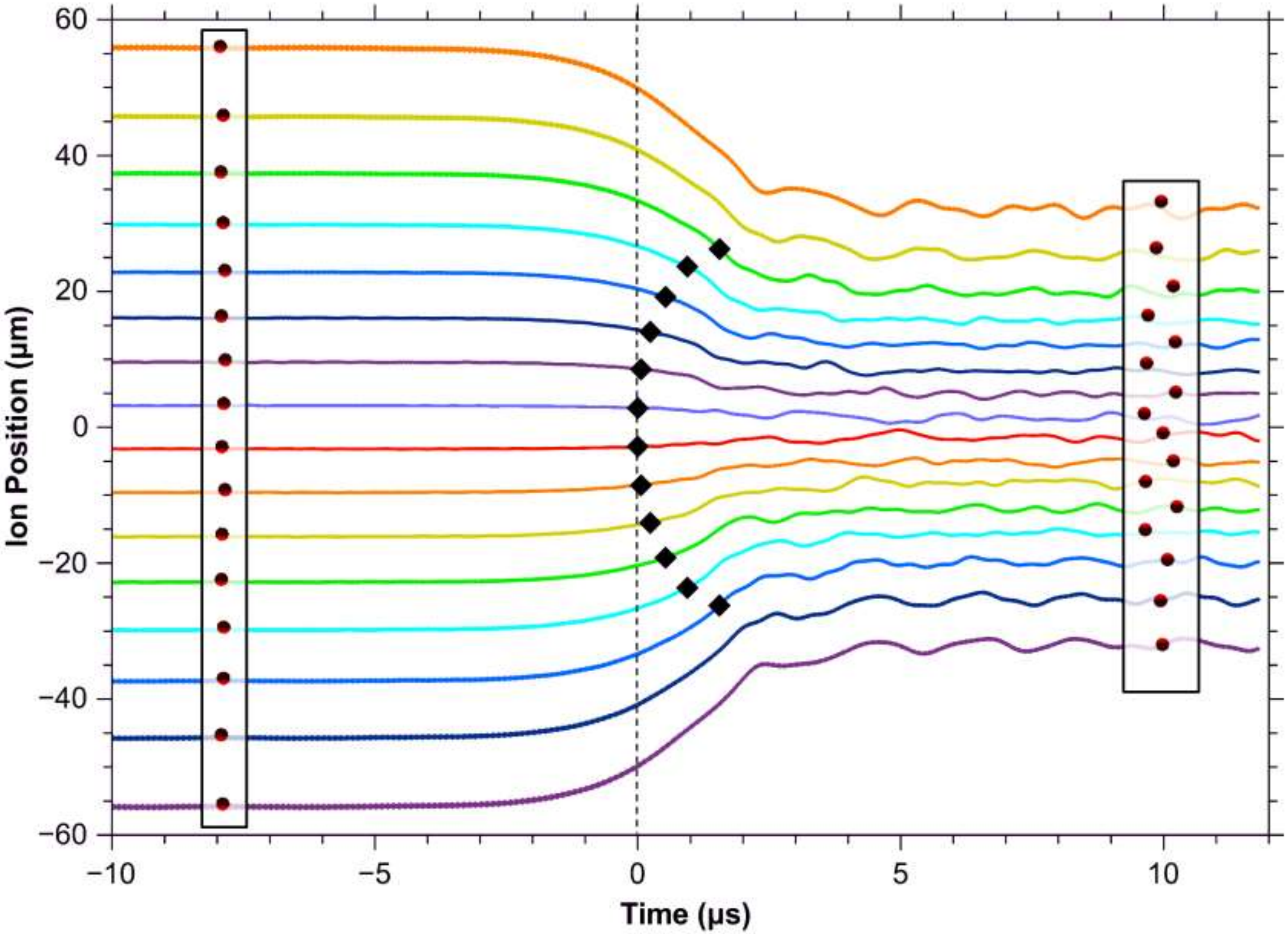
$\omega/2\pi$ = 1.4MHz (rad.),
rad. anisotropy tuned to 100 +3..5%
$\omega/2\pi$ = 160 – 250kHz (ax.)

Laser cooling /
CCD observation





Molecular dynamics simulations

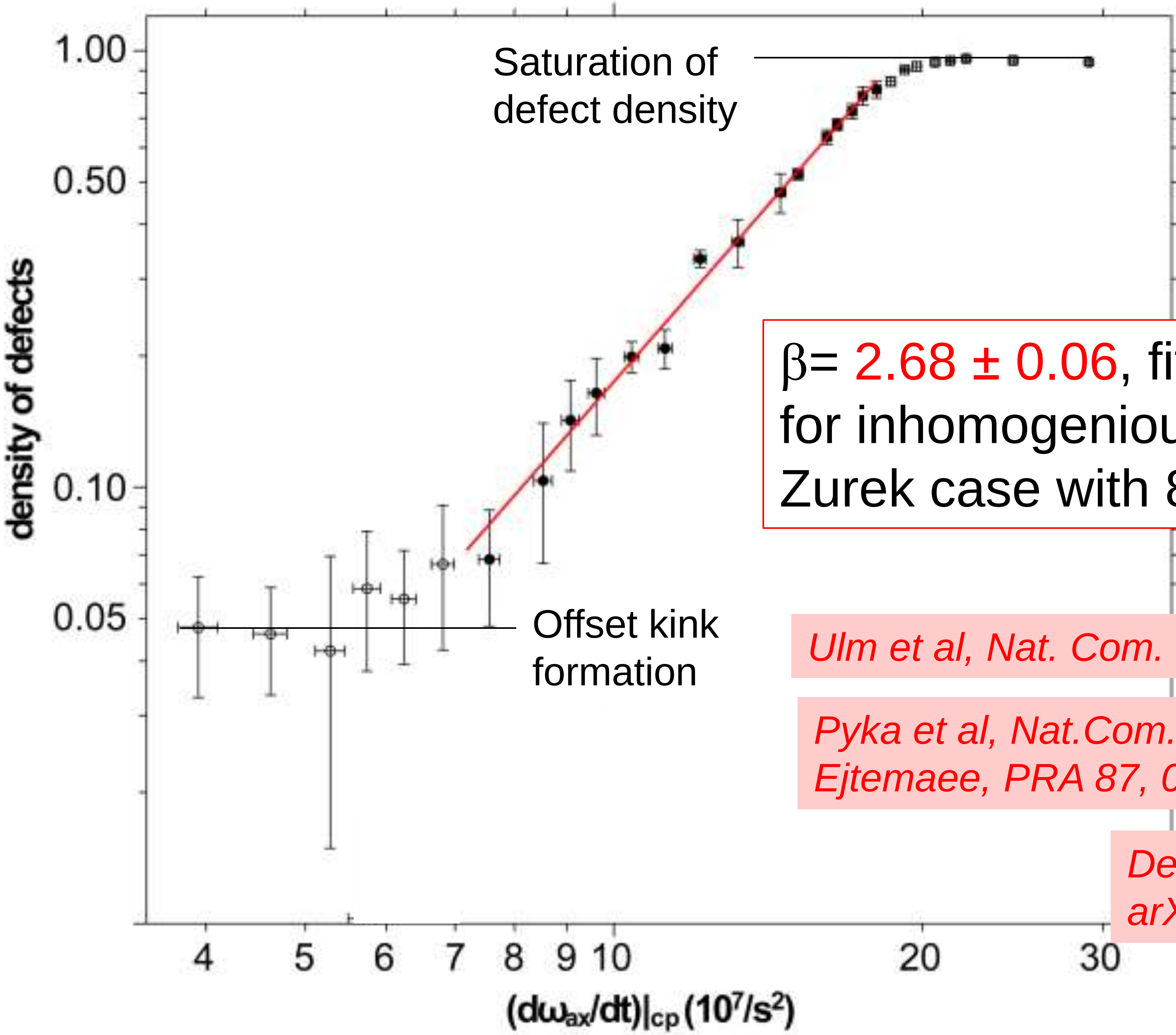


Simulation of trajectories

Small axial excitation

No position flips

Experimental test of the β=8/3 power law scaling



β= 2.68 ± 0.06, fits prediction for inhomogenious Kibble Zurek case with $8/3 = 2.6\overline{6}$

Ulm et al, Nat. Com. 4, 2290 (2013)

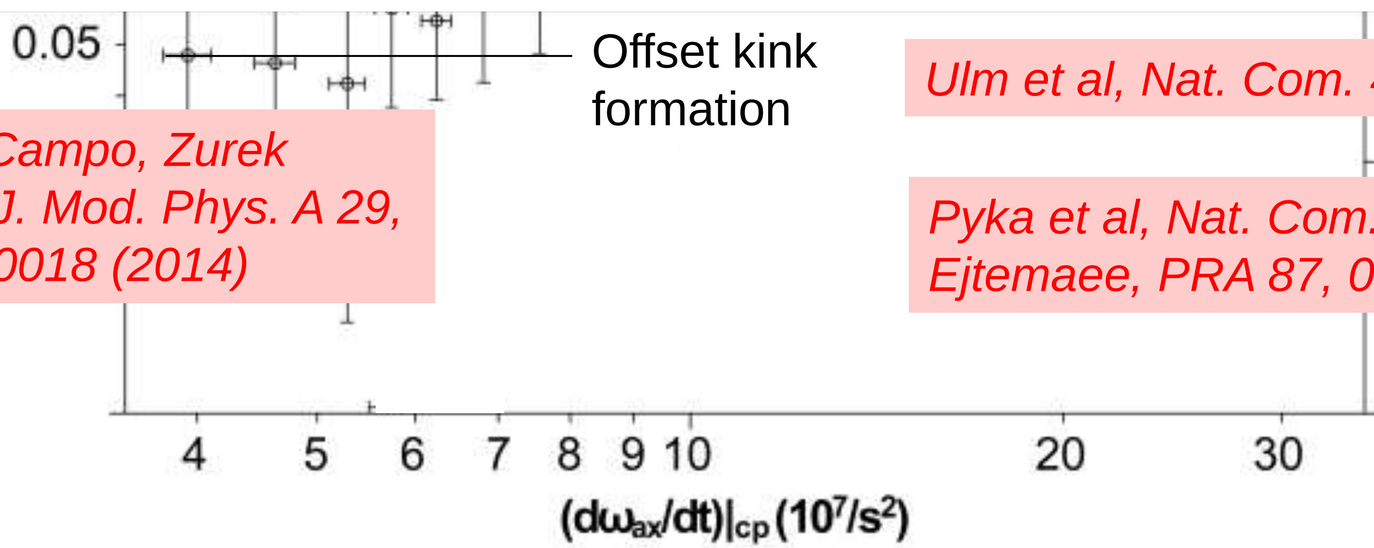
Pyka et al, Nat.Com. 4, 2291 (2013)
Ejtemaee, PRA 87, 051401 (2013)

DelCampo, Zurek arXiv:1310.1600

Experimental test of the β=8/3 power law scaling

Table 1. Experimental results on the topological defect formation in ion Coulomb crystals.[13–15] Data was fitted to a power-law in the quench rate τ_Q of the form $n \propto \tau_Q^{-\alpha}$.

Group	Number of ions	Kink number	Fitted exponent α
Mainz University[14]	16	$\{0,1\}$	2.68 ± 0.06
PTB[15]	29 ± 2	$\{0,1\}$	2.7 ± 0.3
Simon Fraser University[13]	42 ± 1	$\{0,1\}$	$2.1 - 3.1$



Ulm et al, Nat. Com. 4, 2290 (2013)

DelCampo, Zurek
Int. J. Mod. Phys. A 29, 1430018 (2014)

Pyka et al, Nat. Com. 4, 2291 (2013)
Ejtemaee, PRA 87, 051401 (2013)

Experimental testing of fluctuation theorem at the quantum limit

Jarzynski, PRL 78, 2690 (1997)
Crooks, PRE 60, 2721 (1999)

Liphardt, et al., Sci. 296 (2002) 1832

Huber et al., PRL ***101****, 070403 (2008)*

- Work distribution measured with RNA
- Proposal for a test of Jarzynski equ. with a single ion
- Experimental realization – work distribution measued

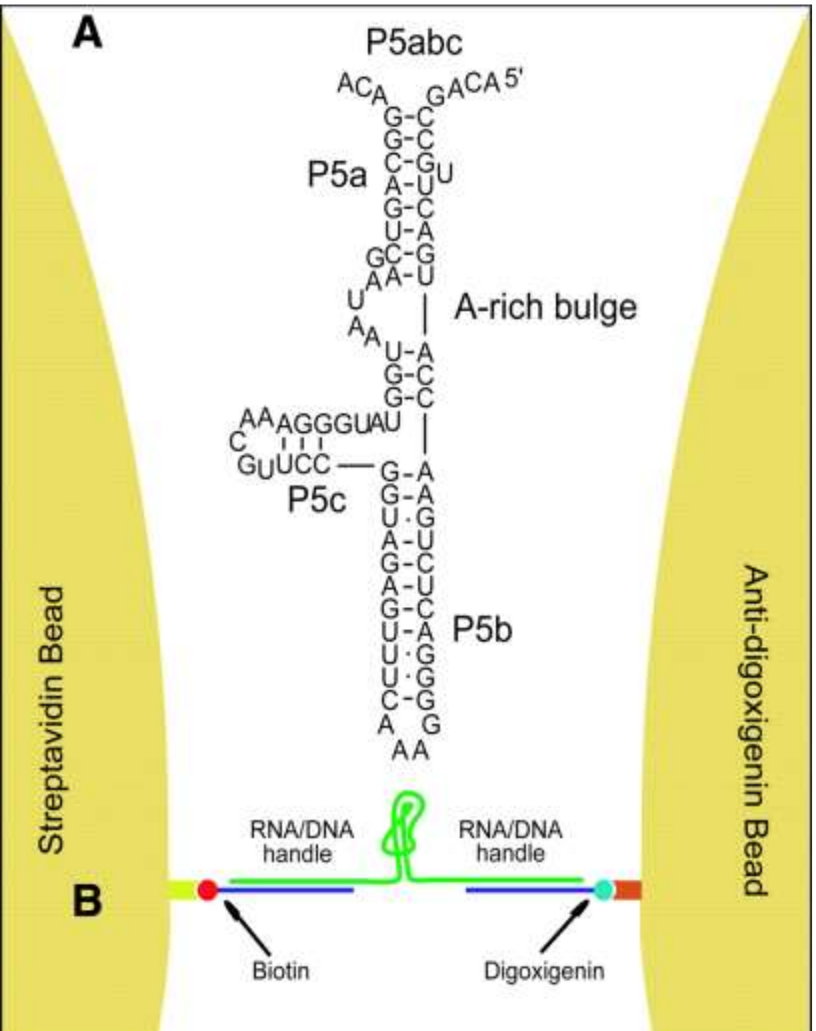
An et al., Nat. Phys.11, 193 (2015)

Kihwan Kim

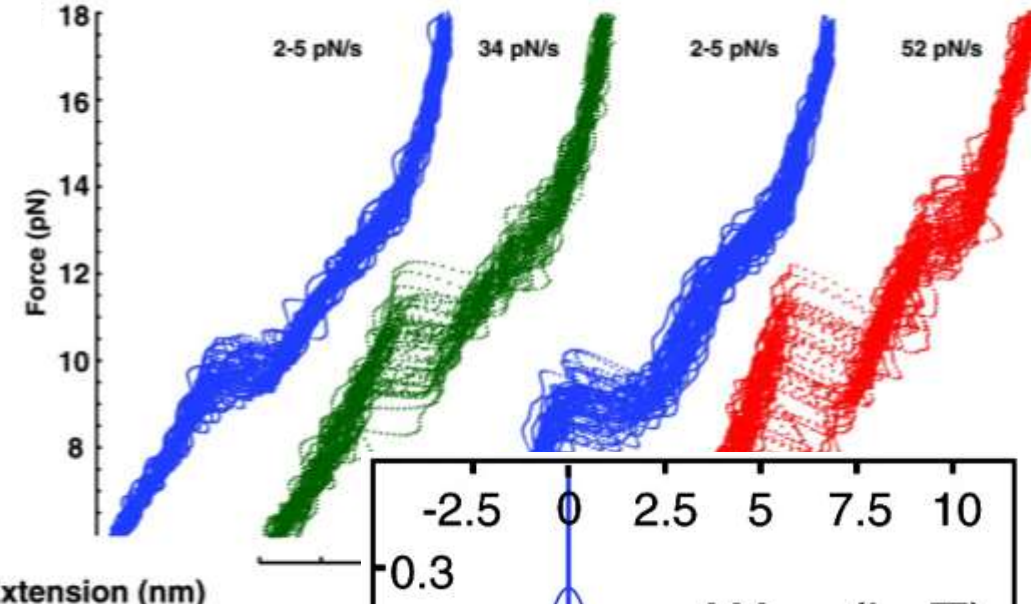
Single molecule streching

Liphardt, et al., Sci. 296 (2002) 1832

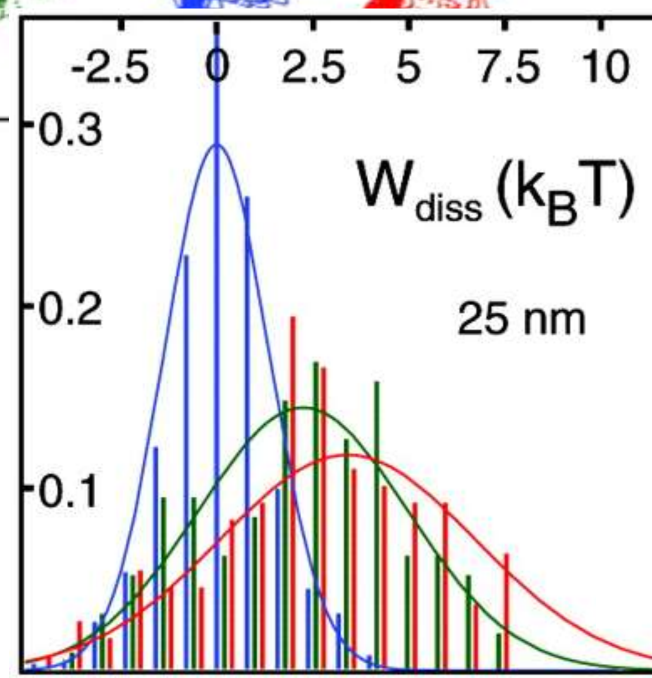
Attach RNA to glass bead of laser tweezer
unfold/refold single RNA molecule



Unfolding at different rates



Work **probability** distribution for slow and fast unfolding



Liphardt, et al., Sci. 296 (2002) 1832

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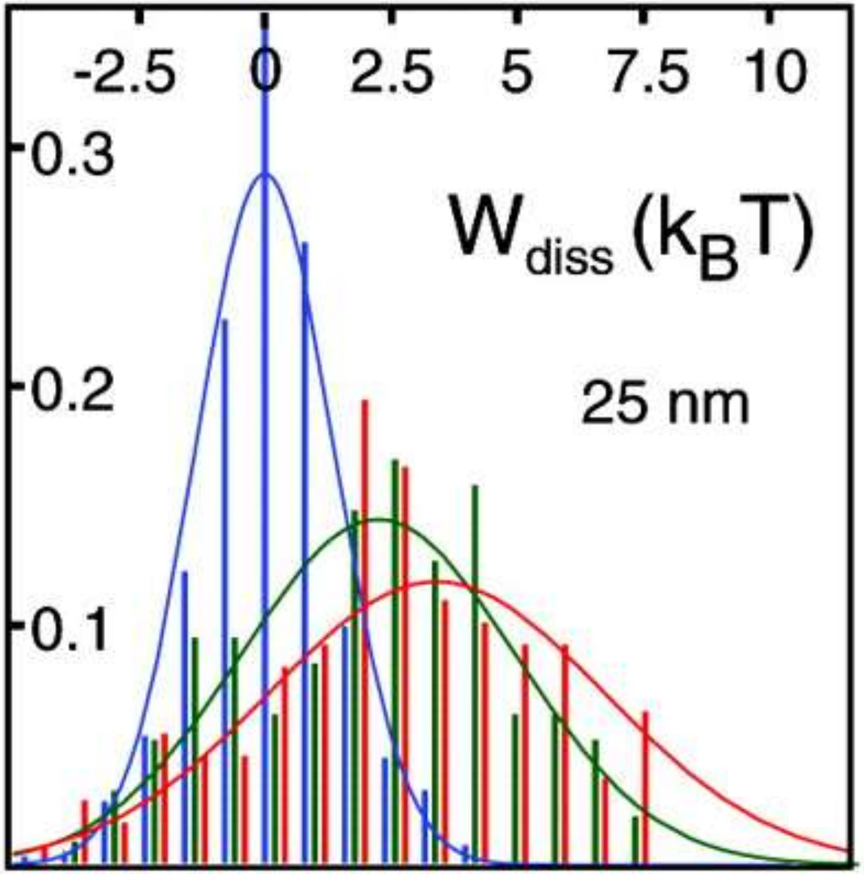
Work **probability** distribution for slow and fast unfolding



Crooks fluctuation theorem:

$$\frac{P(-W)}{P(+W)} = \exp^{-W/k_B T}$$

Verify Crooks fluctuation theorem experimentally

Crooks, Phys. Rev. E 60(1999) 2721

quantum Jarzynski equality

Jarzynski,
Phys. Rev. Lett. 78
(1997) 2690

$$\Delta F = -k_B T \, ln \langle e^{-W/k_B T} \rangle$$

free energy difference

$$\langle e^{-W/k_B T} \rangle = \int dW e^{-W/k_B T} \, P(W)$$

average exponented work

$$P(W) = \sum_{m,n} \delta[W - (E^{\tau}_m - E^0_n)] \, P^{\tau}_{m,n} \, P^0_n$$

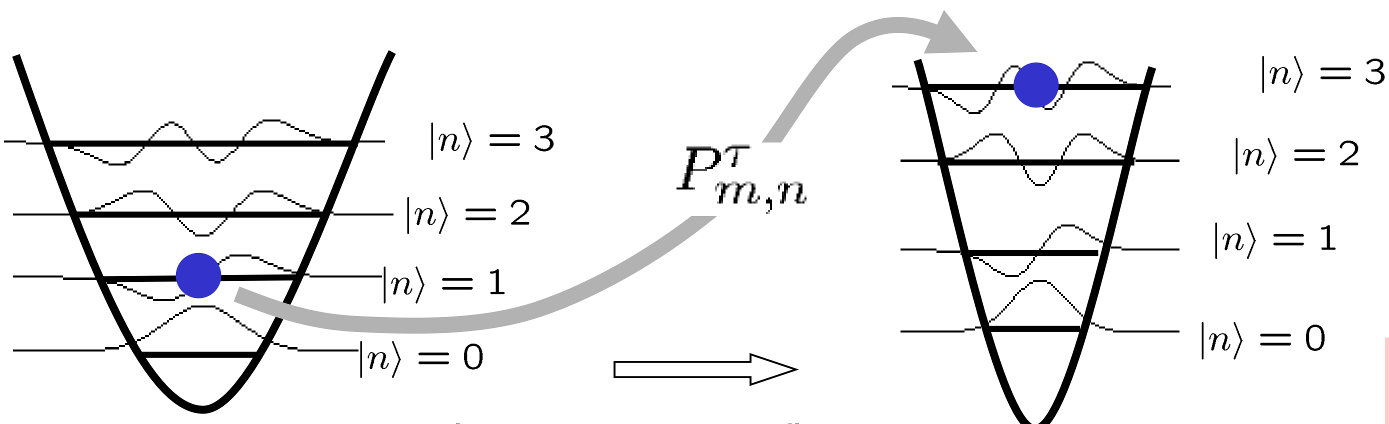
quantum work probabilty

Energy difference

Transition probabilities

Thermal occupation

no expectation value,
but correlation function



increase trap confinement
non-adaibatically

P. Talkner et al.,
Phys. Rev. E 75 R
(2007) 050102

Non-equilibrium phonon States in a Paul trap

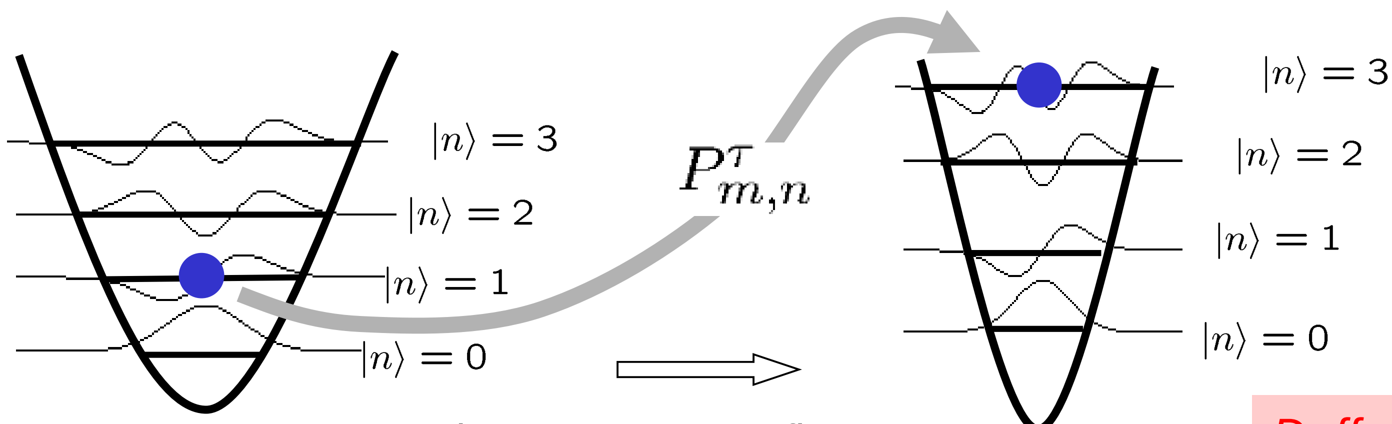
Proposed exp. Scheme:
1) Start with thermal state n=0… ~ 10
2) Determine E^0
3) Act (non-adiabatically) on trap potential
4) Determine E^t

quantum work probabilty

$$P(W) = \sum_{m,n} \delta[W - (E^\tau_m - E^0_n)]\; P^\tau_{m,n}\; P^0_n$$

Energy difference — Transition probabilities — Thermal occupation

no expectation value,
but correlation function

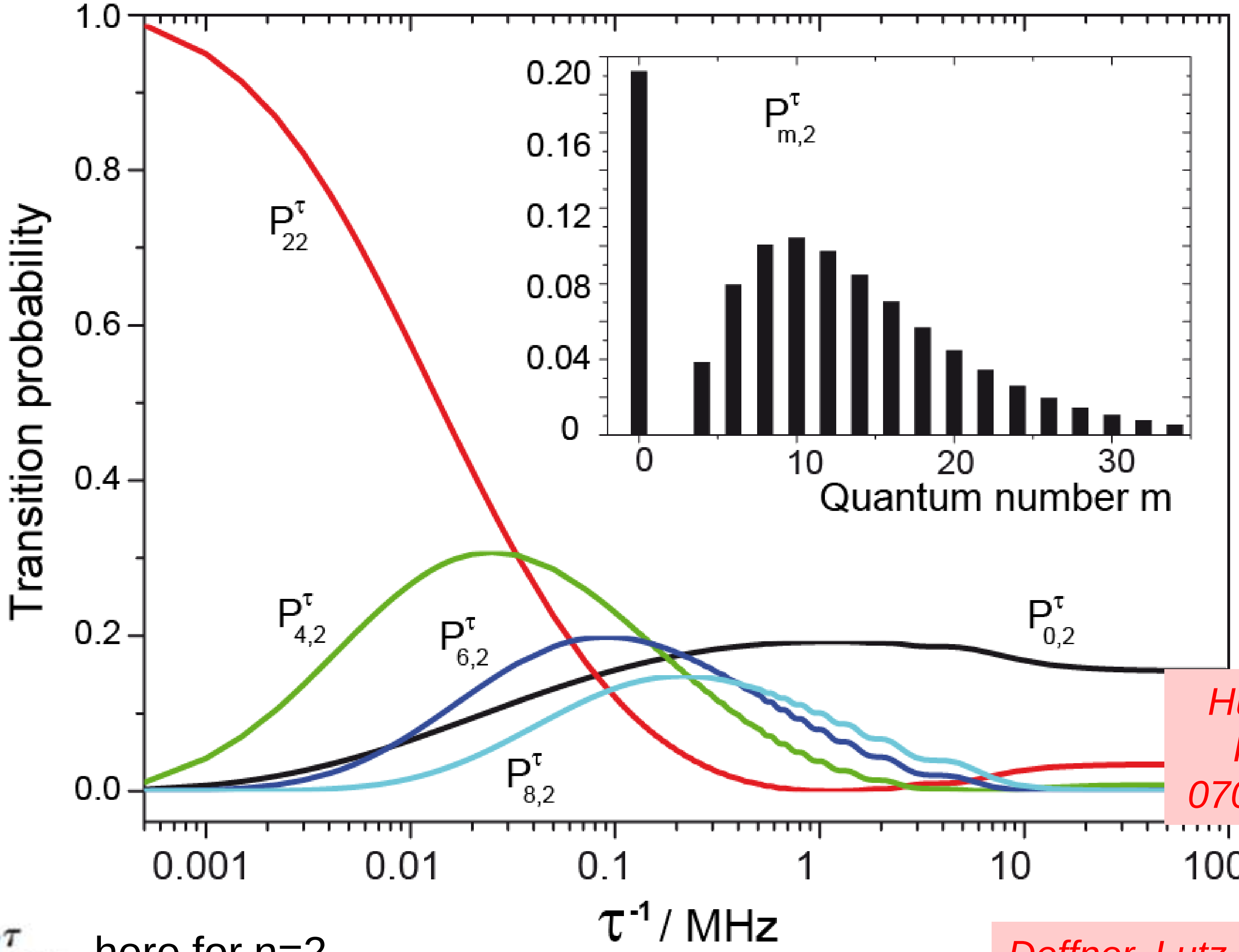


increase trap confinement
non-adaibatically

*Huber et al., PRL **101**, 070403 (2008)*

Deffner, Lutz, Phys. Rev. E 77, 021128 (2008)

Non-equilibrium phonon states



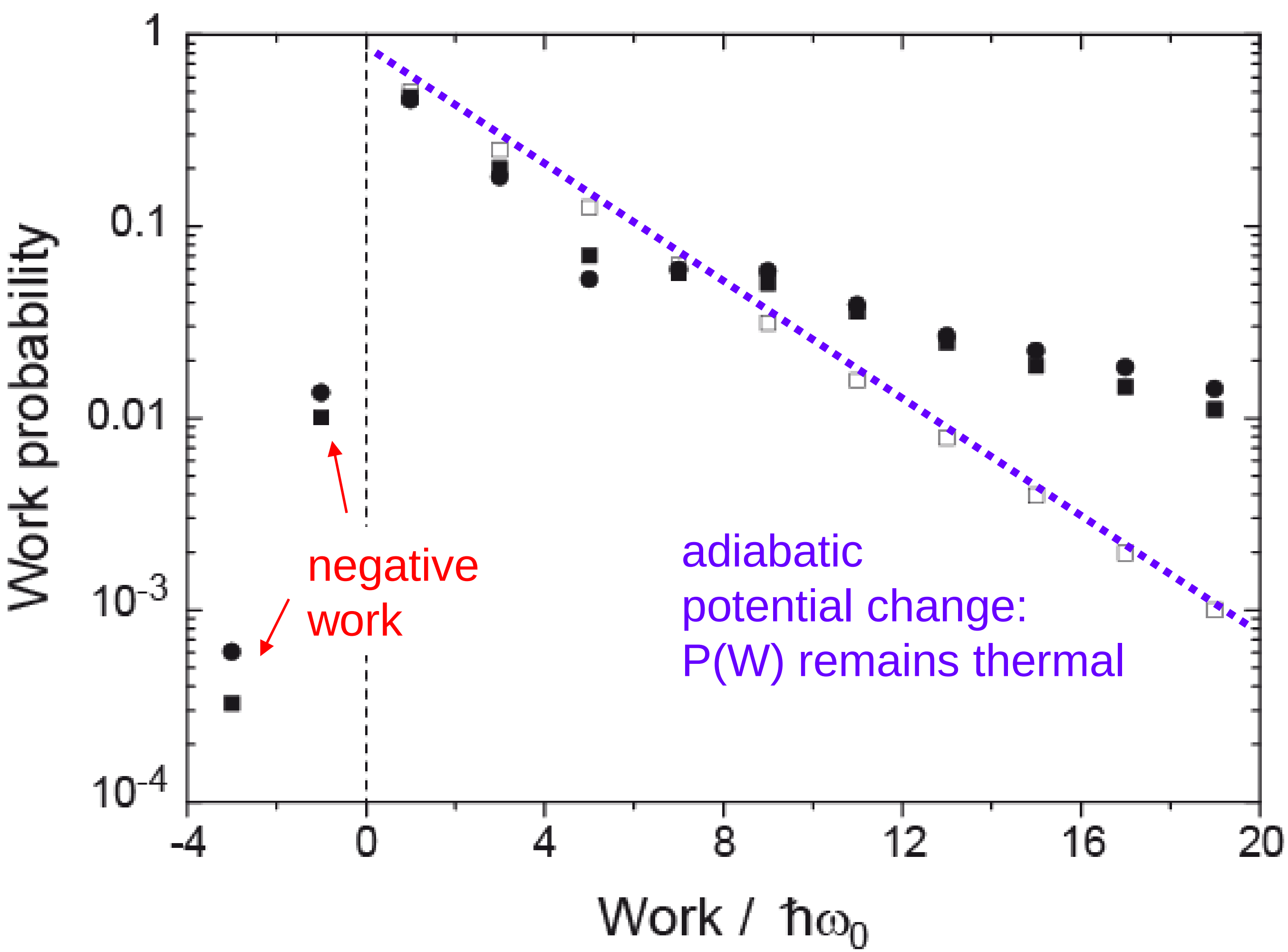
*Huber et al., PRL **101**, 070403 (2008)*

$P^{\tau}_{m,n}$, here for n=2

Deffner, Lutz, Phys. Rev. E 77, 021128 (2008)

Work probability distribution

$$P(W) = \sum_{m,n} \delta[W - (E_m^\tau - E_n^0)]\; P_{m,n}^\tau\; P_n^0$$

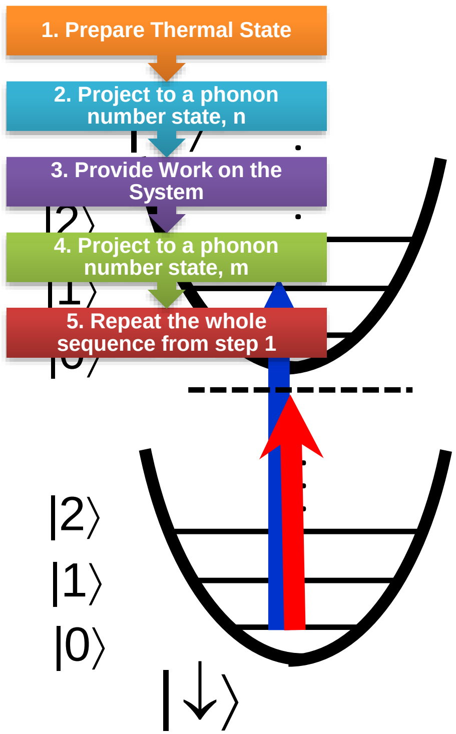


Change ω from 1MHz to 3MHz

- ● in 0.1μs
- ■ in 0.05μs

Huber et al., PRL ***101****, 070403 (2008)*

Provide Work – Displacement Operation



σ_x Dependent Displacement Operation

P. C. Haljan et al., Phys. Rev. Lett. 94, 153602 (2005).

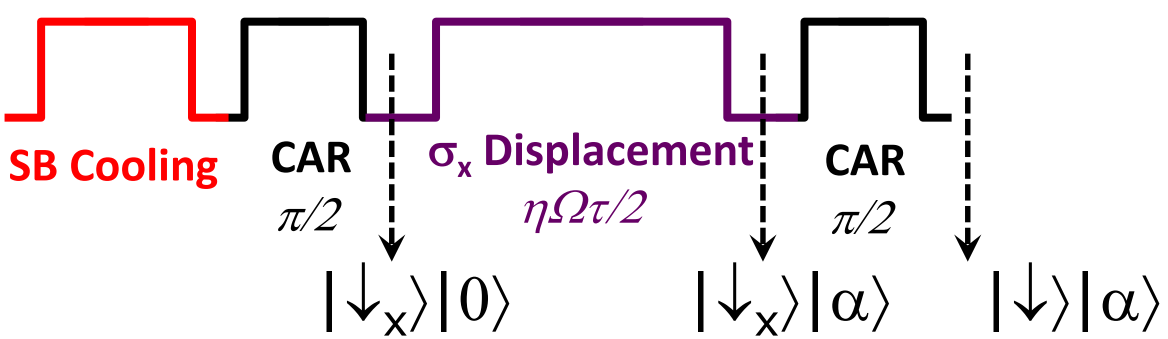
P. J. Lee et al., Journal of Optics B 7, S371 (2005).

$$H_{bsb} = \frac{\eta\Omega}{2}\left(a^\dagger\sigma^+ + a\sigma^-\right)$$

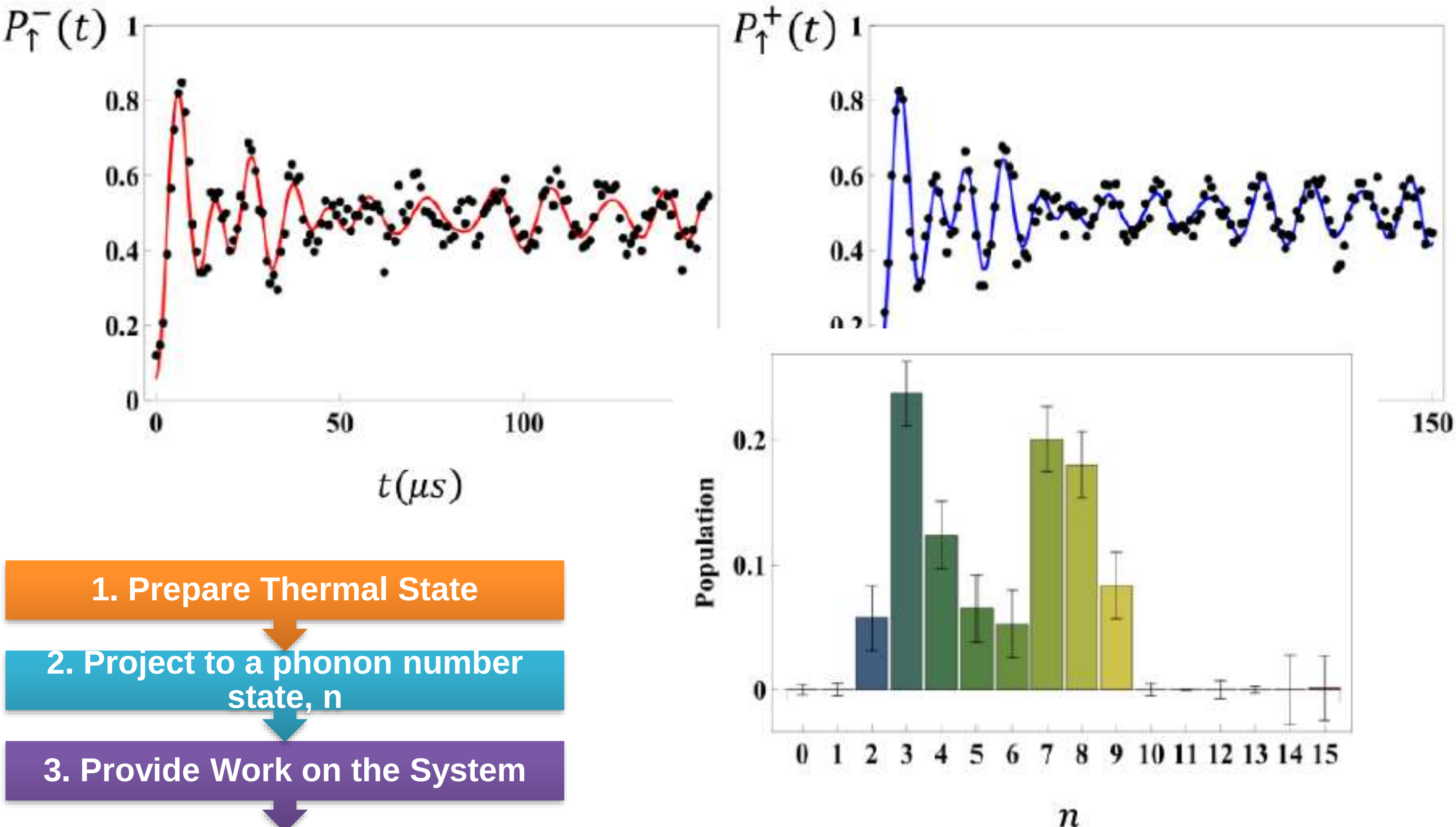
$$H_{rsb} = \frac{\eta\Omega}{2}\left(a^\dagger\sigma^- + a\sigma^+\right)$$

$$H_{bsb} + H_{rsb} = \frac{\eta\Omega}{2}\left(a^\dagger + a\right)\sigma_x$$

Pure Displacement Operation



Final State Measurements – Fitting Methods

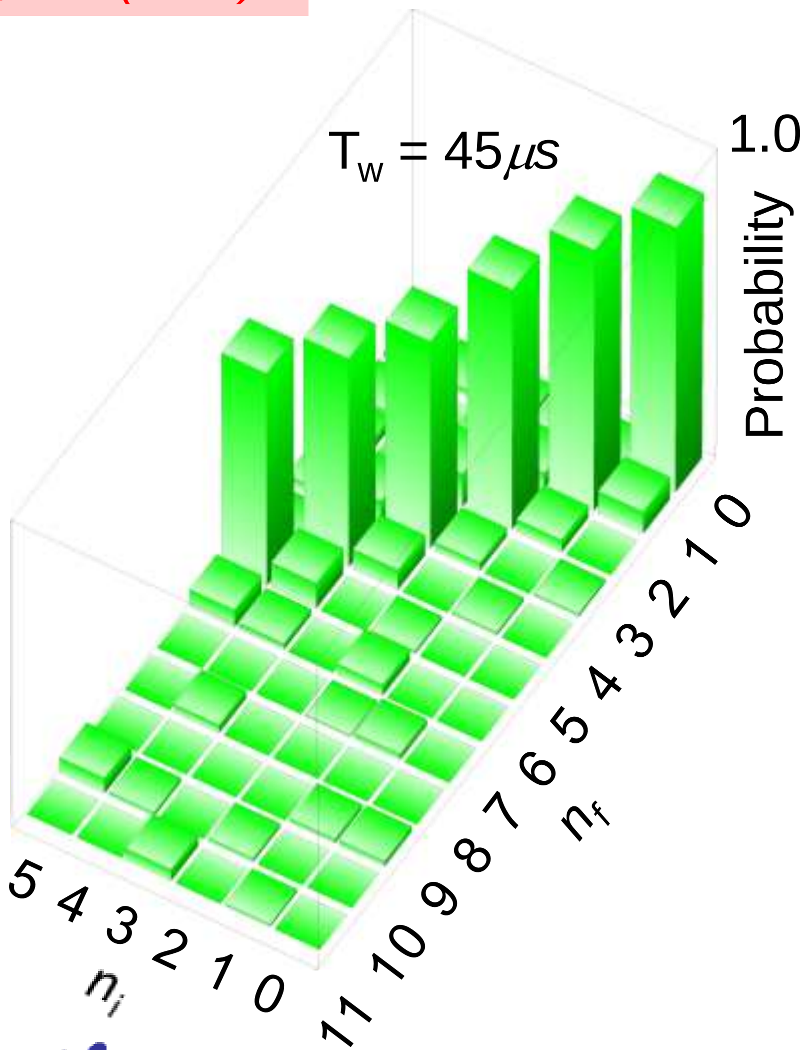


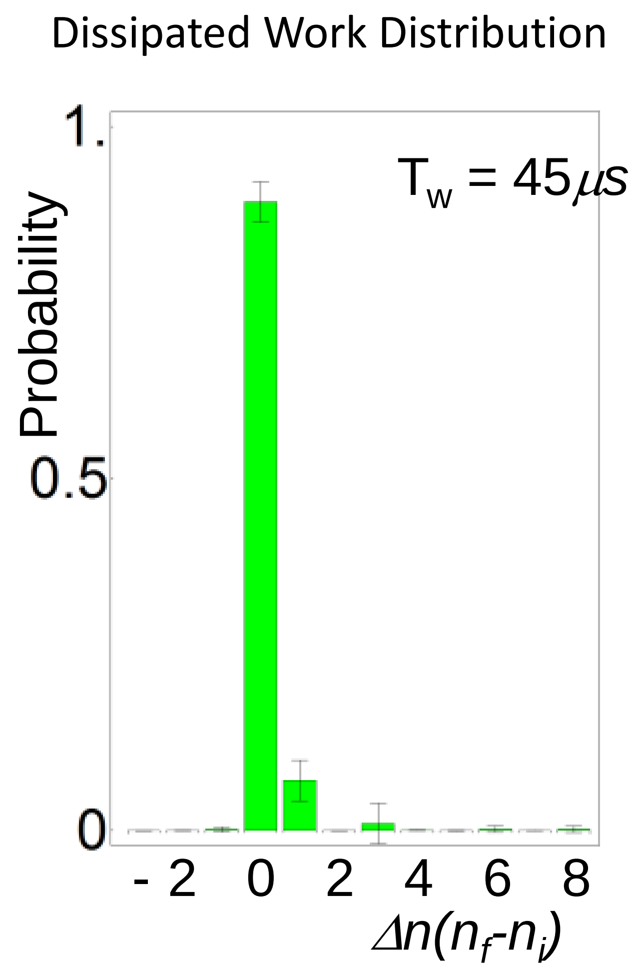
1. Prepare Thermal State
2. Project to a phonon number state, n
3. Provide Work on the System
4. Project to a phonon number state, m
5. Repeat the whole sequence from step 1

An et al., Nat. Phys.11, 193 (2015)

Final State Measurements – Intermediate Work

An et al., Nat. Phys.11, 193 (2015)

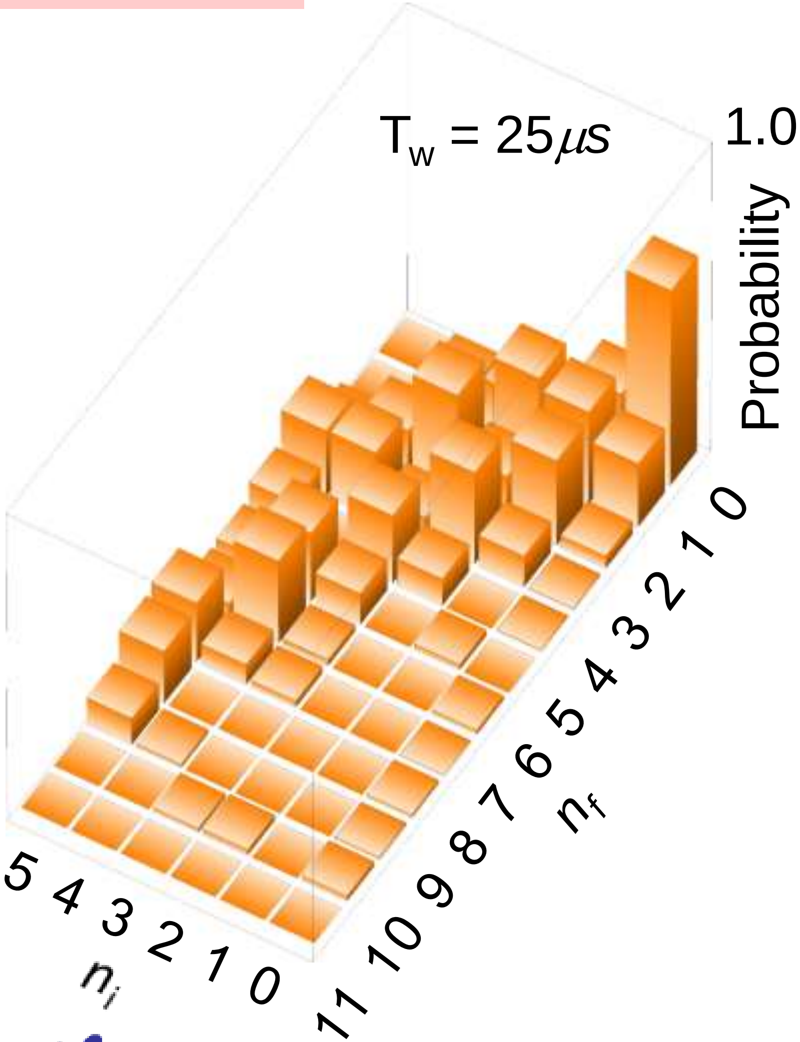




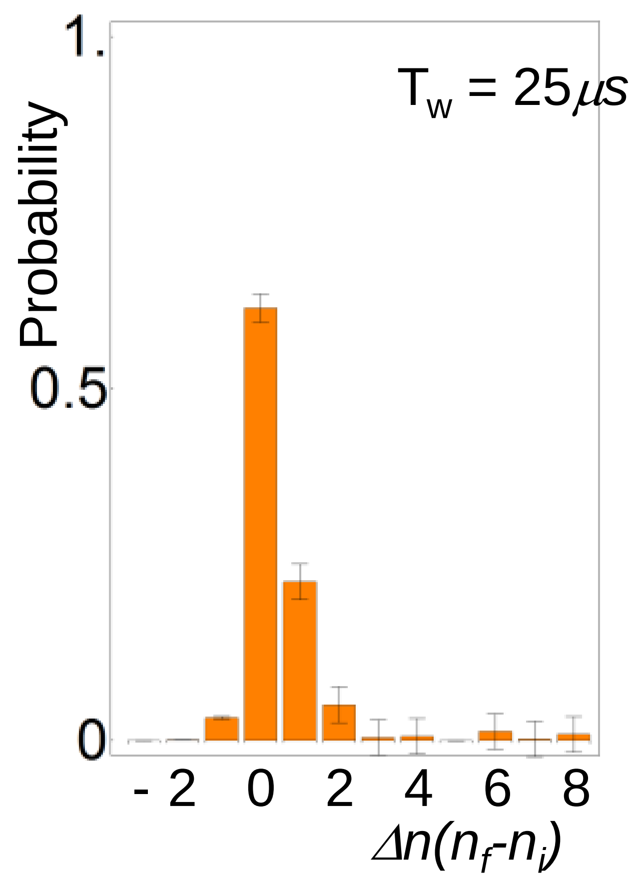
$$\left\langle e^{-\beta W-\beta \Delta F}\right\rangle = 0.989 \pm 0.072$$

Final State Measurements – Intermediate Work

An et al., Nat. Phys.11, 193 (2015)



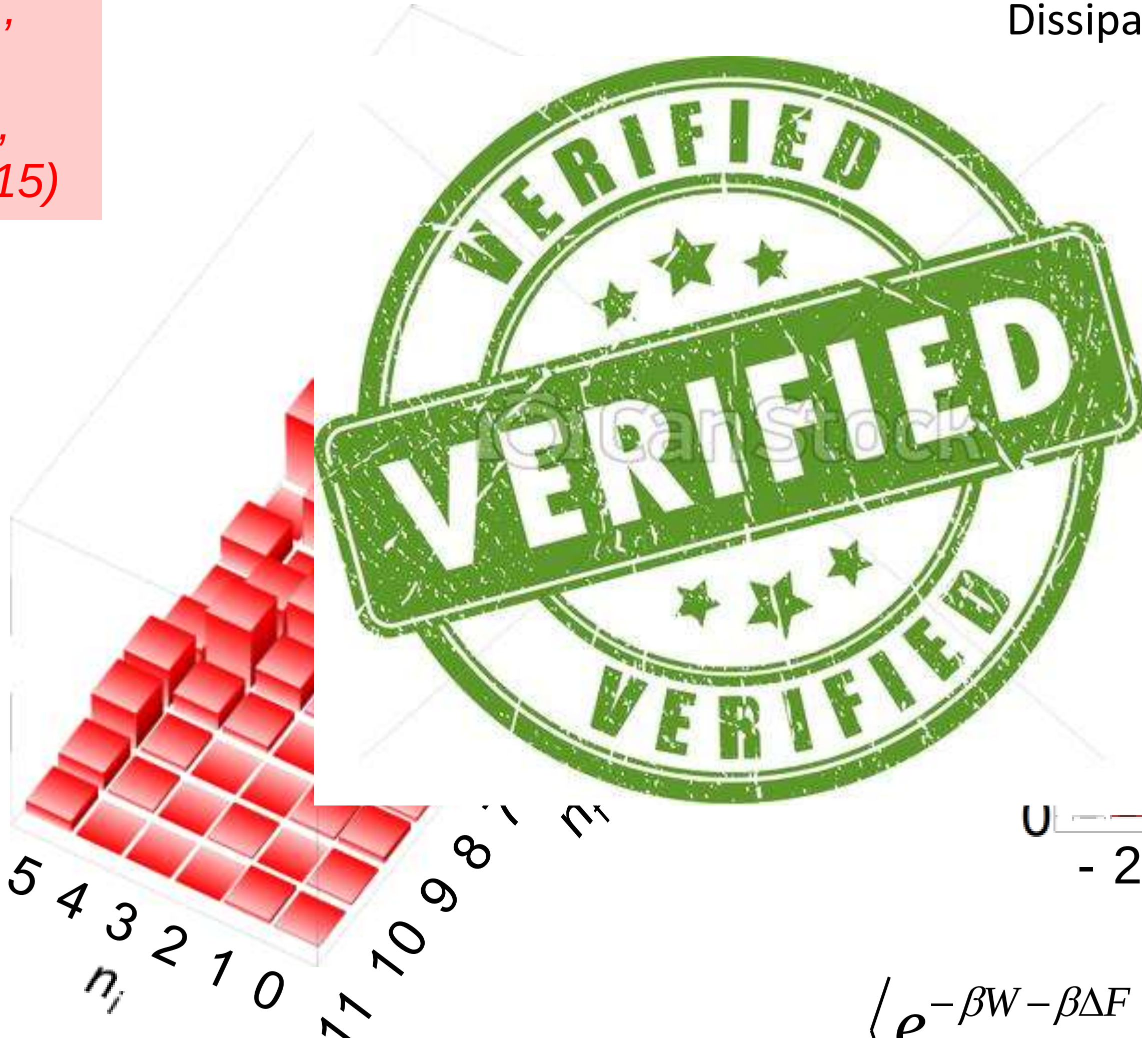
Dissipated Work Distribution



$$\left\langle e^{-\beta W-\beta\Delta F}\right\rangle = 0.995 \pm 0.045$$

Final State Measurements – Non equilibrium Work

An et al., Nat. Phys.11, 193 (2015)



Dissipated Work Distribution

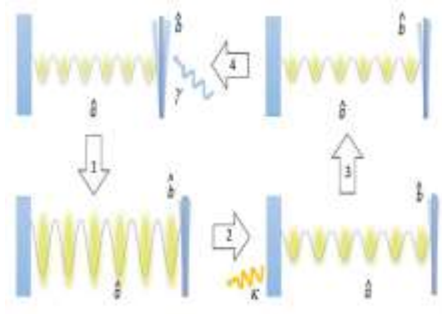
$$\left\langle e^{-\beta W - \beta \Delta F} \right\rangle = 1.032 \pm 0.038$$

Proposals for engines

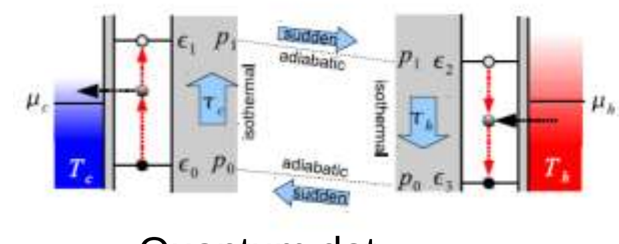
Maser Scovil et al, PRL 2, 262 (1959)

Three Level System
Geva et al., J Chem Phys (1996)

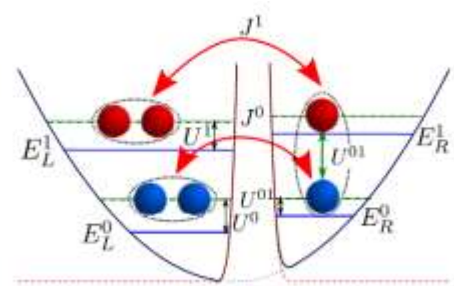
Quantum Thermodynamics
Gemmer et al, Springer, Lect Notes 784 (2009),
Anders, Esposito, NJP 19, 010201 (2017)



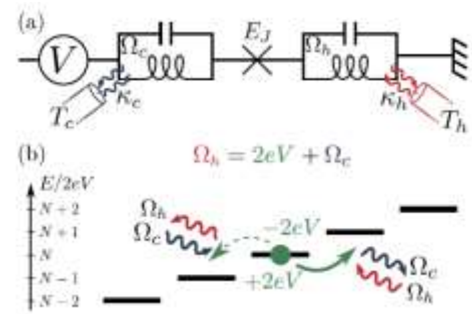
opto-Mechanical
Zhang et al., PRL 112, 150602 (2014)



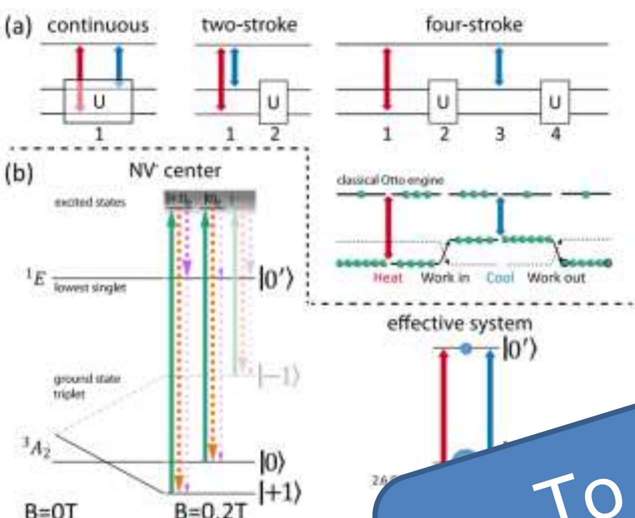
Quantum dot
Esposito et al., PRE 81, 041106 (2010)



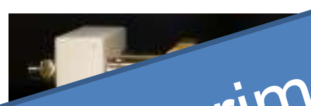
Cold atoms
Fialko et al., PRL 108, 035303 (2012)



Josephs



NV Center
Klatzow et al., PRL 122, 110601 (2019)



ound Phys 38, 506

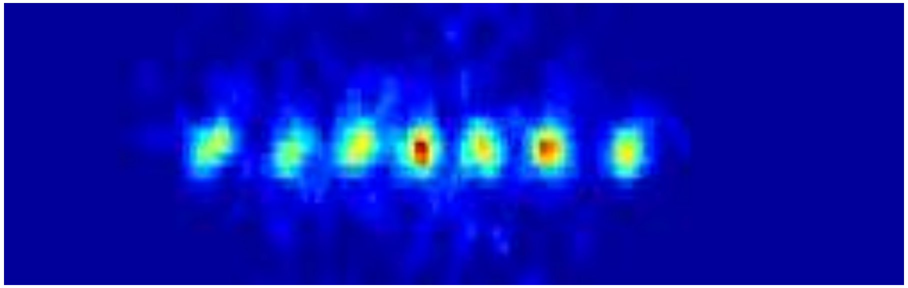
nagel et al., PRL 109, 203006 (2012),
Sci. 352, 325 (2016)

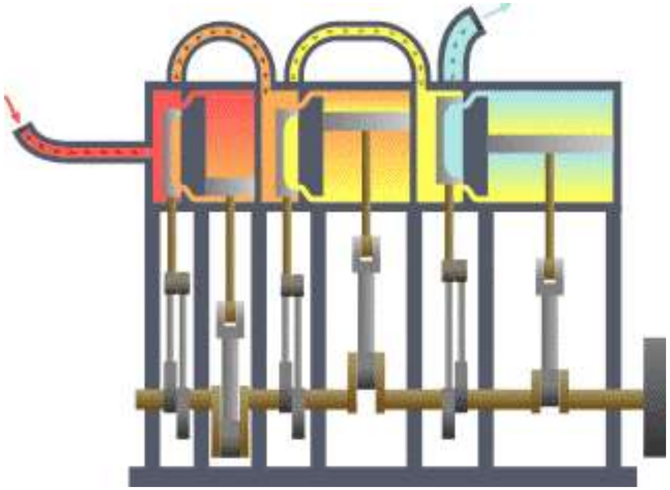
Quantum information driven engines
Cottet et al., PNAS 114, 7561 (2017),
Mohammady et al., NJP 19, 113026 (2017)
Strasberg et al., PRX 7, 021003 (2017)

To few experimental realization of heat engines in the quantum regime

Heat engines

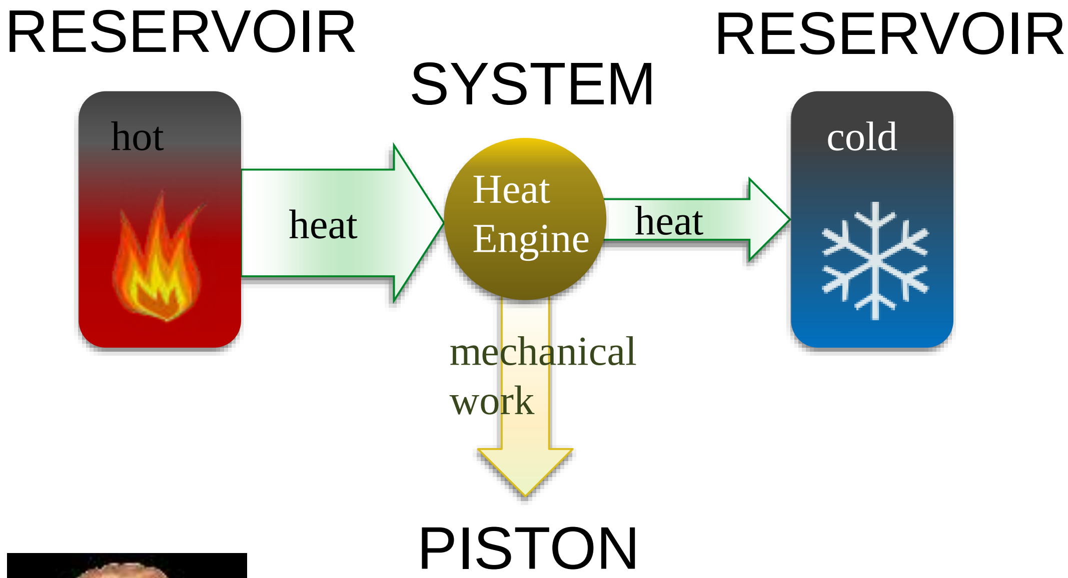
- single-ion **Otto heat** engine – classical operation
- **autonomous** heat engine – study phase stability
- absorption **refrigerator**
- **spin-driven** heat engine in the quantum regime – quantum motion
- *future*: multi-ion crystal **quantum heat** engine





Classical heat engines

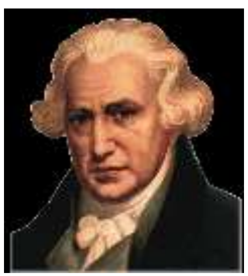
Convert thermal energy into mechanical work



$$\delta U = \delta Q + \delta W$$

Robert Mayer

James Watt (1783): $\eta \cong 5 - 7\%$
Modern power plats: $\eta \cong 30\%$



James Watt

Sadi Carnot

$$\eta = \frac{\text{Work produced}}{\text{Heat absorbed}} = \frac{W}{Q_H} \leq 1 - \frac{T_C}{T_H} = 1 - \frac{\beta_H}{\beta_C}$$

Single ion heat engine

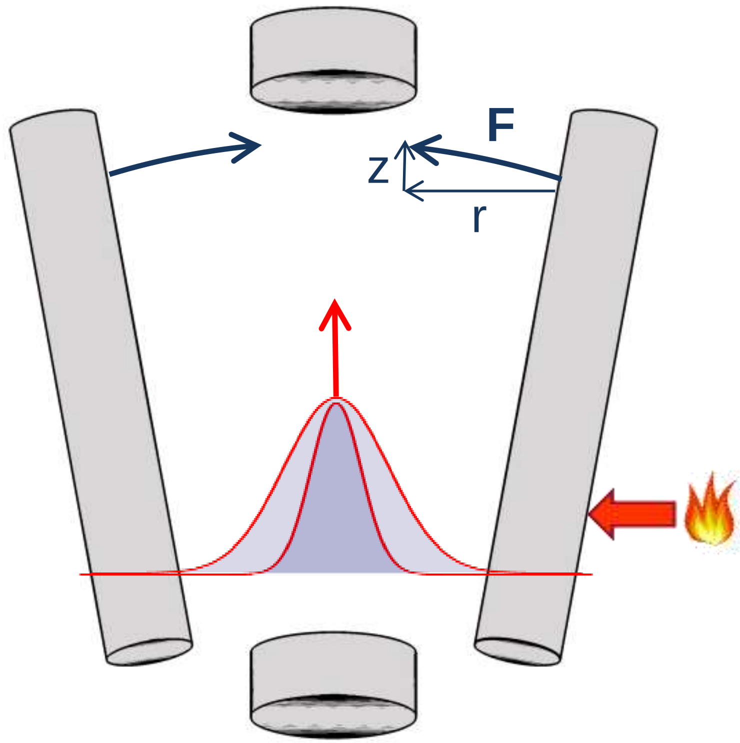
J. Roßnagel, et al. "A single-atom heat engine", Sci. 352, 325 (2016)

selected as one of the top ten breakthroughs in physics in the year 2016 by IOP Physics World

The working principle – single ion HE

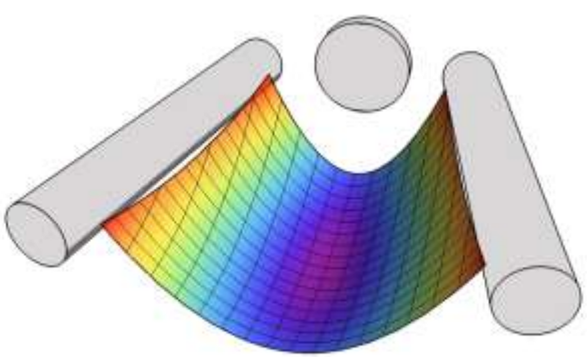
Doppler heating/cooling in radial direction induces axial displacement

Equilibrium position shifted



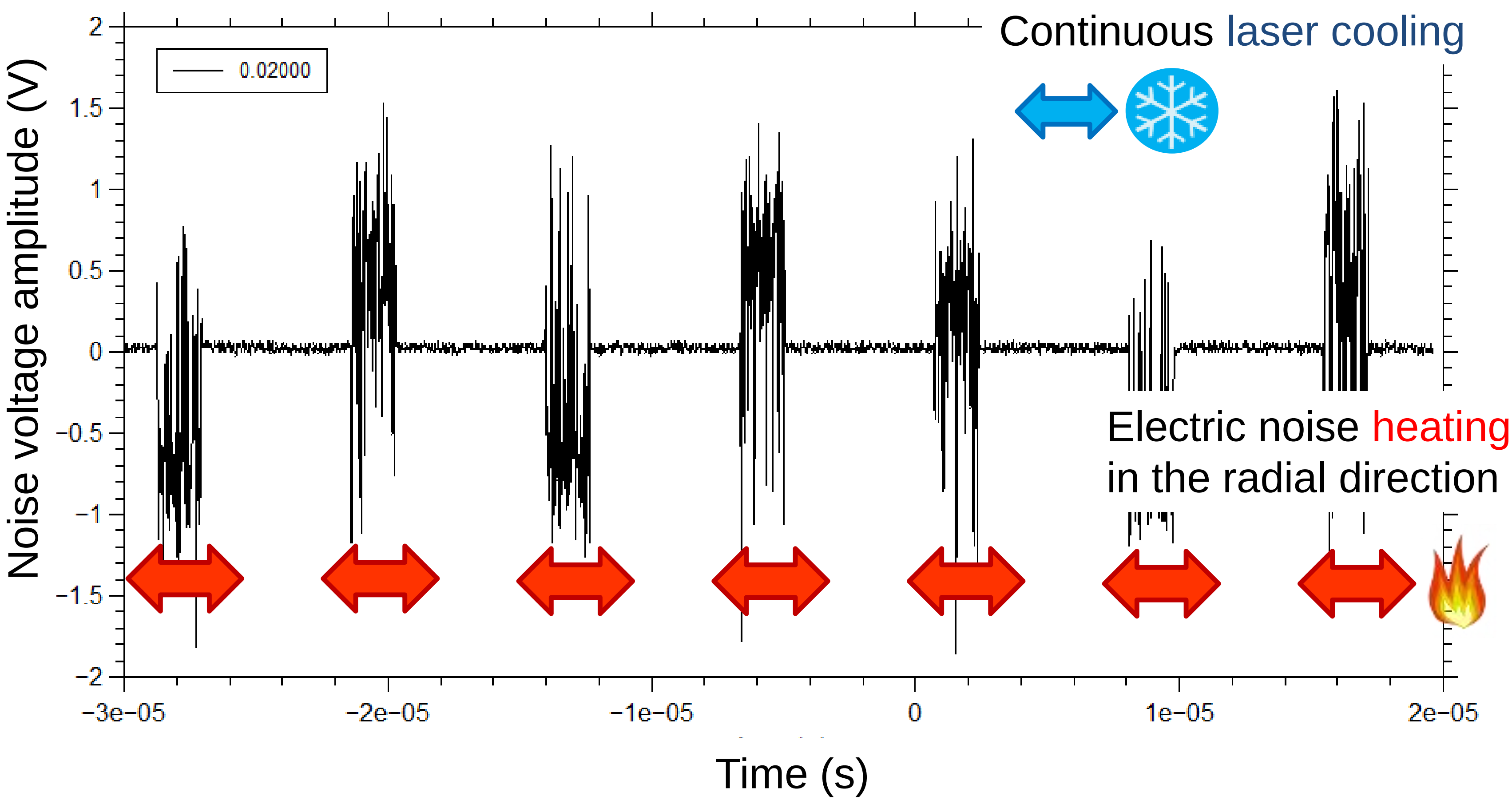
heating

Pseudopotential



To reach reach large axial amplitudes of movement
- strong radial confinement
- weak axial confinement

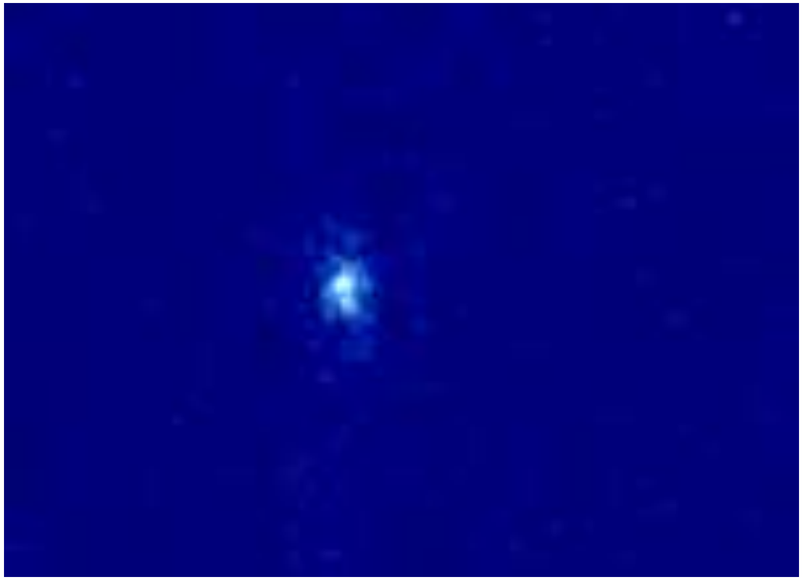
Setting the reservoir temperature by **radial excitation** and cooling



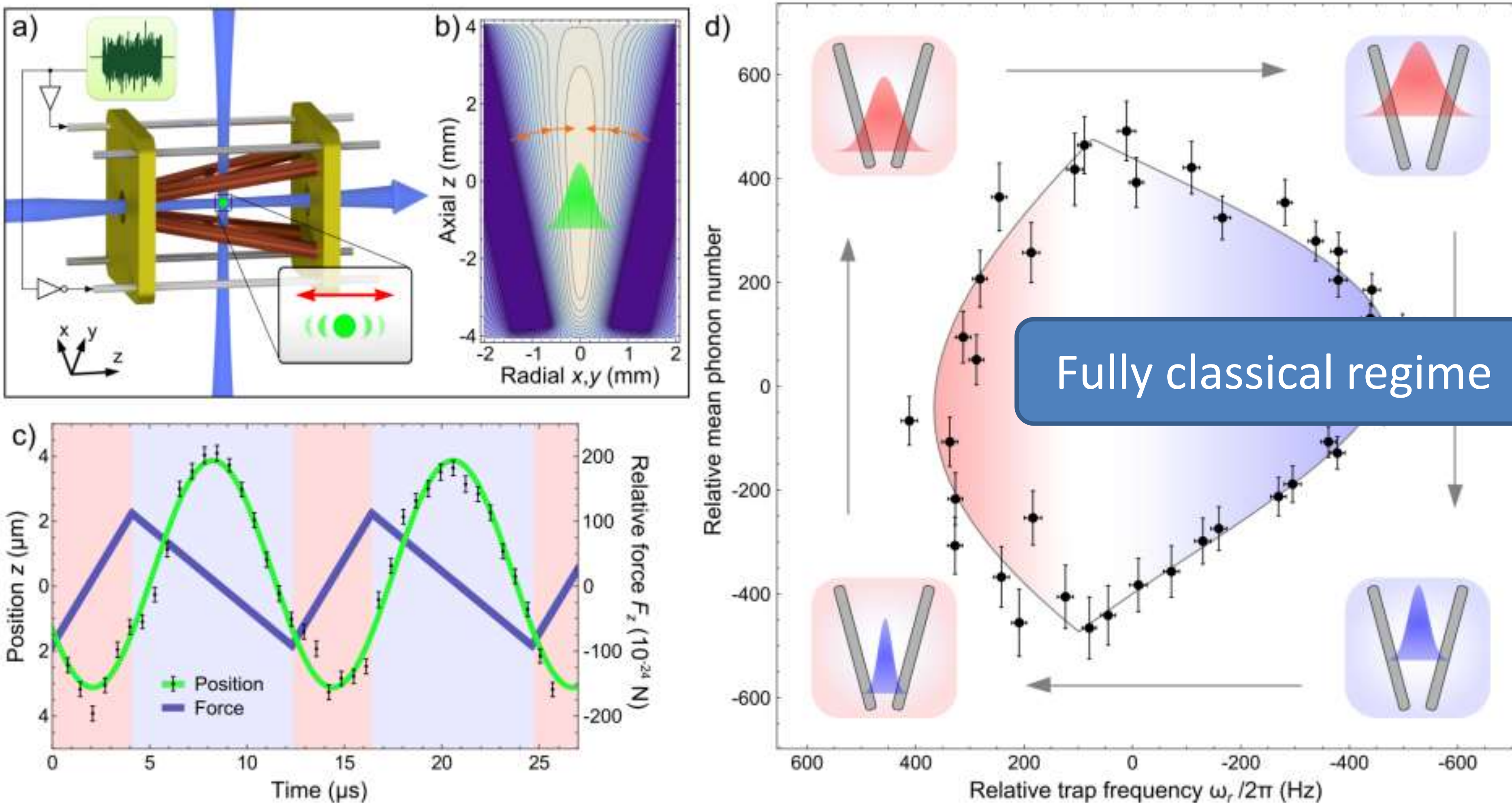
Stroboscopic motion measurements

Princeton Instruments ICCD:

- 8 ns gate time
- 10 MHz frame reate



Working principle and results

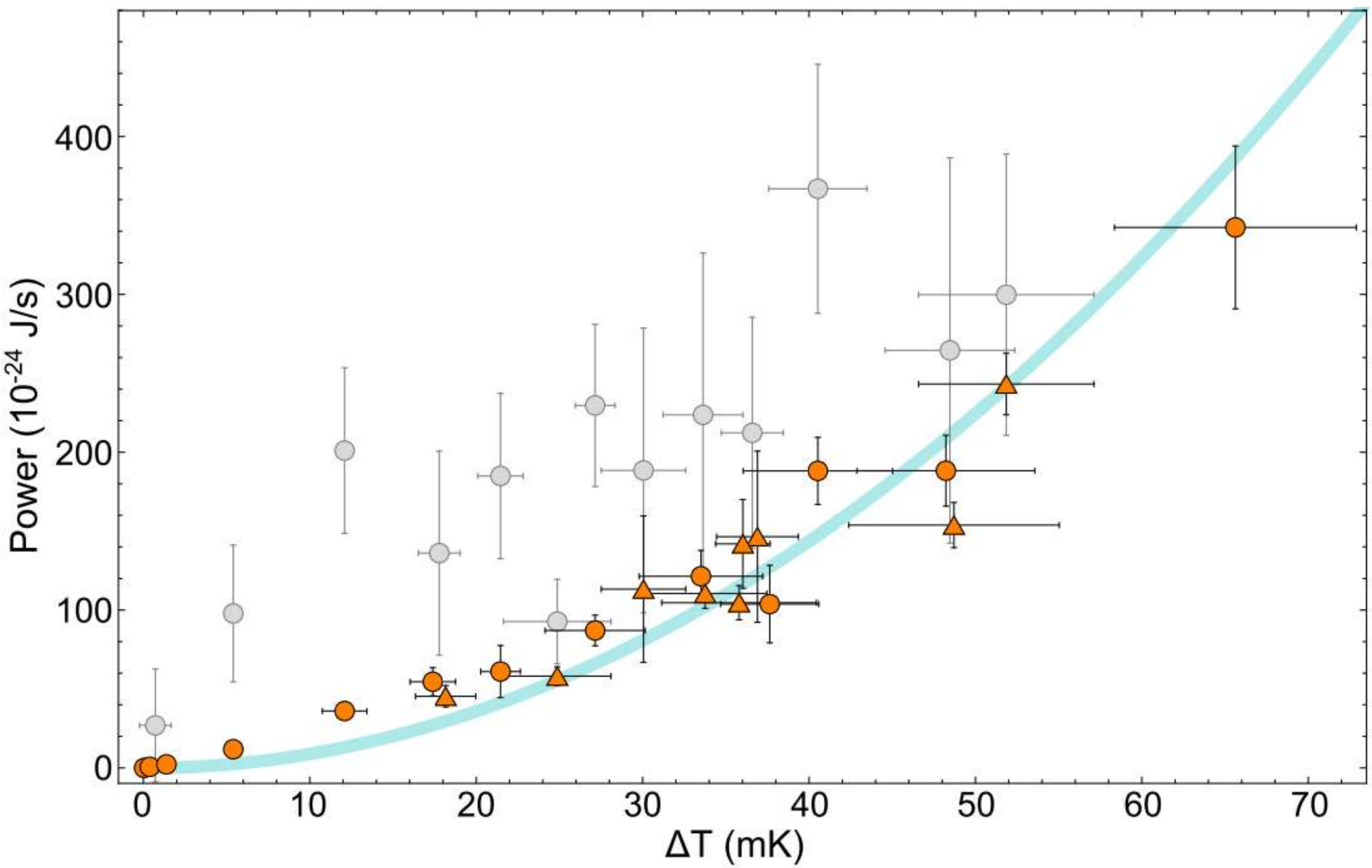


Fully classical regime

$P = 3.4 \times 10^{-22}$ J/s
$\eta = 0.28\%$

J. Roßnagel, et al. "A single-atom heat engine", Sci. 352, 325 (2016)

Heat engine efficiency



$P = 3.4 \times 10^{-22}$ J/s

η = 0.28%

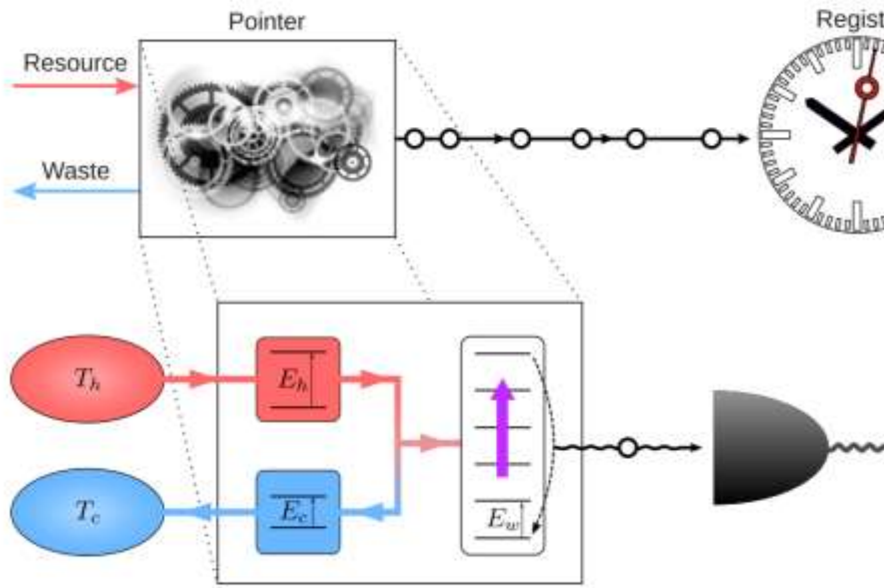
J. Roßnagel, et al. "A single-atom heat engine", Sci. 352, 325 (2016)

Stability of autonomous machine

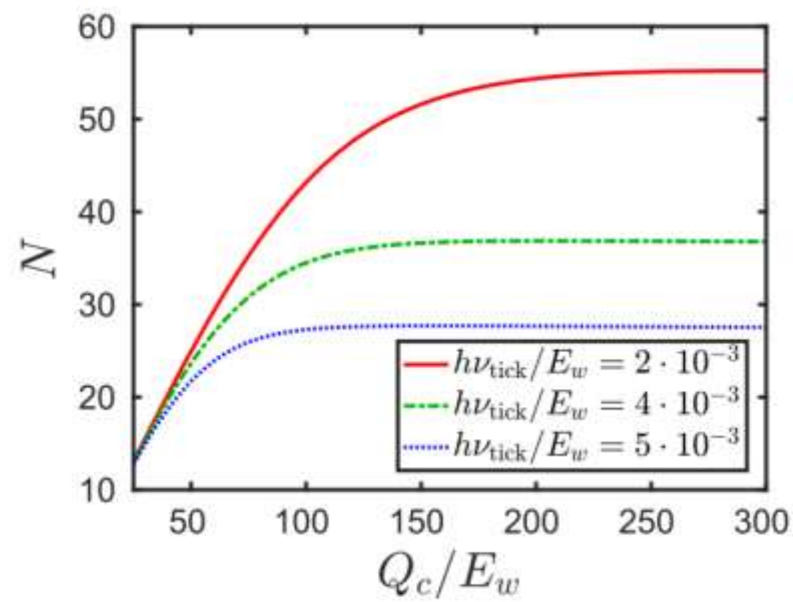
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW X **7**, 031022 (2017)

Autonomous Quantum Clocks: Does Thermodynamics Limit Our Ability to Measure Time?

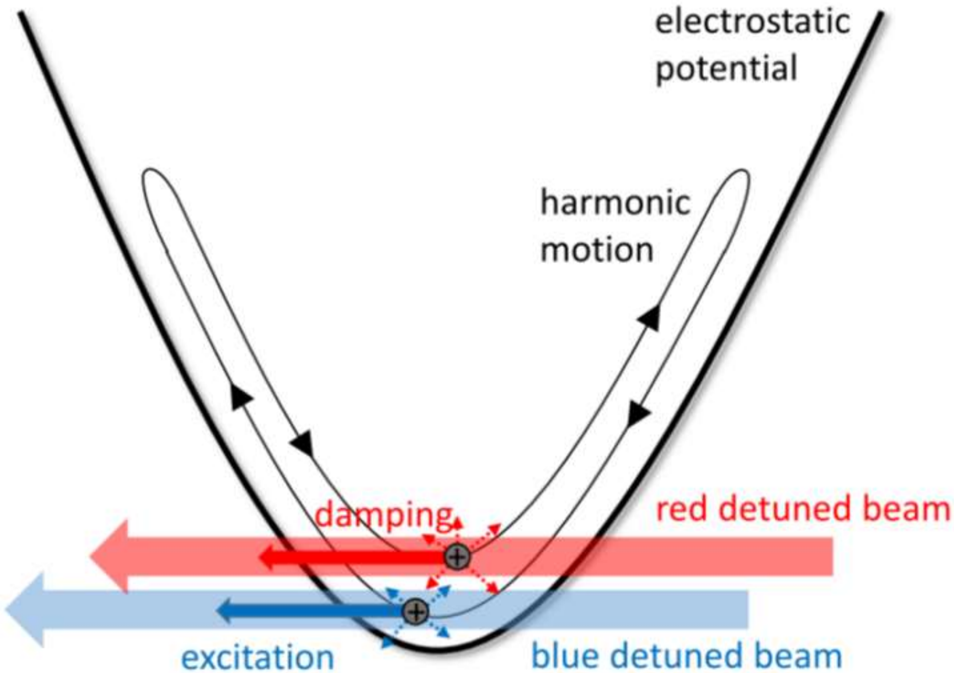
Paul Erker,[1,2] Mark T. Mitchison,[3,4] Ralph Silva,[5] Mischa P. Woods,[6,7] Nicolas Brunner,[5] and Marcus Huber[8]



Prediction:
Accuracy of ticking increases with heat consumption and with entropy production



Our system – the phonon laser



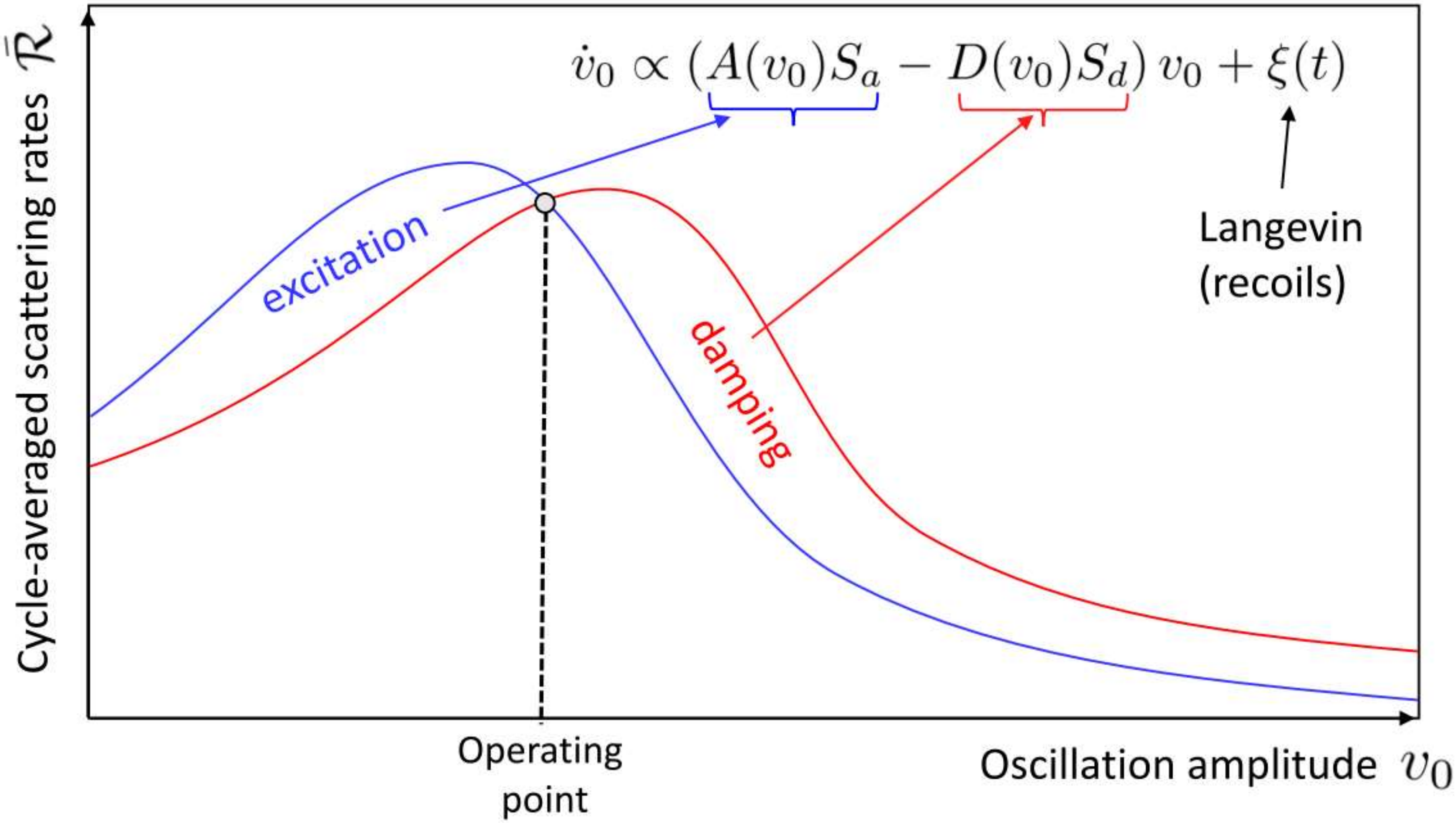
- Blue- and red-detuned beams near dipole transition can lead to autonomous harmonic motion
- Damping and excitation balance during each motional cycle
- Beams are in resonance with trapped ion at separate times: 2ω periodicity in photon emission rates

First demonstration by Udem group MPQ Munich:
K. Vahala et al., Nat. Phys. **5**, 682 (2009)

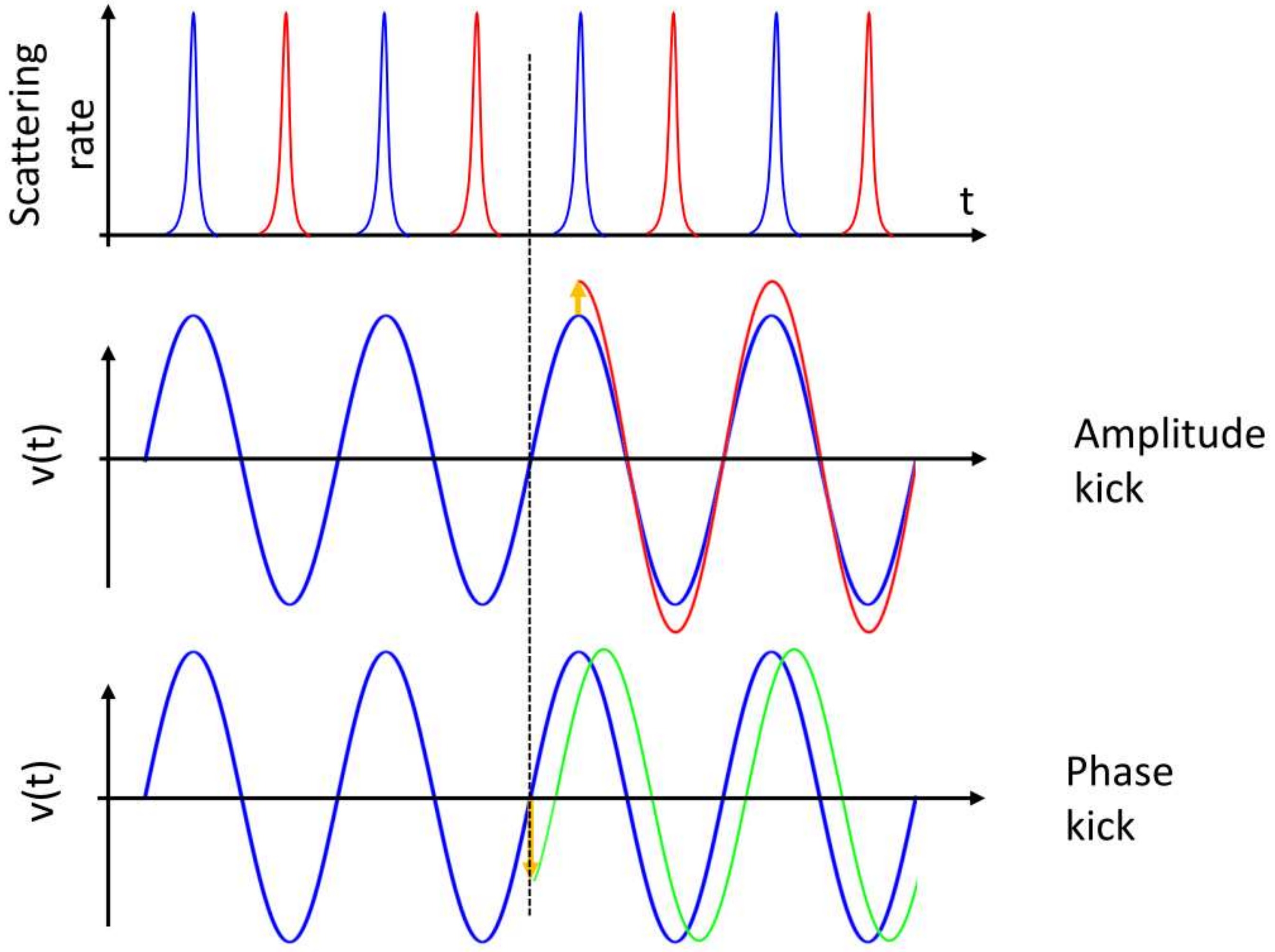
Stable operating point

Stable oscillation: $v(t) = v_0 \cos\left(\omega_{\mathrm{ax}} t + \phi\right)$

Scattering rates: $\mathcal{R}(t) = \frac{\gamma}{2} \frac{S}{1 + \frac{4}{\gamma^2}\left(\delta - k\, v(t)\right)^2}$

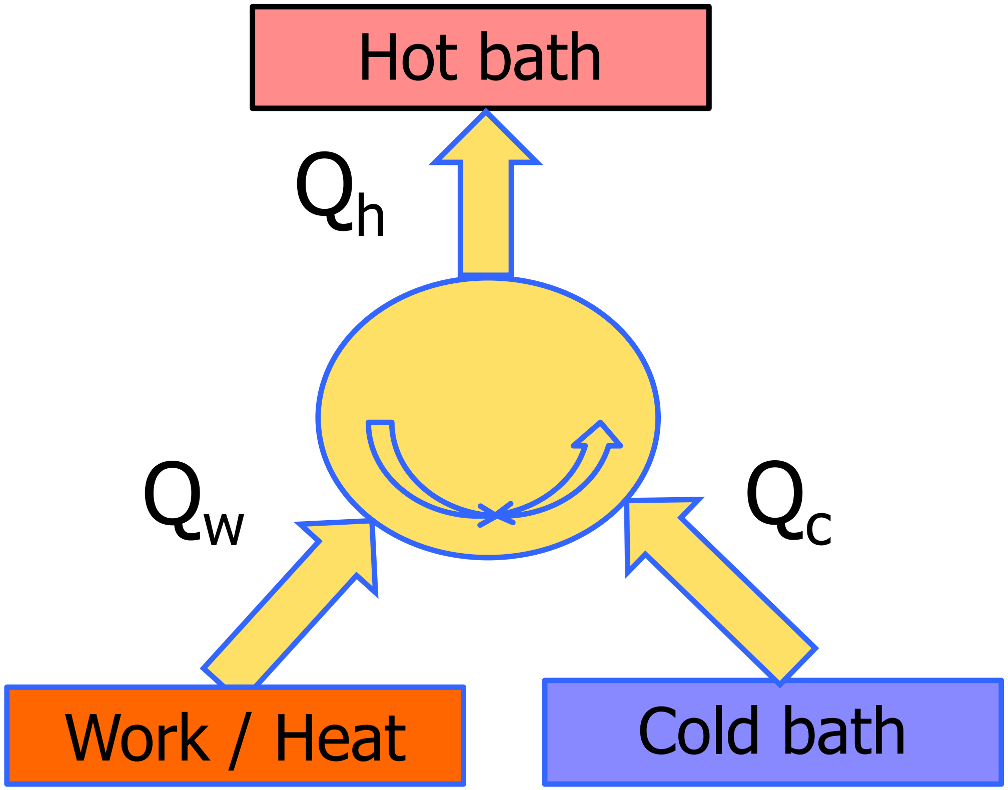


Phase stability



Recoils occur at velocity return points: **Inherent phase stability!**

Refrigerator



$T_w > T_h > T_c$

Dzmitry Matsukevich

Refrigerator: cools cold bath by work

Absorption Refrigerator: Driven by heat instead of work

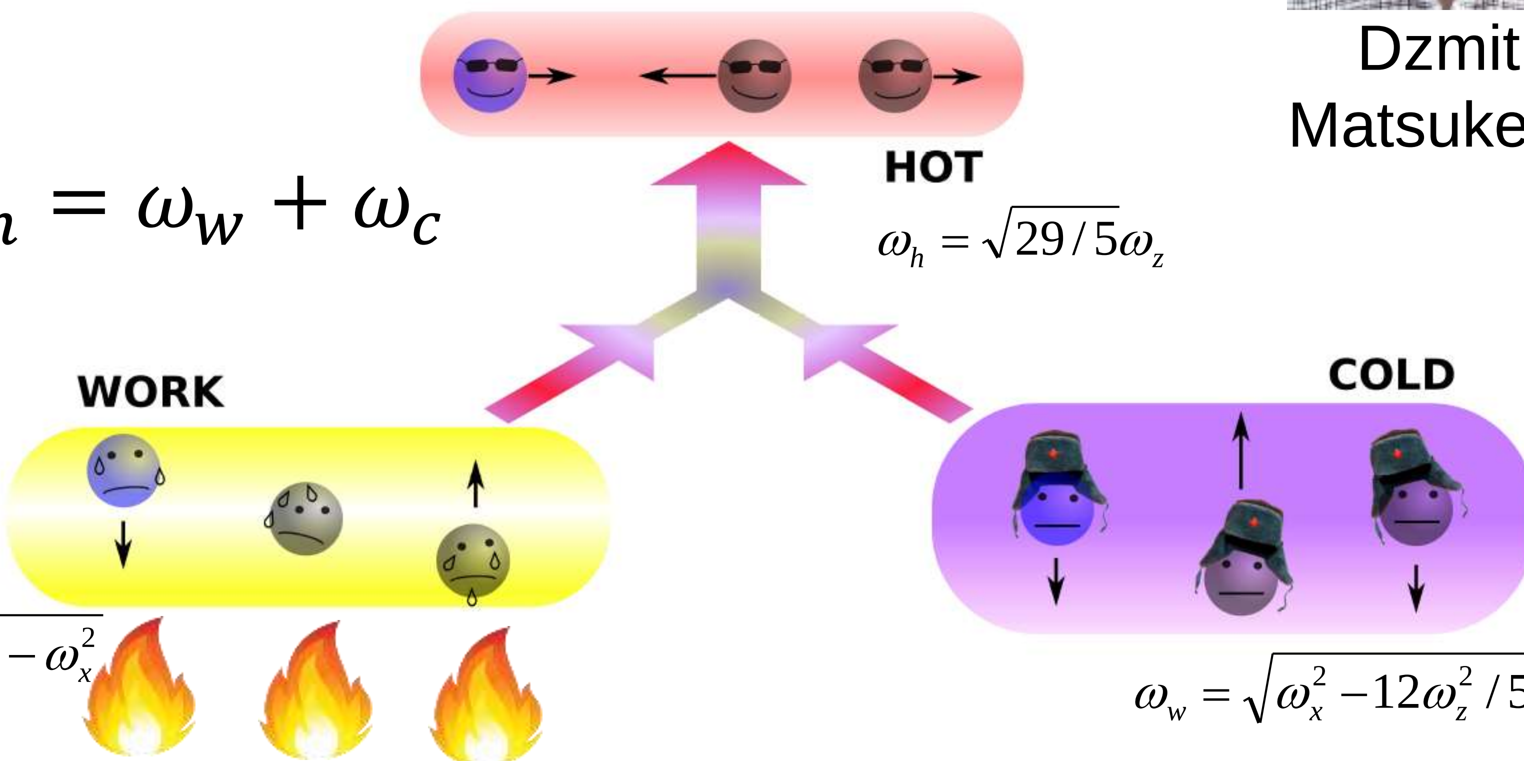
Refrigerator with trapped ions

Harmonic oscillators interacting via **trilinear** Hamiltonian

$$\hat{H} = \hbar\xi(\hat{a}_h^\dagger \hat{a}_w \hat{a}_c + \hat{a}_h \hat{a}_w^\dagger \hat{a}_c^\dagger)$$

$$\omega_h = \omega_w + \omega_c$$

Dzmitry Matsukevich



$$\omega_h = \sqrt{29/5}\,\omega_z$$

$$\omega_w = \sqrt{\omega_z^2 - \omega_x^2}$$

$$\omega_w = \sqrt{\omega_x^2 - 12\omega_z^2/5}$$

Maslennikov et al. Nat. Comm. 10, 202 (2019)

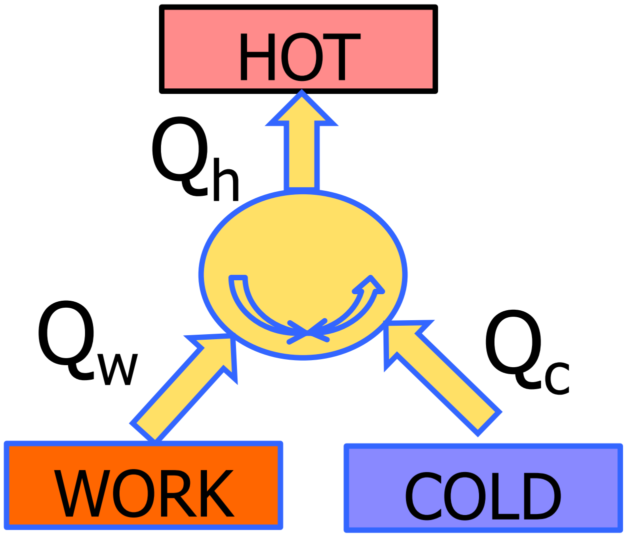
Equilibrium

1st law $\dot{Q}_i = \hbar\omega_i \dot{n}_i$

2nd law $\Delta S = \frac{\dot{Q}_h}{T_h} + \frac{\dot{Q}_w}{T_w} + \frac{\dot{Q}_c}{T_c} = 0$

Coupling Hamiltonian $\dot{n}_h = -\dot{n}_w = -\dot{n}_c$

Phonons from W and C are removed in pairs



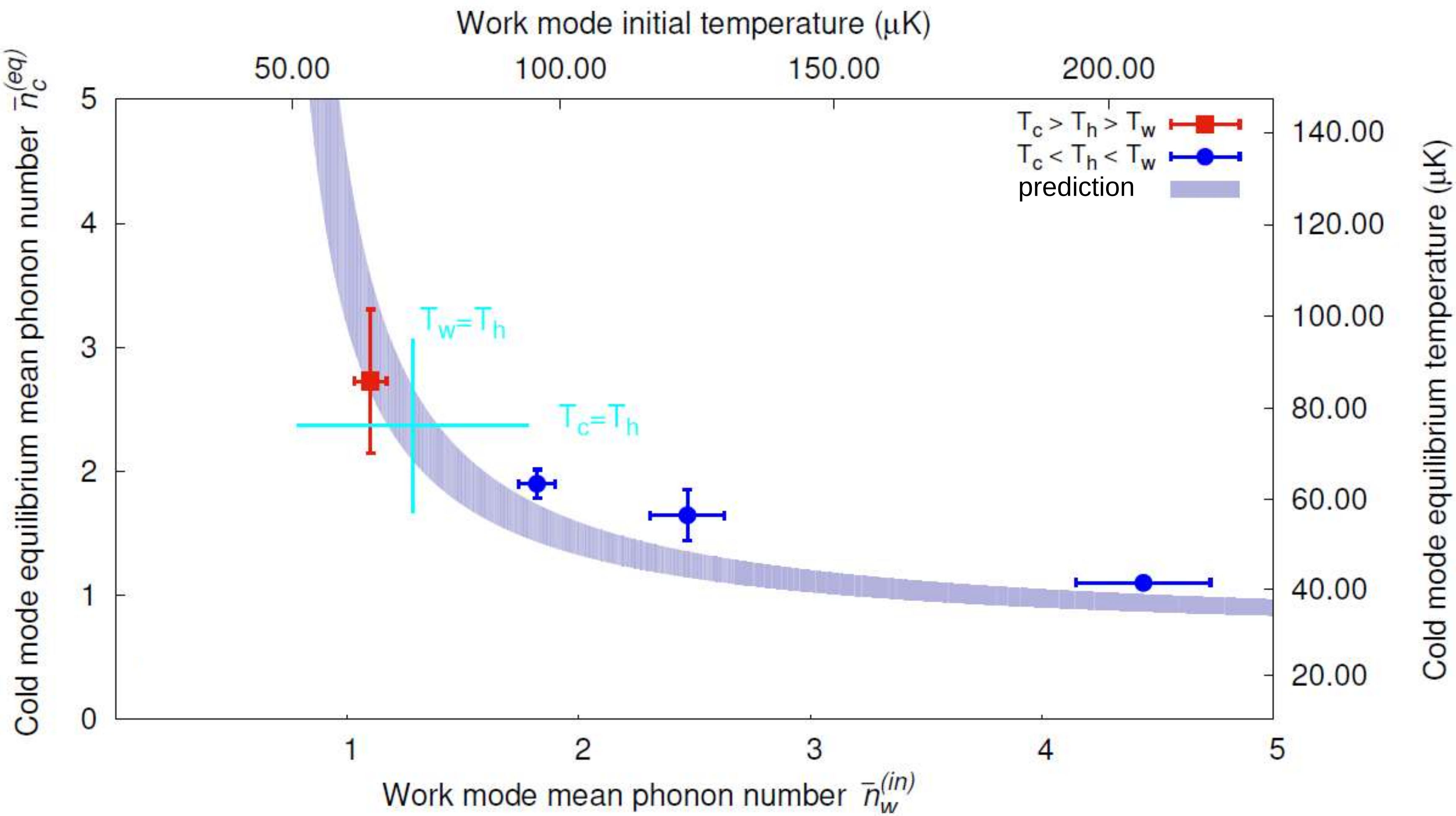
In thermal equilibrium

$$\left(1 + \frac{1}{\bar{n}_h^{(eq)}}\right) = \left(1 + \frac{1}{\bar{n}_w^{(eq)}}\right)\left(1 + \frac{1}{\bar{n}_c^{(eq)}}\right)$$

But: longer evolution leads to non-thermal states

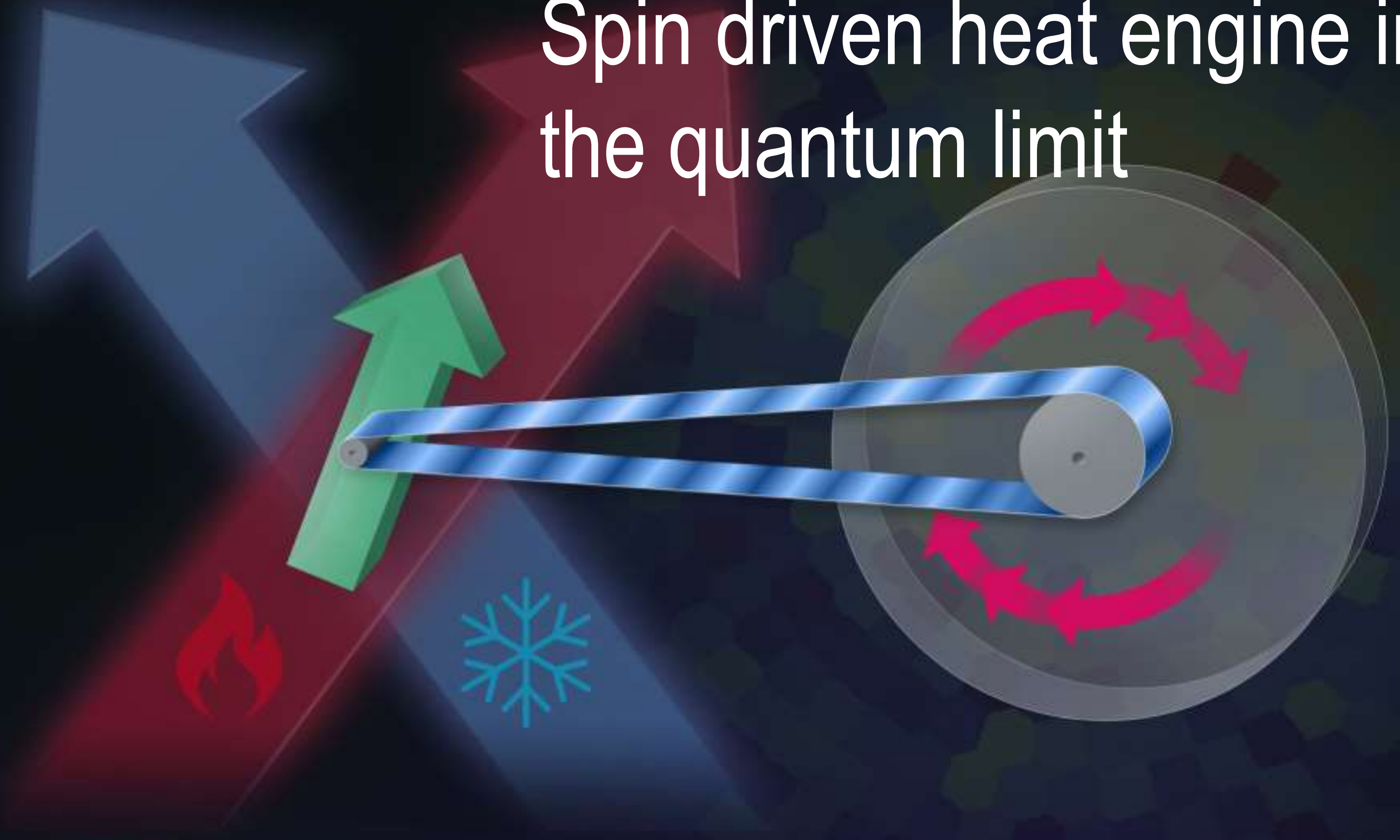
Fridge operation

The higher the work mode phonon number, the colder the cold mode



Maslennikov et al. Nat. Comm. 10, 202 (2019)

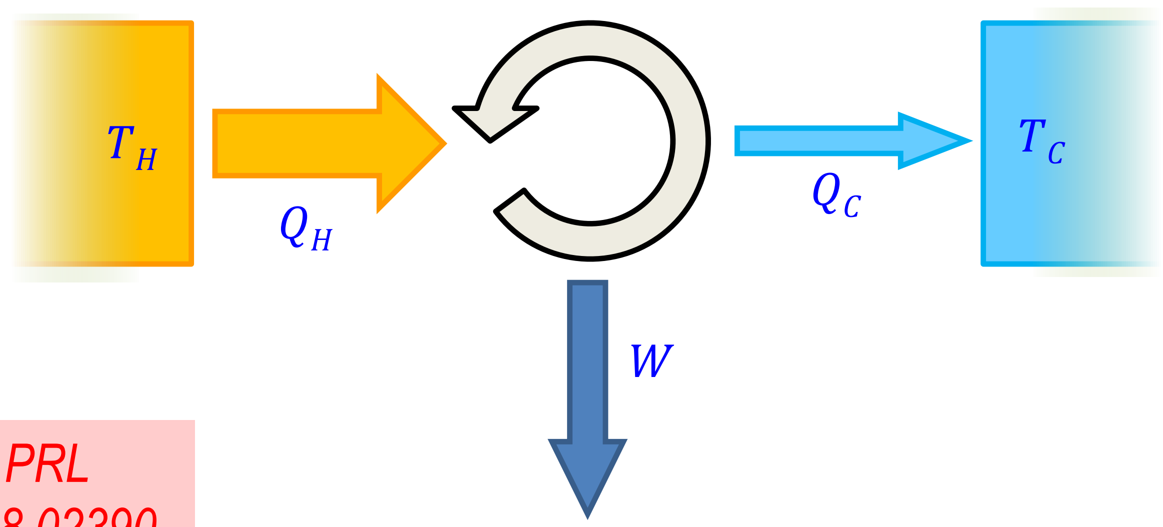
Spin driven heat engine in the quantum limit



“A spin heat engine coupled to a harmonic-oscillator flywheel", Phys. Rev. Lett. 2019 in press, arXiv:1808.02390

Heat-Engine Operation in the Quantum Regime

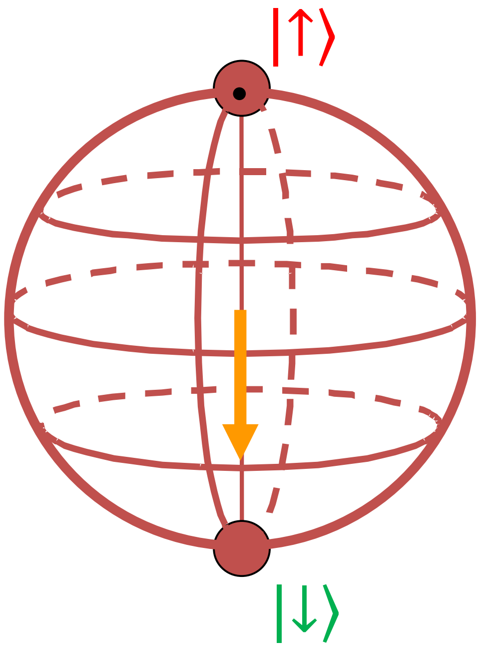
Generic heat engine	Implementation with a trapped $^{40}Ca^{+}$ ion
Working medium	Spin of the valence electron: $\vert\uparrow\rangle$, $\vert\downarrow\rangle$
Thermal baths	Controlling the spin by optical pumping
Gearing mechanism	Spin-dependent optical dipole force
Storage for delivered work	Axial oscillation: $\vert 0\rangle, \vert 1\rangle, \vert 2\rangle$, ...



Lindenfels et al., PRL (2019), arXiv 1808.02390

Spins Thermodynamics

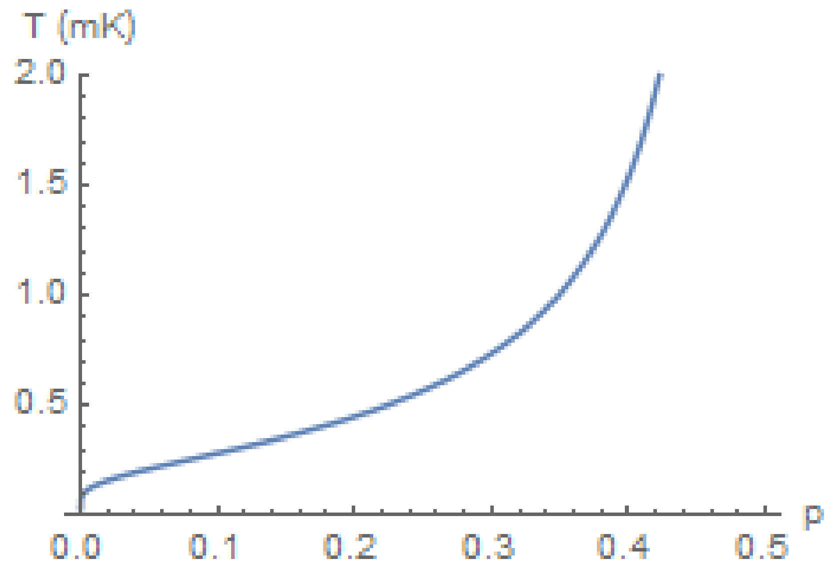
Thermal state



$$\rho = p_\uparrow |\uparrow\rangle\langle\uparrow| + (1 - p_\uparrow)|\downarrow\rangle\langle\downarrow|$$

Spin temperature

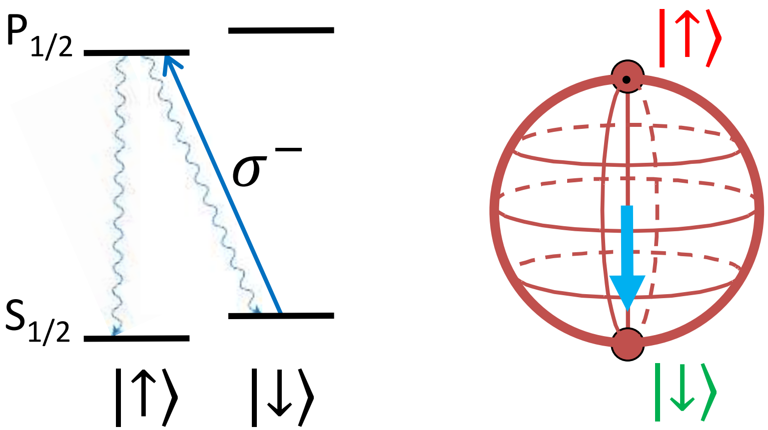
at $2\pi \cdot 13$ MHz Zeeman splitting



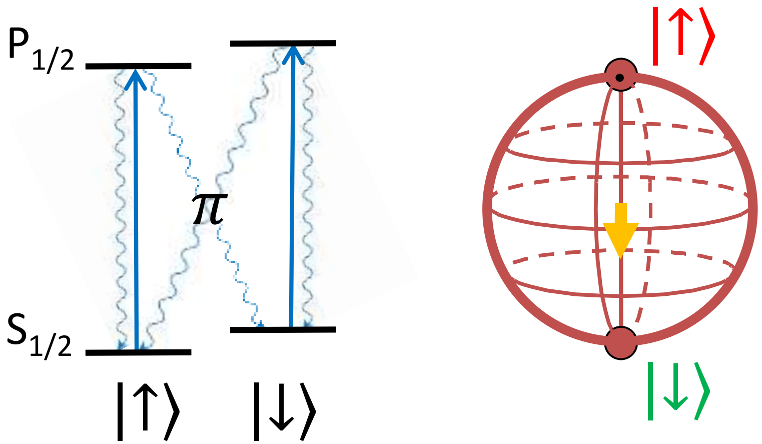
$$p_\uparrow = \frac{1}{1 + \exp(\hbar\omega_L / k_B T)}$$

Controlling the Spins Thermodynamics

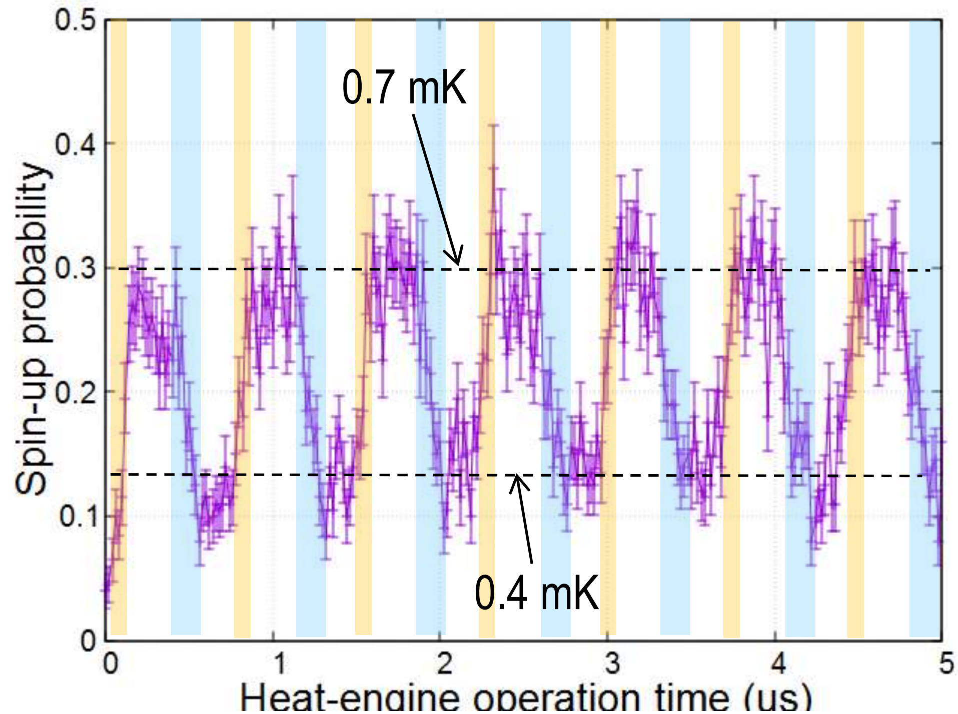
Cold bath: optical pumping



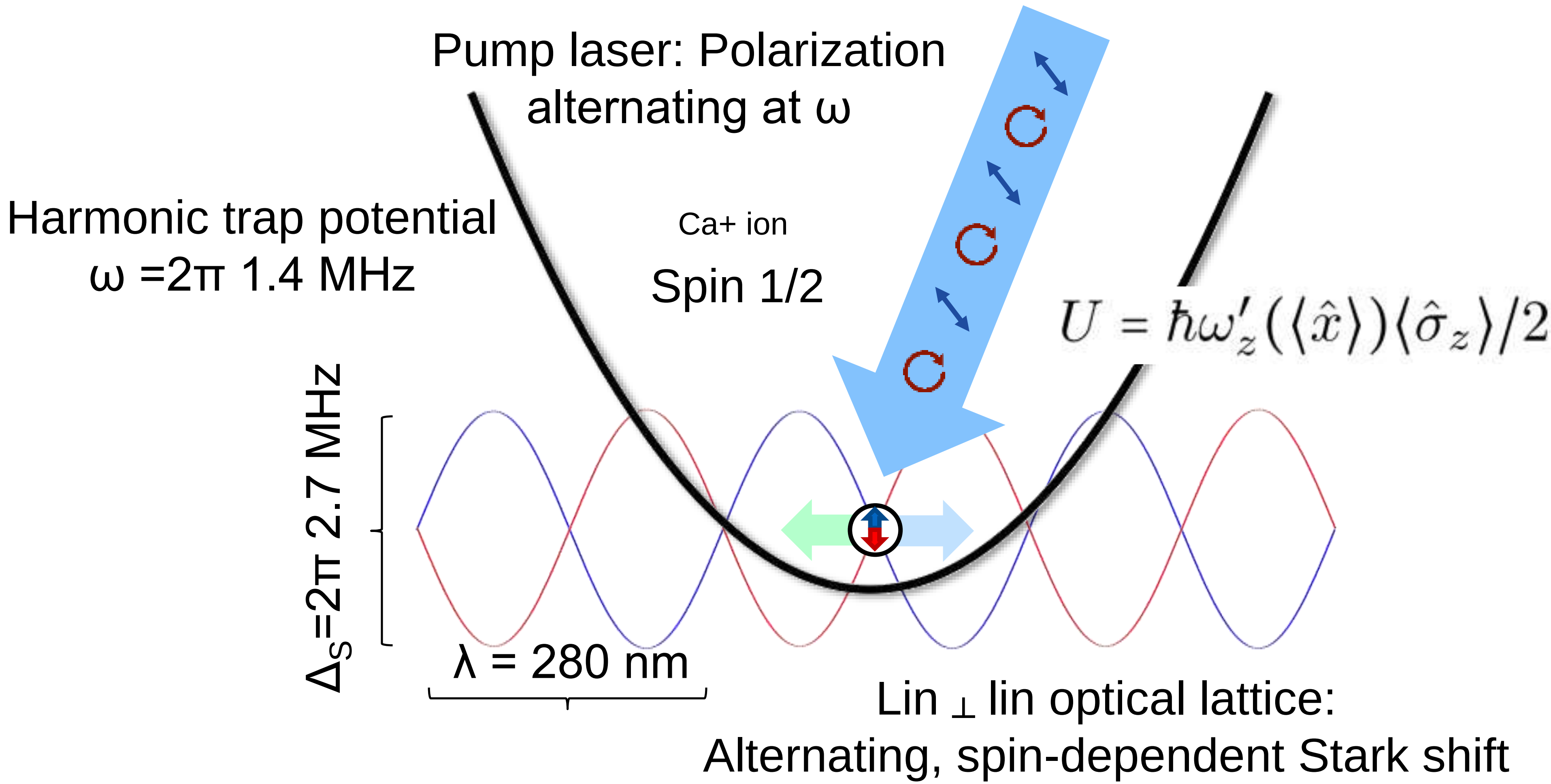
Warm bath: depolarising



Function	Cooling	Heating
Polarisation	circular	linear
Duration	180 ns	130 ns
Excitation ($p_\uparrow$)	0.13	0.30
Temperature	0.4 mK	0.7 mK
Period (= axial oscillation)		*740 ns*



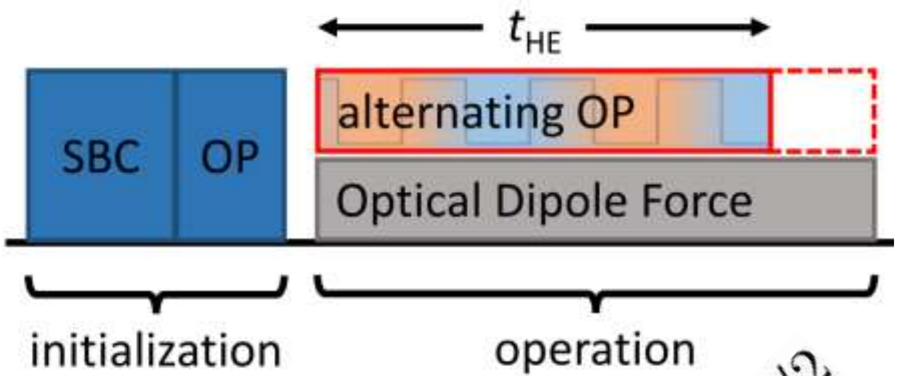
Heat-Engine Operation



Lindenfels et al., PRL (2019), arXiv 1808.02390

Schmiegelow et al., PRL 116, 033002 (2016)

Single-ion operation



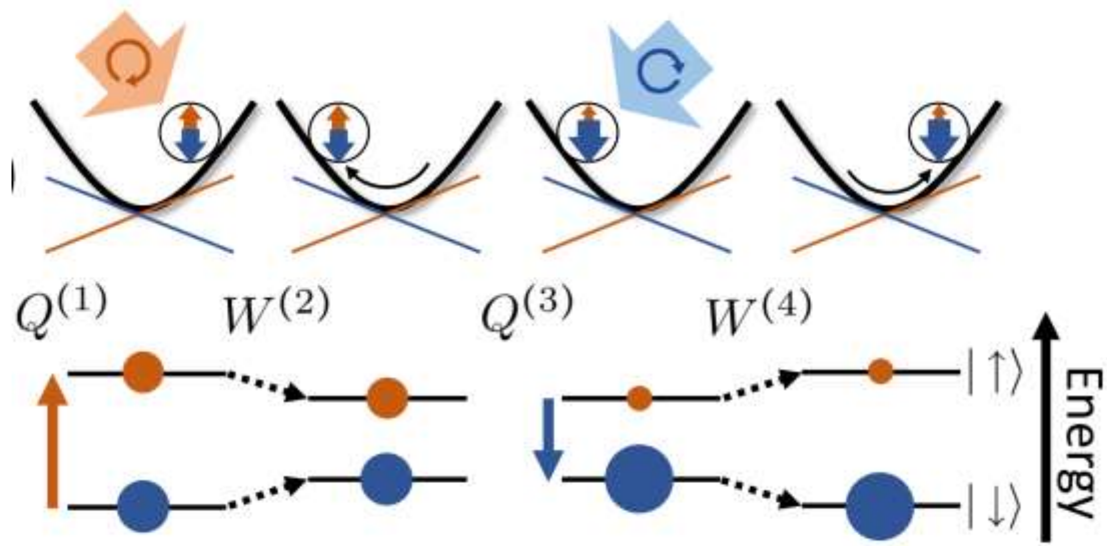
Cooling to |n=0>

Optical pumping to ↑

Alternating optical Pumping: cold – hot

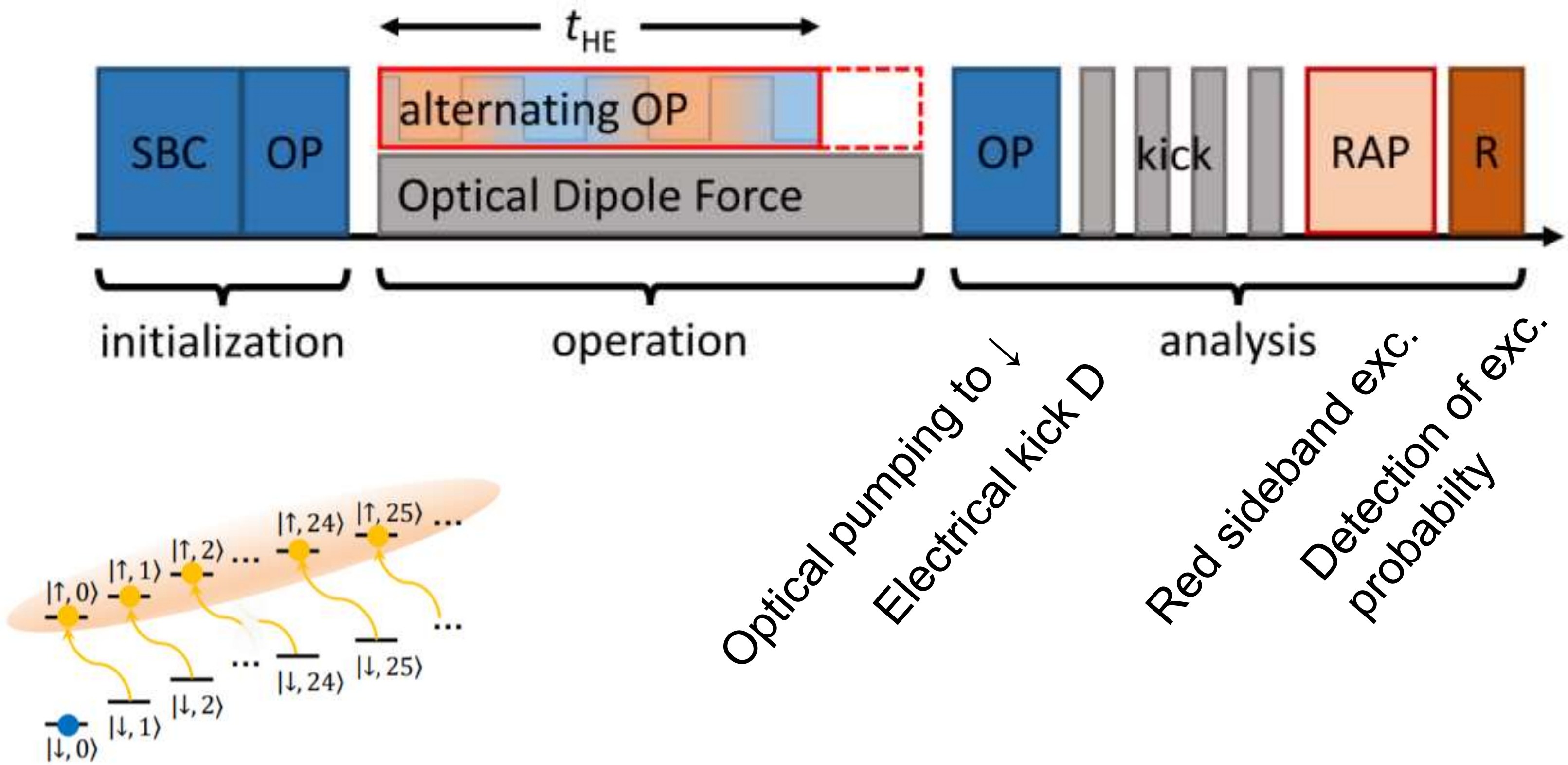
$\mathcal{F} = -\hbar k s w \Delta s \langle \hat{\sigma}_z \rangle / 2$

4-stroke cycle



Lindenfels et al., PRL (2019), arXiv 1808.02390

Single-ion operation and analysis



- Red SB excitation: all motiotal state, except |n=0> transfered to ↑
- Measurement of Q-function:

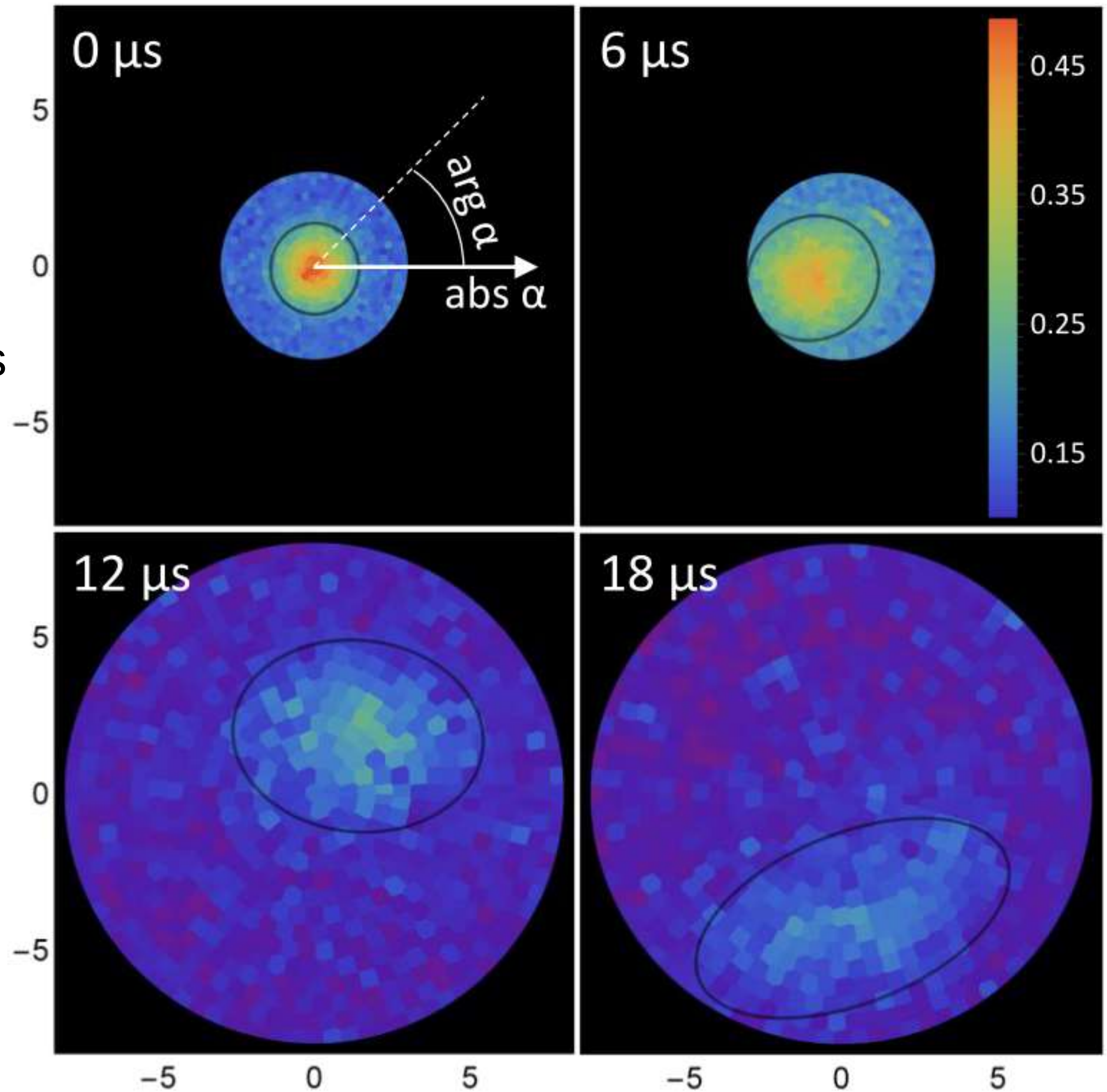
$$\mathcal{Q}(\alpha, \alpha^*) = \frac{1}{\pi} \langle 0| \hat{D}^\dagger(\alpha)\hat{\rho}\hat{D}(\alpha) |0\rangle$$

Lv, et al, Phys. Rev. A 95, 043813 (2017)

Measured Q-function

starting from |n=0>

Q-funct. modelled as
dispaced (β)
squeezed (ζ)
thermal ($\bar{n}$)
distribution



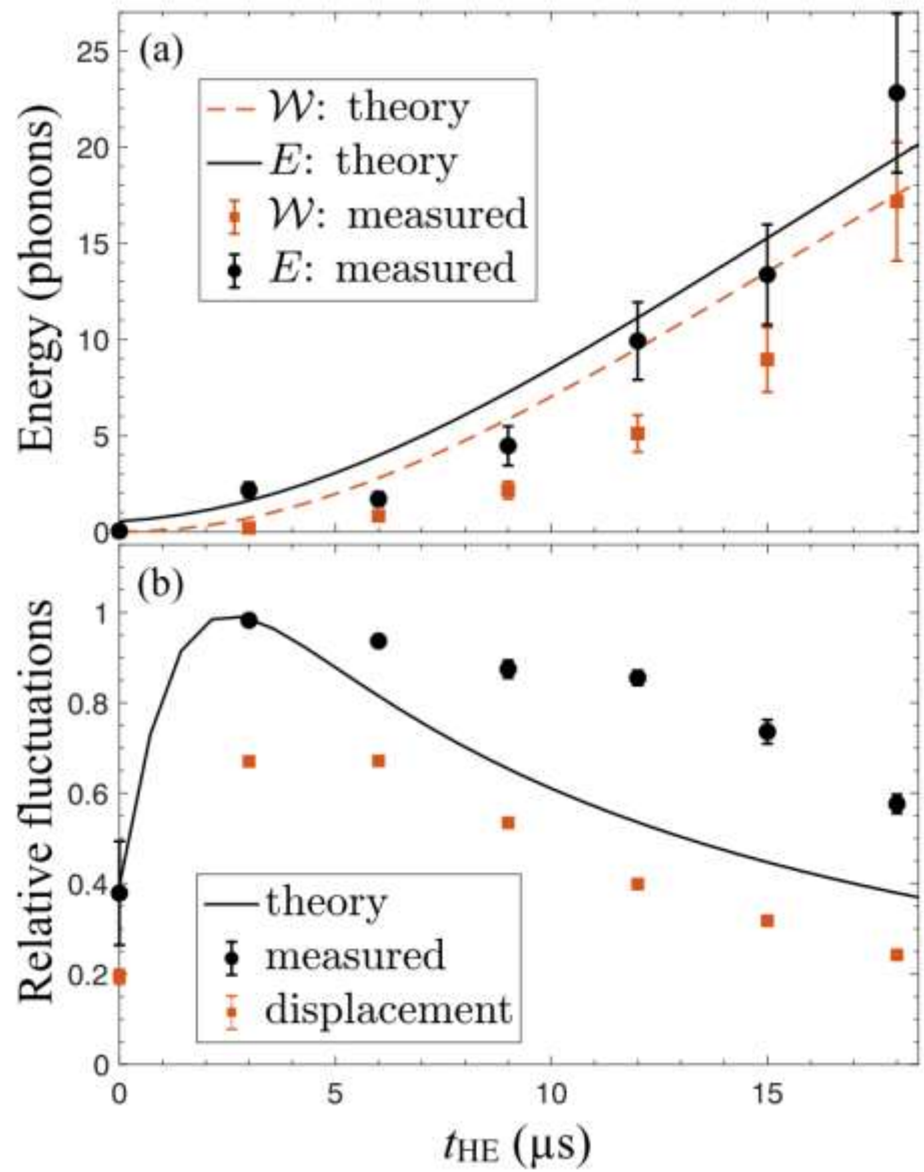
Lindenfels et al., PRL (2019), arXiv 1808.02390

Analysis of the heat engine function

- Reconstruct a density matrix from experimentally determined set {β,ζ,n}
- Determine work E
- Determine HE-ergotropy W

$$\mathcal{W} = \hbar\omega_t|\beta|^2 + \hbar\omega_t \sinh^2(|\zeta|)(2\bar{n}+1)$$
$$E = \mathcal{W} + \hbar\omega_t\bar{n}.$$

- Determine relative energy fluctuations ΔE/E
- Thermal and spin-projection noise contributions



Lindenfels et al., PRL (2019), arXiv 1808.02390

experimental / theory heat engine collaboration

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Ulrich Poschinger

FSK

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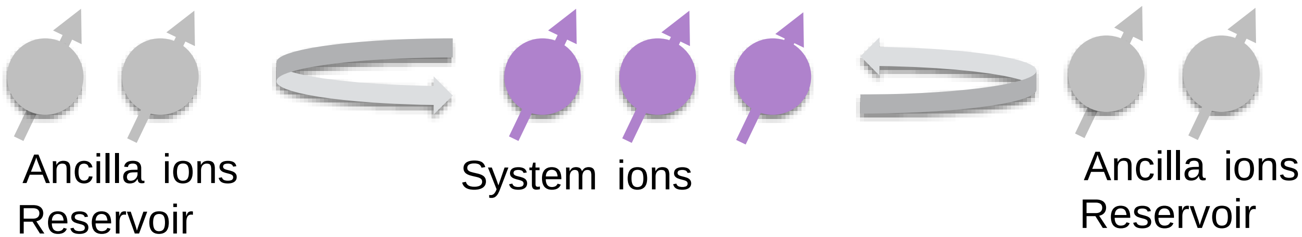
Mark Mitchison

John Goold

Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

Future plans

Realize and analyze engine with full quantum control over working fluid and reservoirs



Goals:

- Investigate the role of multi-particle quantum entanglement in heat engines
- Study close connection between quantum error correction, quantum computing and heat engines