The team

Folman, Retzker, Wrachtrup, Meijer, Lesanowski, Hennrich, Zanthier, Lutz, Budker, Schmiegelow, Walz, Plenio, Jelezko, Calarco, Jamieson, Blatt

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CENTRE FOR QUANTUM COMPUTATION & COMMUNICATION TECHNOLOGY

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DFG-FOR 2724

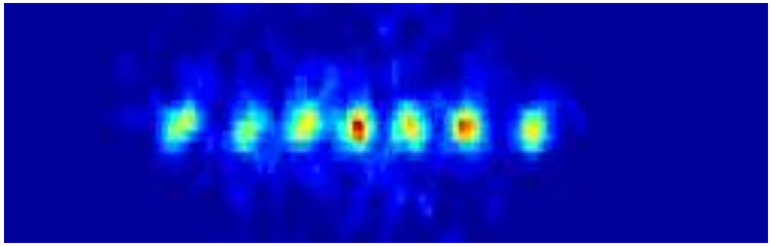
VolkswagenStiftung

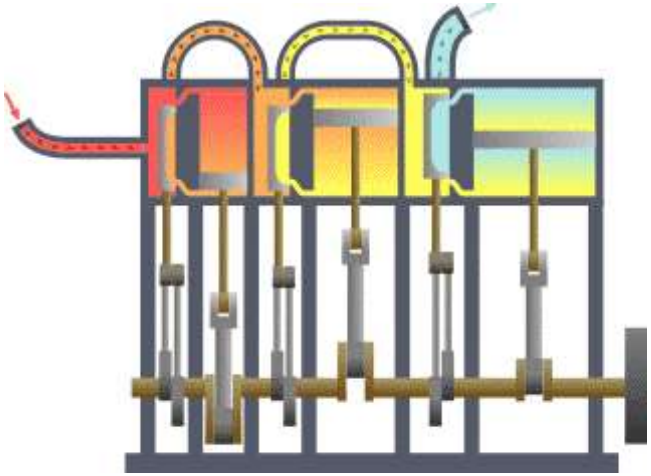
QUANTUM FLAGSHIP

FUNDING OPPORTUNITIES from the FUTURE & EMERGING TECHNOLOGIES scheme

Quantum optics and information with trapped ions

- Introduction to ion trapping and cooling
- Trapped ions as qubits for quantum computing and simulation
- Implanting single ions for a solid state quantum device
- Rydberg excitations for fast entangling operations
- Quantum thermodynamics, heat engines, phase transitions





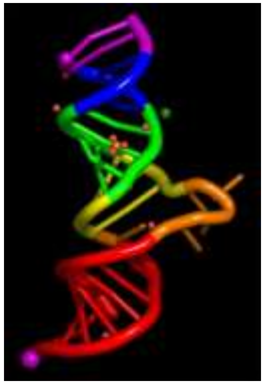
Thermodynamics overview

Large system:
Many degrees of freedom
and many particles

Average values

In equilibrium,
or at least very close to it

Fluctuations unimportant



Small system:
few degrees of freedom
and single particle

Work probability distribution

Thermal fluctuations

Fluctuation theorems

Brownian motion

Quantum system:
Quantized degrees of freedom,
superpositions and entanglement

Probabilistic nature
of quantum processes

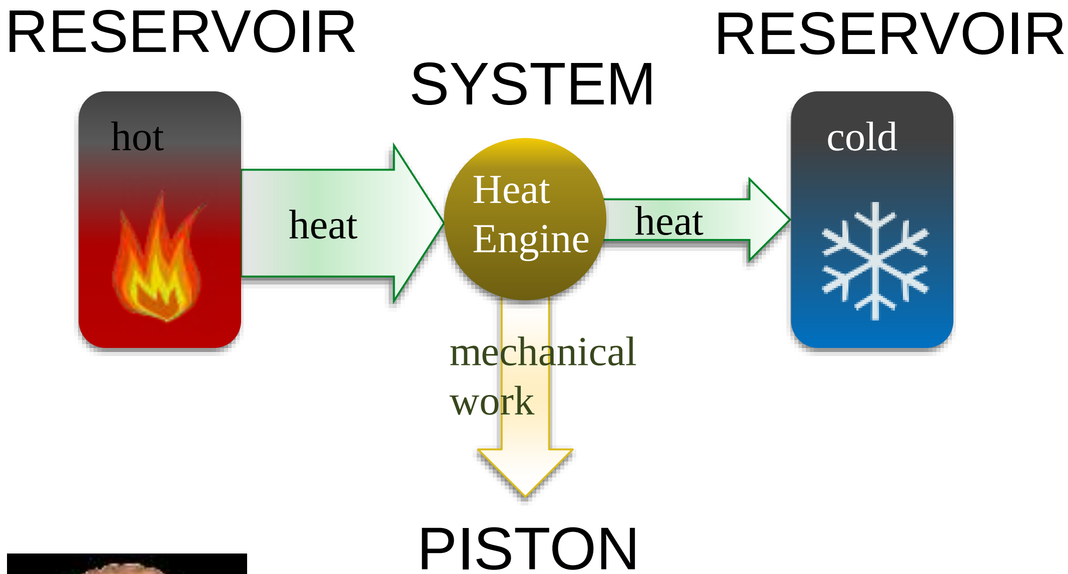
Observation of
system matters

Correlations with
environment matter

Non-classical baths

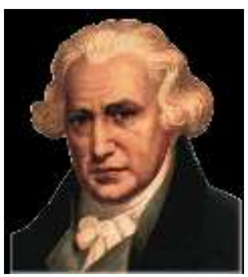
Classical heat engines

Convert thermal energy into mechanical work



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


Robert Mayer


James Watt

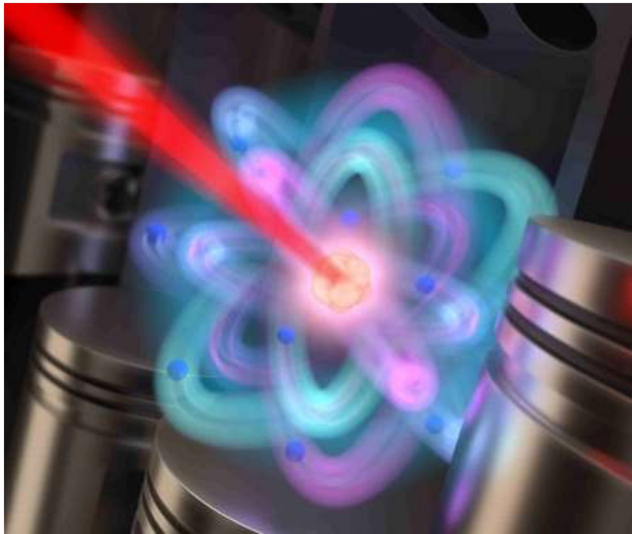
James Watt (1783): $\boldsymbol{\eta} \cong \mathbf{5-7\%}$
Modern power plats: $\boldsymbol{\eta} \cong \mathbf{30\%}$


Sadi Carnot

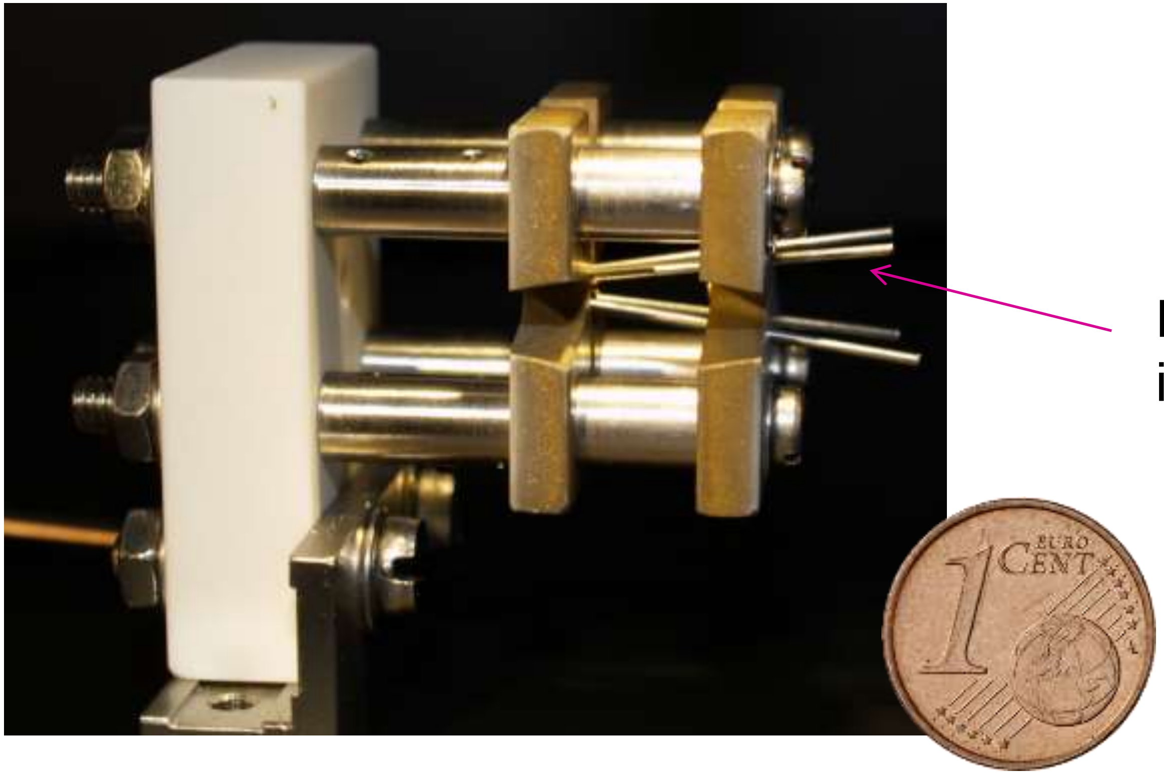
$$\eta = \frac{\text{Work produced}}{\text{Heat absorbed}} = \frac{W}{Q_H} \leq 1 - \frac{T_C}{T_H} = 1 - \frac{\beta_H}{\beta_C}$$

Structure of talk - trapped ion thermodynamics

- **Single-ion** Otto heat engine - classical operation
- **Spin-driven** single ion heat engine - quantum motion
- **Autonomous** heat engine – ticking regularly
- Vision of a **multi-ion crystal quantum heat engine**
- Defect formation in a **structural phase transition – universal Kibble Zureck** scaling law



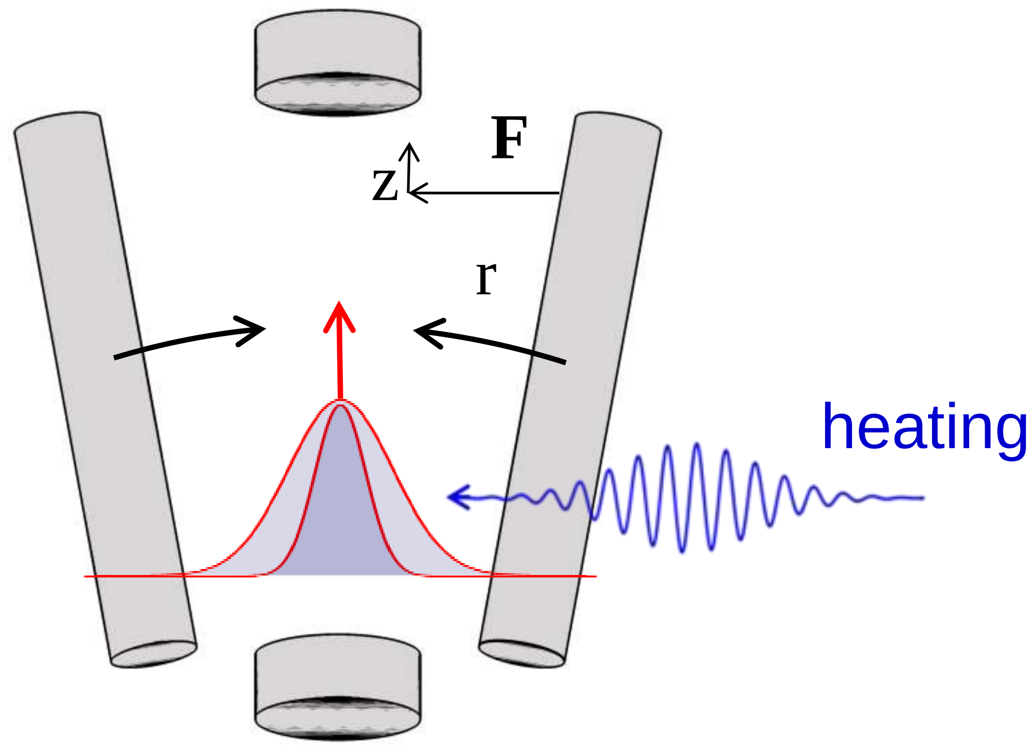
Setup of single ion heat engine



Distance ion – endcaps: 4mm
Distance ion – electrodes: 1.5mm
RF driving: $1000V_{pp}$ at 30MHz
Axial trap frequency: 35kHz
Radial trap frequency: 6MHz

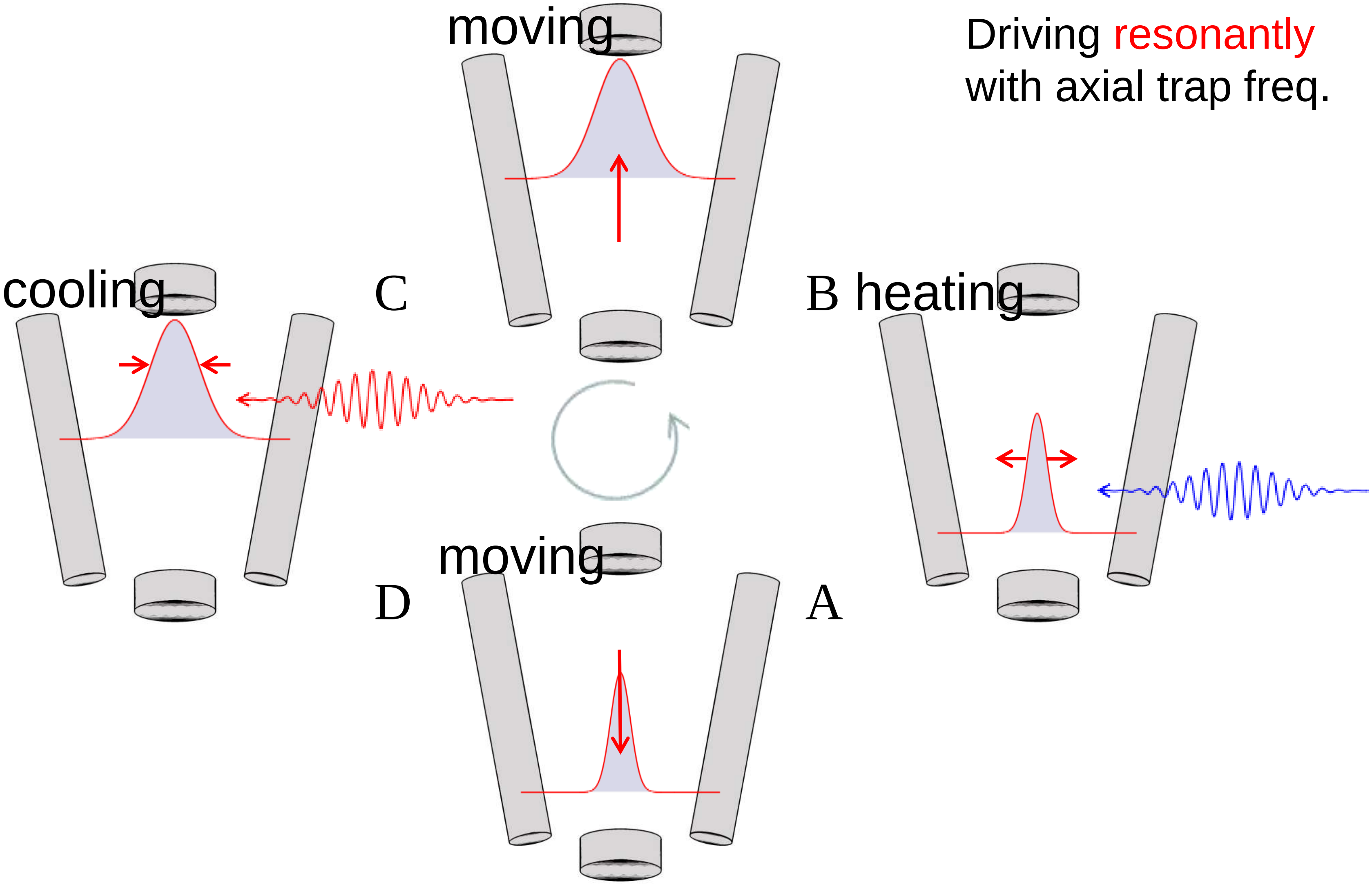
Scheme of operation – single ion heat engine

- Radial heating
- Axial equilibrium position shifted
- Radial cooling
- Axial position shifted back



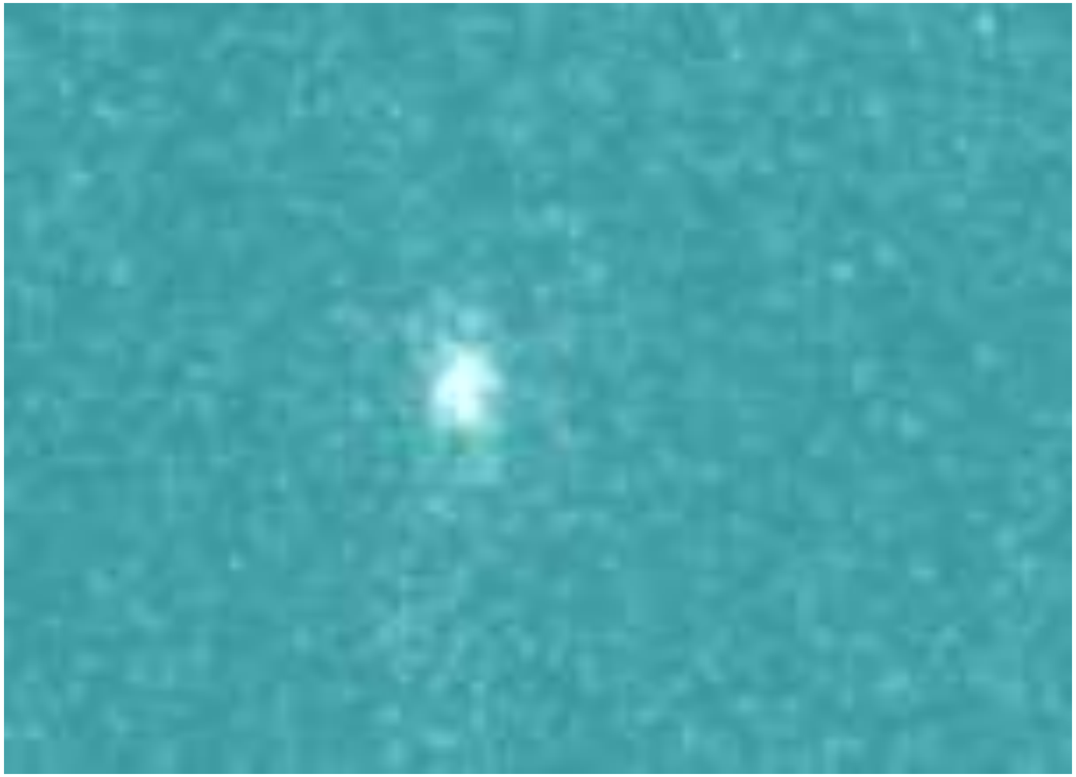
Working cycle

Driving resonantly
with axial trap freq.

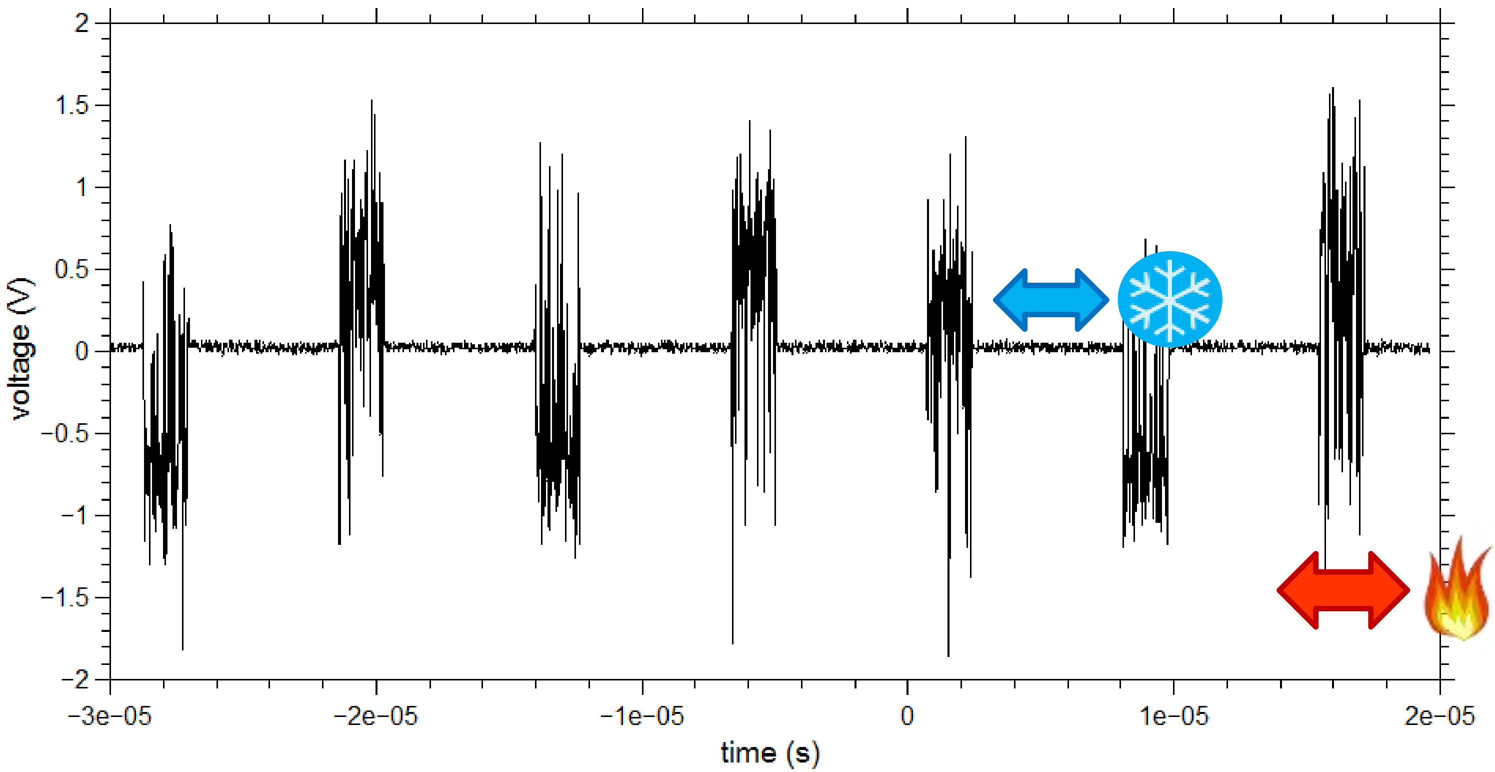


Stroboscopic motion measurements

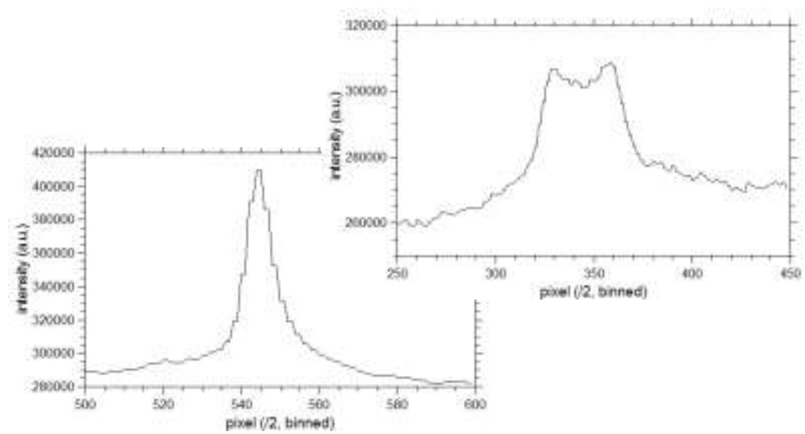
Princeton Instruments ICCD:
- 8 ns gate time
- 10 MHz frame reate



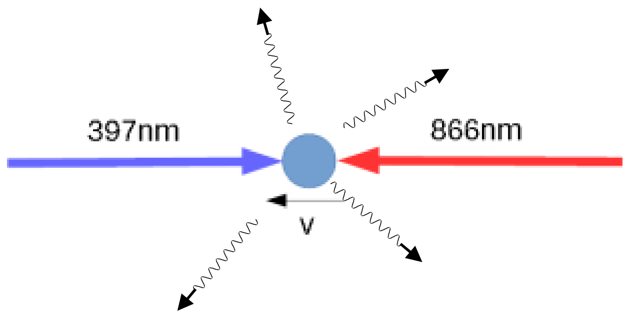
Thermal radial excitation



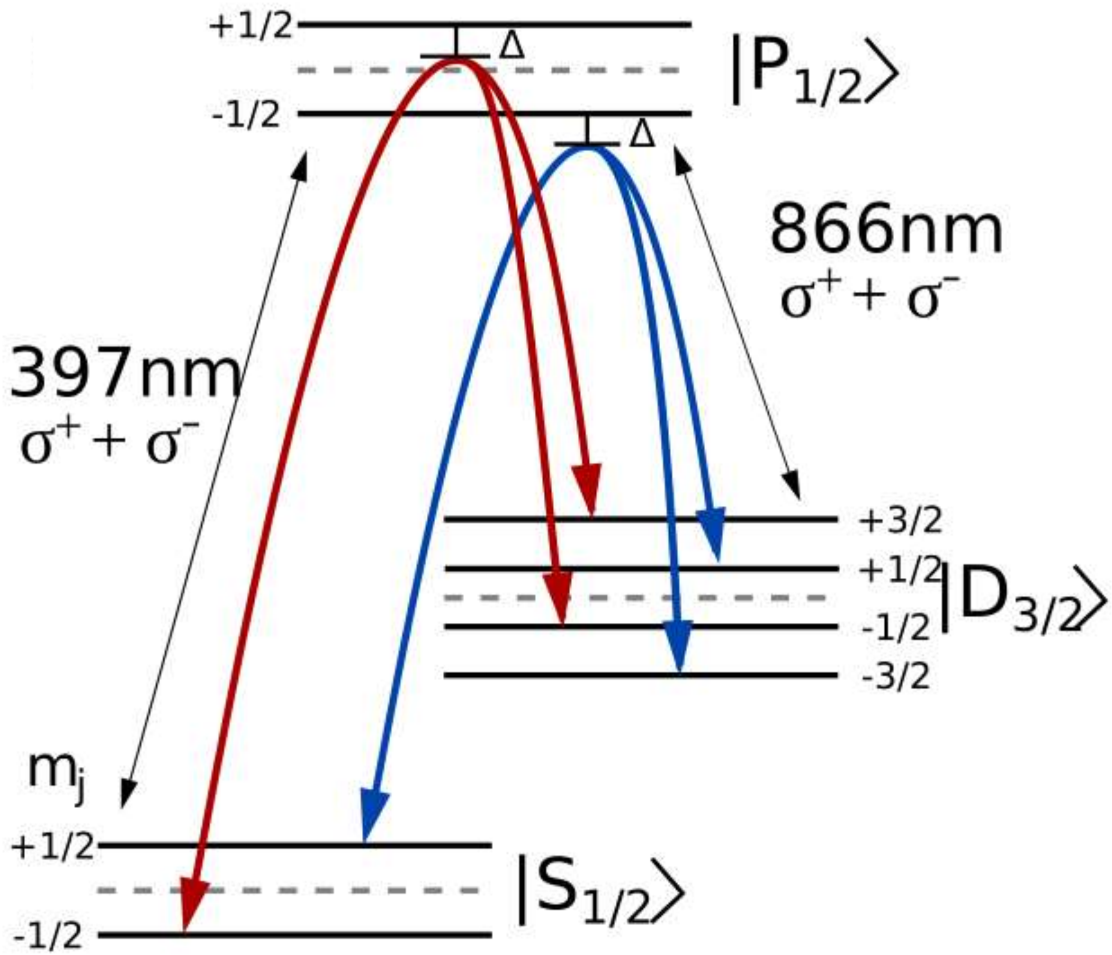
- Continuously: laser cooling
- At alternating times: additional electric noise in radial direction



Stroboscopic thermometry by EIT



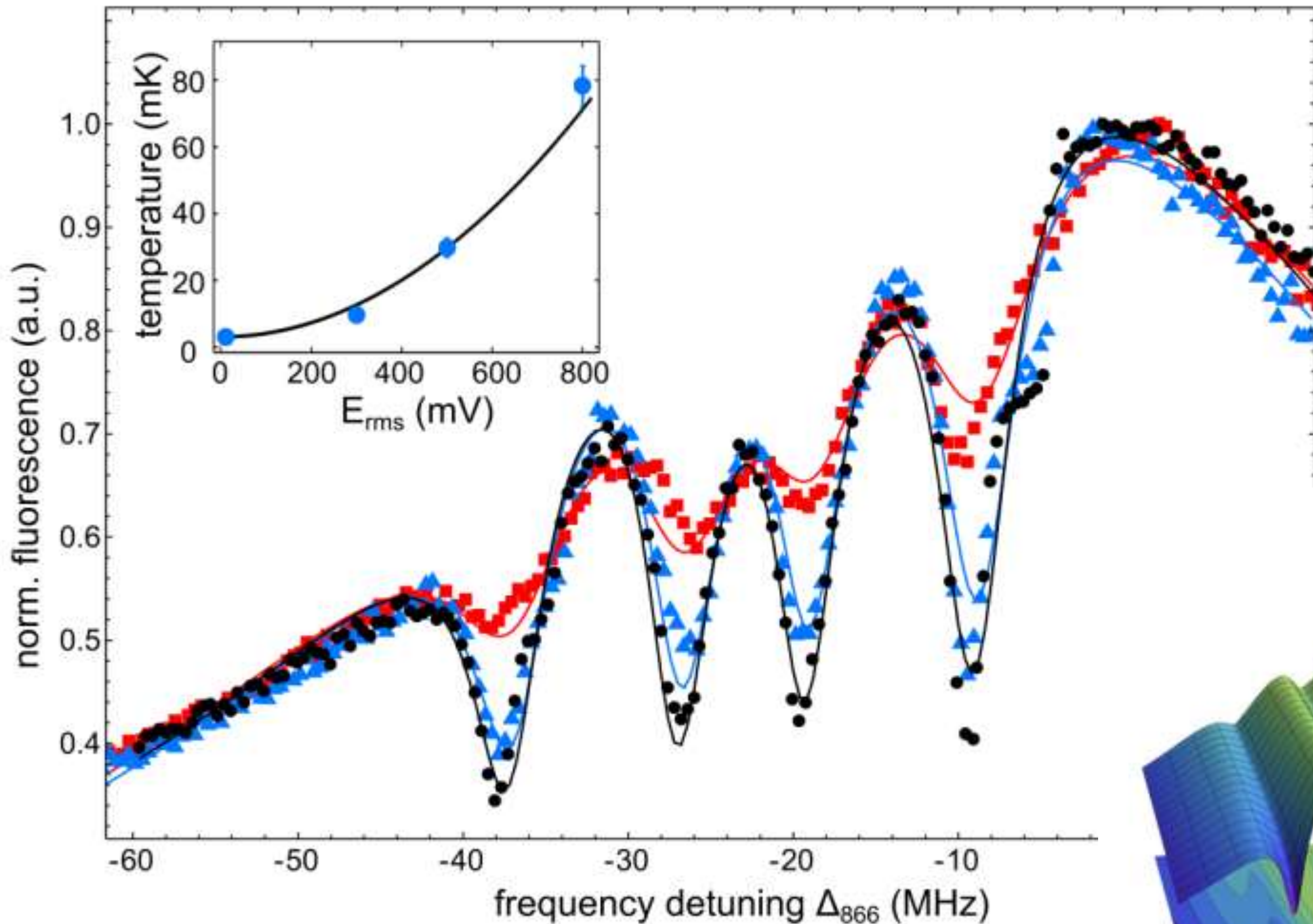
- Sensing ion motion in Δk-direction from the scattered intensity



Roos et al., Phys. Rev. Lett. 85, 5547 (2000)

Peters, Wittrock, Blatt, Halfmann, PRA 85, 063416 (2012)

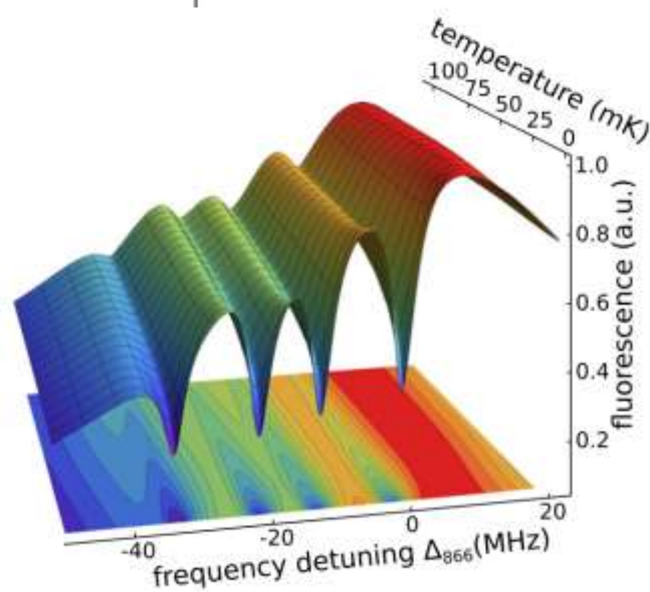
Stroboscopic thermometry by EIT



46mK

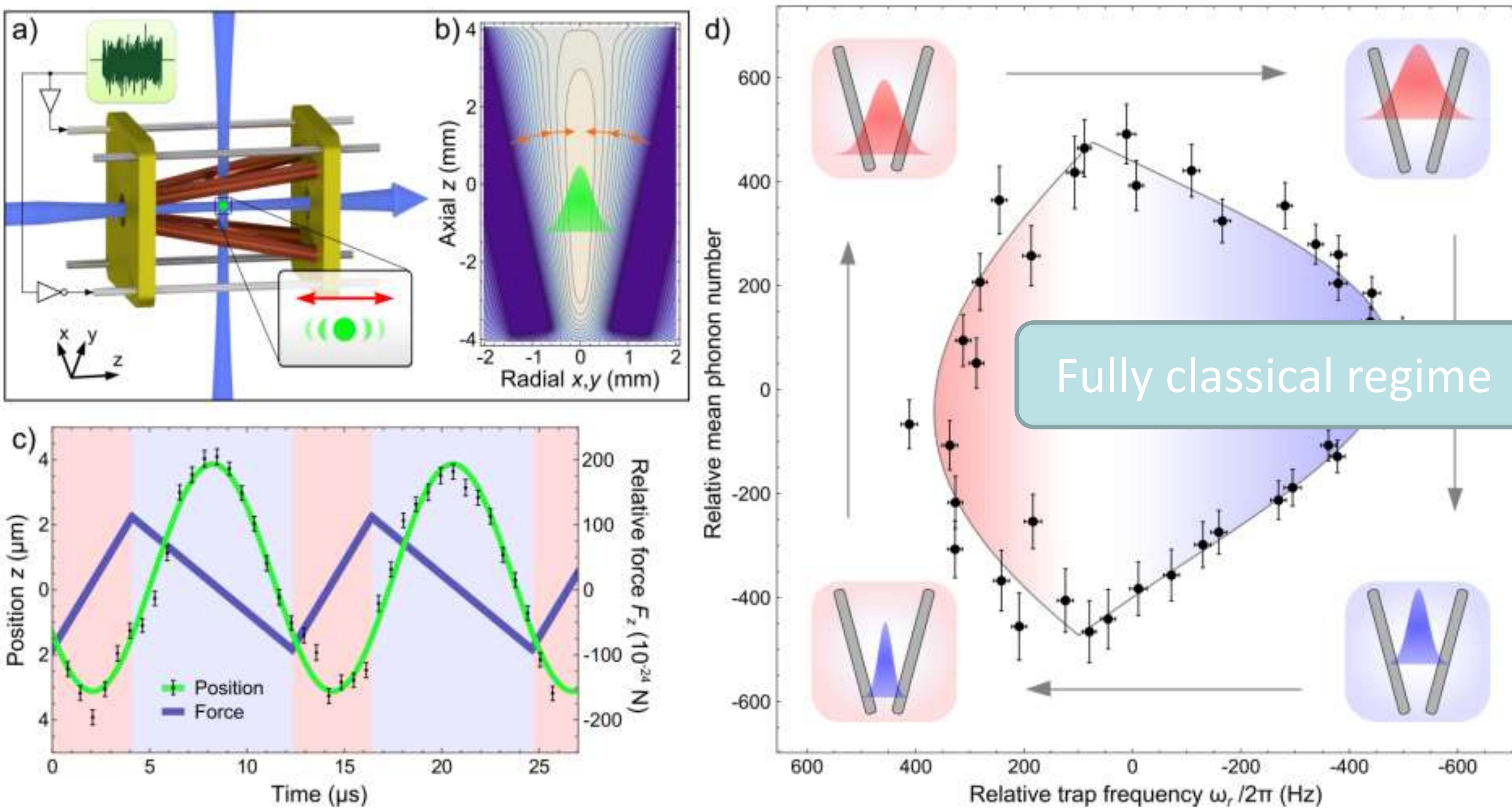
9mK

3mK



Roßnagel, et al, "Fast thermometry for trapped ions using dark resonances", NJP 17, 045004 (2015).

Working principle and results



Fully classical regime

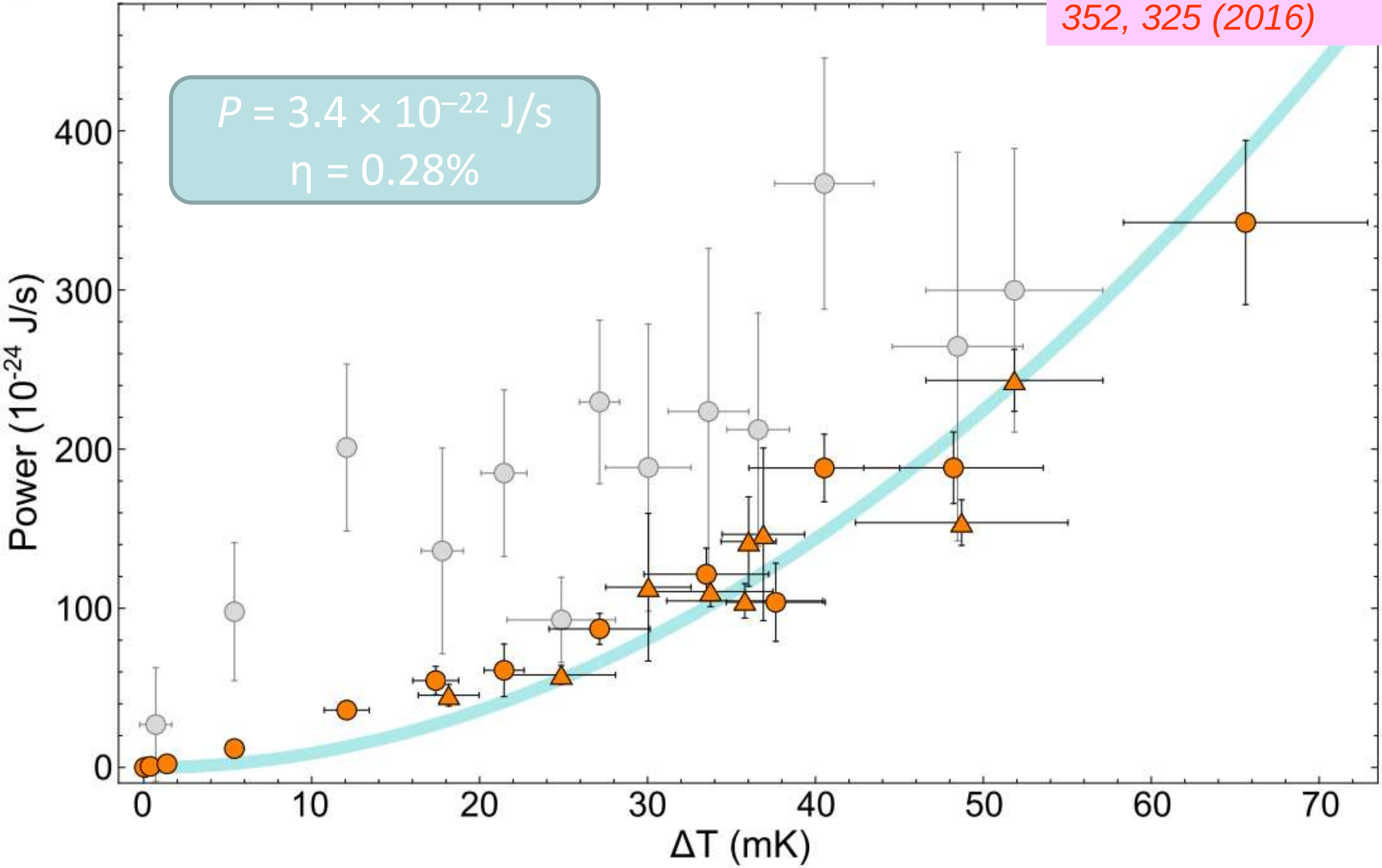
$P = 3.4 \times 10^{-22}$ J/s

$\eta = 0.28\%$

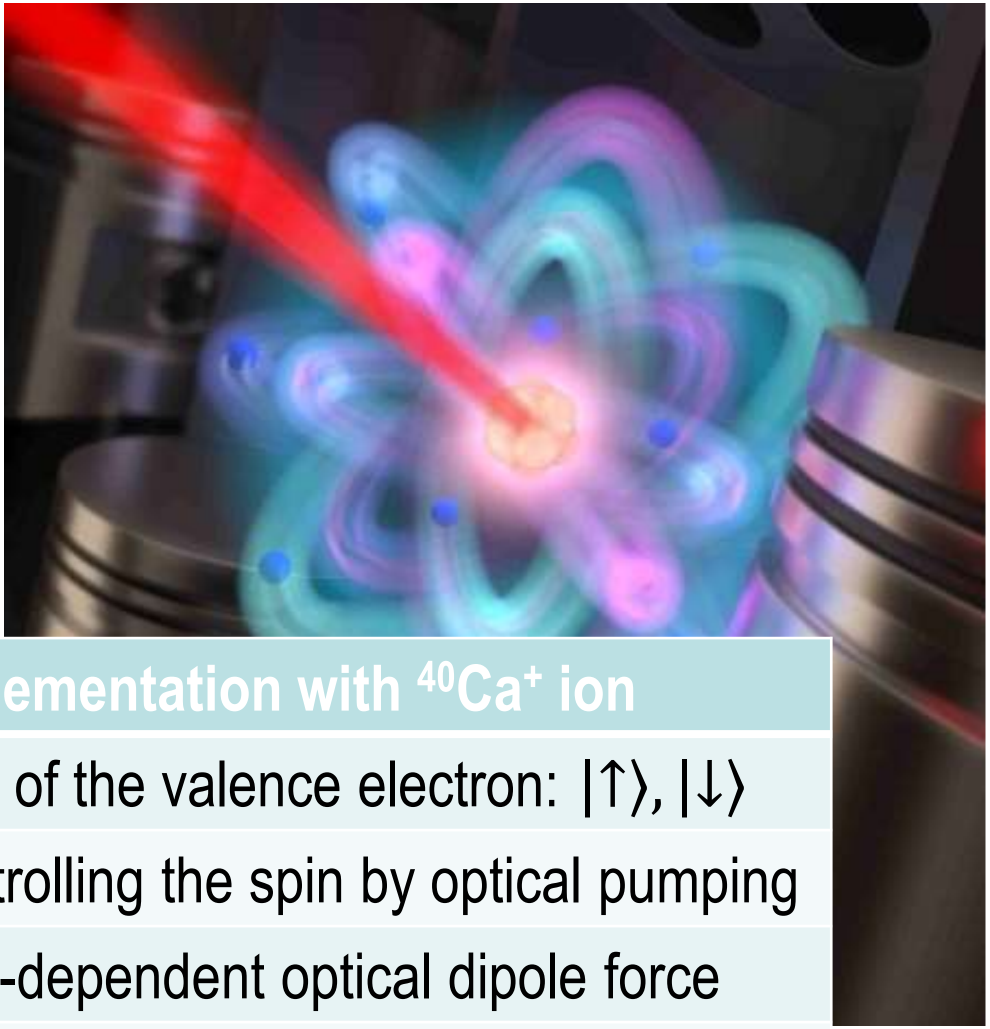
Roßnagel, et al, "A single-atom heat engine", Science 352, 325 (2016)

Power versus temperature difference

Roßnagel, et al, Sci. 352, 325 (2016)



Spin-driven heat engine coupled to harmonic-oscillator flywheel

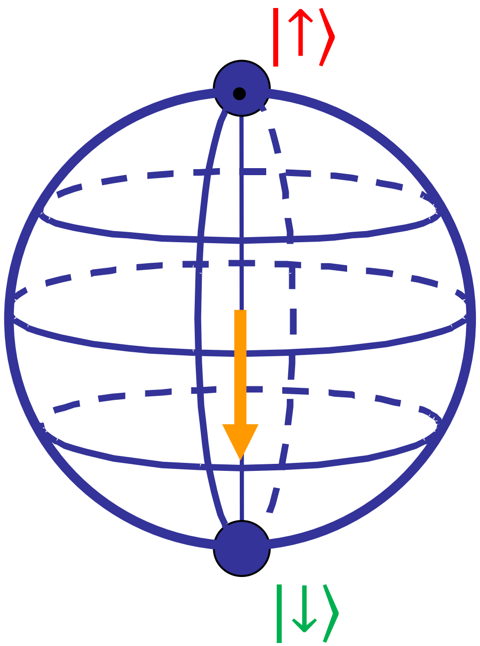


Generic heat engine	Implementation with $^{40}Ca^{+}$ ion
Working medium	Spin of the valence electron: $\lvert\uparrow\rangle$, $\lvert\downarrow\rangle$
Thermal baths	Controlling the spin by optical pumping
Gearing mechanism	Spin-dependent optical dipole force
Storage for delivered work	Axial oscillation: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

arXiv:1808.02390

Spins Thermodynamics

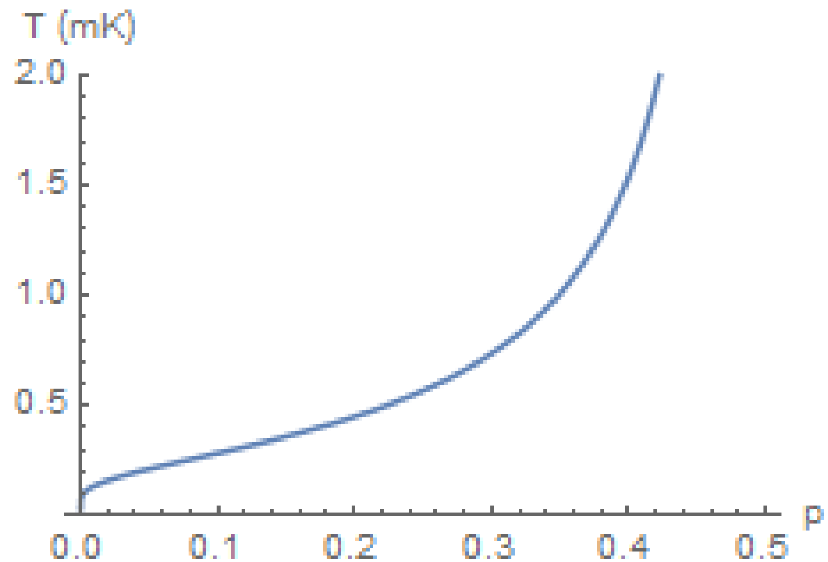
Thermal state



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

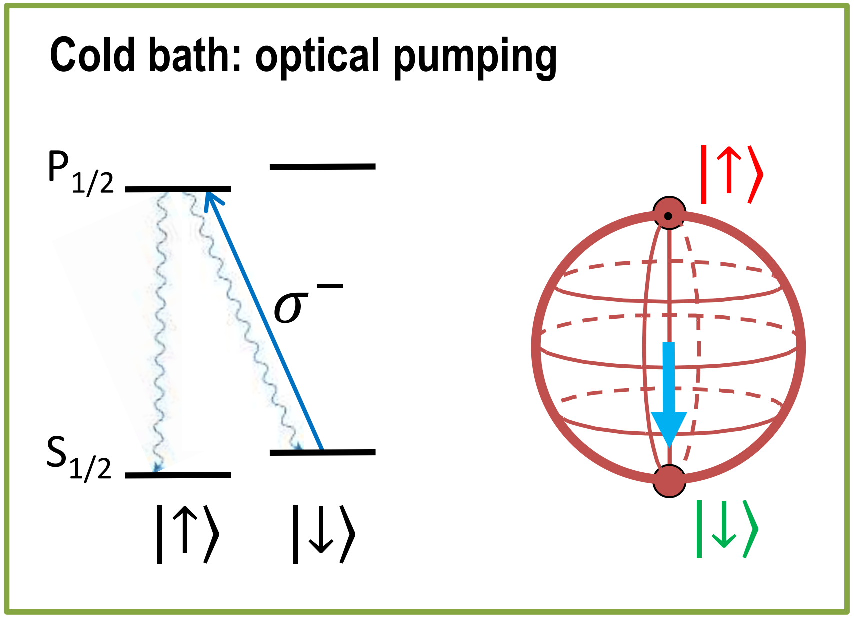
Spin temperature

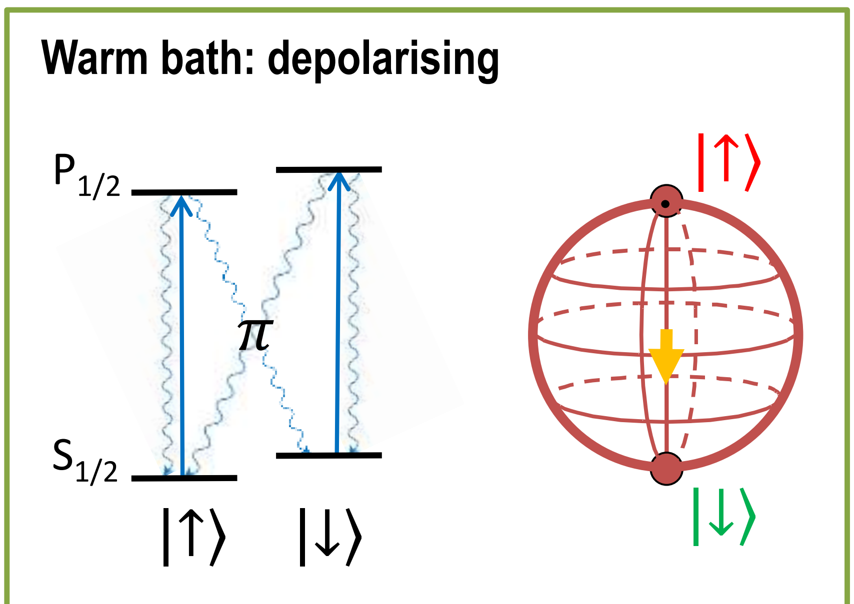
at $2\pi \cdot 13\ \mathrm{MHz}$ Zeeman splitting



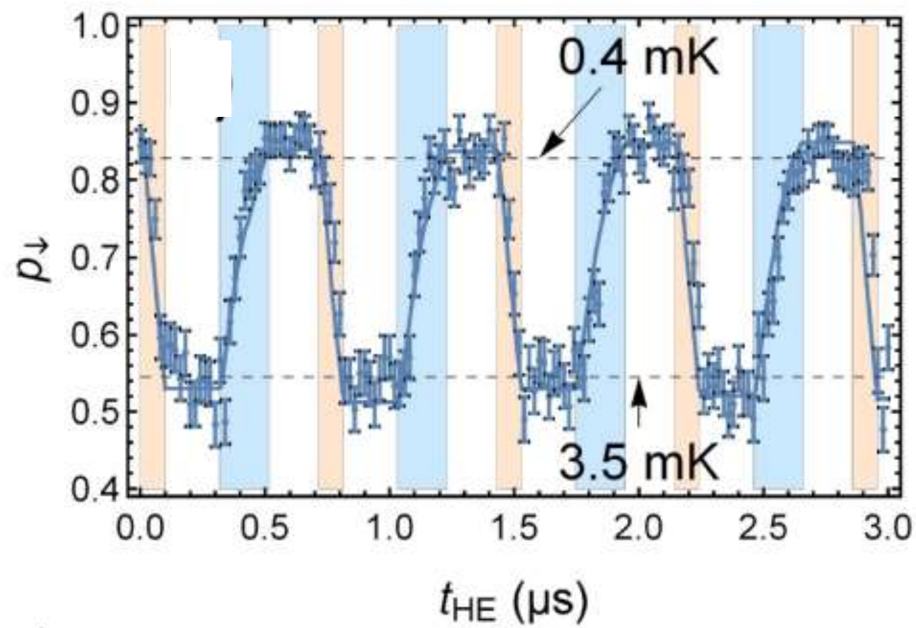
$$p_{\uparrow} = \frac{1}{1 + \exp(\hbar\omega_L / k_B T)}$$

Controlling the Spins Thermodynamics





Function	Cooling	Heating
Polarisation	circular	linear
Duration	180 ns	130 ns
Excitation ($p_\uparrow$)	0.545(2)	0.828(3)
Temperature	0.4 mK	3.5 mK
Period (= axial oscillation)		*740 ns*

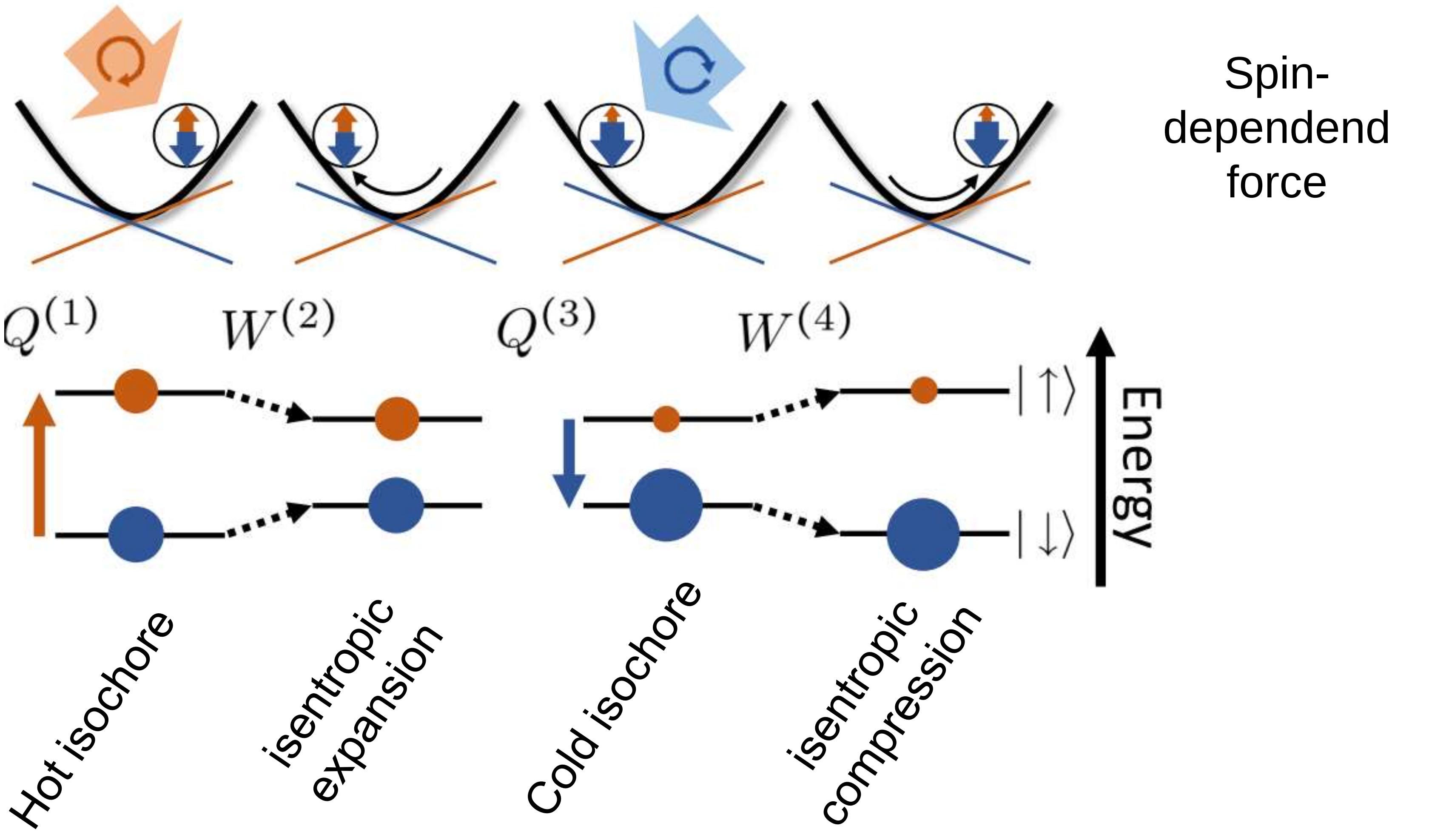


4-stroke engine cycle

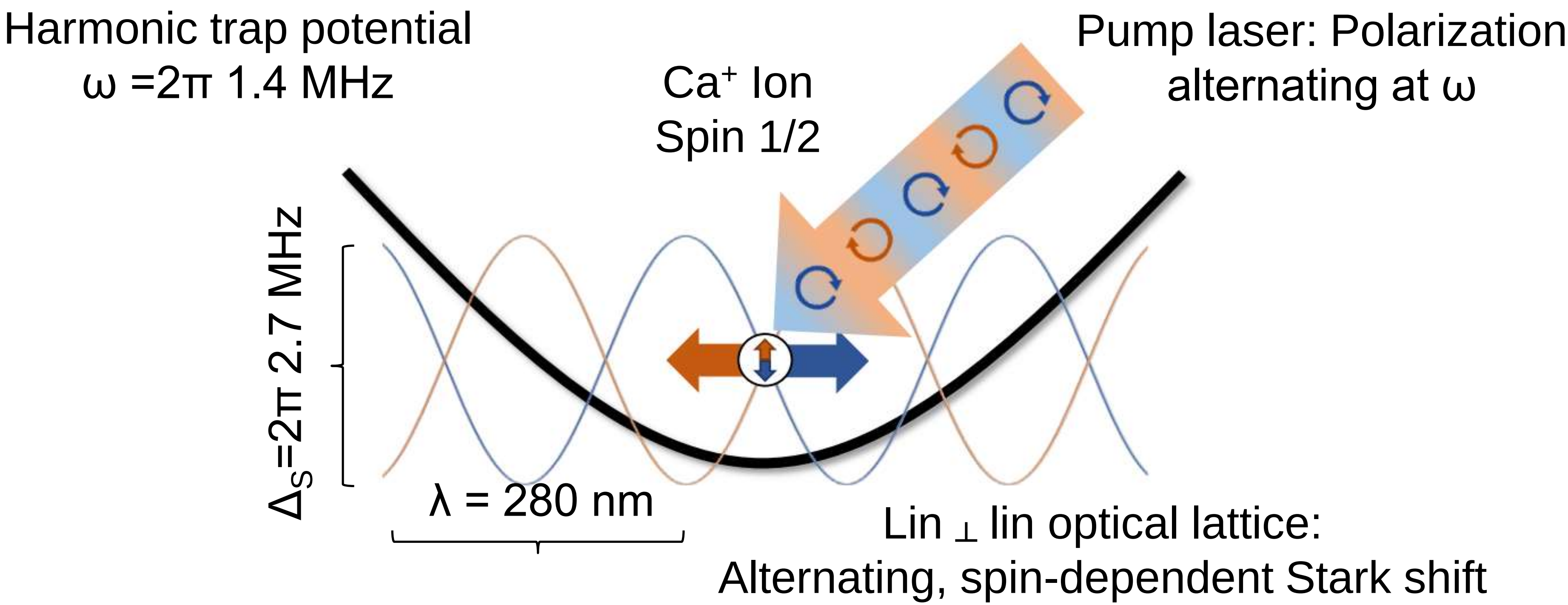
Harmonic trap potential
ω =2π 1.4 MHz

Ca^+ Ion
Spin 1/2

Pump laser: Polarization
alternating at ω



Heat-Engine setup



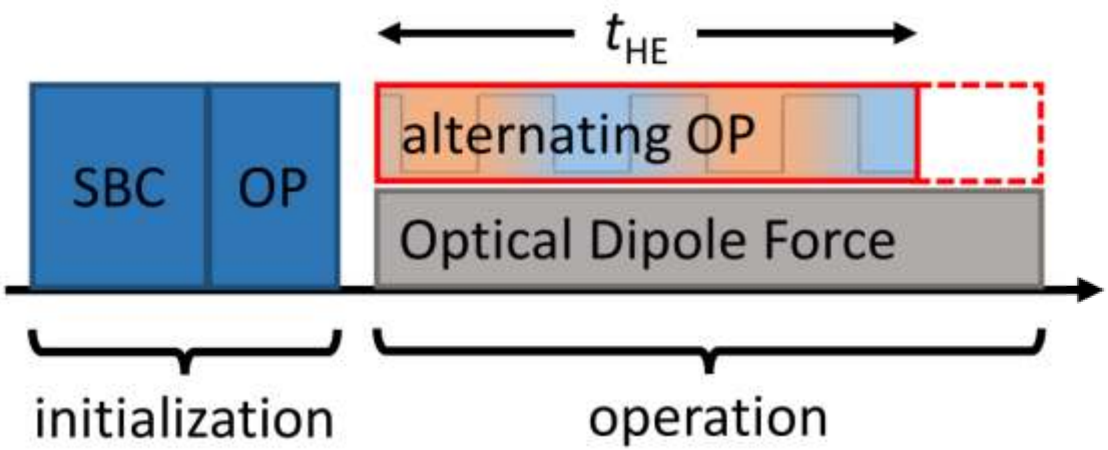
$$\hat{H} = \hat{H}_{\mathrm{HO}} + \hbar\left(\omega_z + \Delta_S \sin(k_{\mathrm{SW}}\hat{x})\right)\frac{\hat{\sigma}_z}{2}$$

$$\langle\hat{\sigma}_z\rangle = -\tanh(\hbar\omega'_z/2k_B T)$$

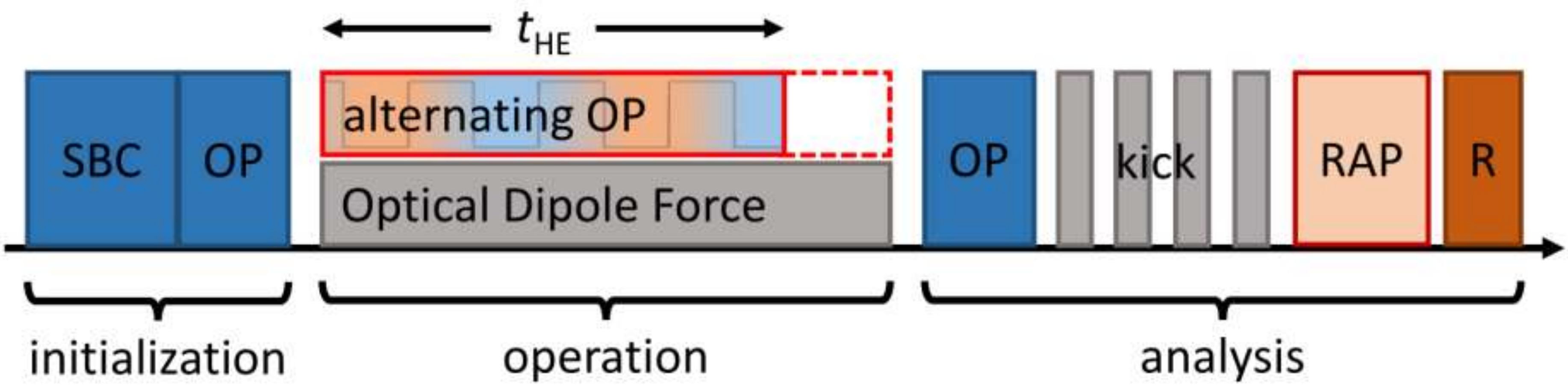
$$\omega'_z(\langle\hat{x}\rangle) = \omega_z + \Delta_S k_{\mathrm{SW}}\langle\hat{x}\rangle \qquad k_{\mathrm{SW}}\langle\hat{x}\rangle \ll 1$$

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

Heat-Engine protocol



Heat-Engine protocol and readout of flyweel



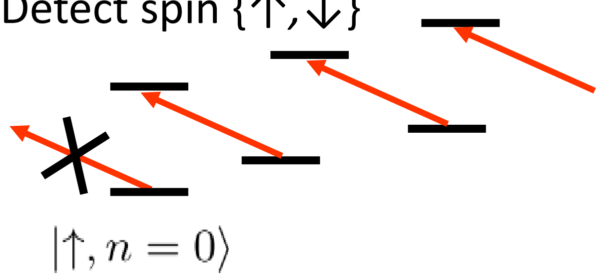
$$Q(\alpha, \alpha^*) = \frac{1}{\pi} \langle 0| \hat{D}^\dagger(\alpha)\hat{\rho}\hat{D}(\alpha)|0\rangle$$

Q function: ground state population after displacement α

Dingshun Lv et al., PRA 95, 043813 (2017)
S. An et al., Nature Phys. 11, 193 (2015)

Measurement:

1. Perform spin independent voltage kick *D*
2. Robust population transfer for $n \neq 0$ via rapid adiabatic passage on red sideband
3. Detect spin {↑,↓}



arXiv:1808.02390

Measured Q-function

Q function after 0, 6, 12, 18µs heat engine operation

Model Q function by displaced, squeezed thermal states (DSTS):

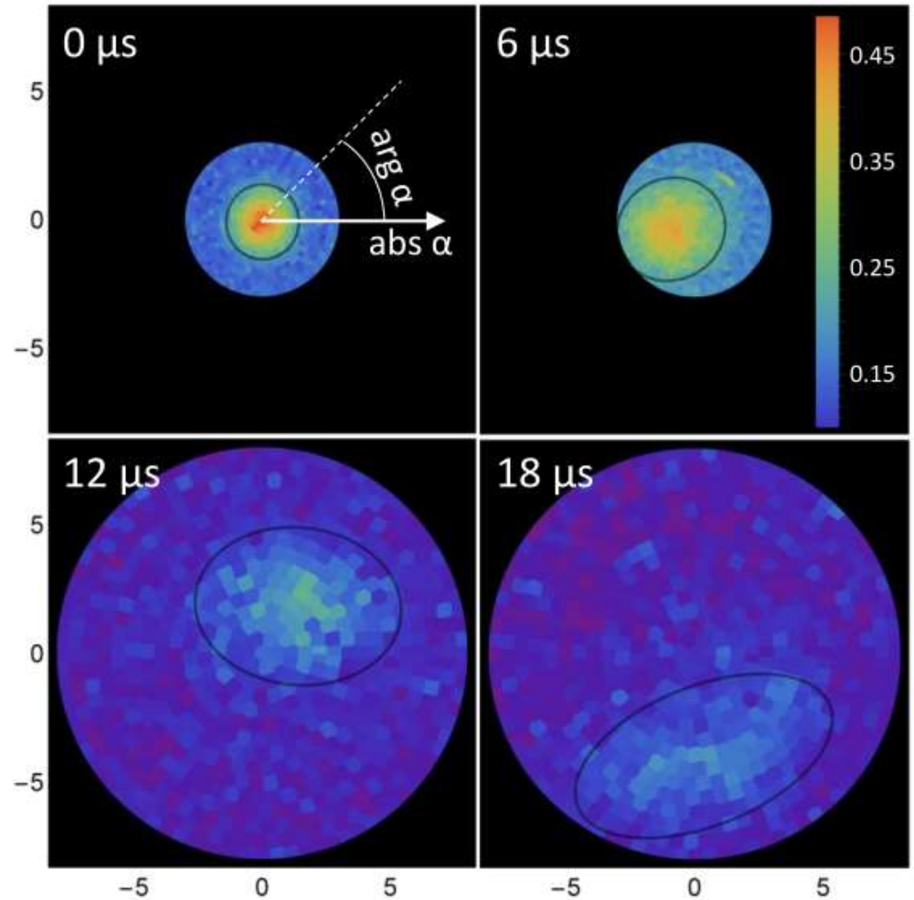
$$\hat{\rho}_{\mathrm{DST}}(\beta,\zeta,\bar{n}) = \hat{D}(\beta)\hat{S}(\zeta)\hat{\rho}_{\mathrm{th}}(\bar{n})\hat{S}^{\dagger}(\zeta)\hat{D}^{\dagger}(\beta),$$

$$\hat{\rho}_{\mathrm{th}}(\bar{n}) = \sum_{n}\frac{\bar{n}^{n}}{(\bar{n}+1)^{n+1}}\left|n\right\rangle\left\langle n\right|,$$

$$\hat{S}(\zeta) = \exp\left(\frac{1}{2}\left[\zeta(\hat{a}^{\dagger})^{2}-\zeta^{*}\hat{a}^{2}\right]\right),$$

$$\hat{D}(\beta) = \exp\left(\beta\hat{a}^{\dagger}-\beta^{*}\hat{a}\right),$$

Reveal: $\{\beta,\zeta,\bar{n}\}$ for engine time t_{HE}



Mark Mitchison (Trinity)

John Goold (Trinity, Dublin)

arXiv:1808.02390

Outcome

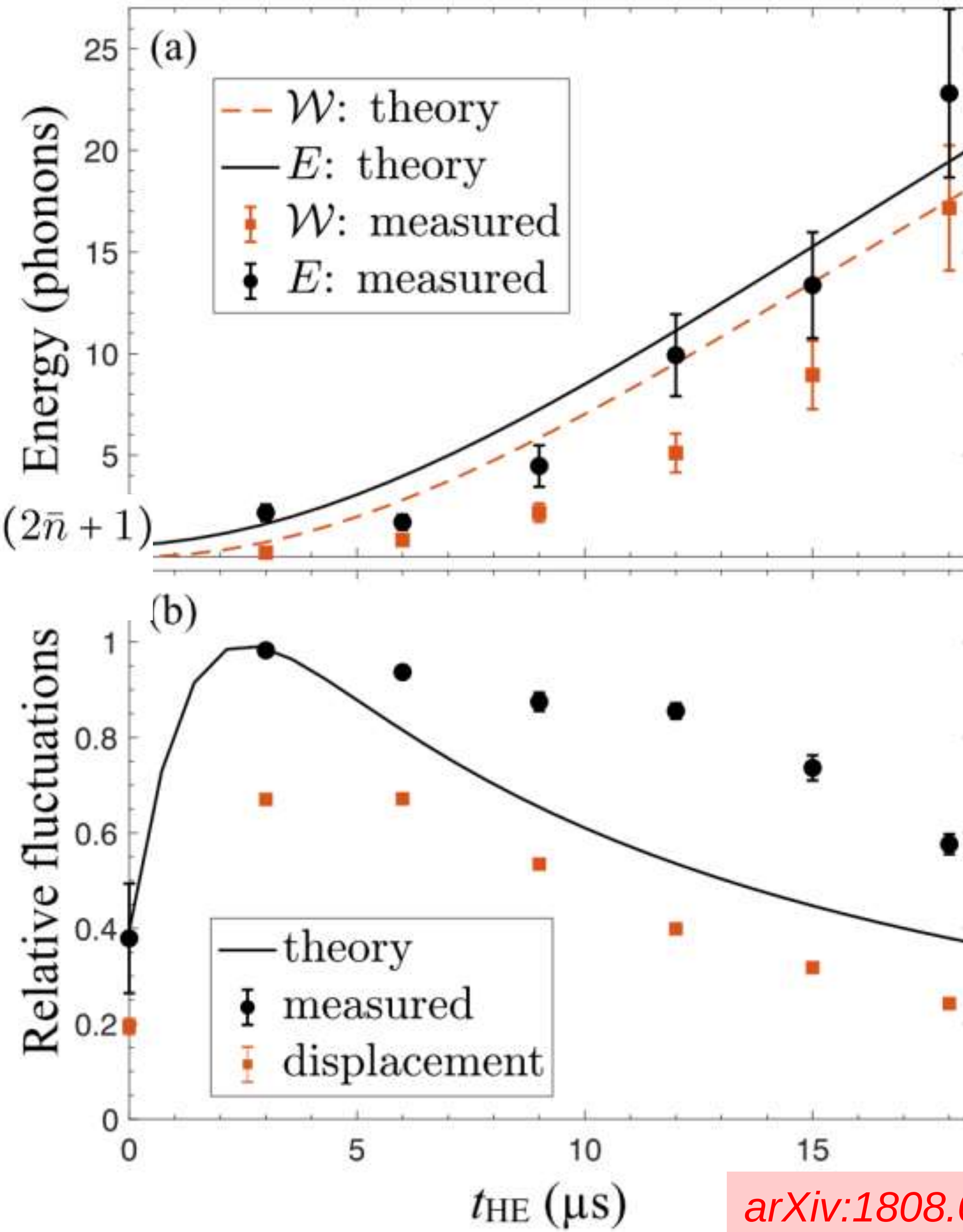
Mean energy

$E = \mathrm{Tr}[\hat{H}_{\mathrm{HO}}\hat{\rho}_{\mathrm{DST}}]$

Ergotropy

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

$E = \mathcal{W} + \hbar\omega_t\bar{n}.$



Ergotropy: dominated by coh. displacement β, with add. contribution from squeezing ζ

arXiv:1808.02390

Model

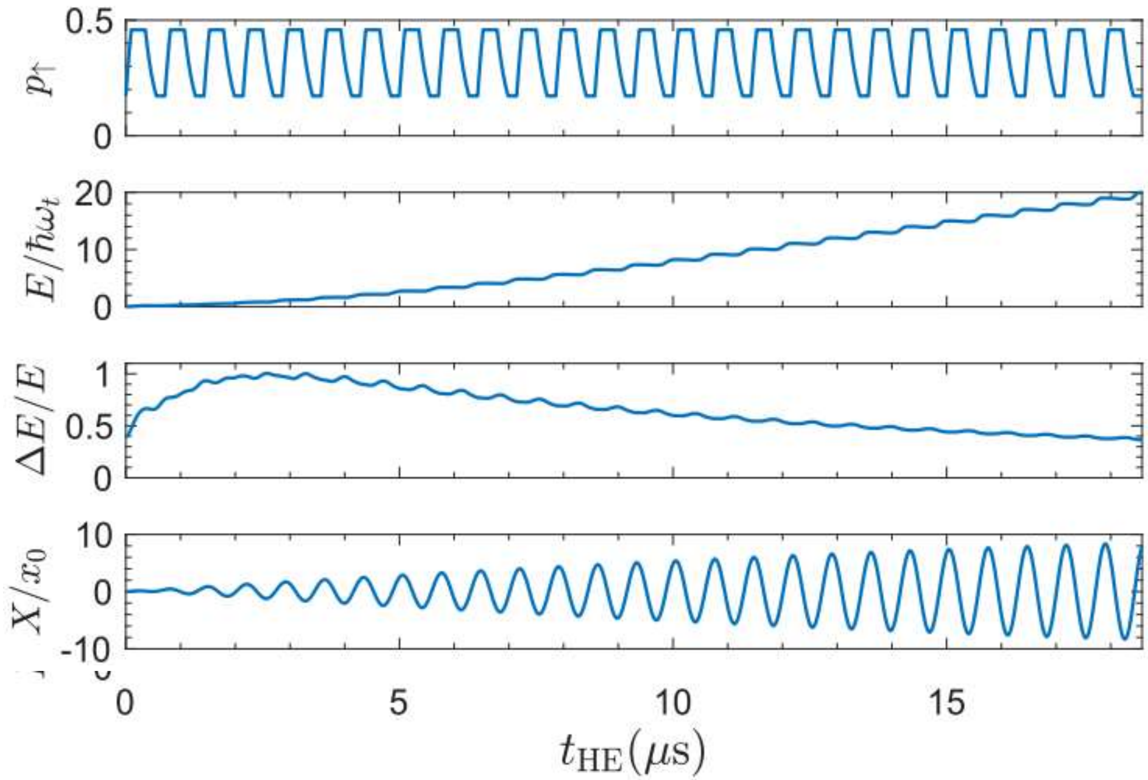
$$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = \frac{1}{\mathrm{i}\hbar}[\hat{H}, \hat{\rho}] + R_+(t)\mathcal{D}[\hat{\sigma}_+]\hat{\rho} + R_-(t)\mathcal{D}[\hat{\sigma}_-]\hat{\rho}$$

Master equ.

$$R_+ = t_h^{-1}\ln(p_\uparrow^h/p_\uparrow^c)$$
$$R_- = t_c^{-1}\ln(p_\downarrow^h/p_\downarrow^c)$$

Optical pumping rates to emulate temperatures

$$\hat{\rho} = p_\downarrow \hat{\Pi}_\downarrow \otimes \hat{\rho}_\downarrow + p_\uparrow \hat{\Pi}_\uparrow \otimes \hat{\rho}_\uparrow$$

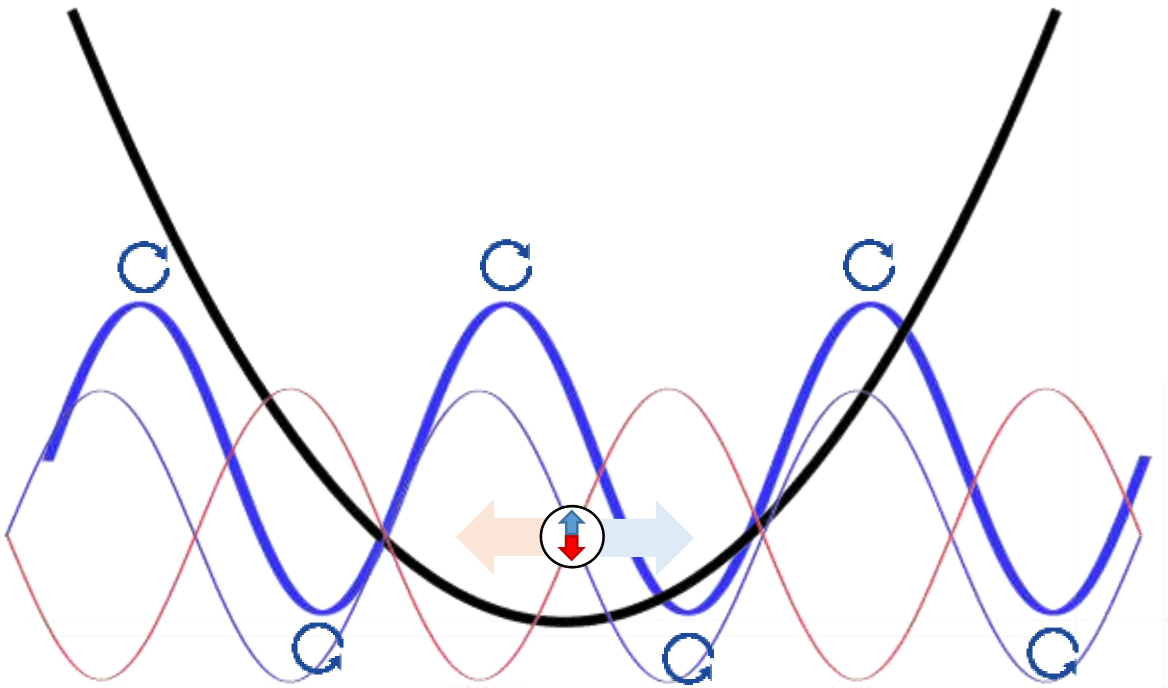


Product state:
scattered photons
in HE process destroy
quantum correlations
spin - flyweel motion

arXiv:1808.02390

Future extension: autonomous spin-driven engine

- Remove alternating pumping beam
- Add resonant lattice with alternating polarization
- „Temperature gradient“ should lead to self-excitation

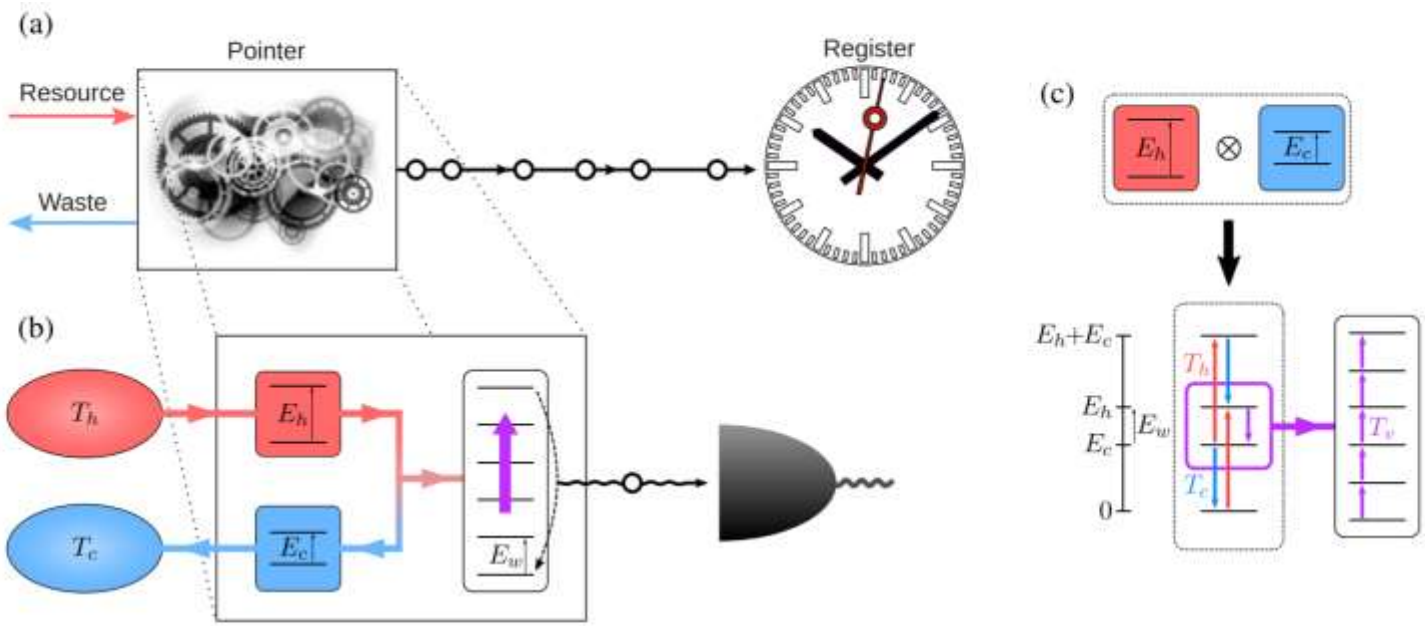


Autonomous clock-work proposal

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

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

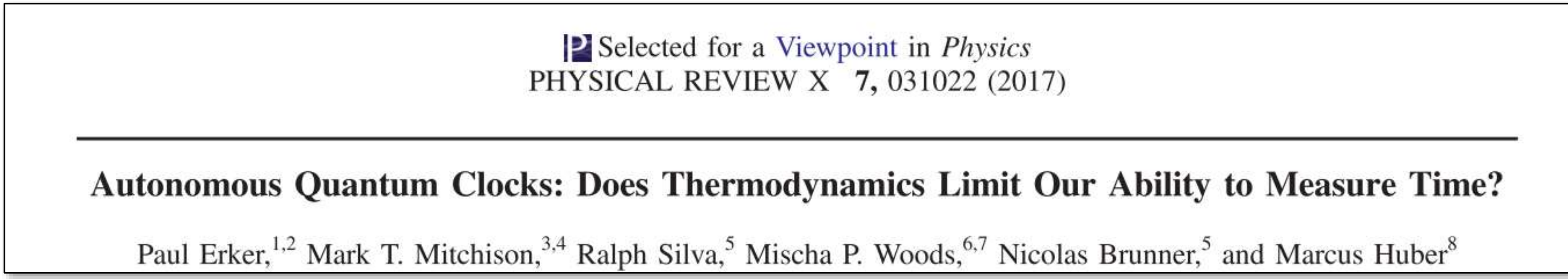
Paul Erker,[1,2] Mark T. Mitchison,[3,4] Ralph Silva,[5] Mischa P. Woods,[6,7] Nicolas Brunner,[5] and Marcus Huber[8]



… laws of thermodynamics dictate a trade-off between the amount of dissipated heat and the clock's performance in terms of its accuracy and resolution…

Autonomous clock-work proposal

Vahala et al., Nat. Phys. 5, 682 (2009)



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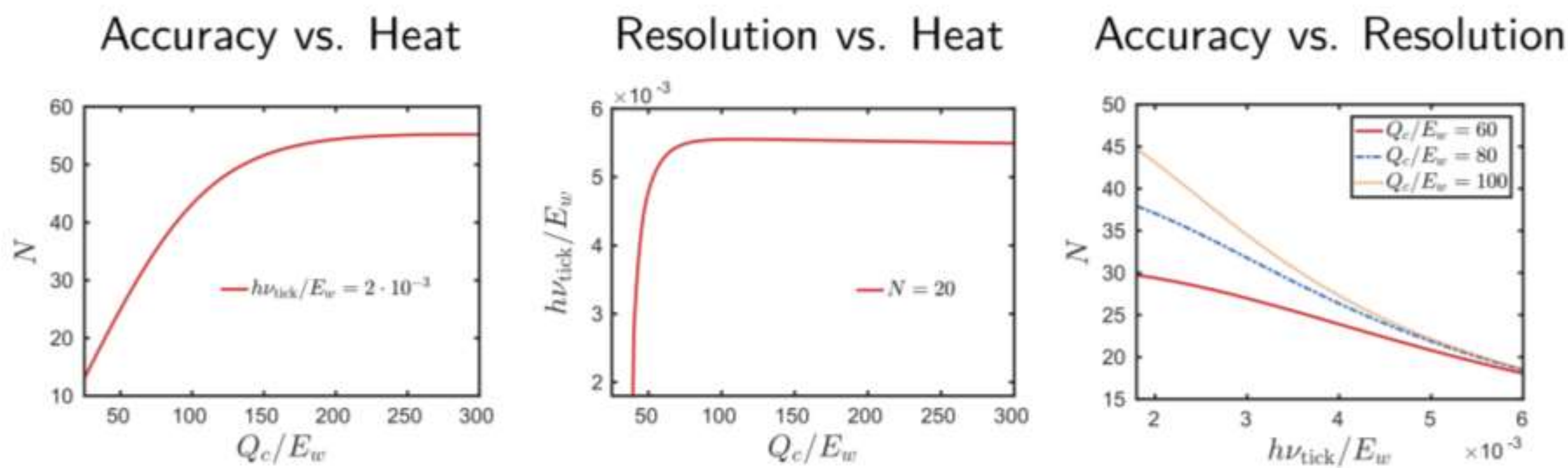
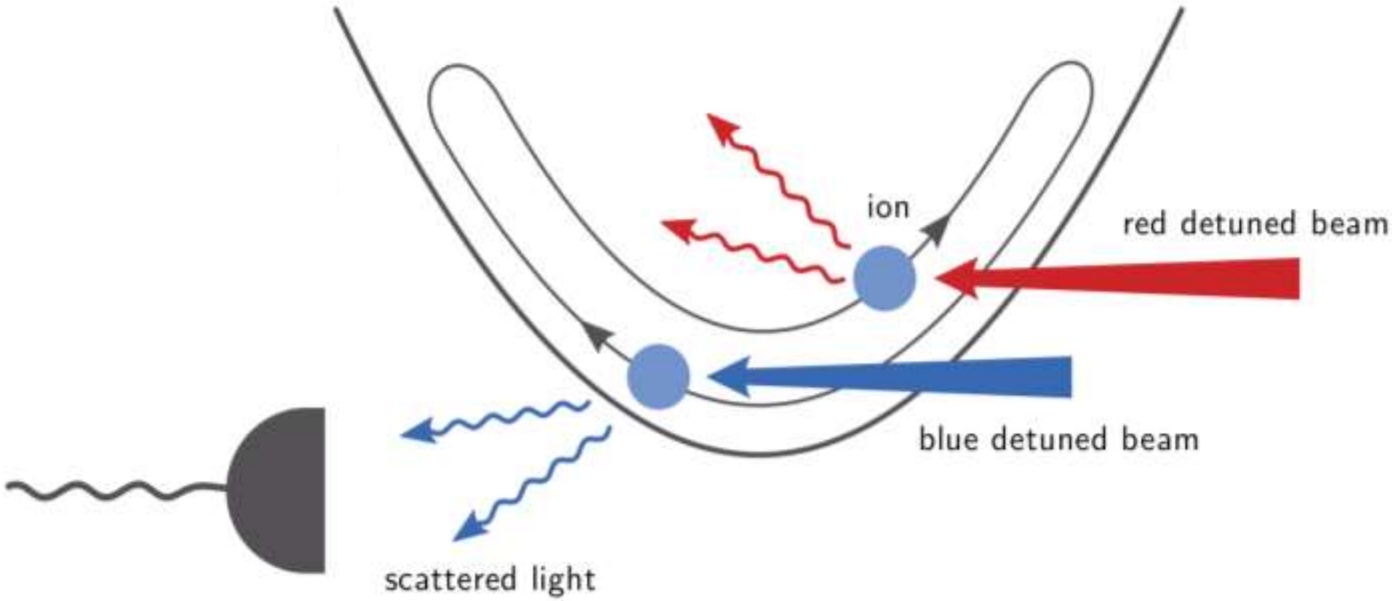


… laws of thermodynamics dictate a trade-off between the amount of dissipated heat and the clock’s performance in terms of its accuracy and resolution…

Phonon laser

Vahala et al., Nat. Phys. 5, 682 (2009)

- Blue- and red-detuned beams near-resonant beams ➡ autonomous harmonic motion
- Damping and excitation balance
- Doppler shift ➡ resonance at separate times 2ω periodicity in photon emission rates
- Observe regular photons counting
- Reveal phase stability



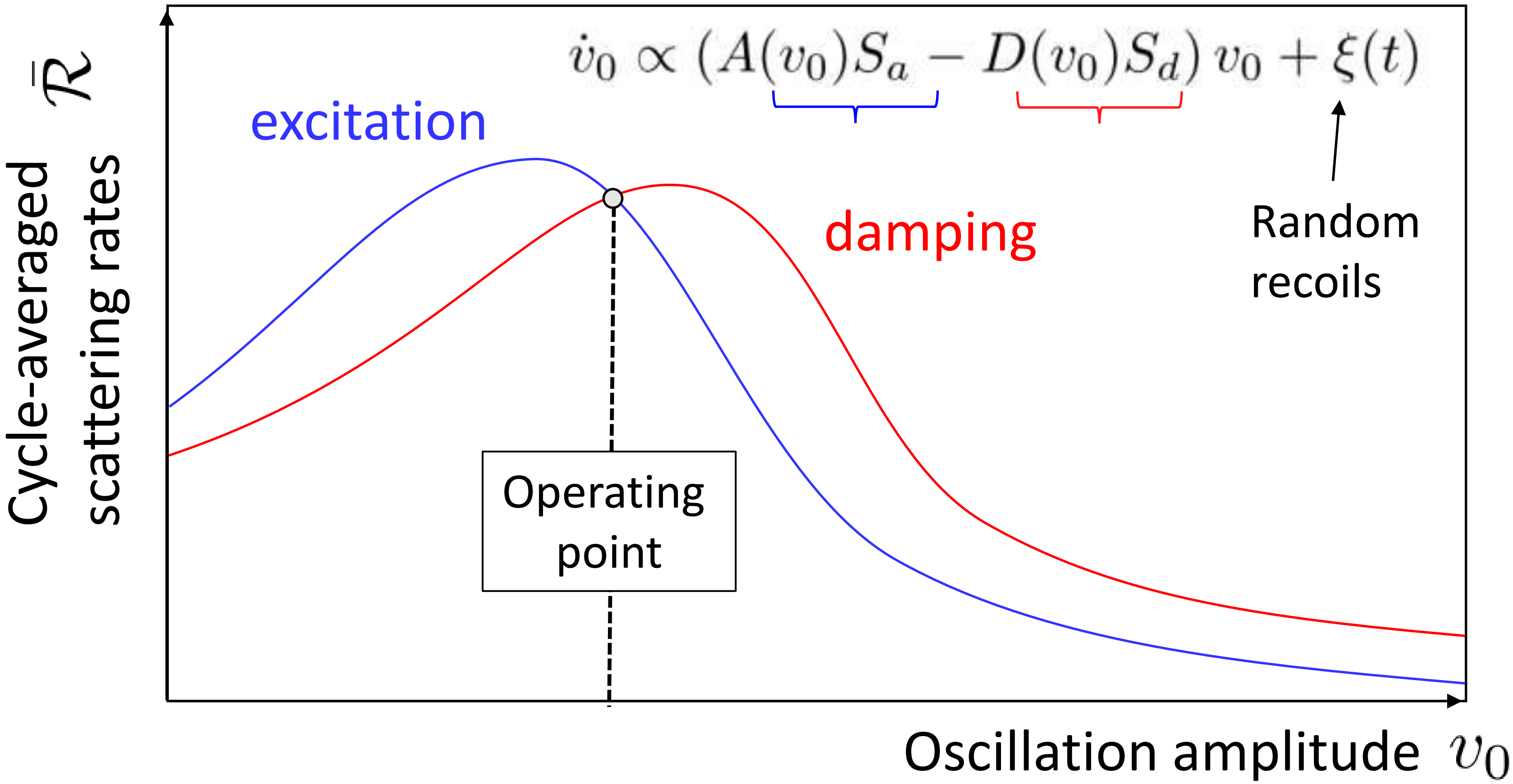
Wagner et al, in preparation

Stable operating point in oscillation

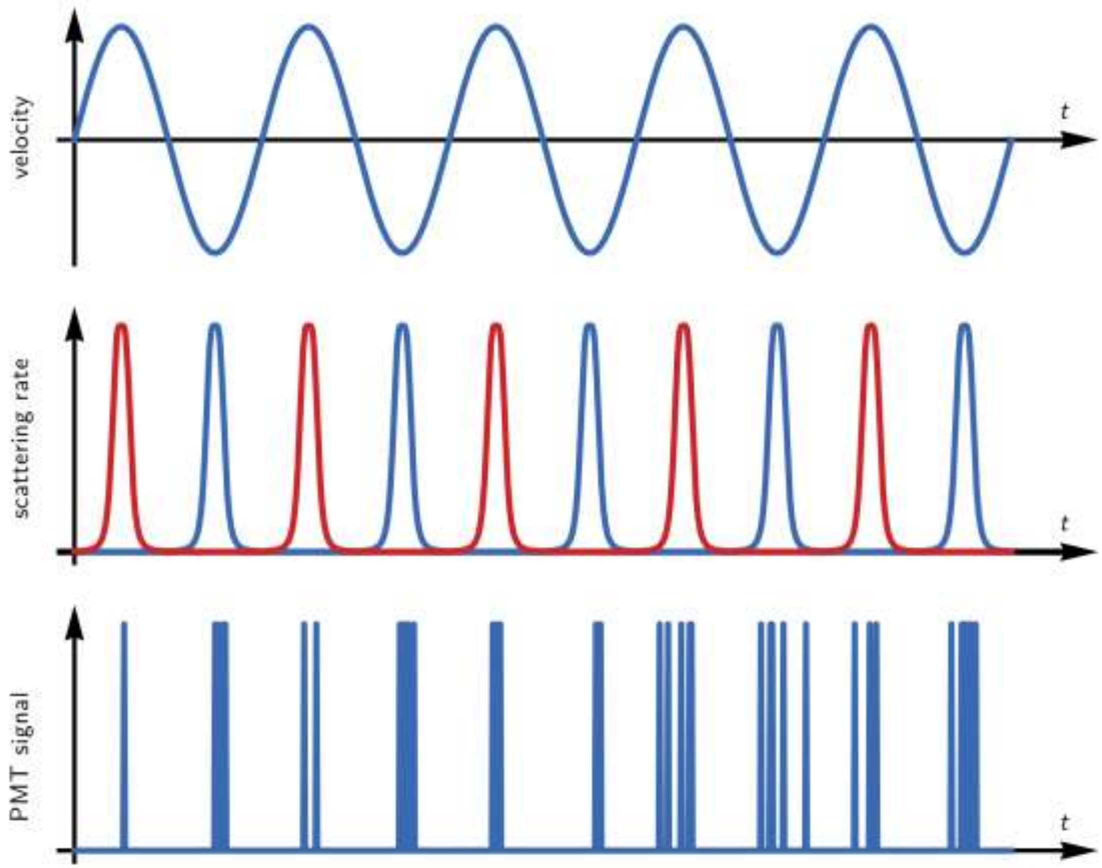
Vahala et al., Nat. Phys. 5, 682 (2009)

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

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



Oscillation Detection



Ion oscillates

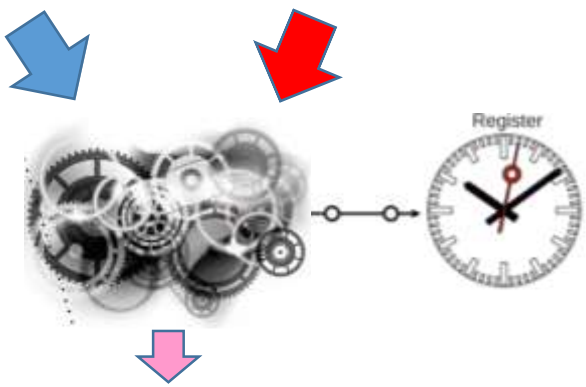
Scattering rate is modulated

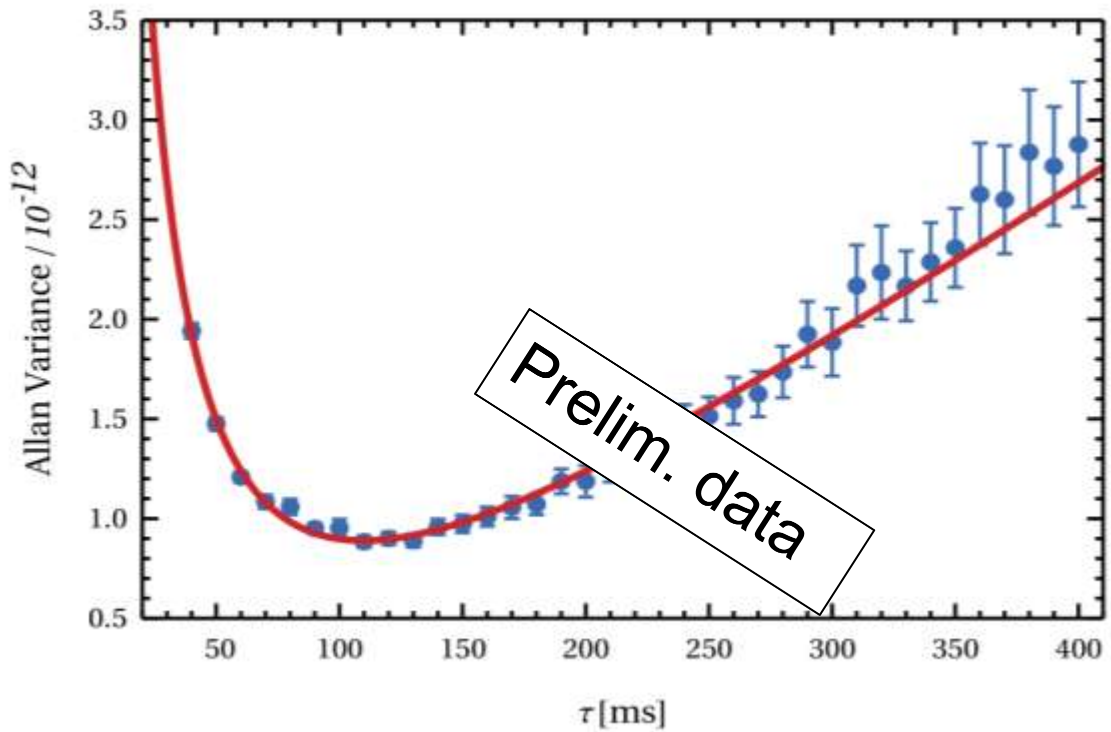
Modulated signal at detector

Stability analysis of clockwork

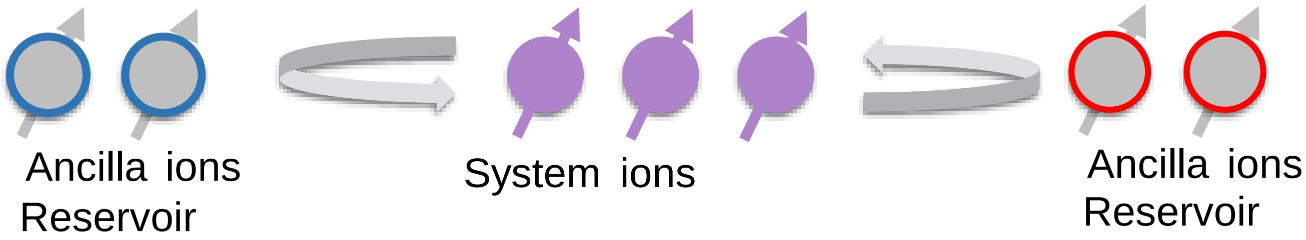
- Record photon klicks
- analyze their Allan variance
- Vary laser power of Cooling/heating
- Connection between
  scat. rate (heat consumption / entropy increase) and
  oscillator phase stability ?

Does thermodynamics limit our ability to measure time?





future goals: multi-ion machines / reservoirs



Ion crystal:

- Implement multi-ion spin-driven engines
- Fully controlled ancilla-bath, non-Markowian
- Quantum entanglement in heat engines
- Interconnection between quantum error correction, quantum computing and heat engines

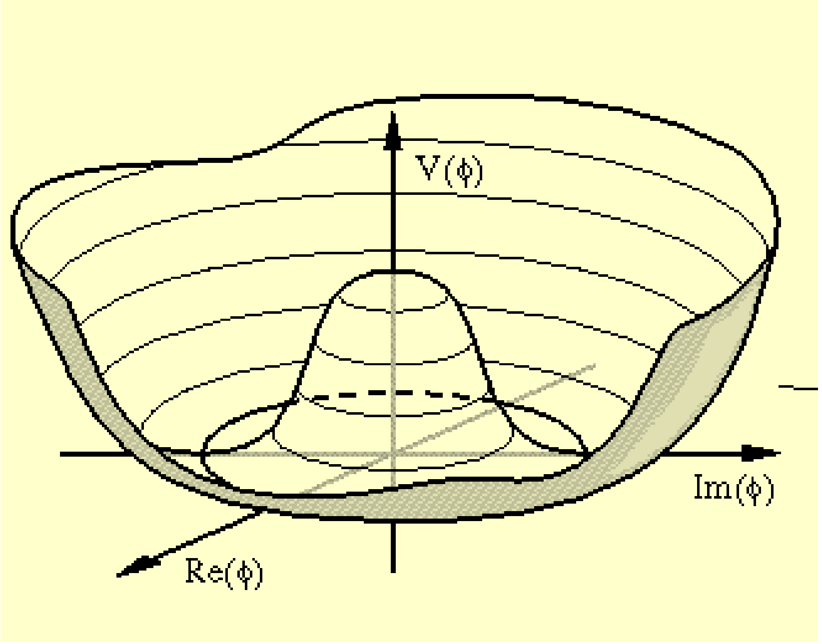
DFG-FOR 2724

Observation of the Kibble Zurek scaling law for defect formation in ion crystals

Universal principles of defect formation

Thomas Kibble
(Imperial London)

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



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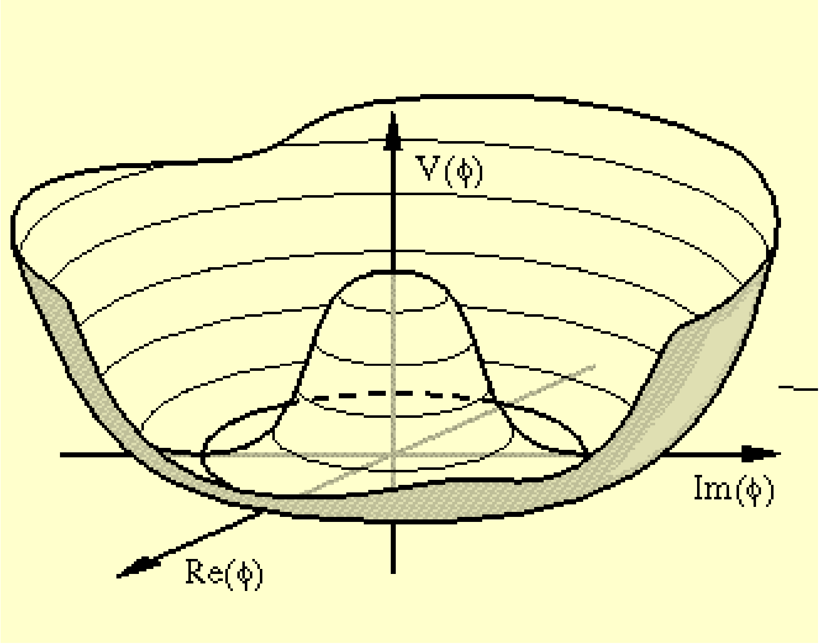
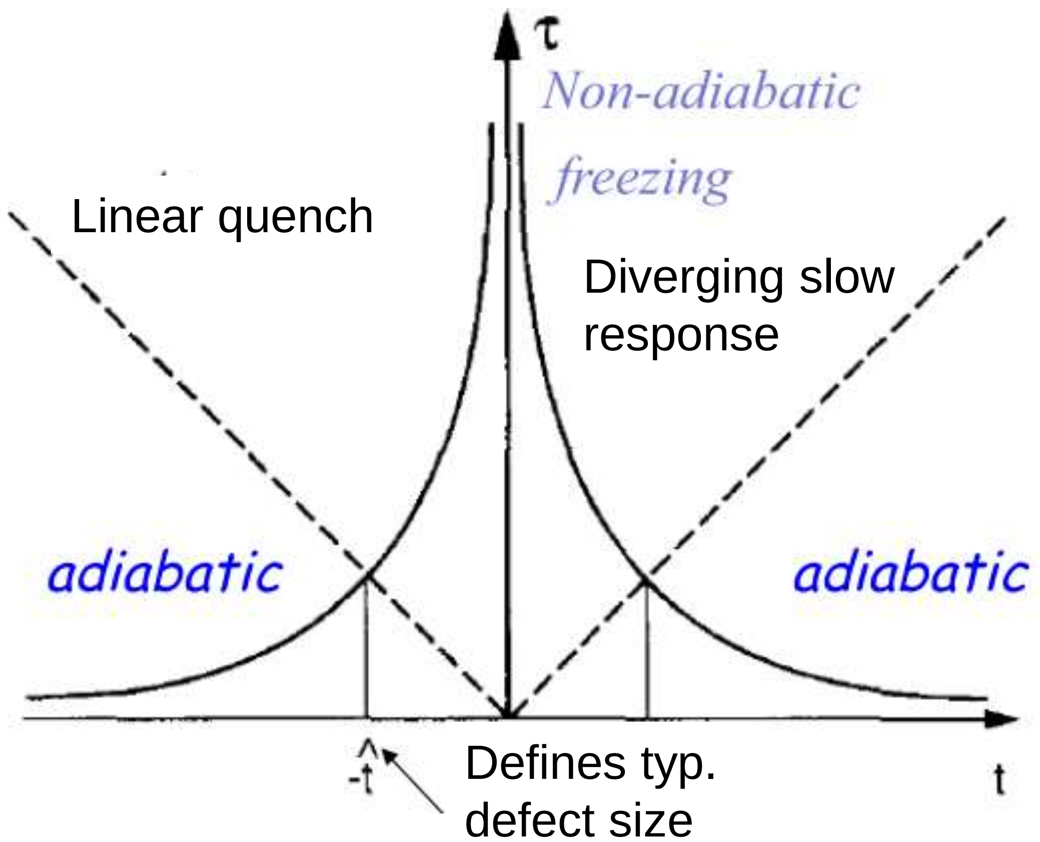


Free energy landscape changes across the critical point from a single well to a double well potential

Spontaneous symmetry breaking

Universal principles of defect formation

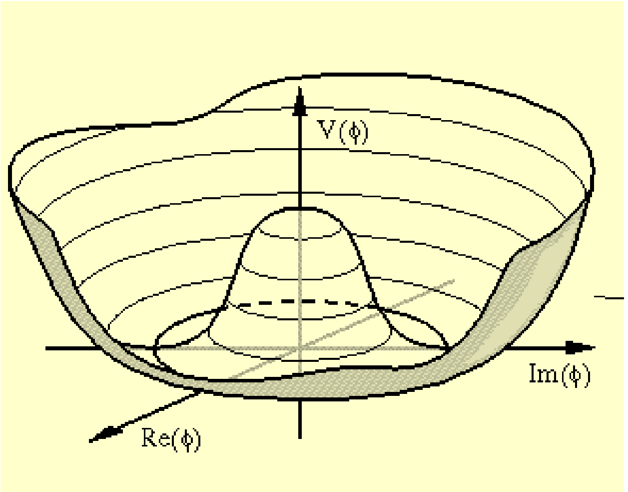
- System response time, thus information transfer, diverges when approaching critical point
- At some moment, the system becomes non-adiabatic and freezes



Universal principles of defect formation

W. Zurek
(los Alamos)

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



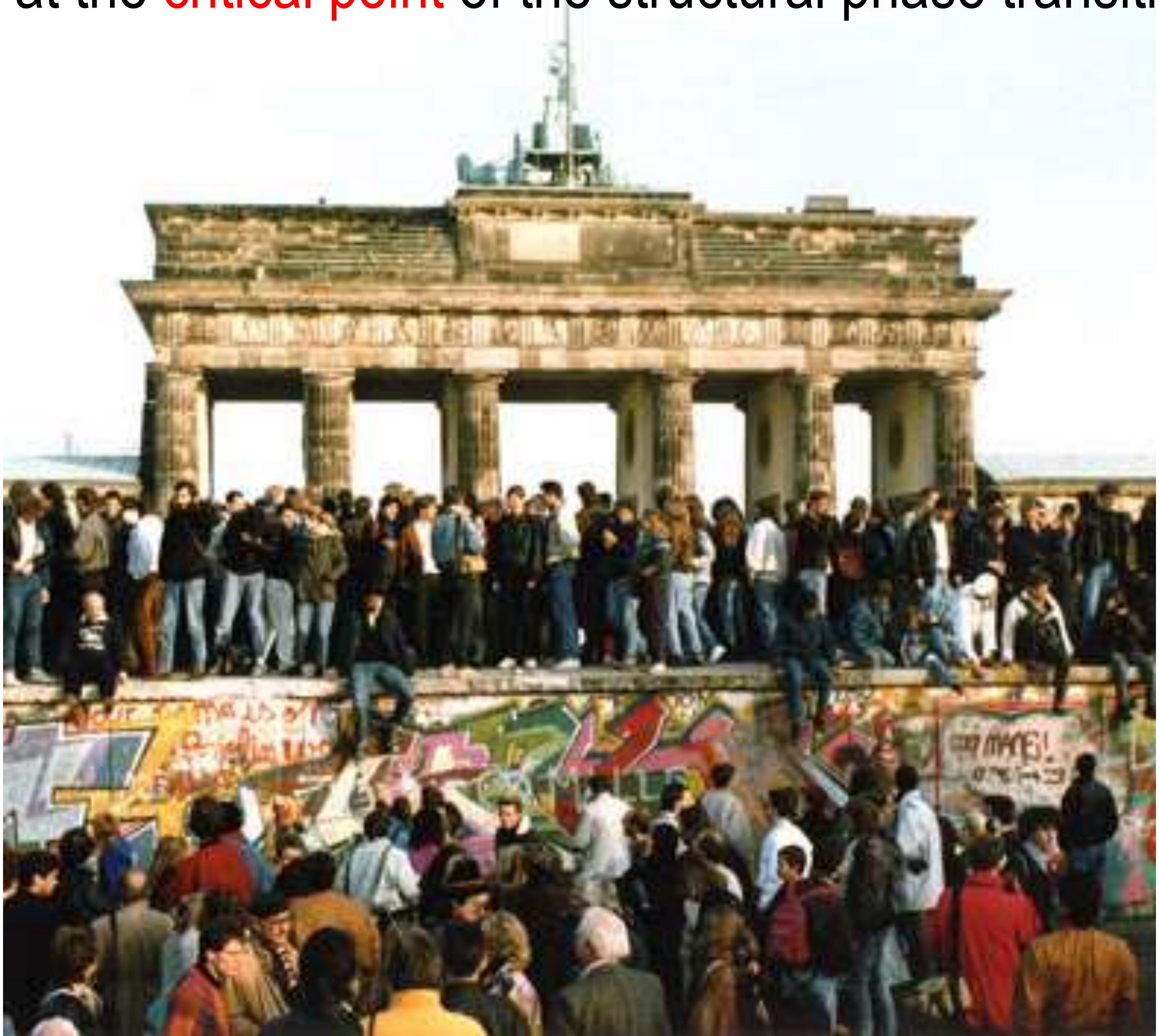
1985 (Zurek)
Sudden quench though the critical point leads to defect formation, experiments in solid state phys. may test theory of universal scaling

- Experiments with rapid cooling of liquid crystals observe structures
- Experiments for vortex formation in liquid ^{3}He
- Experiments with vortexes in superconductors

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

Germany before the structural phase transition

Berlin at the critical point of the structural phase transition



Germany after the structural phase transition

Proposal for KZ physics with ion crystal

PRL 105, 075701 (2010) PHYSICAL REVIEW LETTERS week ending 13 AUGUST 2010

Structural Defects in Ion Chains by Quenching the External Potential: The Inhomogeneous Kibble-Zurek Mechanism

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(Received 12 February 2010; revised manuscript received 1 July 2010; published 11 August 2010)

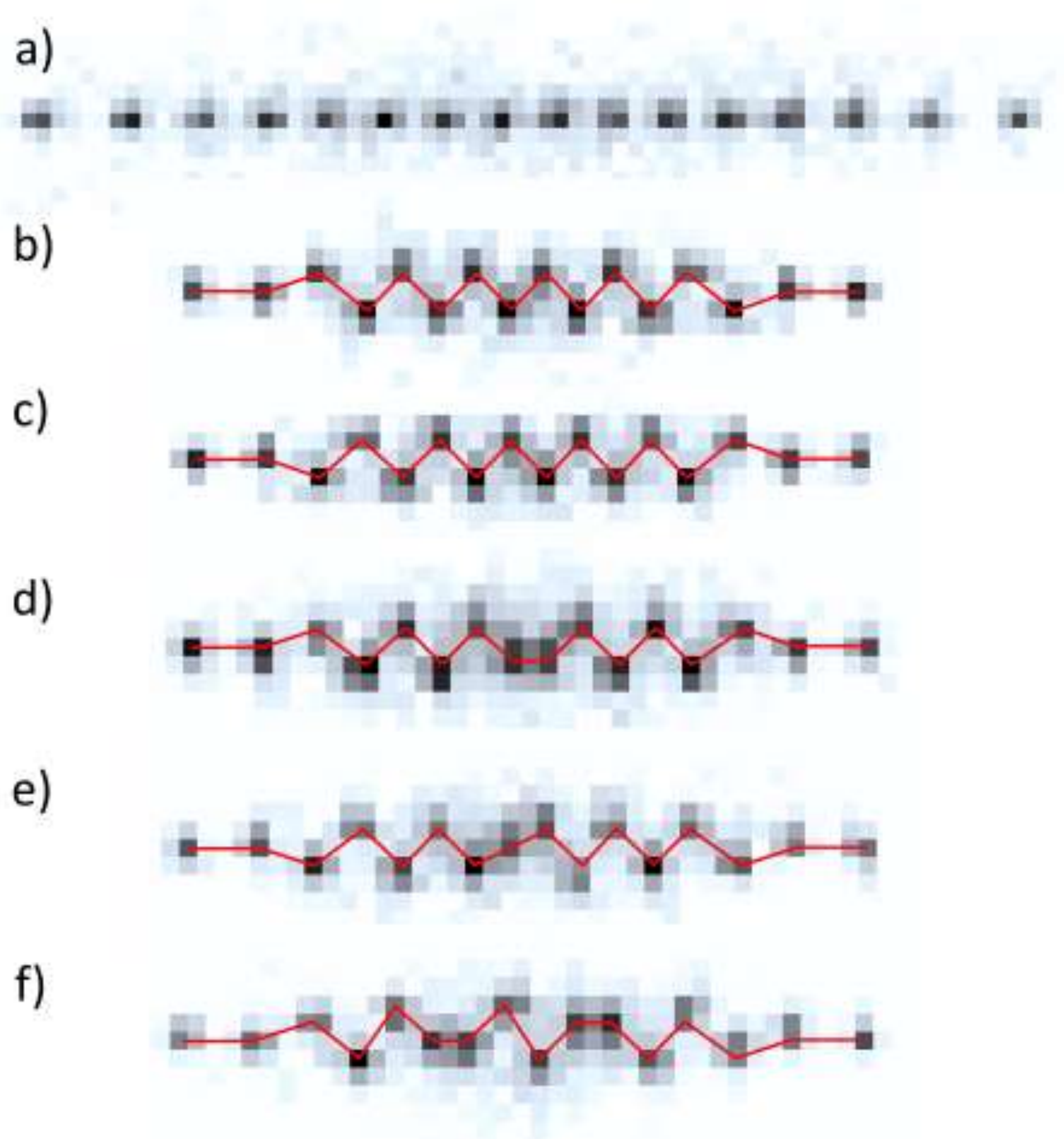
- Landau Ginzburg theory of phase transition for ion trap situation
- Universal scaling found
- Prediction of for the inhomogenious case

New Journal of Physics
The open-access journal for physics

Spontaneous nucleation of structural defects in inhomogeneous ion chains

Gabriele De Chiara[1,2], Adolfo del Campo[3,4,6], Giovanna Morigi[1,5], Martin B Plenio[3,4] and Alex Retzker[3,4]

Defect formation in ion crystals



Linear

Zig-zag

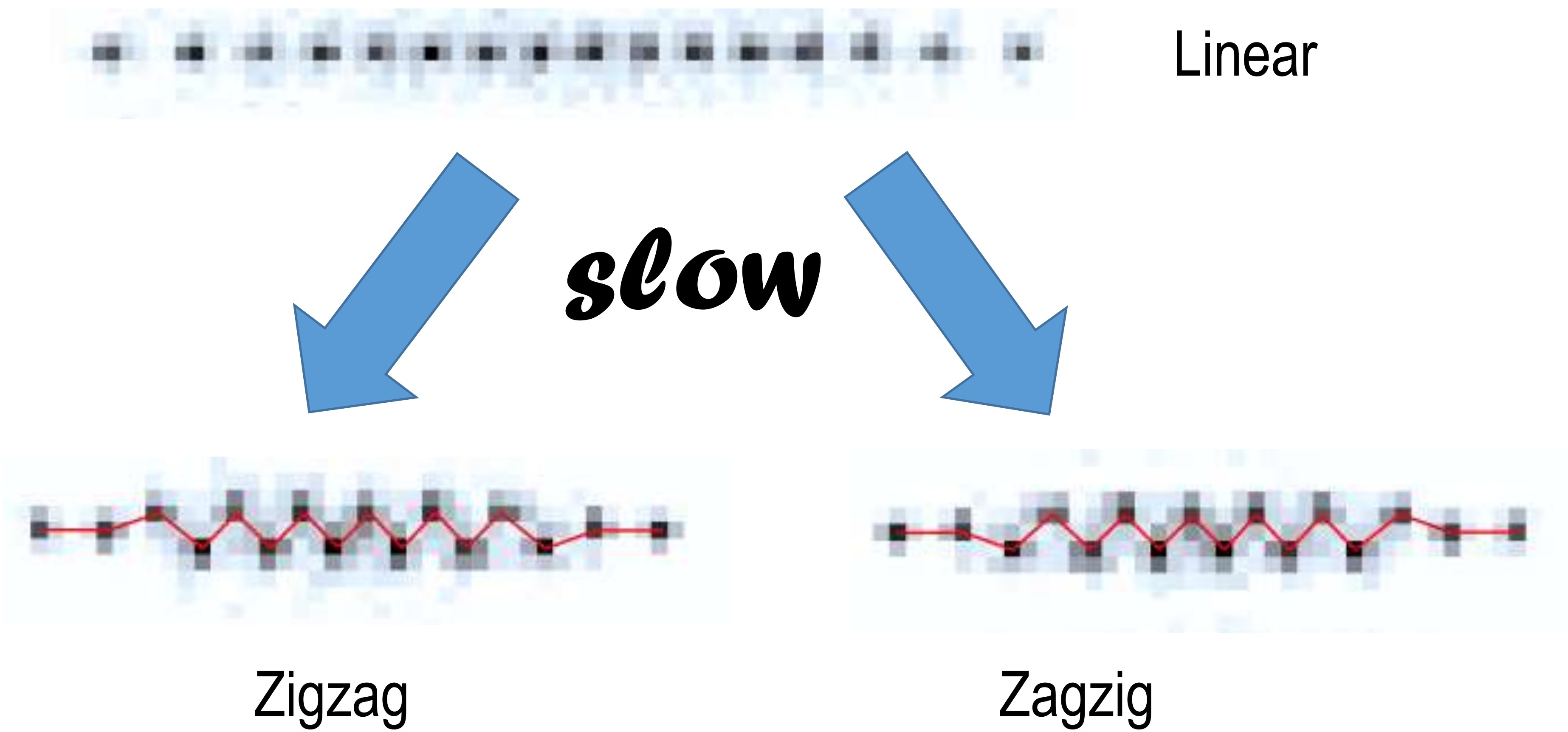
Zag-zig

Defect

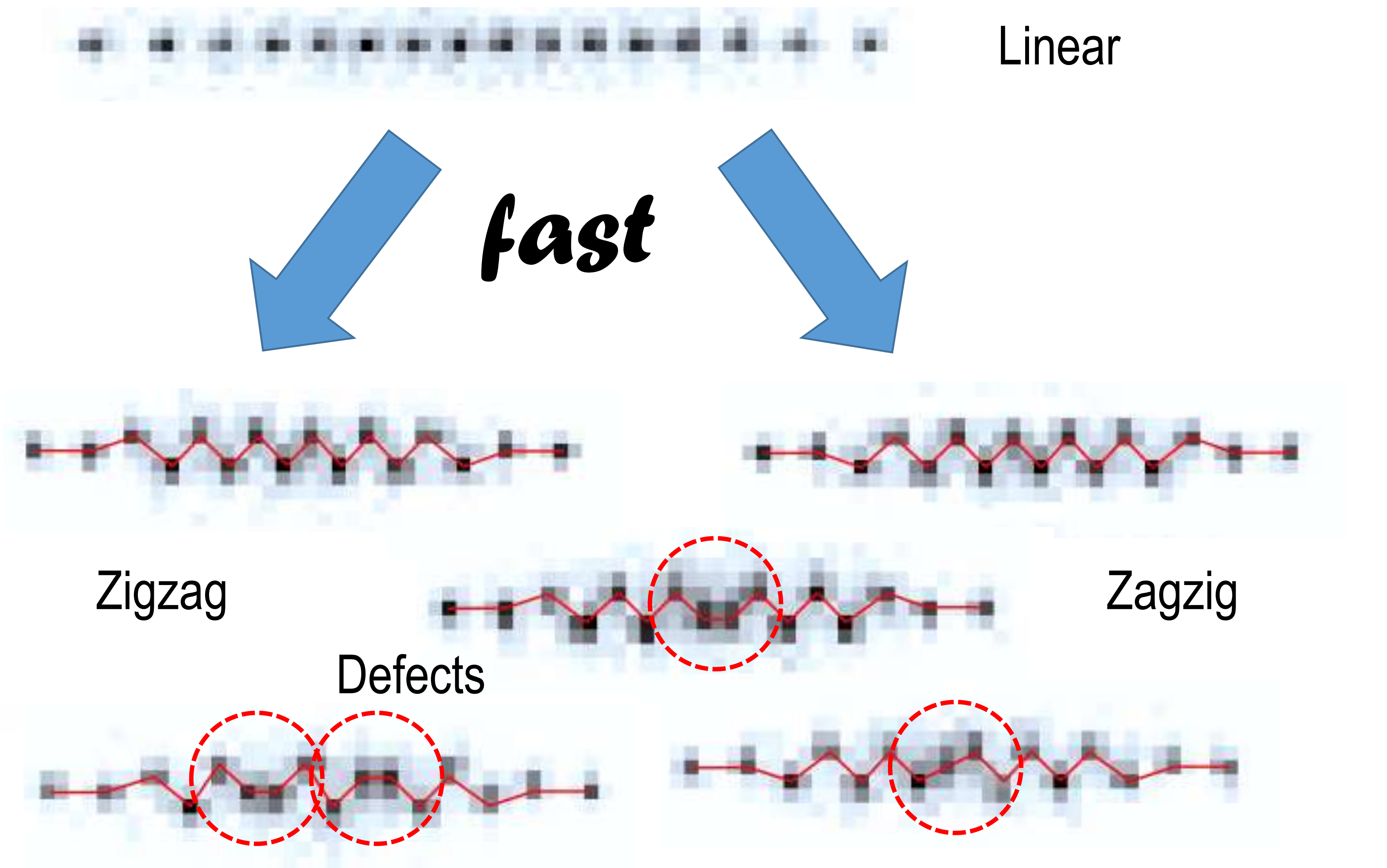
Defect

Double defect

Structural configuration change in ion crystals



Structural configuration change in ion crystals

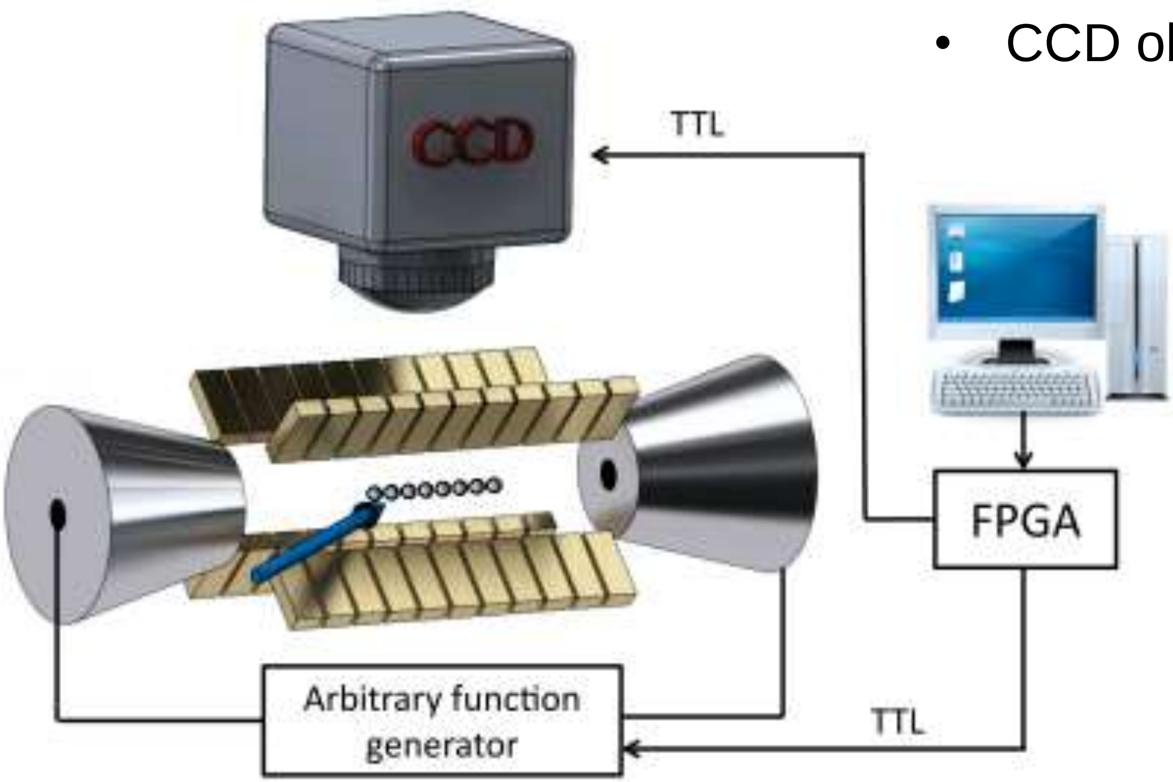


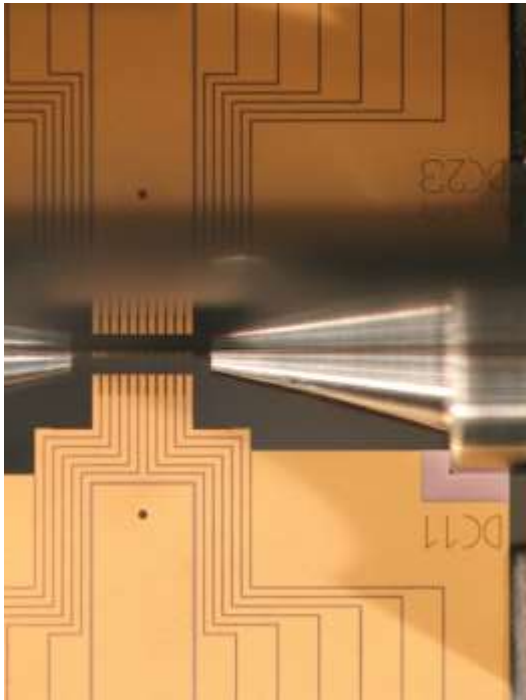
Experimental setup and parameters

- Trap with 11 segments
- Controlled by FPGA and arbitray waveform gen.

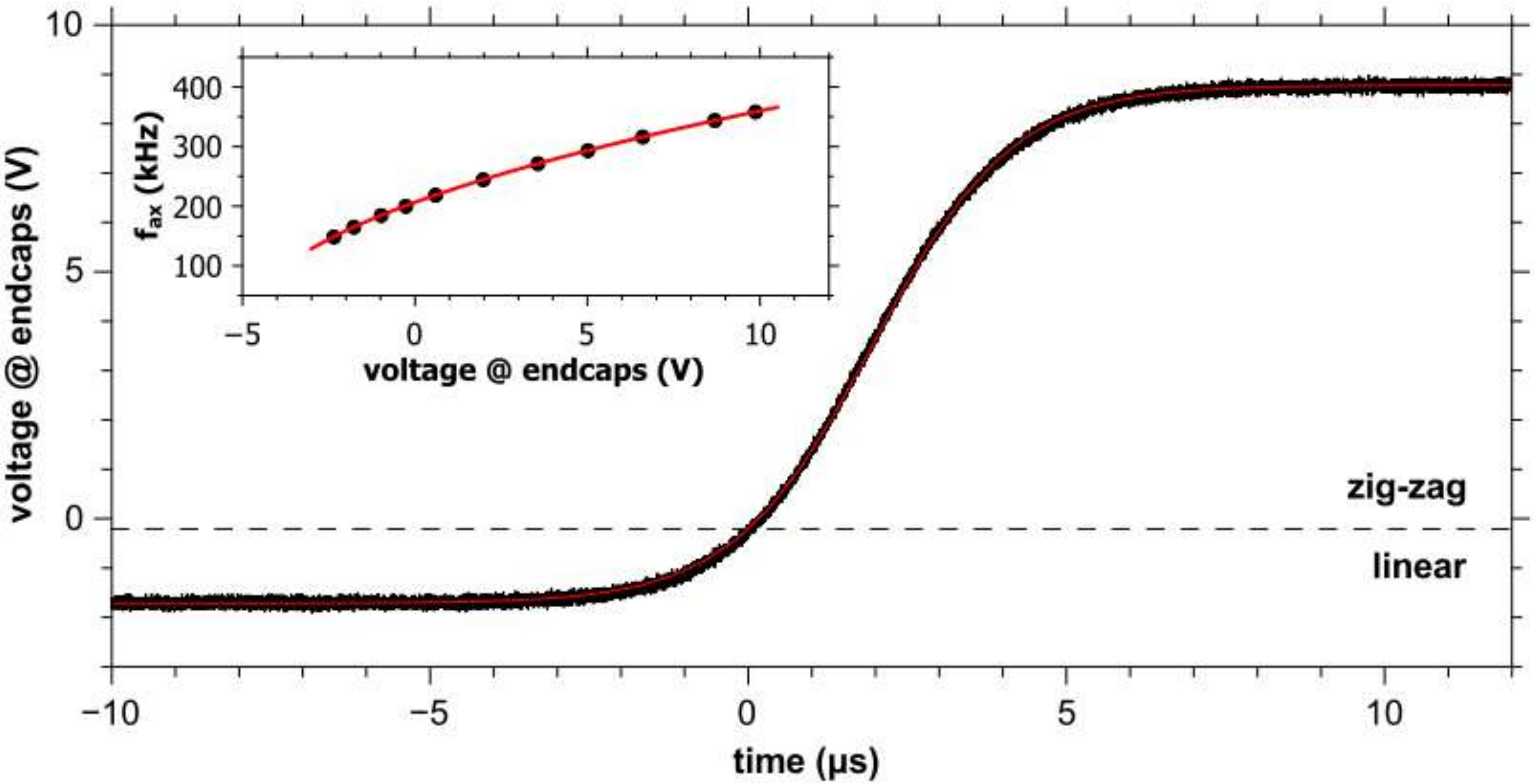
  $\omega/2\pi$ = 1.4MHz (rad.)
  $\omega/2\pi$ = 160 – 250kHz (ax.)

- Laser cooling /
- CCD observation



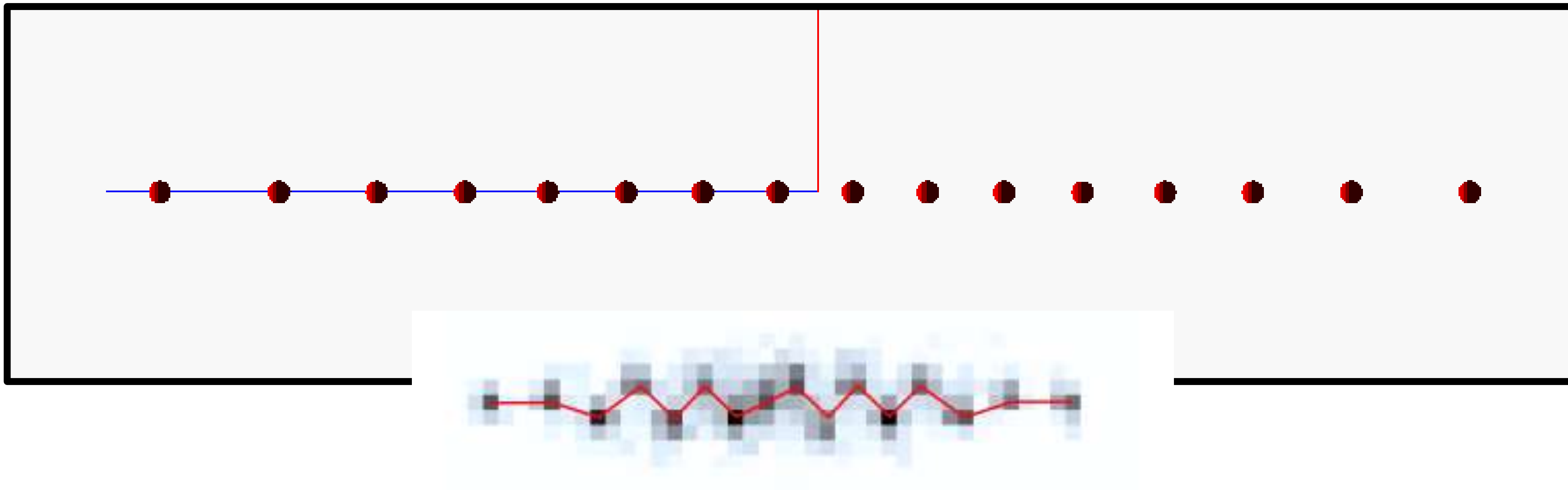


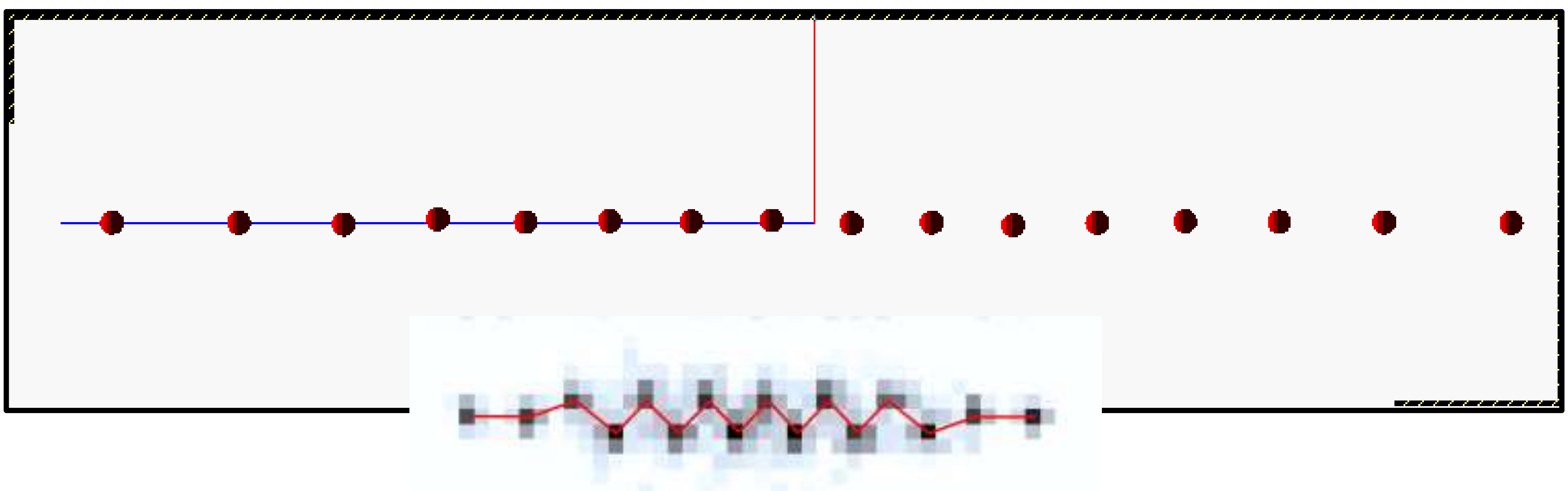
Smooth axial compression over critical point



- Exponential soft start and stop
- Low excitation of axial breathing mode
- Slope at critical point variable for variable quench times
- Acurate frequency determination

Molecular dynamics simulations



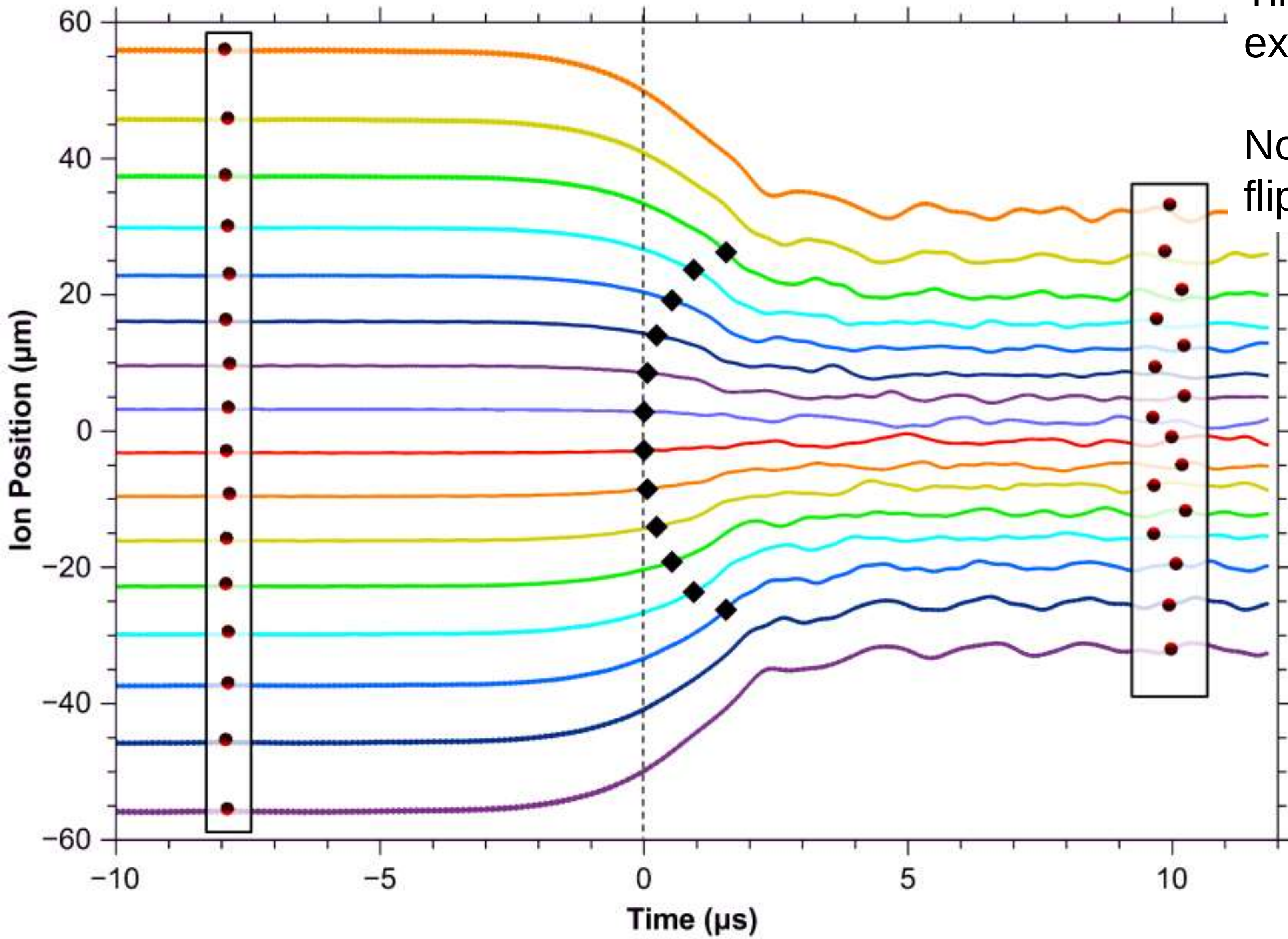


Molecular dynamics simulations

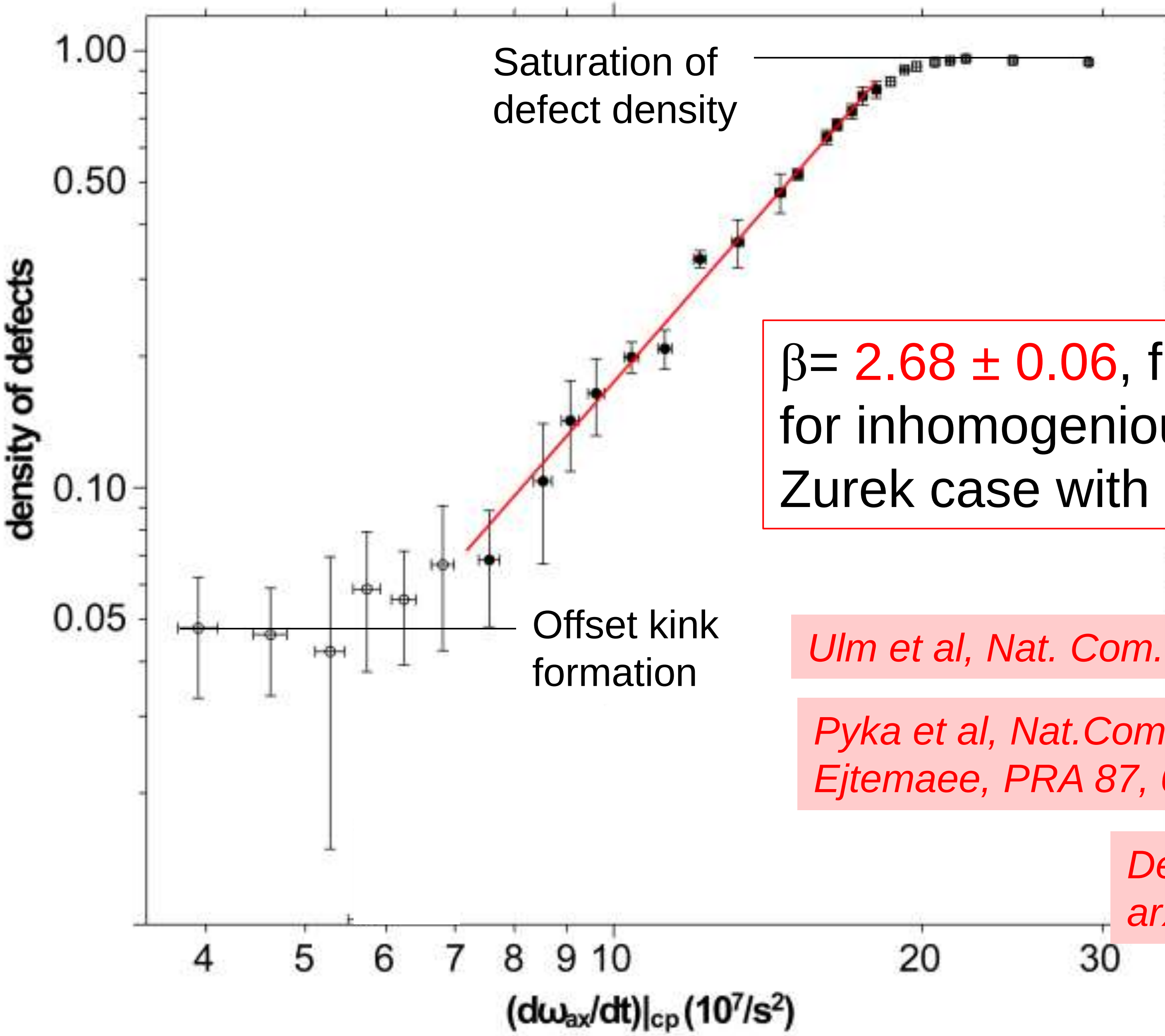
Simulation of ion trajectories

Tiny 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)

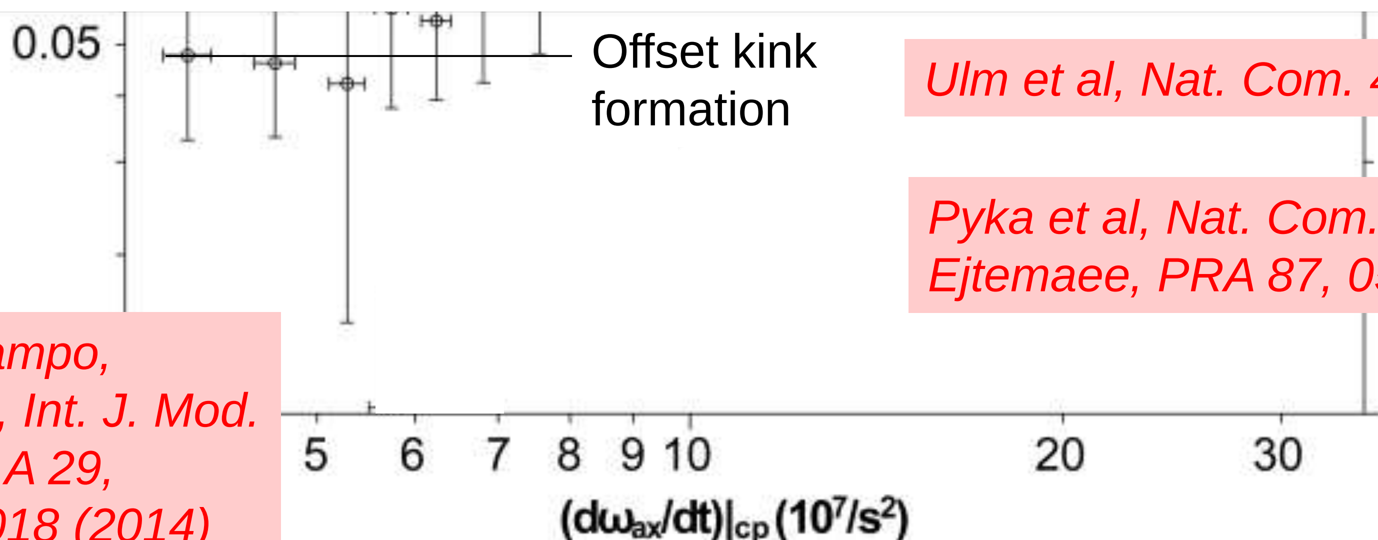
Pyka et al, Nat.Com. 4, 2291 (2013)
Ejtemaee, PRA 87, 051401 (2013)

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)

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

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

Modern Quantum technologies with trapped ions

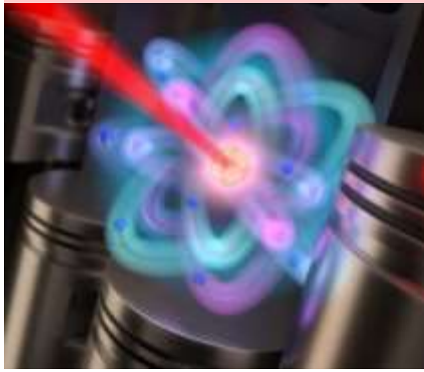
F. Schmidt-Kaler

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

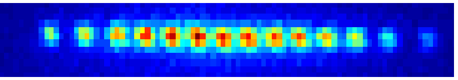
Rydberg ions

PRL 115, 173001
arXiv:1905:05111

Sci. 352, 325
arXiv:1808.02390

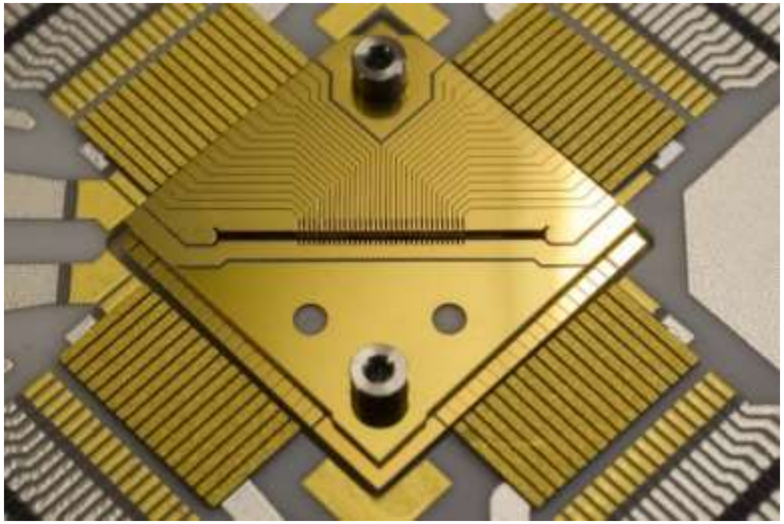


Ion heat engines

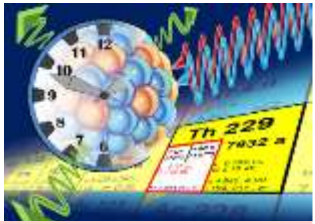


Universal trapped-ion Quantum Computer

PRL 119, 150503
PRX 7, 031050
PRX 7, 041061

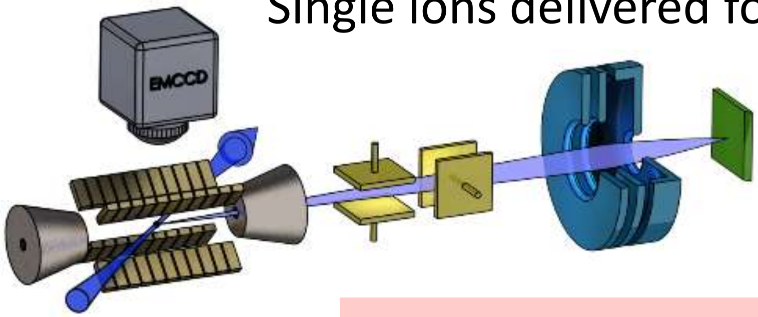


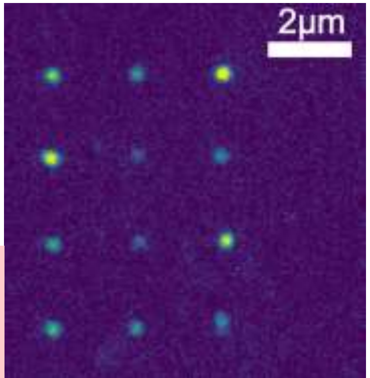
Exotic ions: $\bar{H}^+$ / Th^+



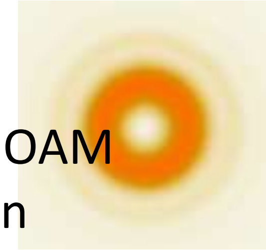
PRA 99, 023420

Single ions delivered for solid state QC





PRL 117, 043001
arXiv:1902.05308



Transfer of optical OAM to a bound electron

Nat.Com. 7, 12998
PRL 119, 253203
JOSA B 36, 565