A single ion spin heat engine coupled to a harmonic oscillator flyweel

- Trapped ion basics
- Trapped ion quantum computing
- Single-ion Otto heat engine
- Spin-driven heat engine
- Future: multi-ion crystal quantum heat engine

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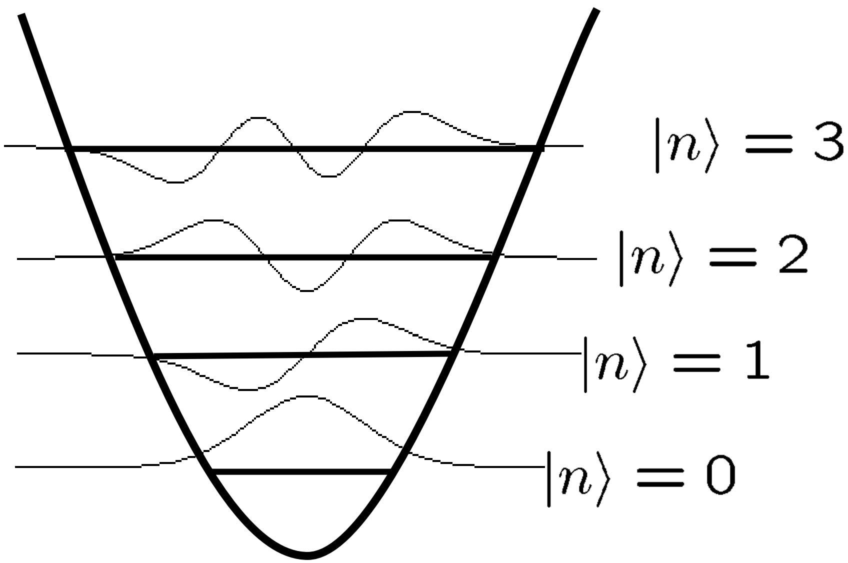
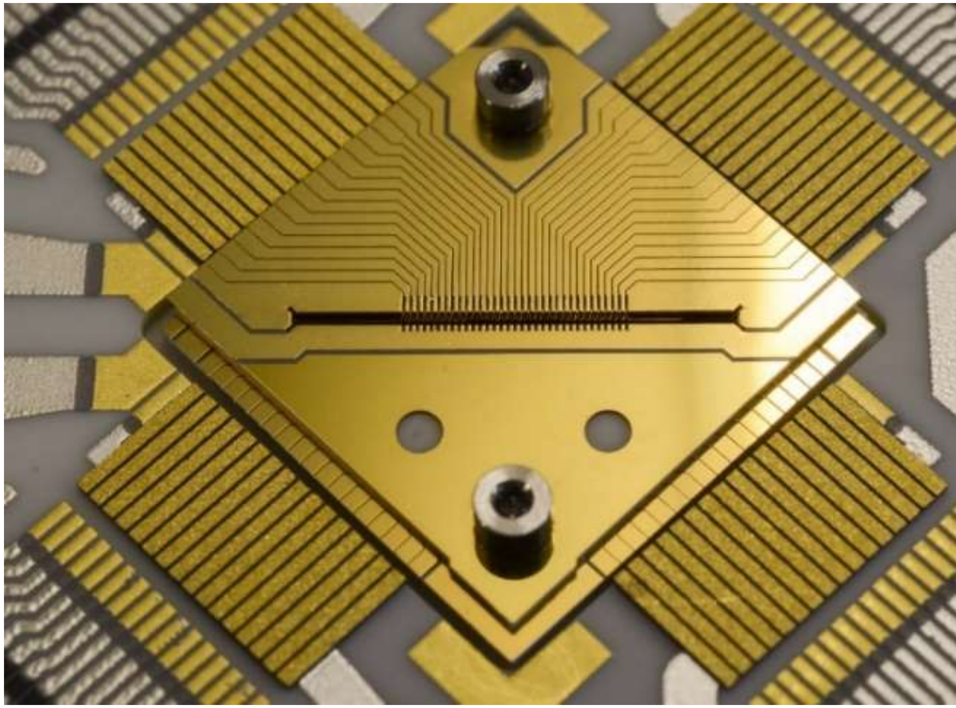
Harmonic oscillator wavefunctions in a Paul trap

$$H_{oscillator} = \hbar\omega_{ax}(a^\dagger a + \tfrac{1}{2})$$





$\Delta x \sim 10$nm

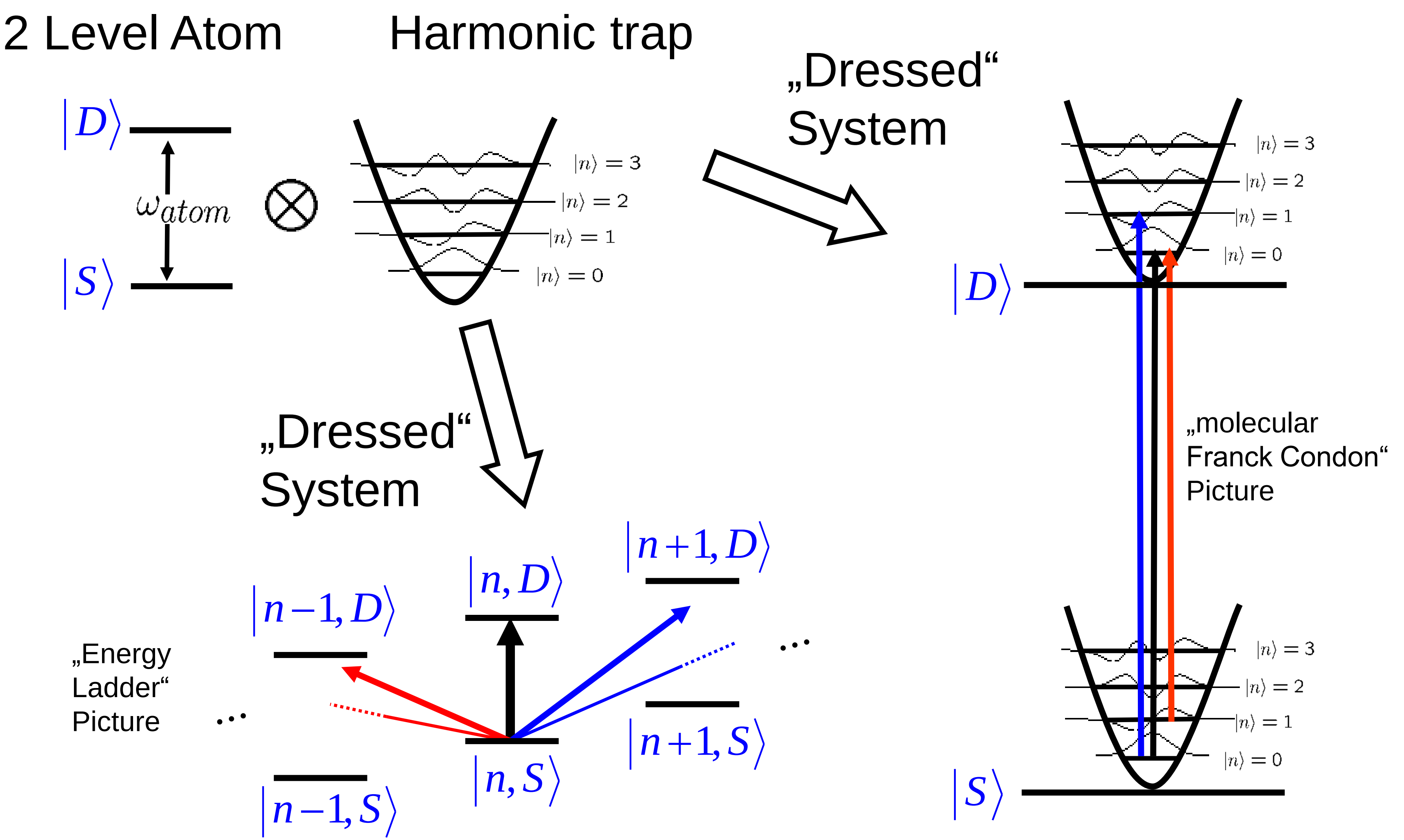
$\Delta\omega/2\pi \sim 1$MHz

$\dot{n} \sim 3$/s

Eigen functions and energies:

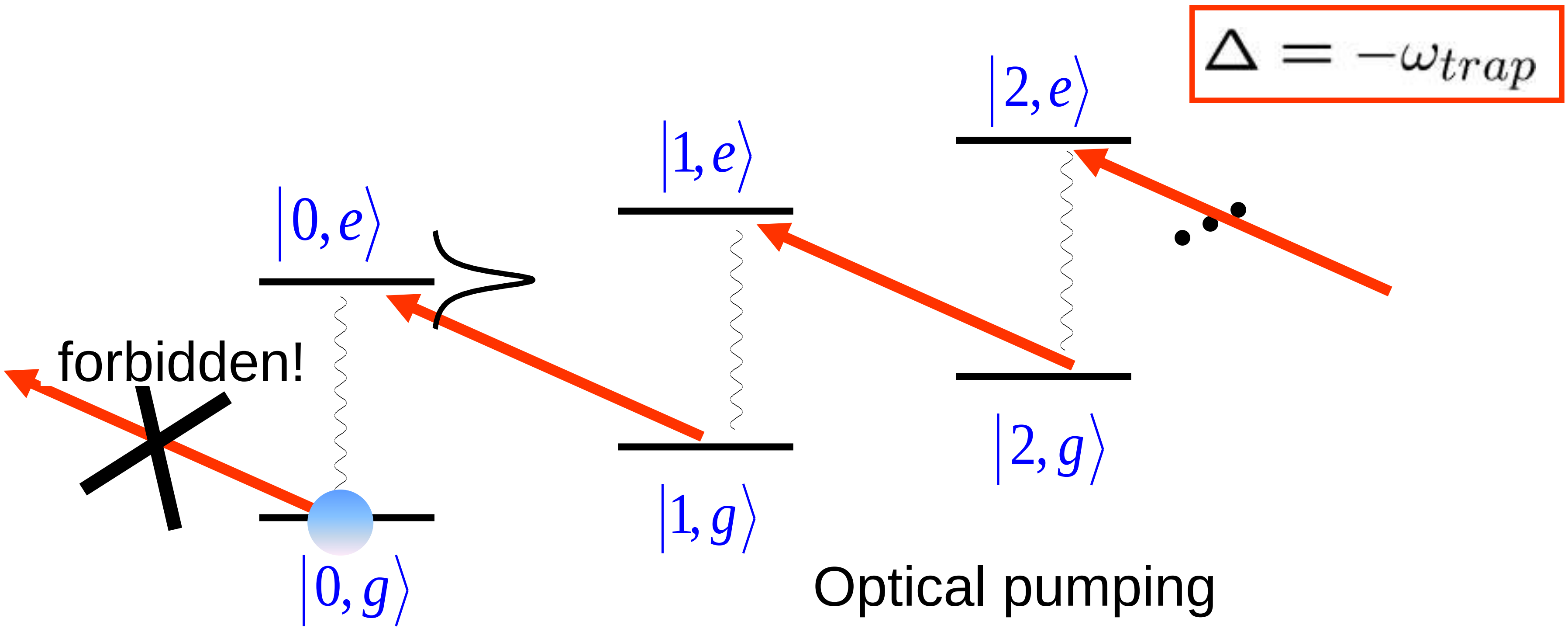
$$E(n) = \hbar\omega_{ax}(n + \tfrac{1}{2})$$

Laser Excitation of a single Ion



Allows for preparing and measuring phonons

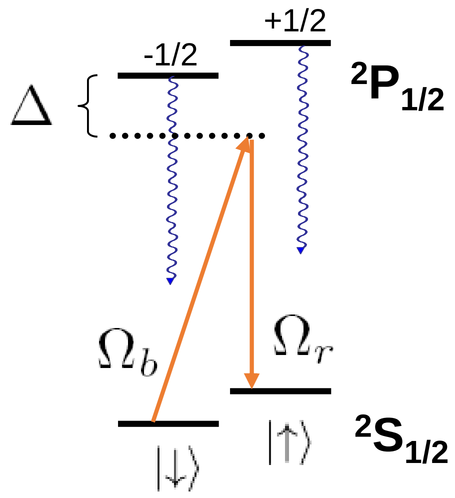
Sideband cooling into the motional ground state

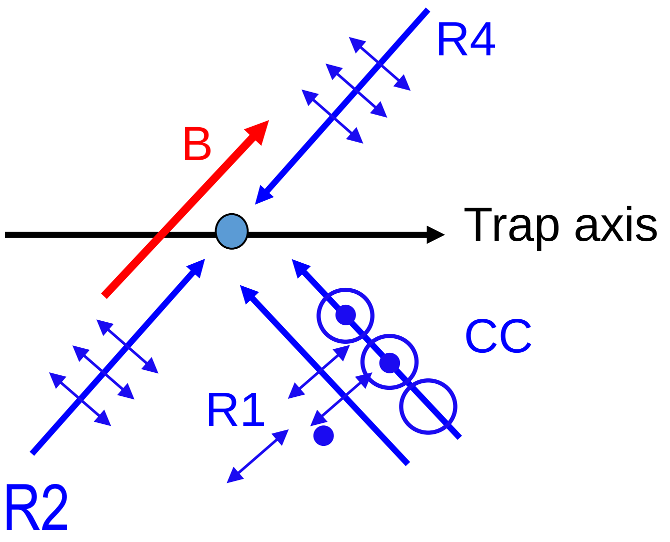


Optical pumping
into the ground state

Signature: no further excitation allowed
„Dark state“ |0>

Single ion qubit manipulation

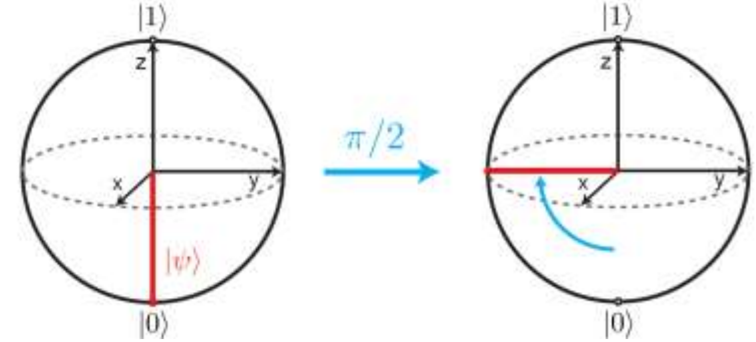


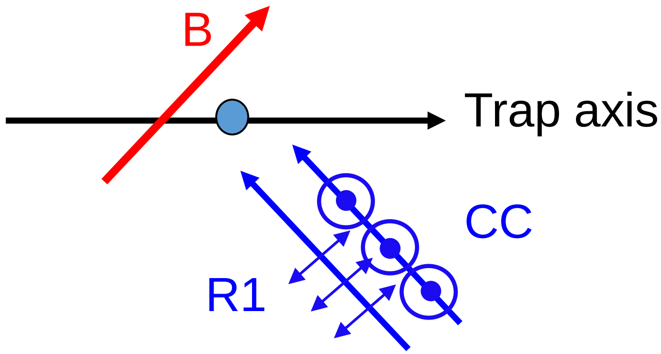


- Single photon detuning Δ much larger than natural linewidth
- Very small spont. scattering rate
- Effective two-level system

Four beams near 397nm used pairwise in different configurations

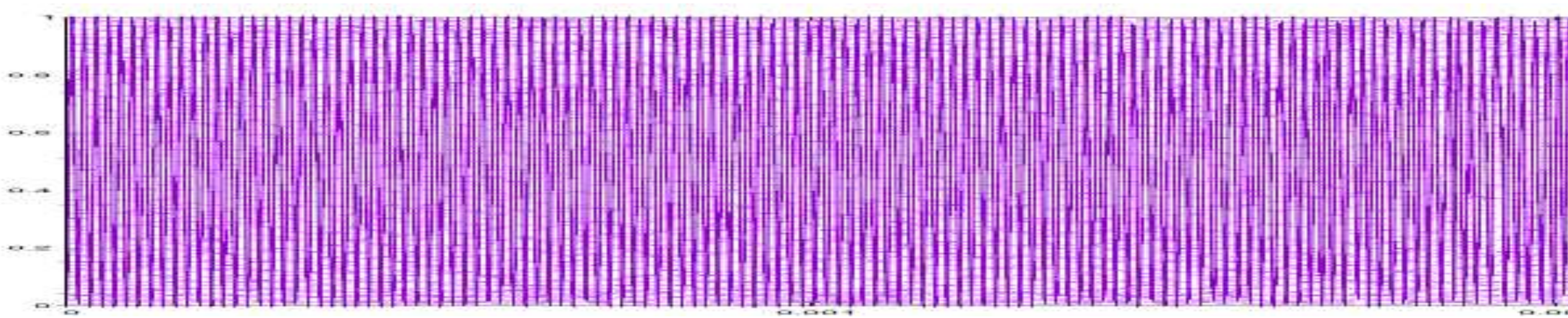
Single qubit rotation





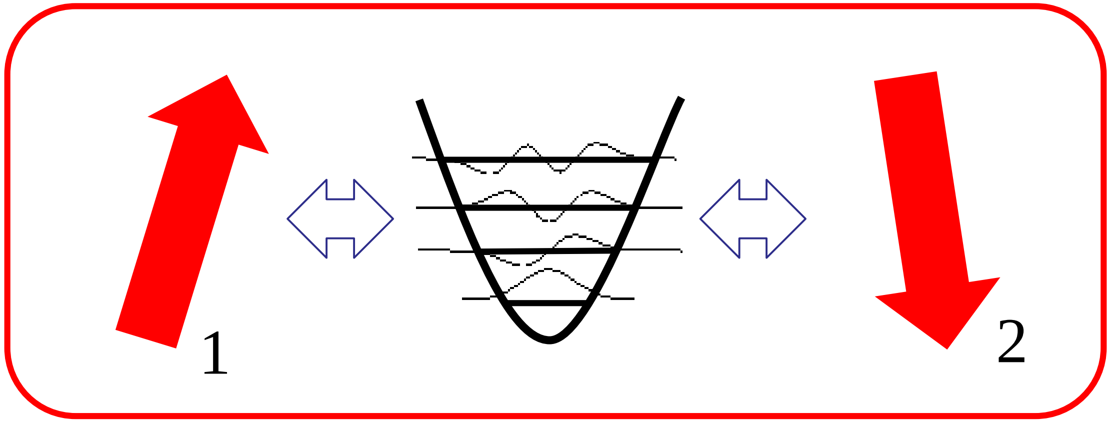
- Copropgating beams
- No effective k-vector
- No coupling to ion motion
- 99,9949(2) % fidelity gates

$$\Omega_{Raman} \propto \frac{\Omega_r \Omega_b}{\Delta}$$



Designed qubit interactions

Interaction of spin 1 and 2
due to coupling to common mode of vibration

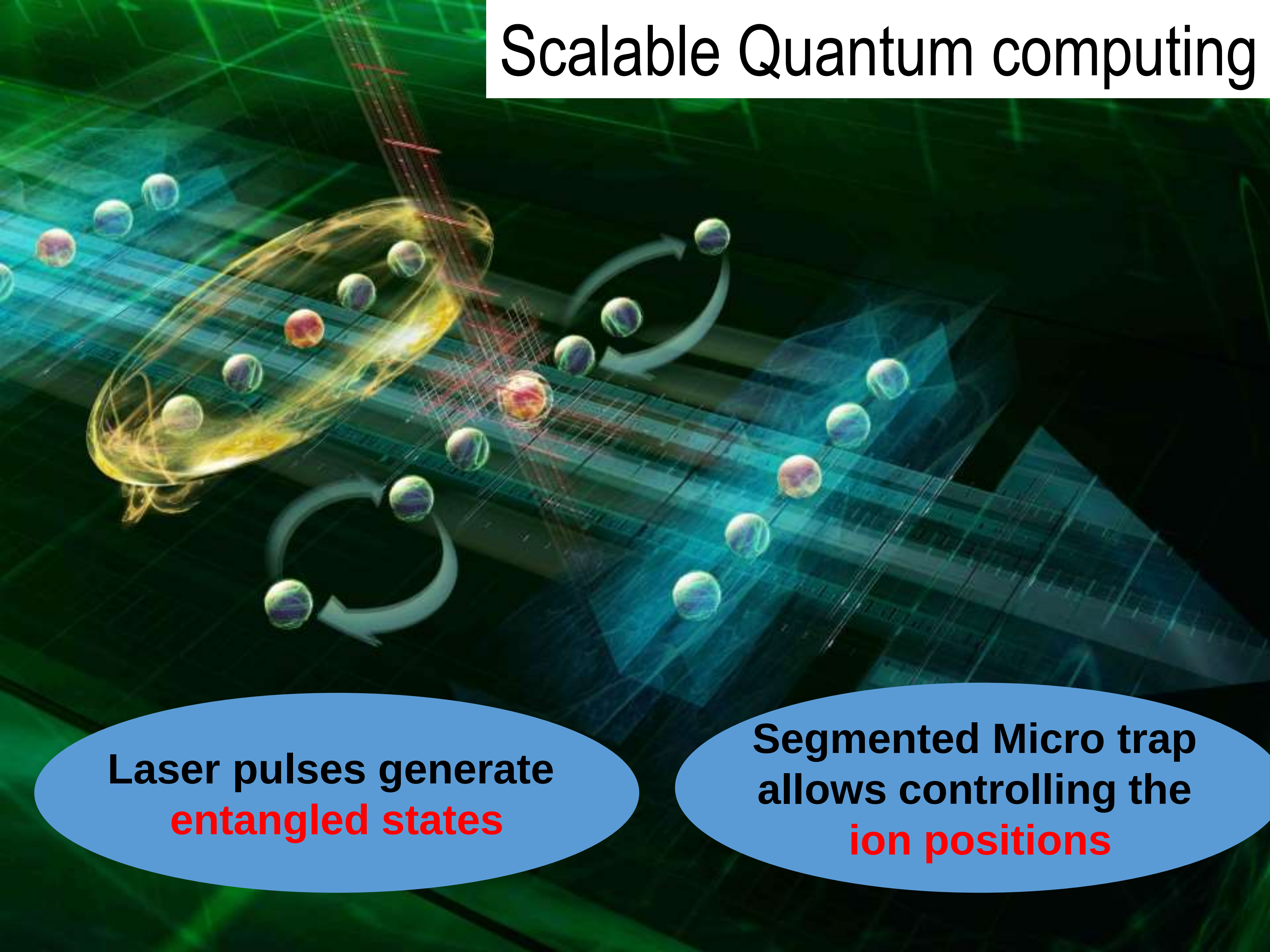


Spin-dependent
light forces

*Monroe, et al, Science **272**, 1131 (1996)*
Leibfried et al., Nature 412, 422 (2003)
*McDonnell et al. PRL **98**, 063603 (2007)*

*Poschinger et al, PRL **105**, 263602 (2010)*

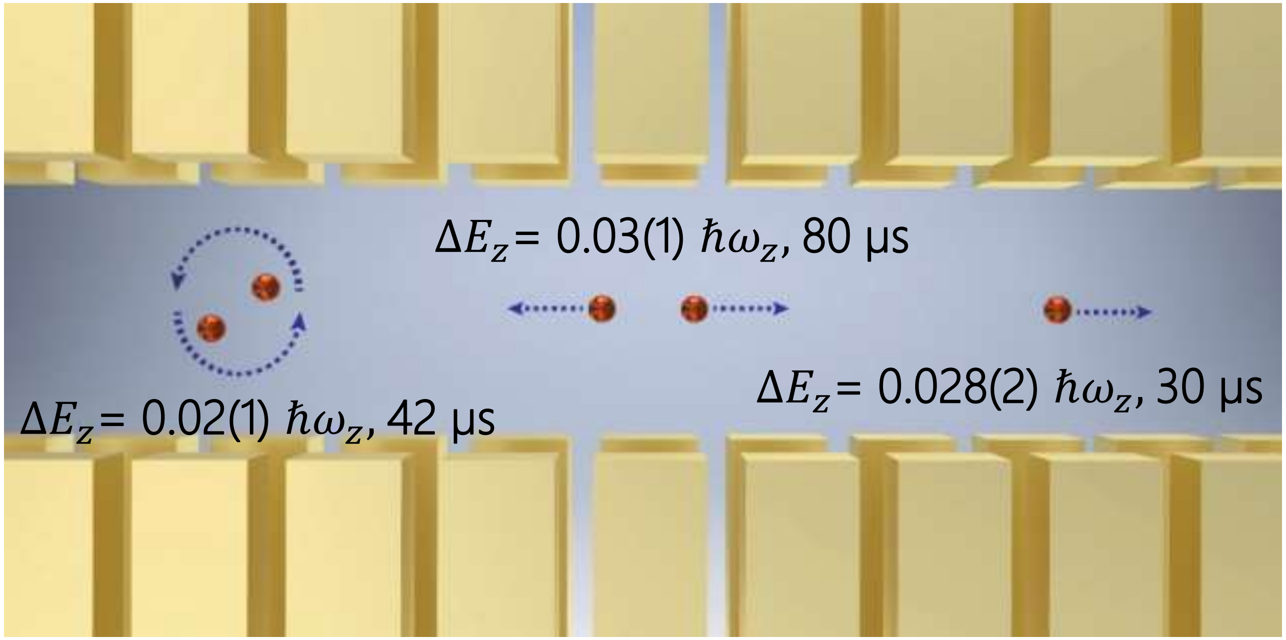
Scalable Quantum computing



Laser pulses generate entangled states

Segmented Micro trap allows controlling the ion positions

Ion movement – qubit register reconfigration

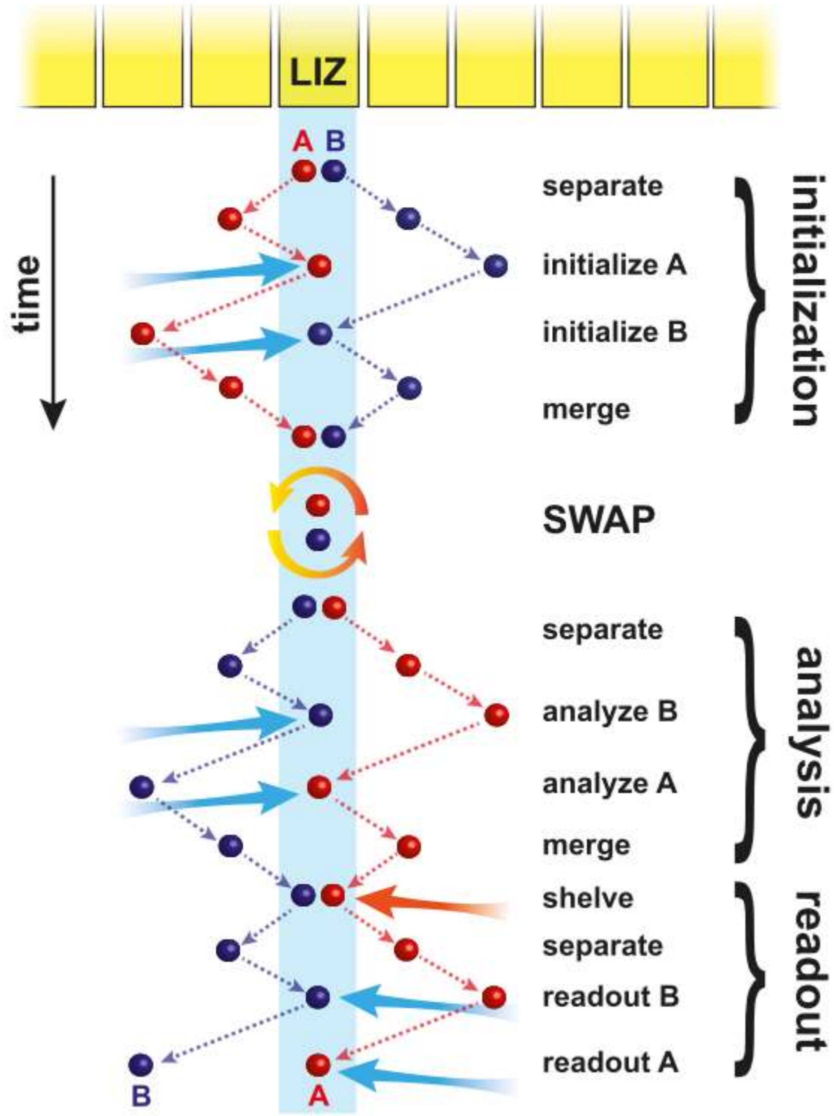


- Shuttle ion crystal
- Separate two-ion crystal
- Merge into two-ion crystal
- Swap ion positions
- Shuttle single ion

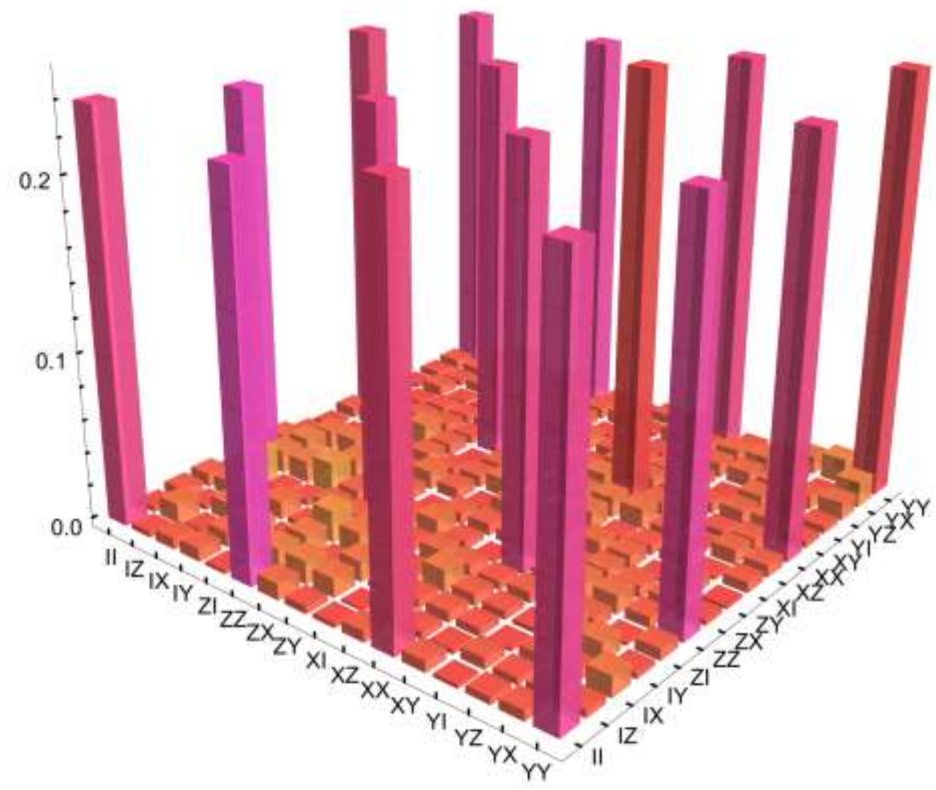
Geometric phase gate
99.5(1)% fidelity on *radial* mode

Walter et al., PRL109, 080501 (2012)
Kaufmann et al, NJP 16, 073012 (2014)
Kaufmann et al, RPA 95, 052319 (2017)

2- and 3-qubit shuttle and swapping



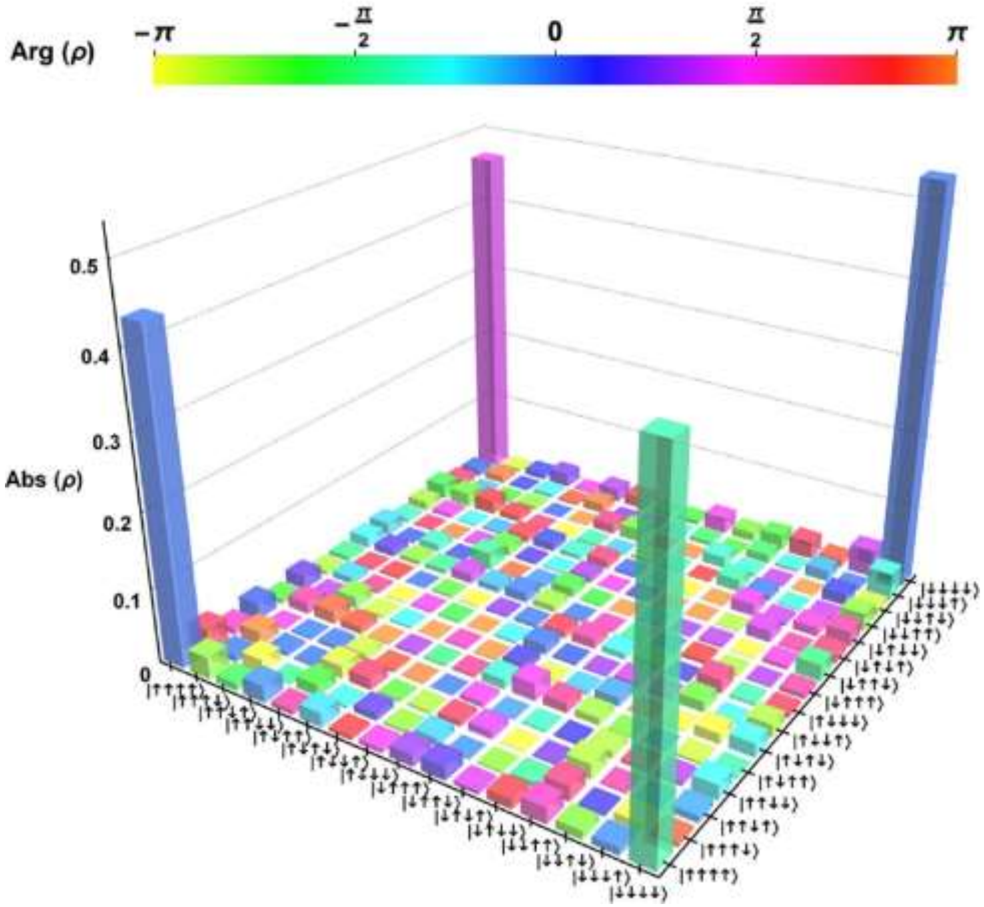
Process tomography data



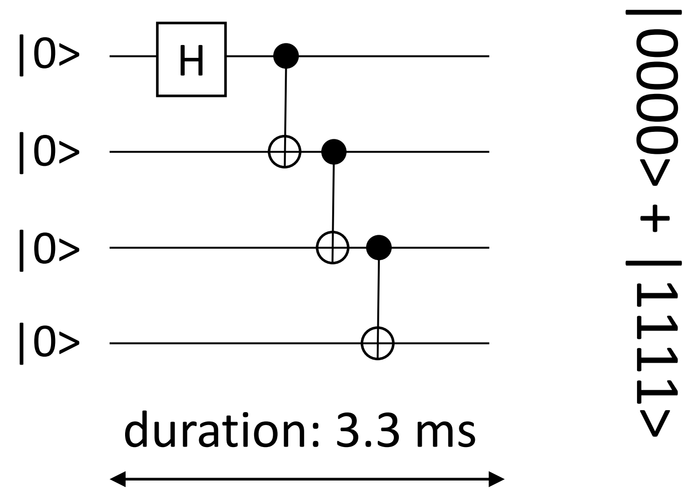
mean process fidelity 99.96(13)%

Kaufmann et al., PRA 95, 052319 (2017)

“Knitting together” a 4-ion GHZ state



equivalent circuit:



Full state tomography yields **94.7 % fidelity** from about 50k measurements.

Experimental sequence uses **> 300 shuttling operations** for SB cooling, state preparation, quantum circuit, state analysis.

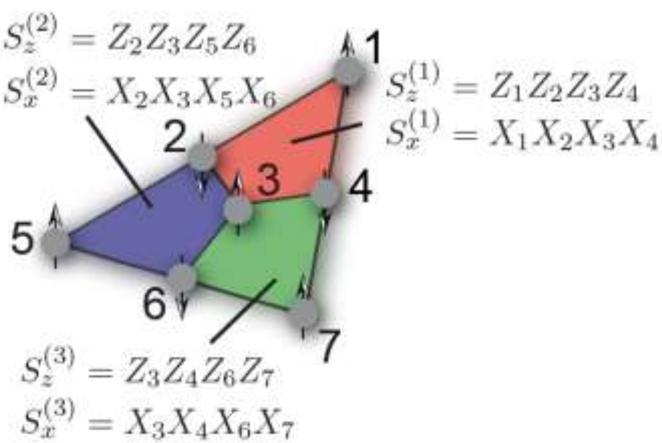
Kaufmann et al, PRL 119, 150503 (2017)

Key figures, now and future, for trapped ion-QC

- Gates, read-out of spin state better $1 - 10^{-4 \ldots 5..6}$, typ. 30µs, few µs
- Qubit register reconfiguration operations, few µs to 100µs …. ~ 1µs
- Long coherence times, up to a few seconds …. ≥ seconds with dynamical decoupling pulse sequences, decoherence-free substates, >10s …minutes

Optimization of speed and fidelity required, challenge scalability to > 50 qubits

Goal: Implementing topological error correction



Bermudez et al, Phys. Rev. X 7, 041061, Nigg et al., Sci. 234, 302 (2014)

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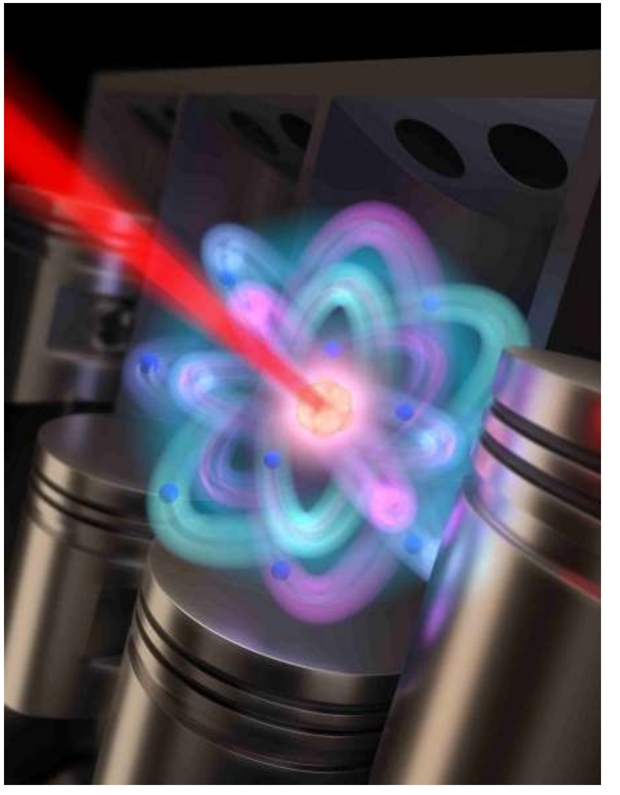
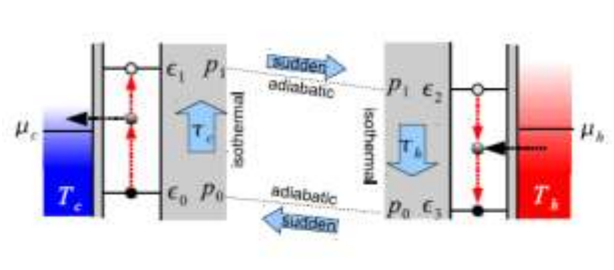


Proposals

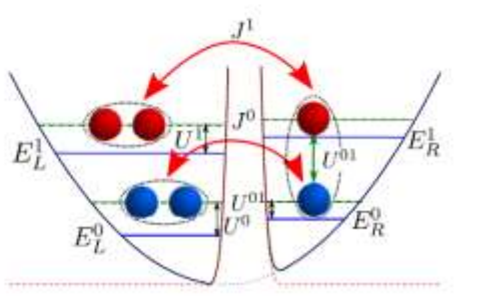
Maser Scovil et al, PRL 2, 262 (1959)

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

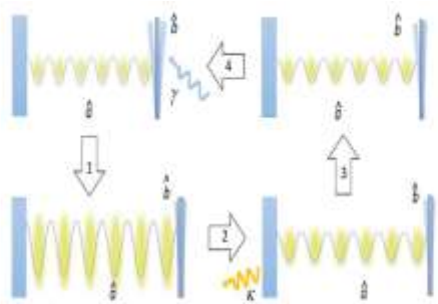
Quantum Thermodynamics
Gemmer et al, Springer, Lect Notes 784 (2009),
Anders, Esposito, NJP 19, 010201 (2017)



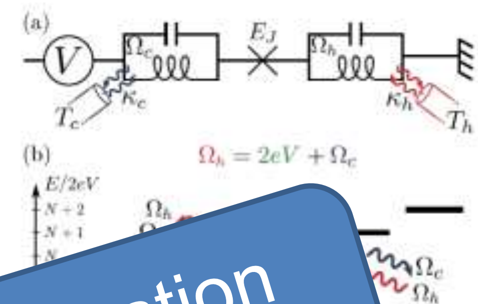
Quantum dot
Esposito et al., PRE 81, 041106 (2010)



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



Opto-Mechani
Zhang et



Cavity
041418(R)

driven heat
engine
Anders et al., Found Phys 38, 506 (2008)

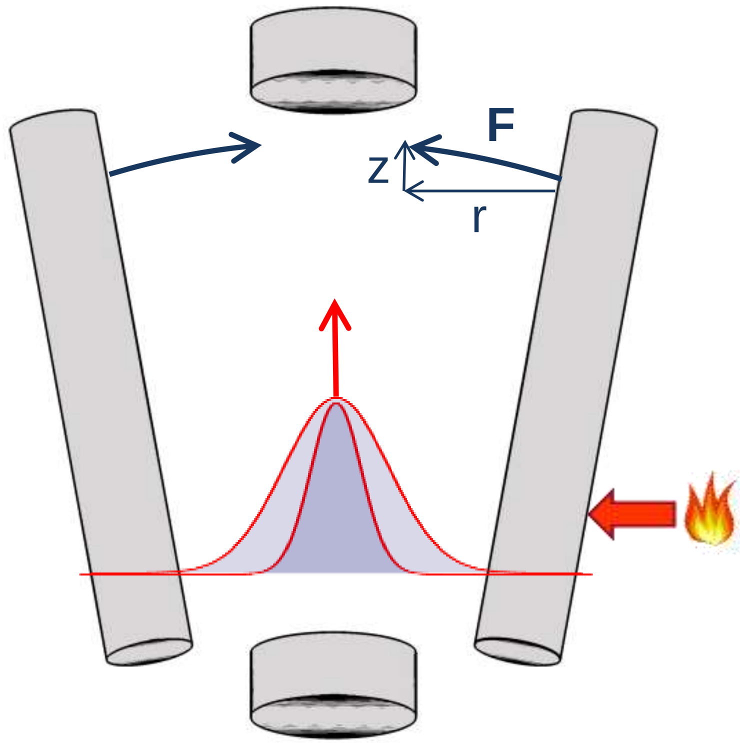
Quantum information driven engines
Cottet et al., PNAS 114, 7561 (2017),
Mohammady et al., NJP 19, 113026 (2017)
Strasberg et al., PRX 7, 021003 (2017)

Wishful, to have experimental realization of heat engines in the quantum regime

The working principle – single ion HE

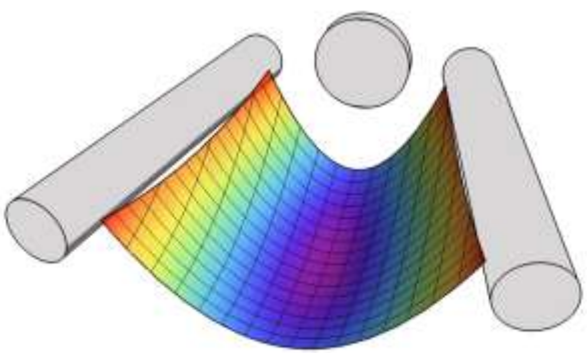
Doppler heating/cooling in radial direction induces axial displacement

Equilibrium position shifted



heating

Pseudopotential



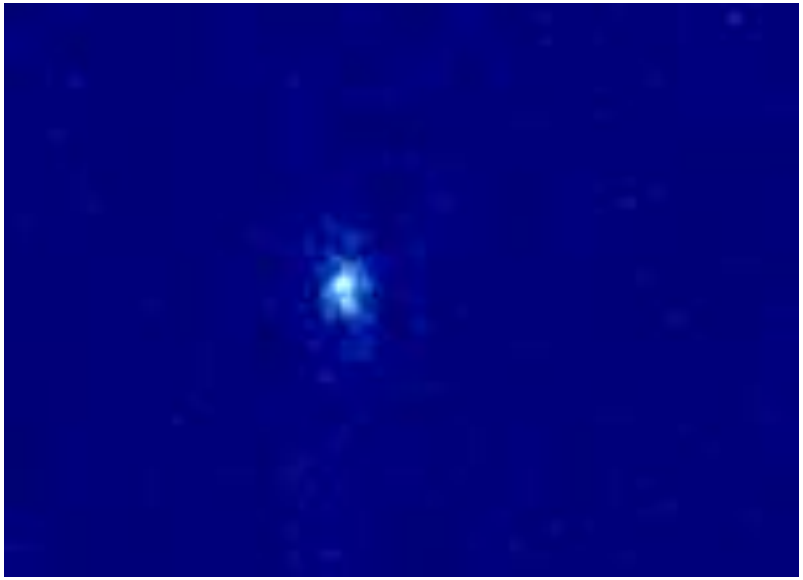
To reach reach large axial amplitudes of movement

- strong radial confinement
- weak axial confinement

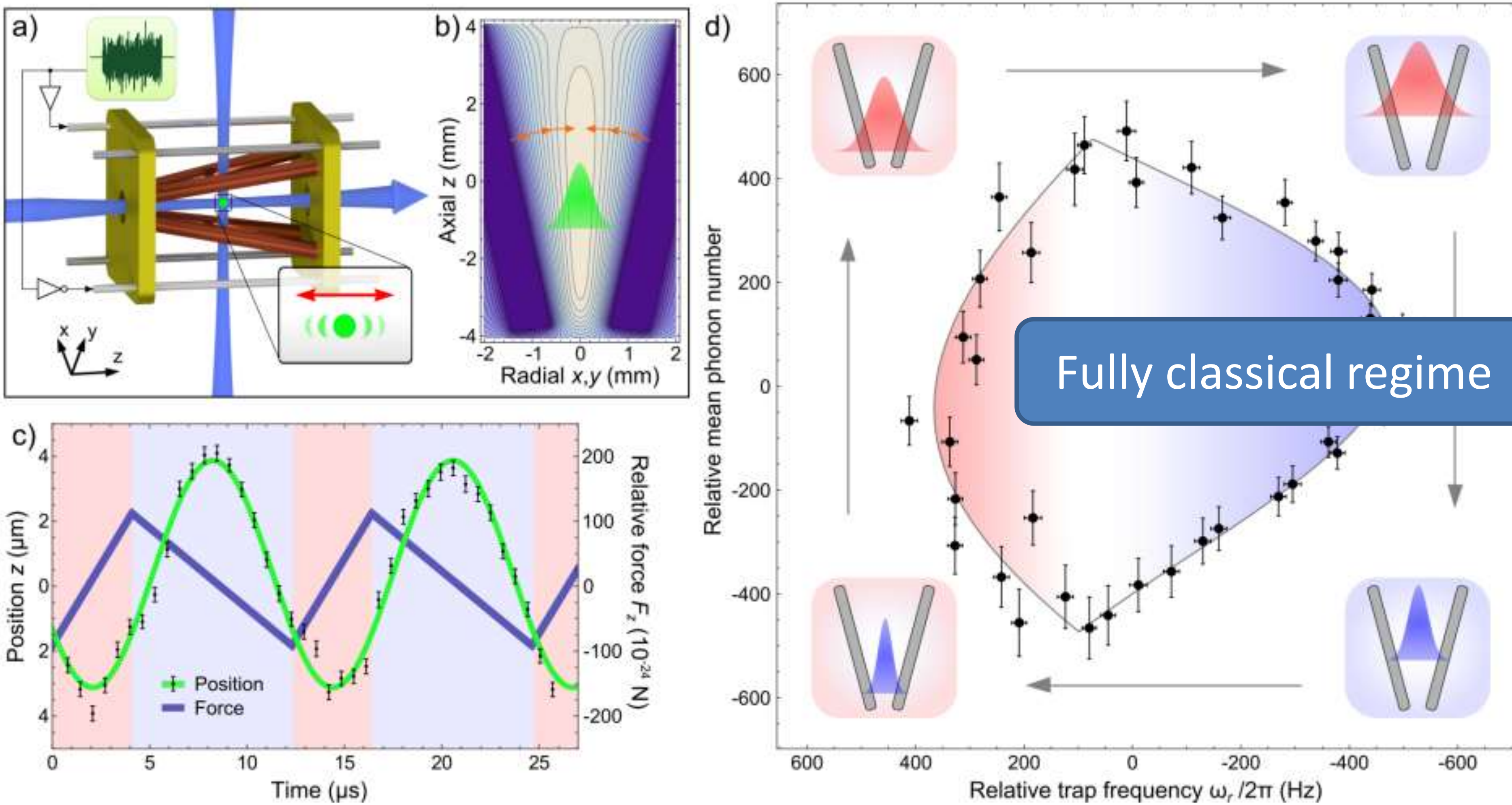
Stroboscopic motion measurements

Reading the position of the piston

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



Working principle and results



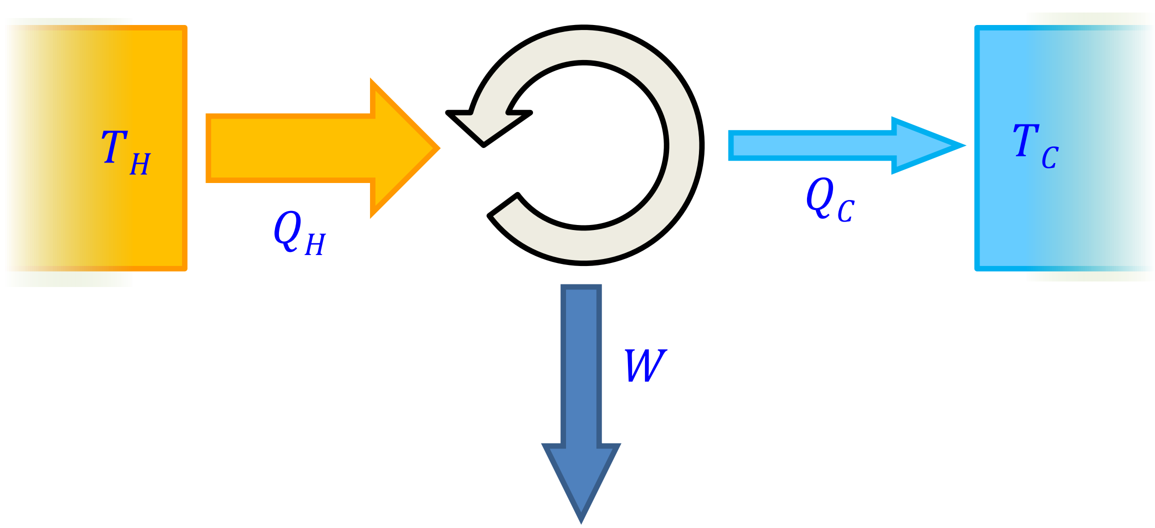
Fully classical regime

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

Roßnagel, et al. Sci. 352, 325 (2016)

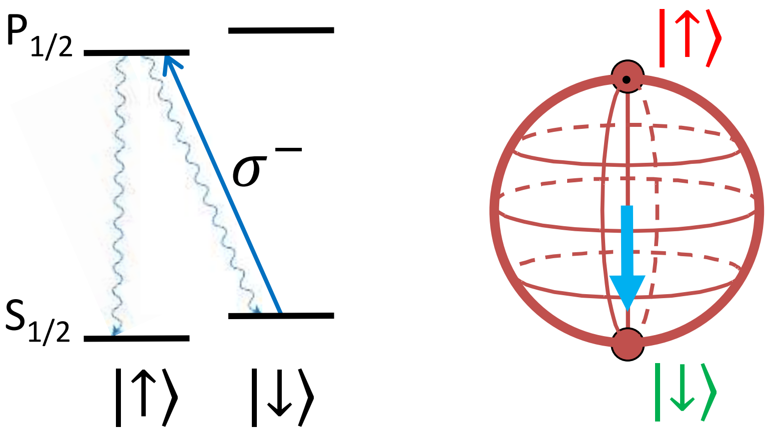
Heat-Engine Operation in the Quantum Regime

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

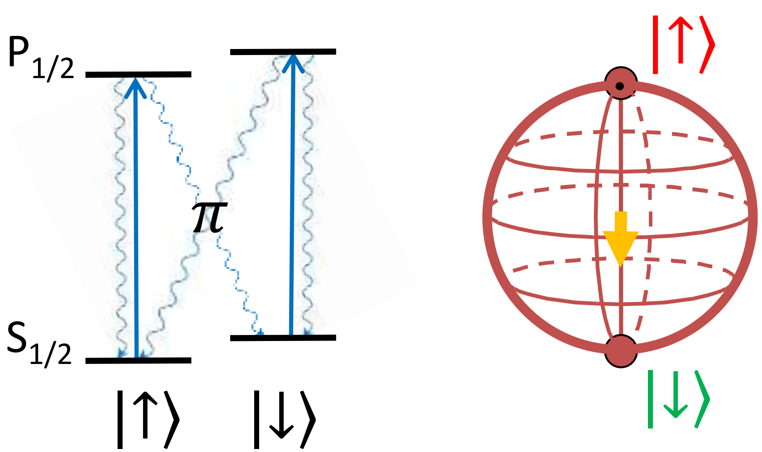


Controlling the Spins Thermodynamics

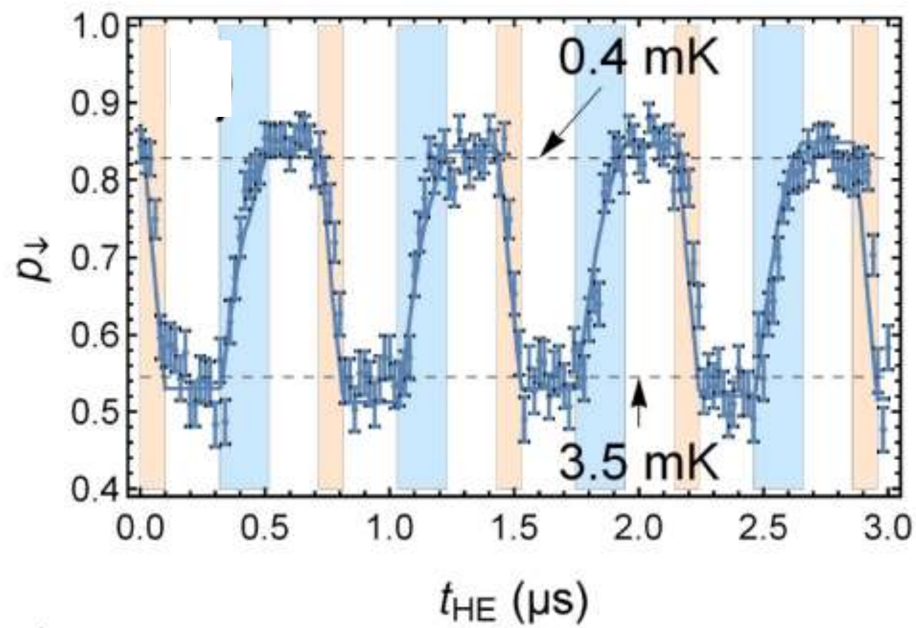
Cold bath: optical pumping



Warm bath: depolarising



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

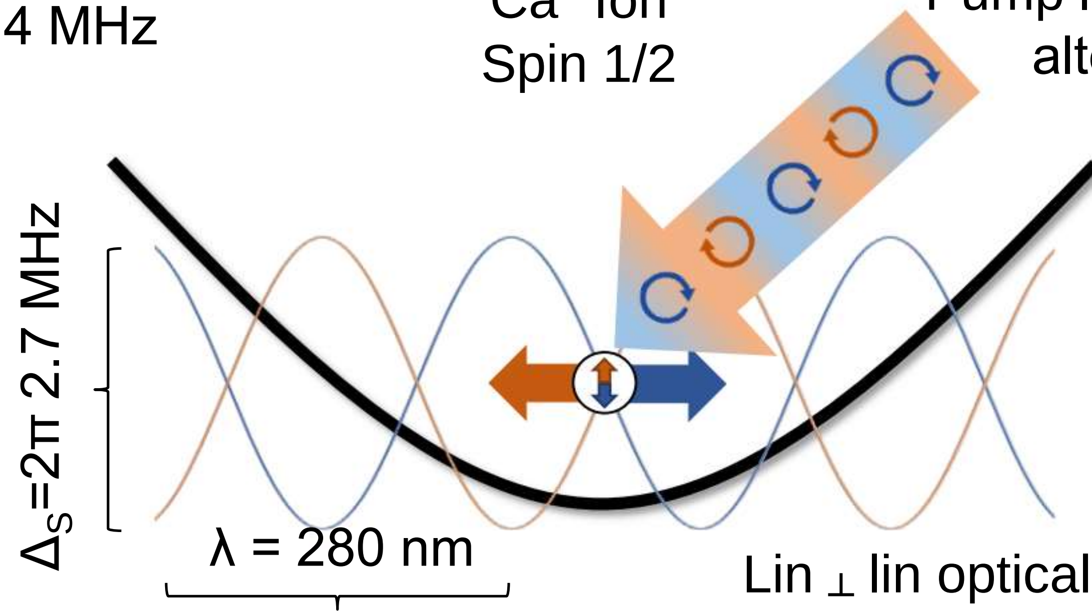


Heat-Engine setup

Harmonic trap potential
$\omega = 2\pi$ 1.4 MHz

Ca$^+$ Ion
Spin 1/2

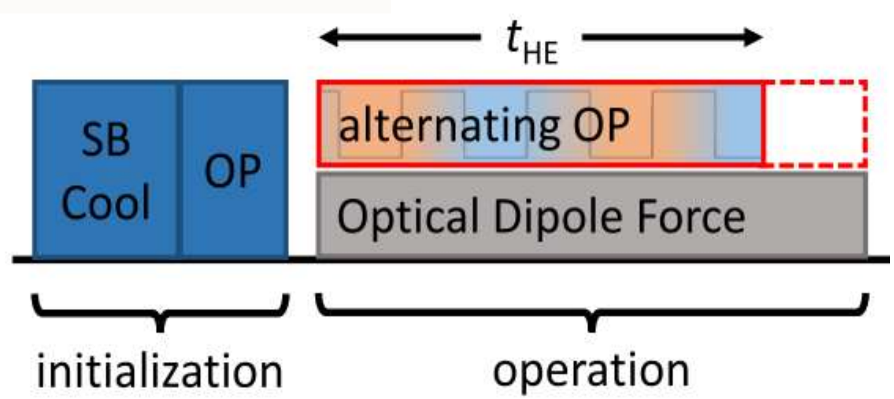
Pump laser: Polarization
alternating at ω



Lin ⊥ lin optical lattice:
Alternating, spin-dependent Stark shift

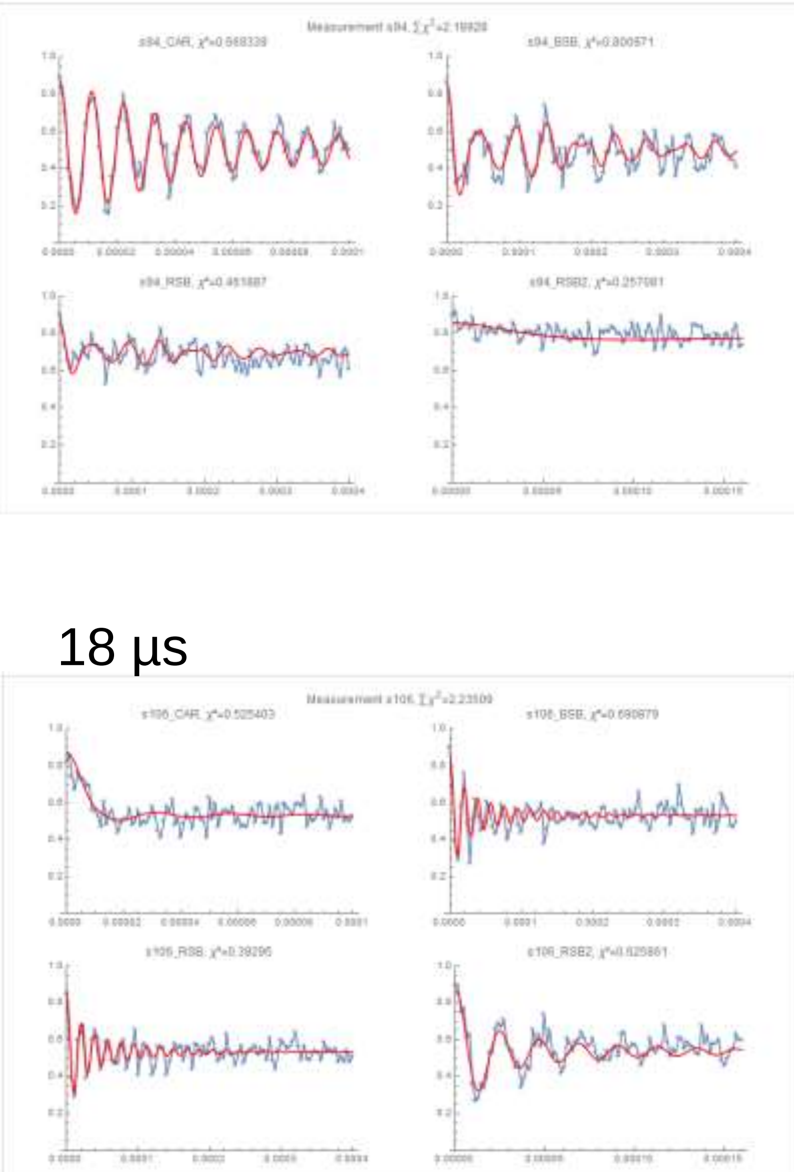
Schmiegelow et al., PRL 116, 033002 (2016)

Protocol:



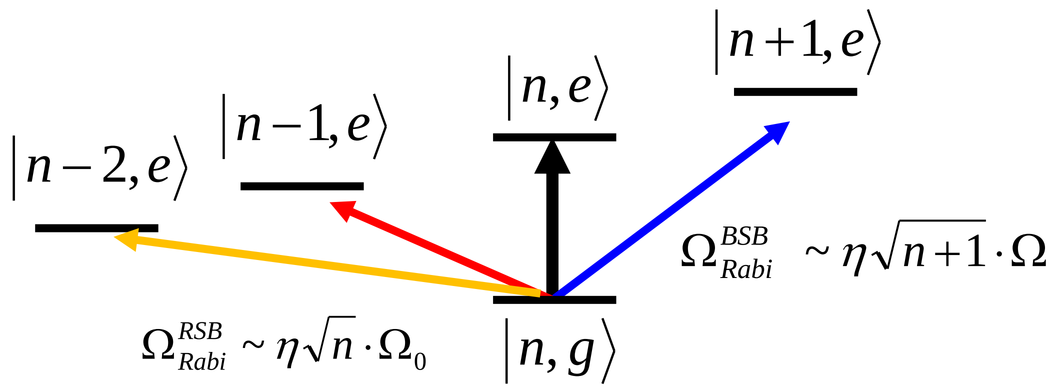
Analysis - photon number distributions

0 µs



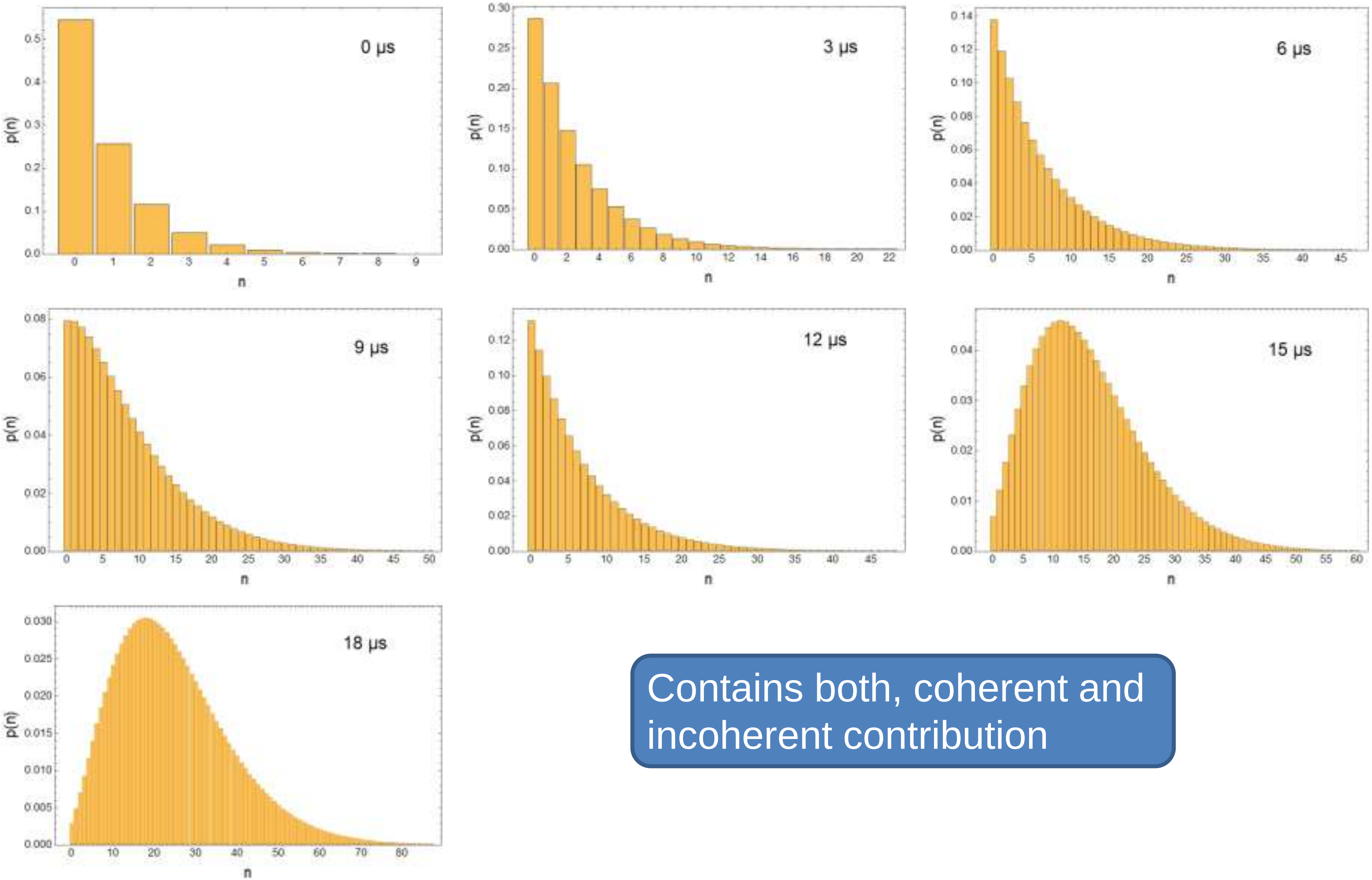
18 µs

Driving Rabi-Oscillation on
C, BSB, RSB, RRSB



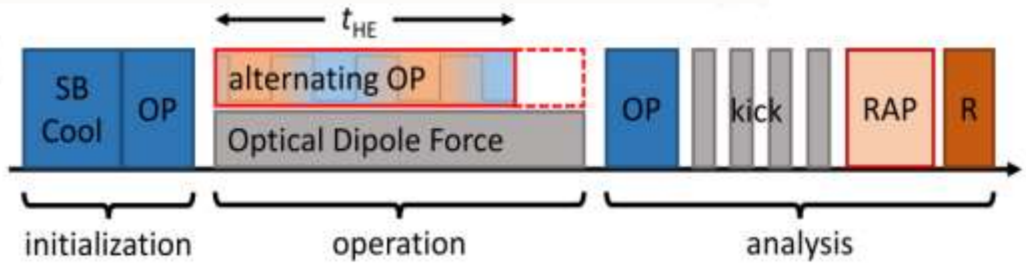
Fitting Rabi-Oscillation
to phonon number distributions p_n

Analysis - photon number distributions

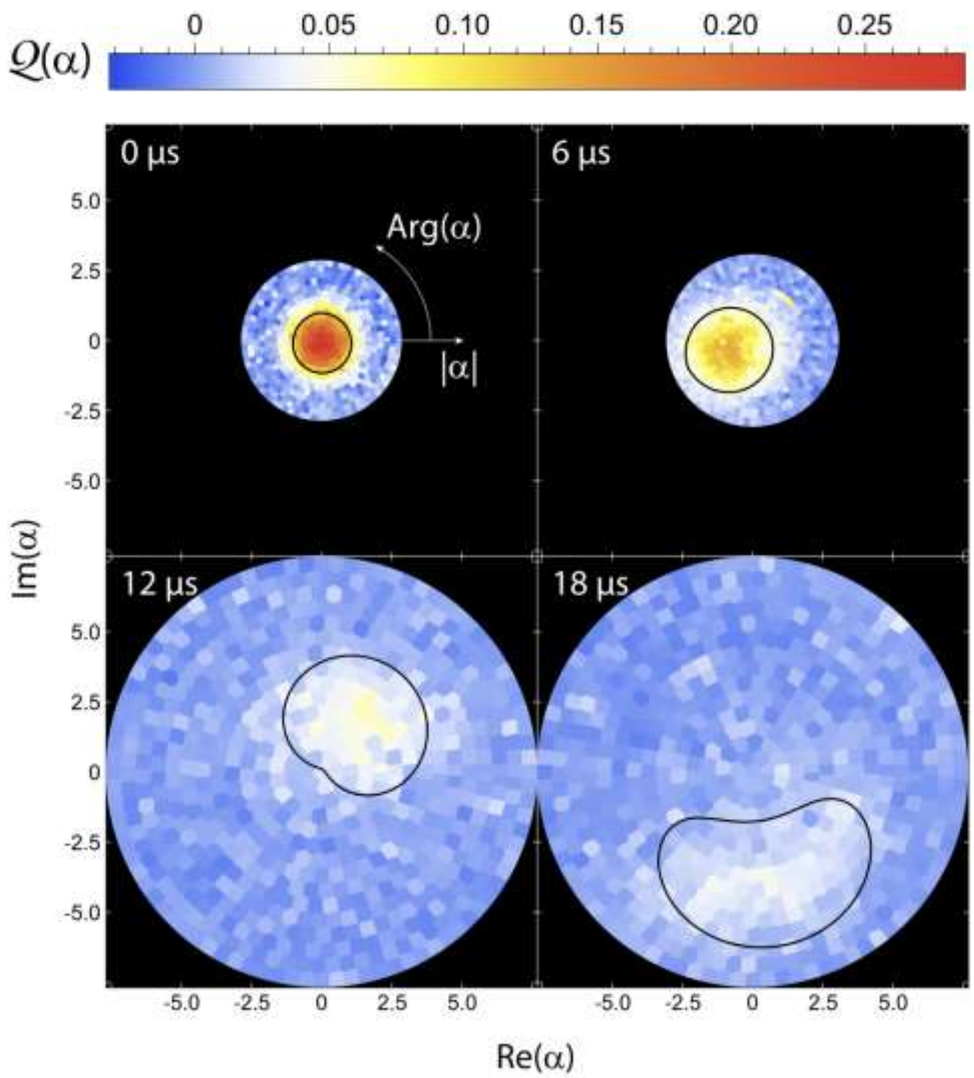


Contains both, coherent and incoherent contribution

Analysis – Q-function



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



Operation in the QM regime - analysis of work fluctuations

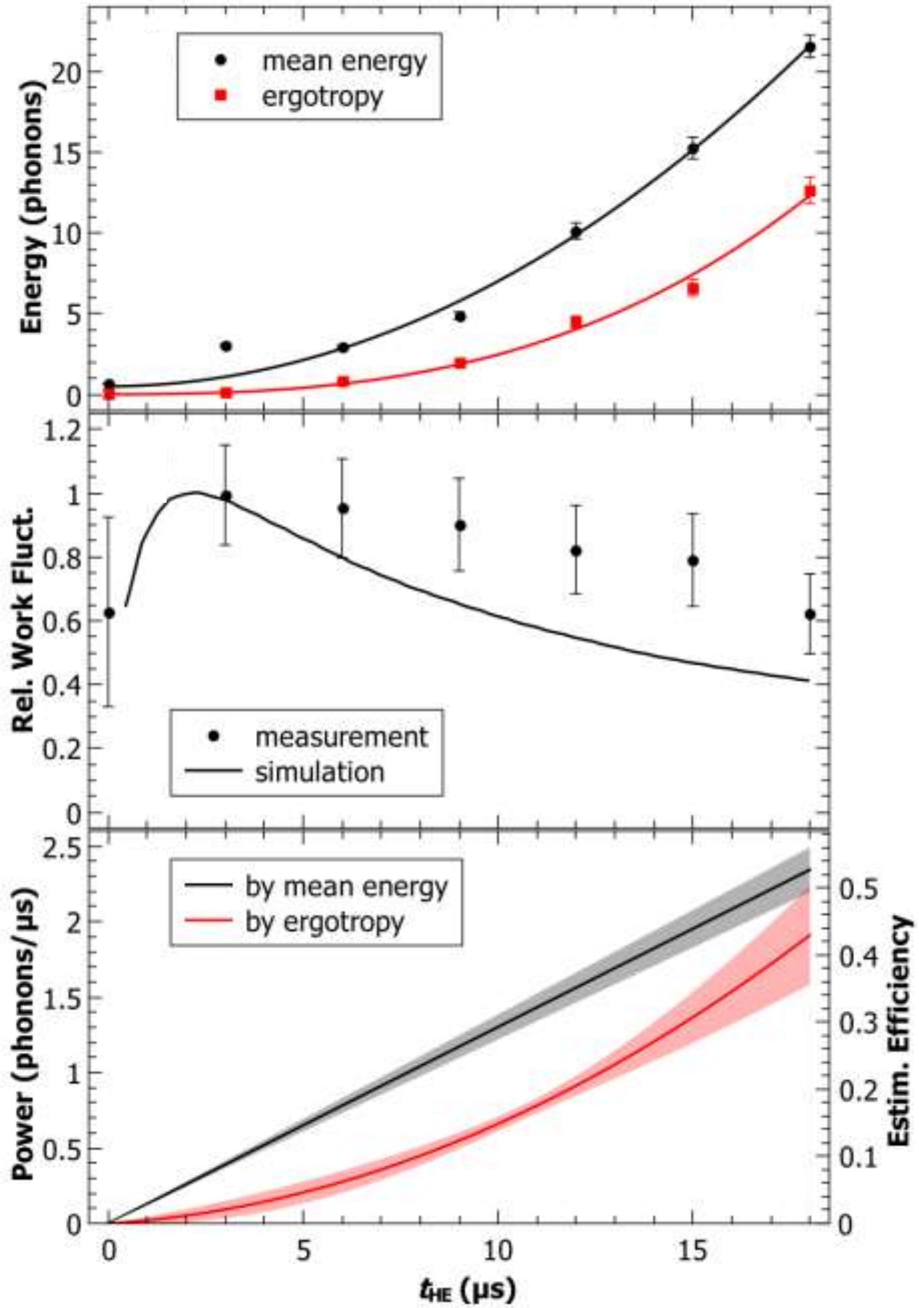
Poschinger et al,

Outcome

the Q-function

- Mean energy
- Coherent displacement
- Relative fluctuations
- Ergotropy

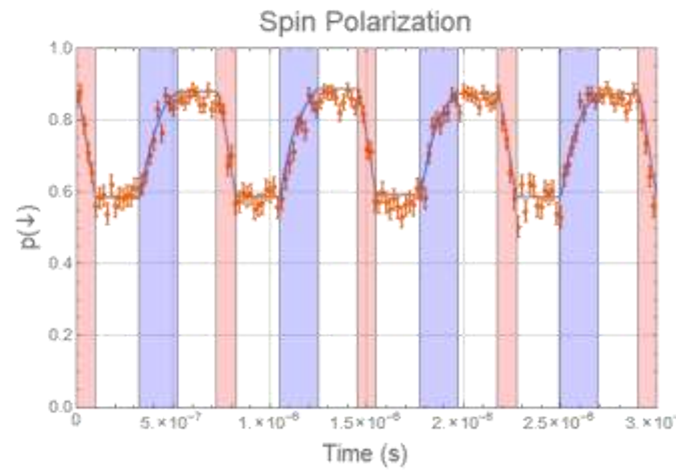
measured for the machine starting from n=0 after an operation time *t*



Poschinger et al,

Simple Model

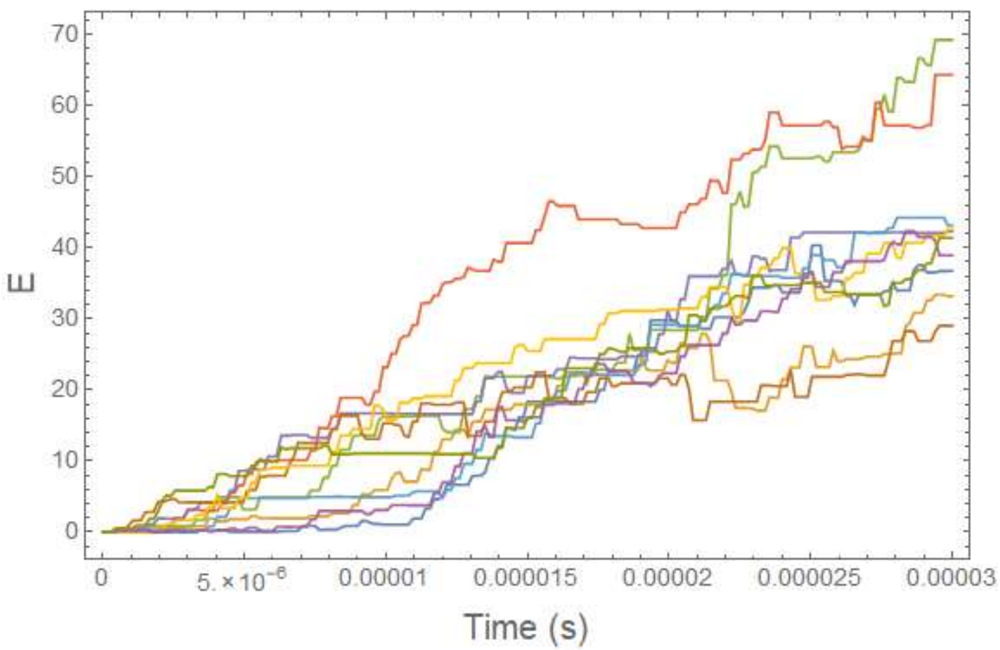
Spin polarization



Classical equation of motion:

$$m\ddot{x} = -\omega x^2 + \mathcal{S}(t)\Delta_S^{(0)} \sin(kx)$$

Numerically calculated trajectories

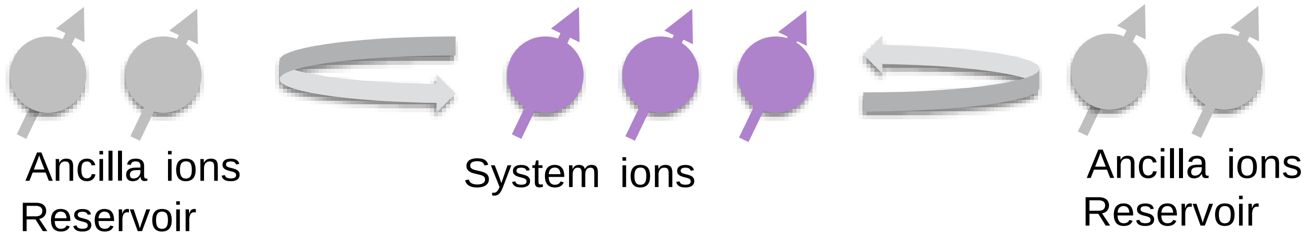


- Fluctuations between different realizations
- Width of calculated energy distribution fits data

Poschinger et al,

Goals:

- Autonomous machine operation



- 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

The team

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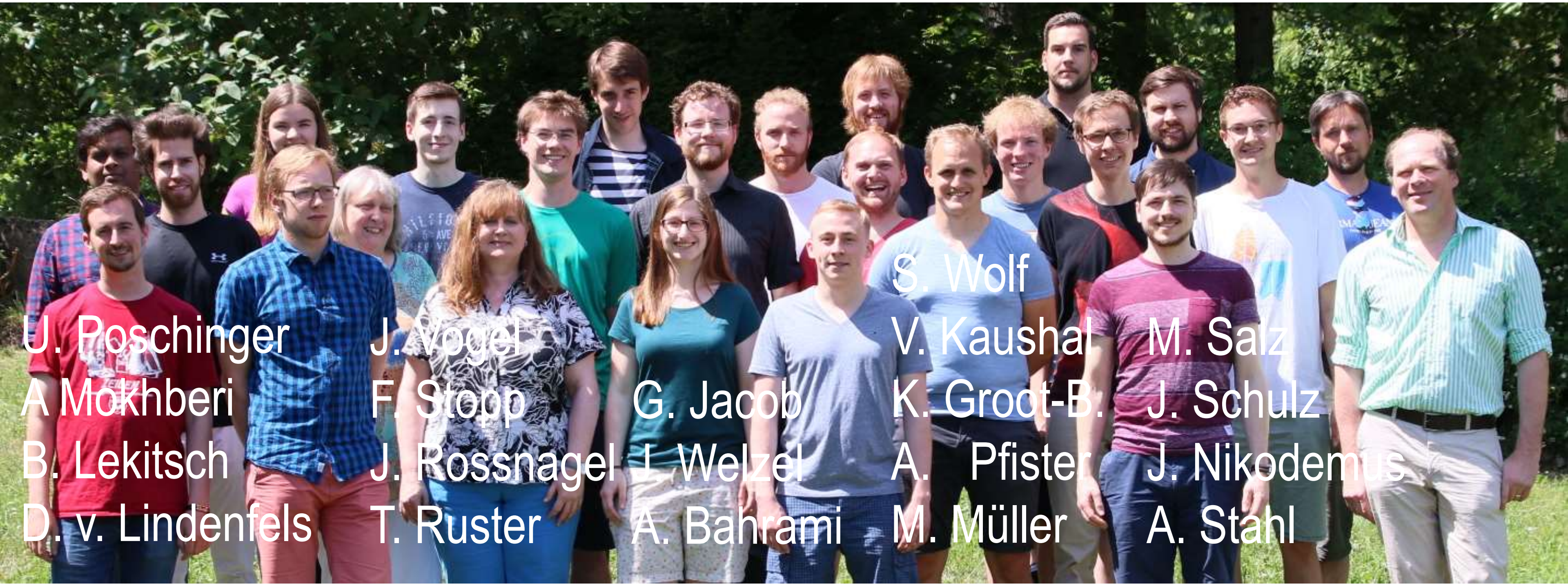

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