Working Group 3

Implementations: from classical to quantum thermodynamic experiments

Quantum Thermodynamics

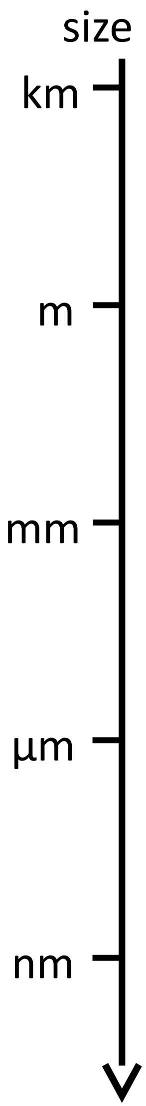
cost

Experimenters in mesoscopic electron systems, cold atoms, trapped ions and quantum optics, all share the common interest of understanding relaxation, thermalisation, non-equilibrium and general thermodynamic properties of their systems.

WG3 will aim to reconcile quantum information and thermodynamic techniques to test and explore thermodynamic and non-equilibrium relations at the classical-quantum boundary and into the quantum regime.

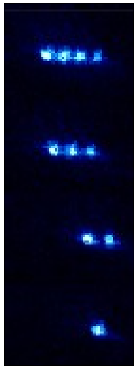
- WG3 from QUT-Website -

Road towards a Quantum Heat Engine

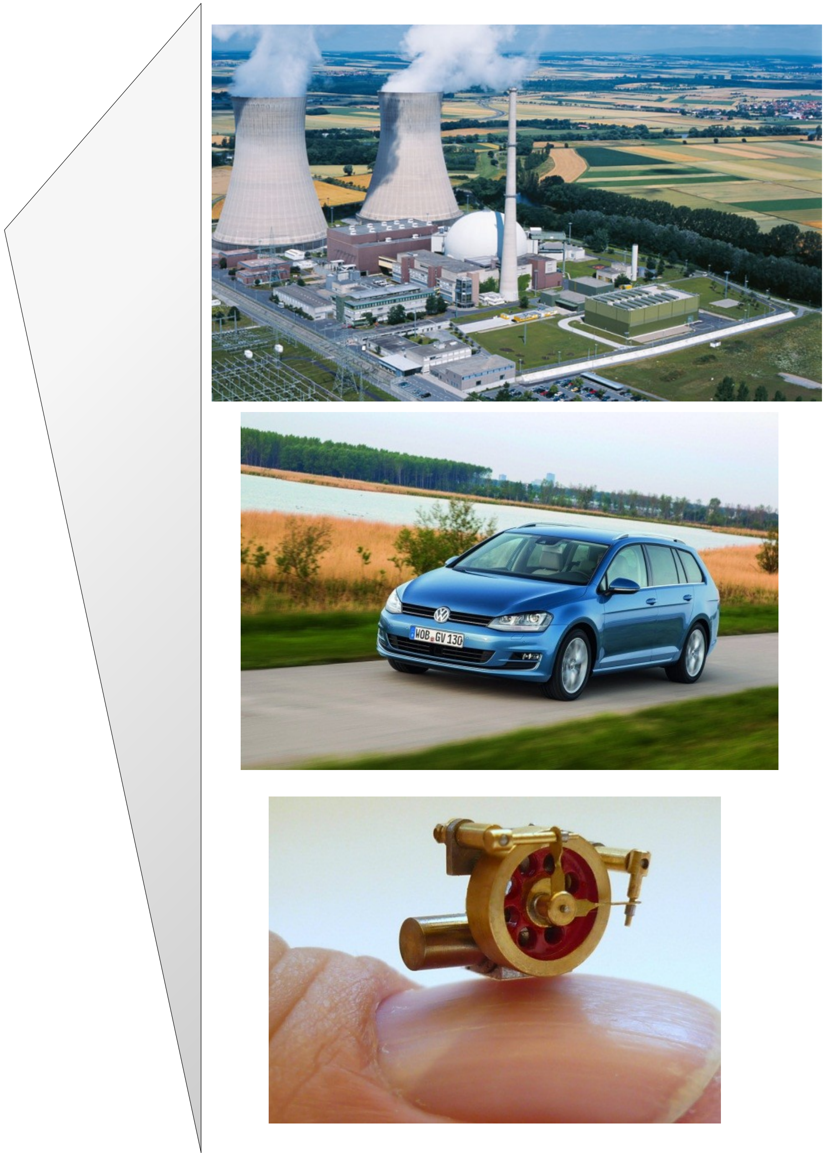


Large system:
Many degrees of freedom
and many particles

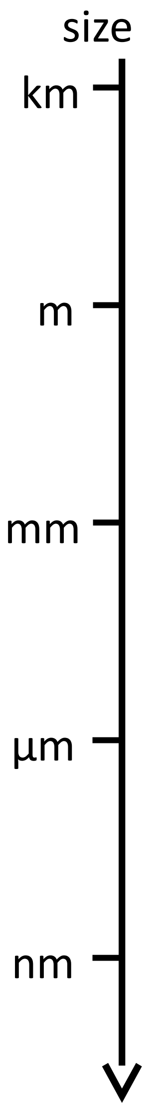
Small system:
few degrees of freedom
and single particles



Quantum system:
Quantized degrees of
freedom,
superpositions and
entanglement



Road towards a Quantum Heat Engine



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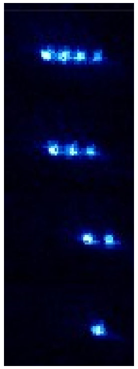

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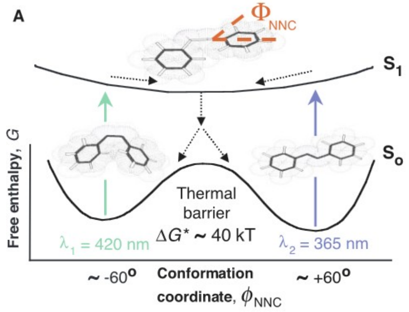
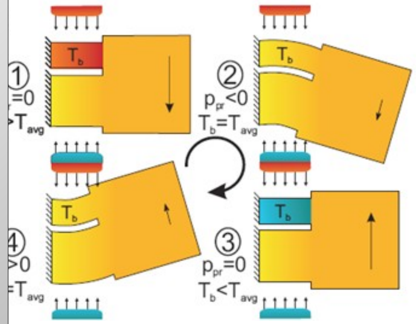


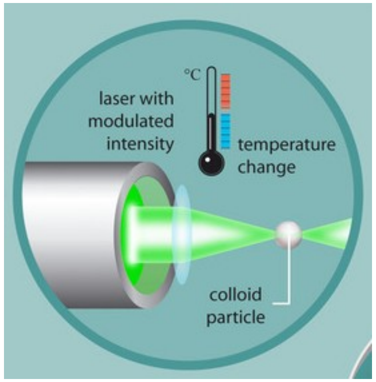
Molecular Machine

Hugel *et al*.,
Science **276** (2002)



Piezo-resistive machine

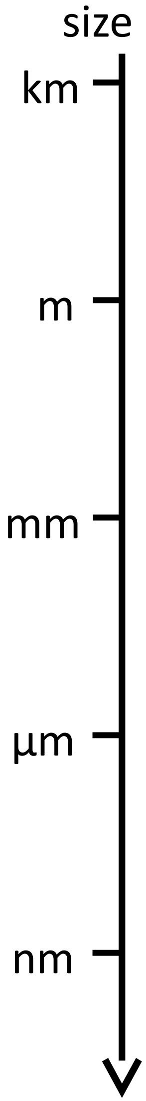
Steeneken *et al*.,
Nature Phys. **7** (2011)



Colloid-particles

Blickle *et al*.,
Nature Phys. **8** (2012)

Road towards a Quantum Heat Engine



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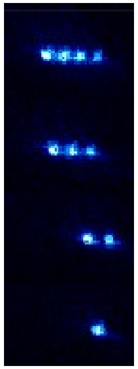


Quantum system:
Quantized degrees of freedom, superpositions and entanglement

- **MASER Heat Engine**
  Scovil, Schulz-DuBois, PRL (1959)
- **Three Level System**
  Geva, Kosloff, J.Chem.Phys (1996)
  Alicki, J. Phys. A (1979)
- **Cold Atoms**
  Fialko, Hallwood, PRL (2012)
- **Opto-mechanical machine**
  Zhang *et al*., PRA 90, 023819(2014)
- **Quantum dot engine**
  Esposito et al., *PRE 81, 041106*(2010)
- **Flux Qubit Engine**
  Niskanen et al., *PRB* 76,174523(2007)

Broad Spectrum of Approaches

Optomechanical System

Quantum Dots/Solid State

Trapped Ions

Cold
Atoms/BEC

Cicuit QED

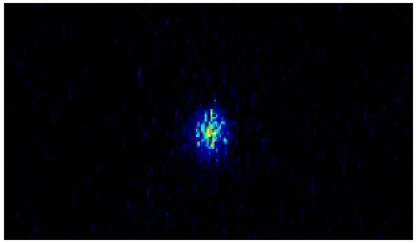
A Single Ion Heat Engine

classical

quantum

Single Ion Heat Engine

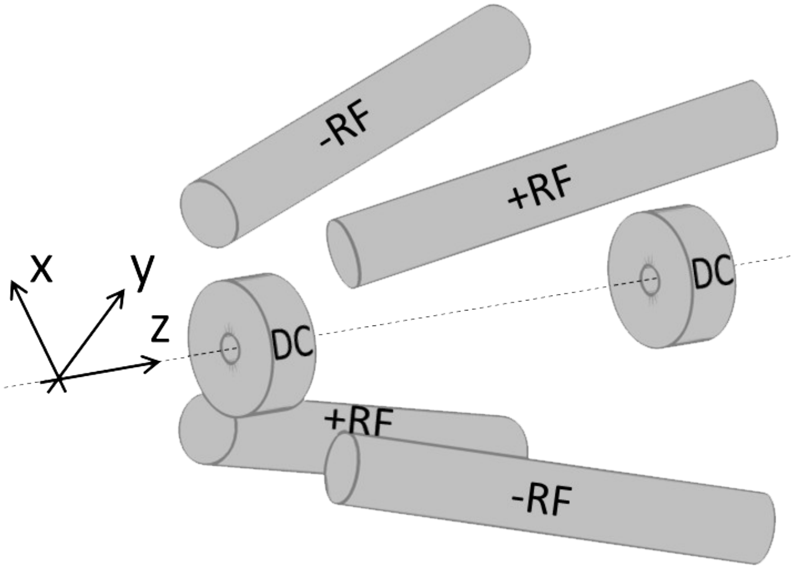
- Thermodynamics in the limit of single particles
- Single ion in a Paul trap as a model system:
  - Perfect harmonic oscillator / excellent preparation, manipulation and analysis
  - Coupling to reservoirs
  - Cooling to the ground state

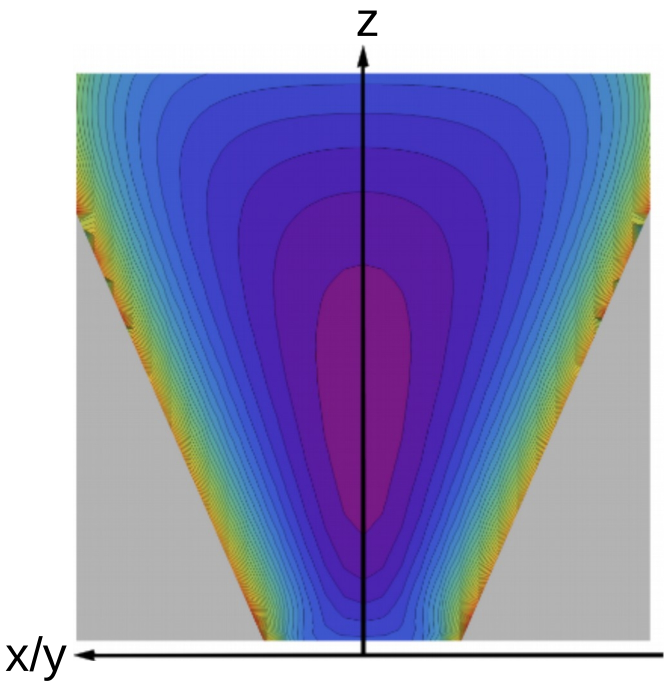


- **Implementation of engineered reservoirs**
  - Non-classical bath interaction
- **Potential to reach quantum regime**
  - Driving the engine with single phonons

Abah et al.,PRL 109,203006 (2012)

The Tapered Paul Trap

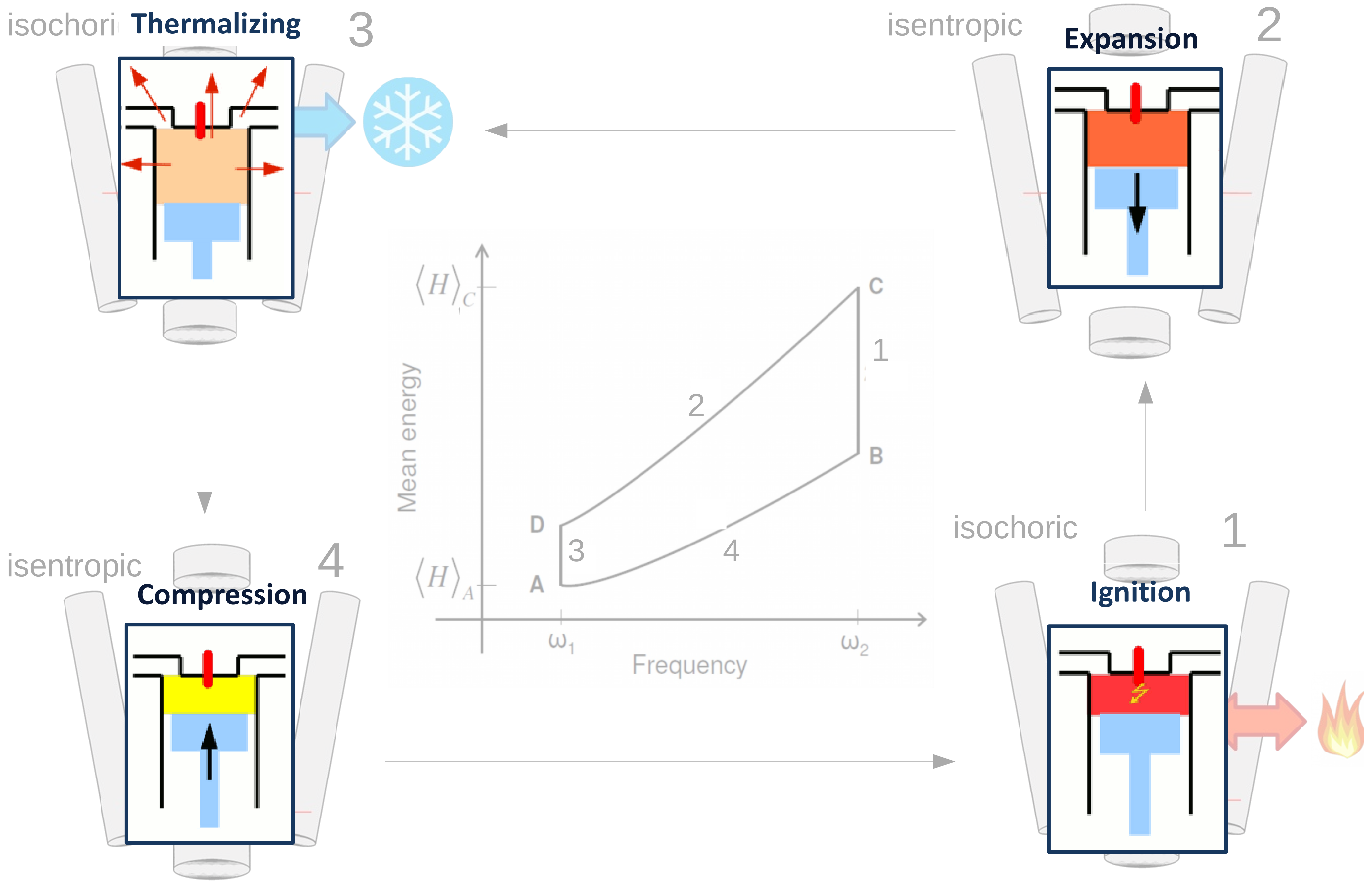




$$\omega_{x,y} \rightarrow \omega_{x,y}(z)$$

$$H = \sum_{i\in\{x,y,z\}} \hbar\omega_{0i}\left(a_i^{\dagger}a_i + \frac{1}{2}\right) - C\cdot\hat{z}\,(\omega_{0x}^2\hat{x}^2 + \omega_{0y}^2\hat{y}^2) \qquad C = \frac{2m\tan\theta}{r_0}$$

Working Principle



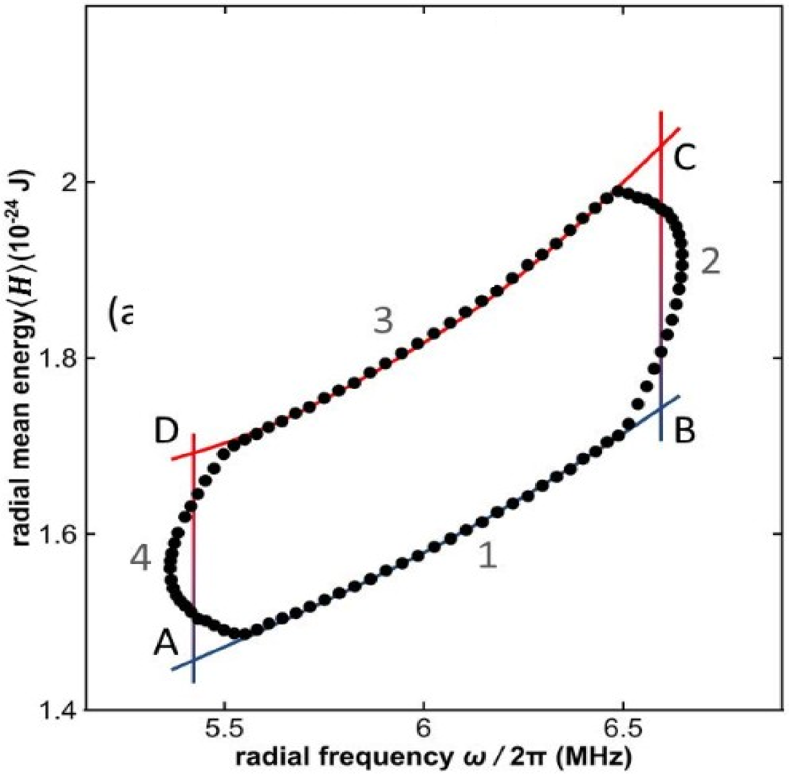
isochori **Thermalizing** 3

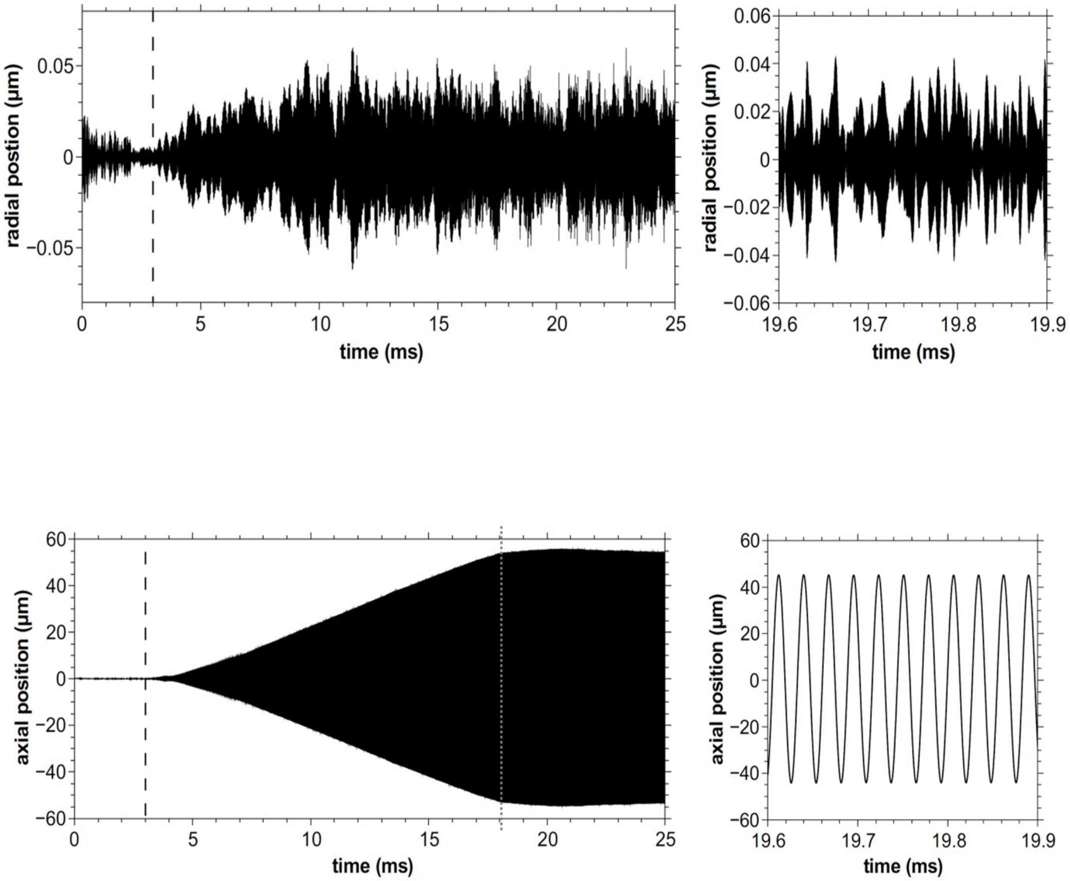
isentropic **Expansion** 2

isochoric **Ignition** 1

isentropic **Compression** 4

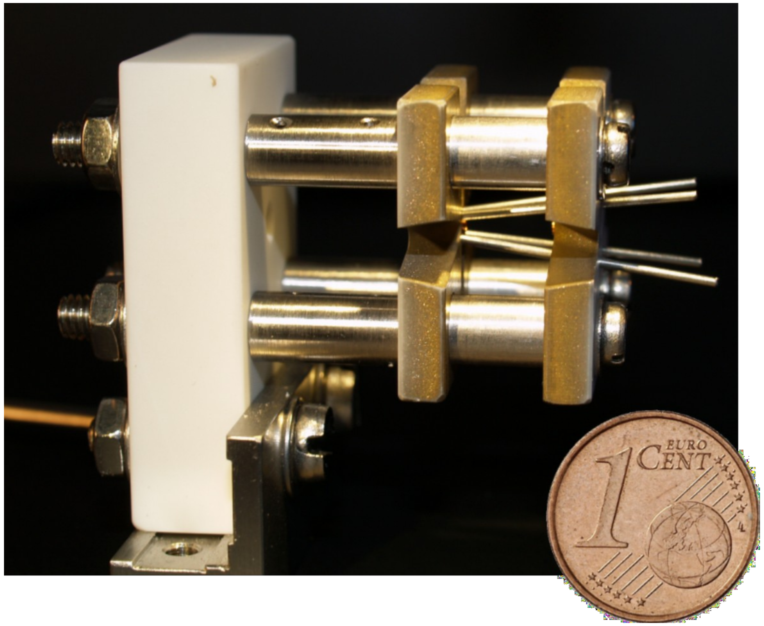
Simulating the Heat Engine



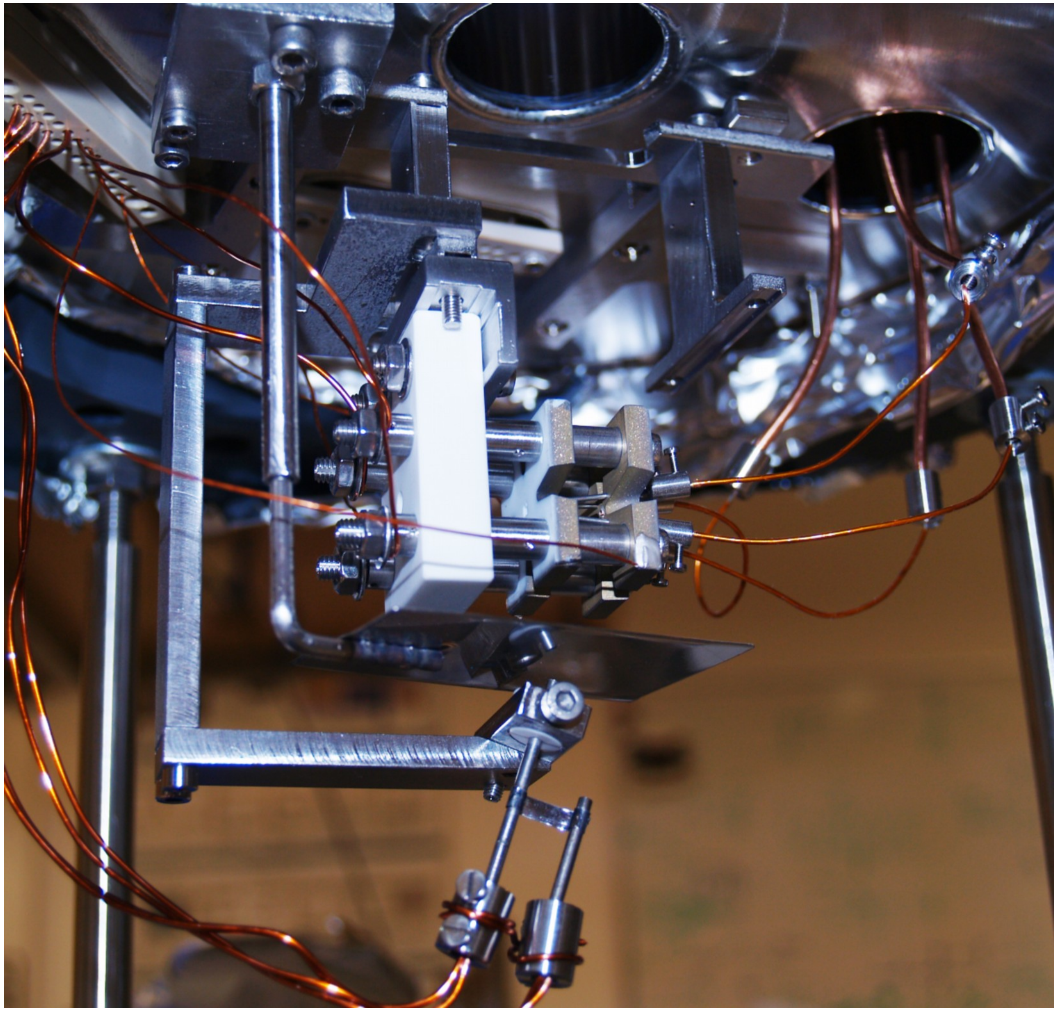


Abah et al.,PRL 109,203006 (2012)

Experimental Setup



Distance ion – endcaps: 4mm
Distance ion – electrodes: 1.5mm
RF driving: 800Vpp at 21 MHz
Axial trap frequency: 30…300 kHz
Radial trap frequency: 400…1000 kHz



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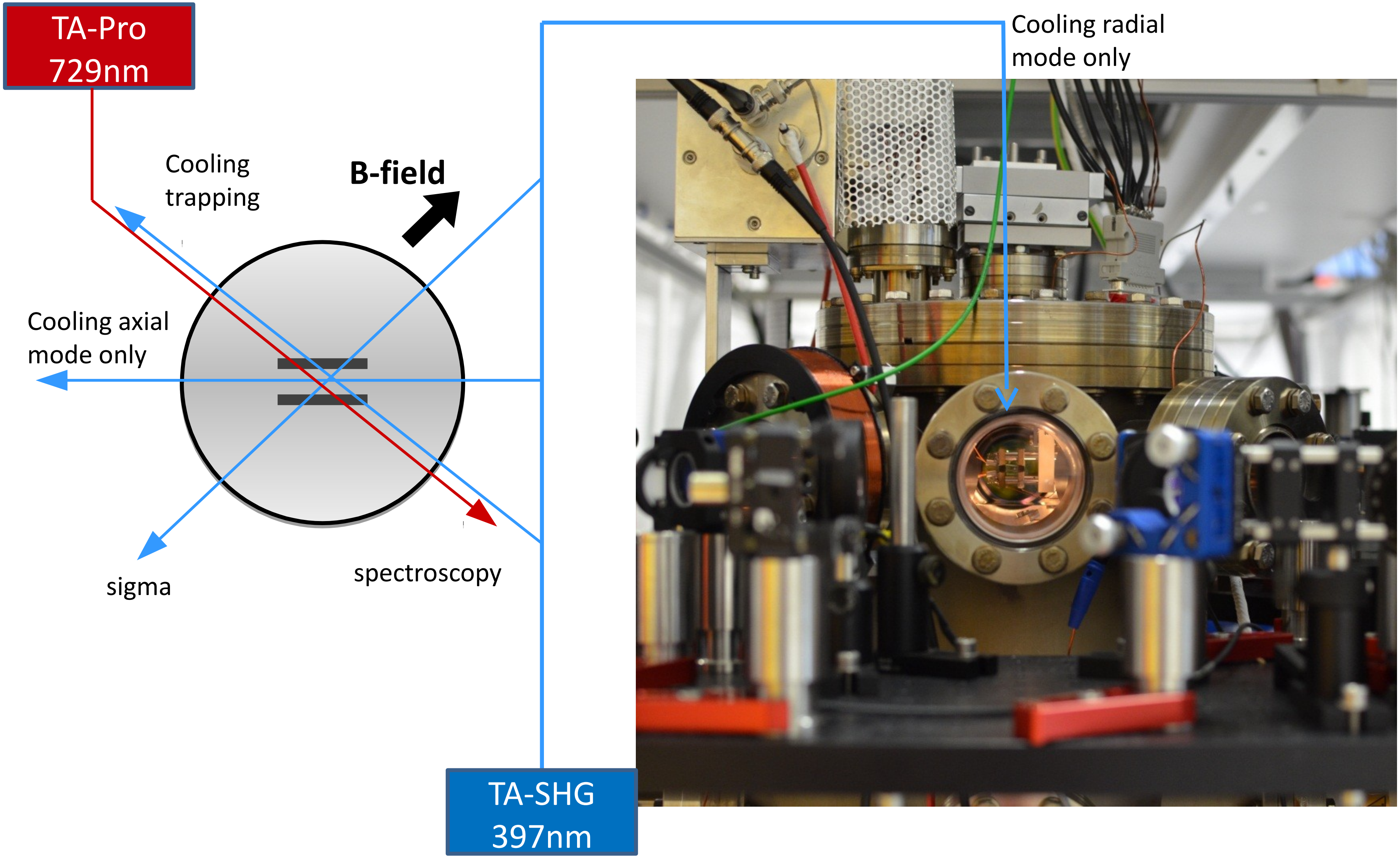


TA-Pro
729nm

Cooling
trapping

B-field

Cooling radial
mode only

Cooling axial
mode only

sigma

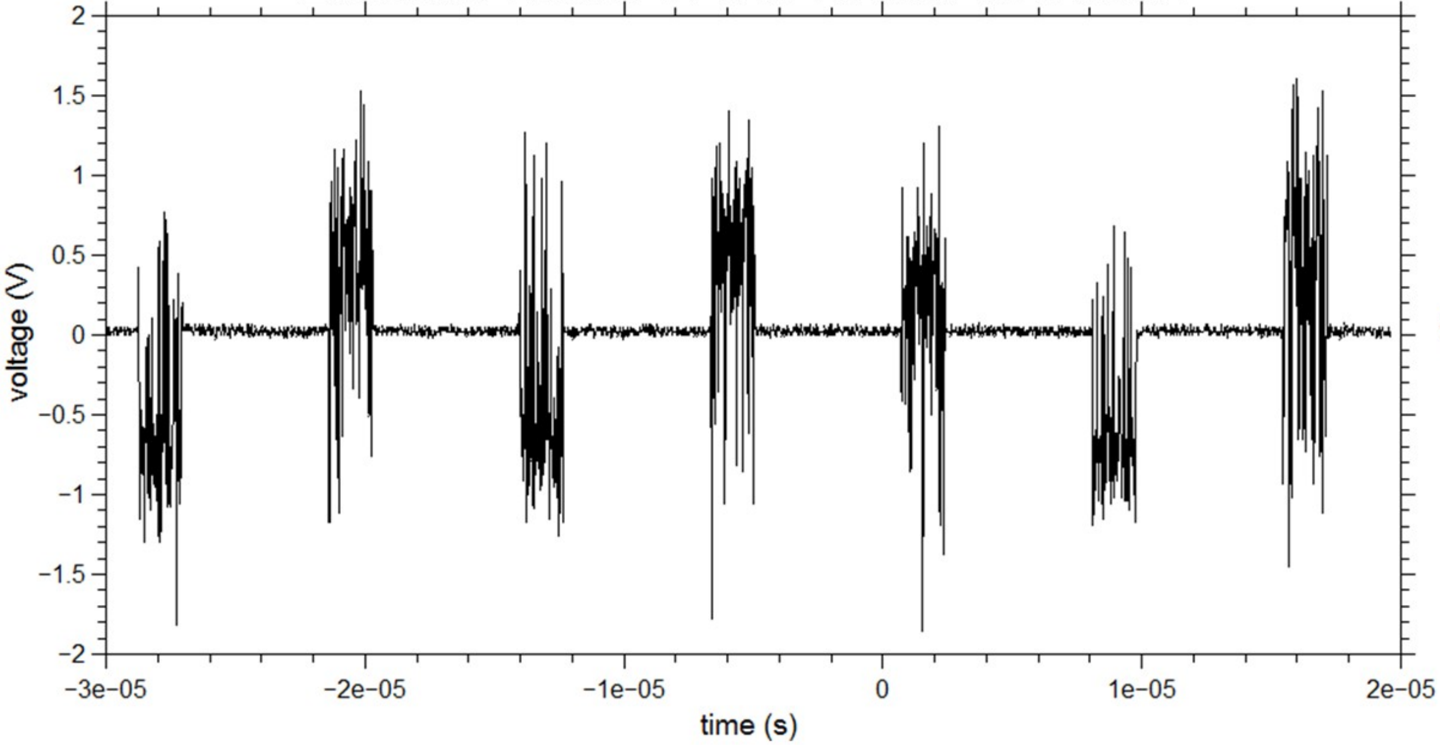
spectroscopy

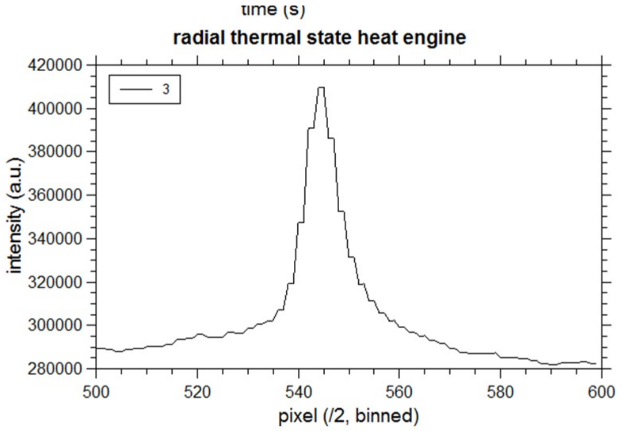
TA-SHG
397nm

Radial Thermal Excitation

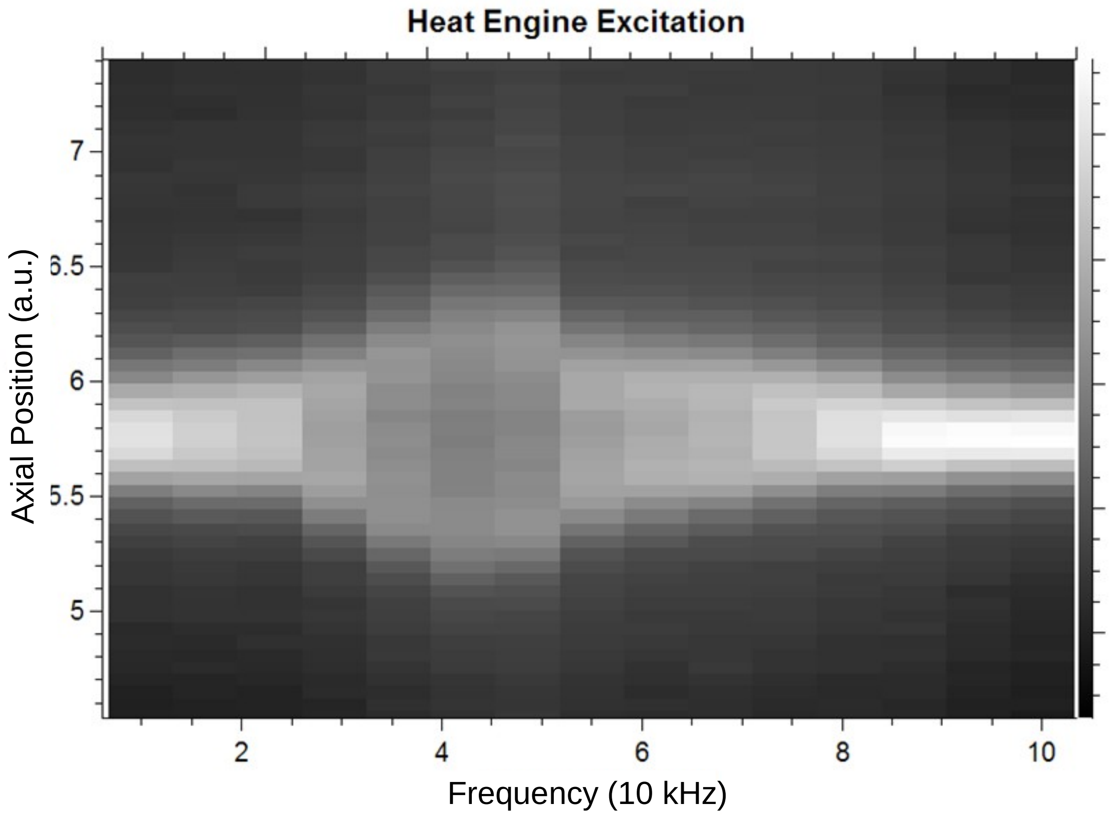
Continuous laser cooling ↔ ❄

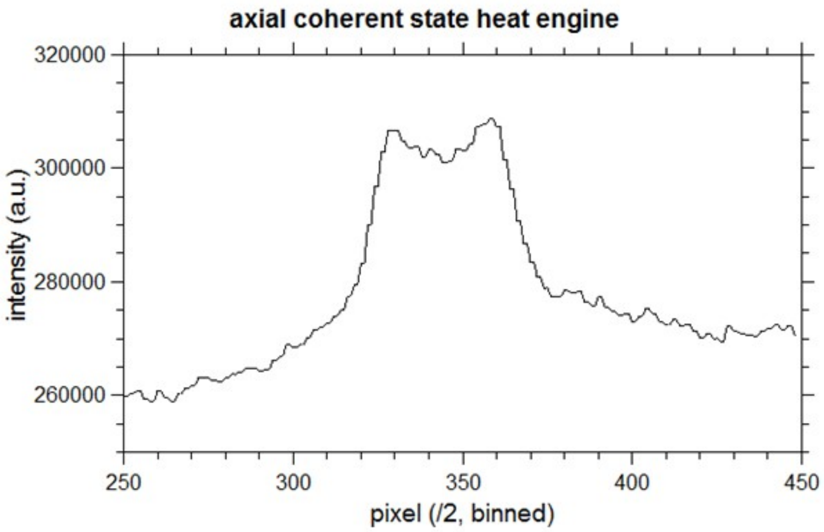
Electric noise in the radial direction ↔ 🔥





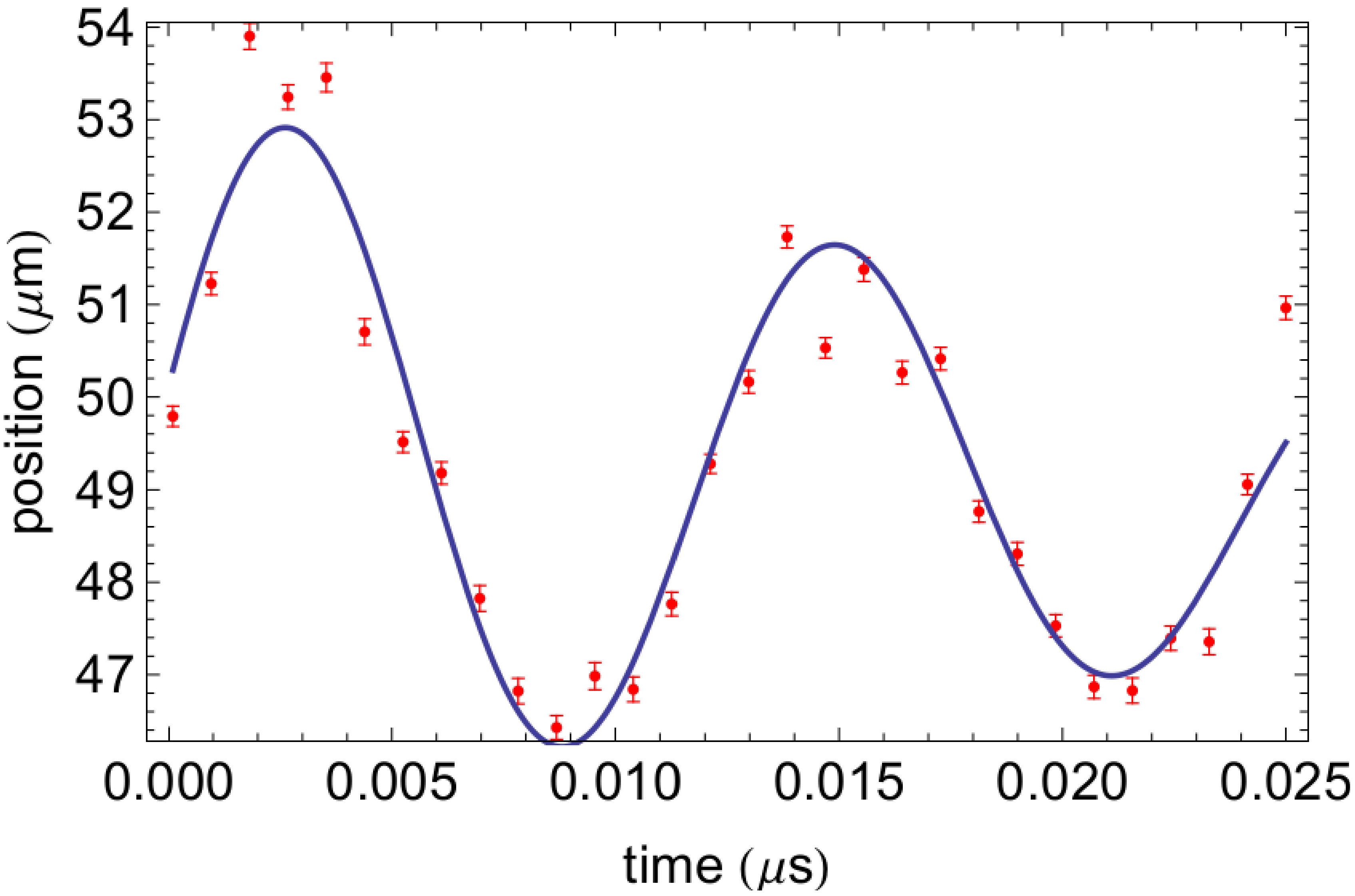
First Results





Preliminary Results

First Results



Preliminary Results

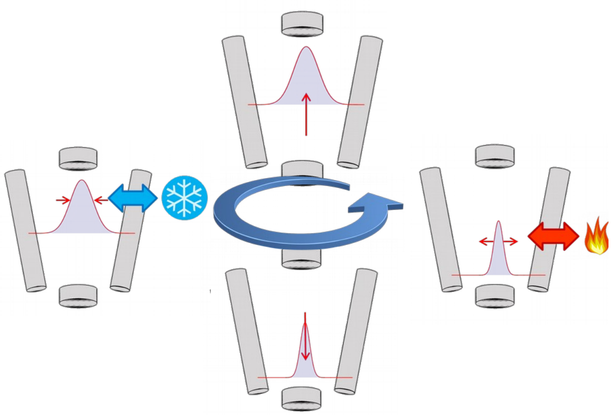
First Results

Princeton Instruments ICCD:
8 ns gate time
10 MHz frame rate

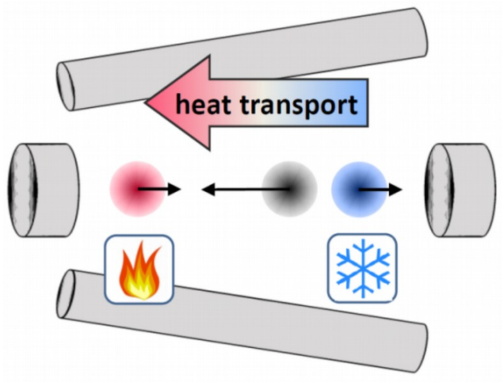
Preliminary Results

Plans for the Future

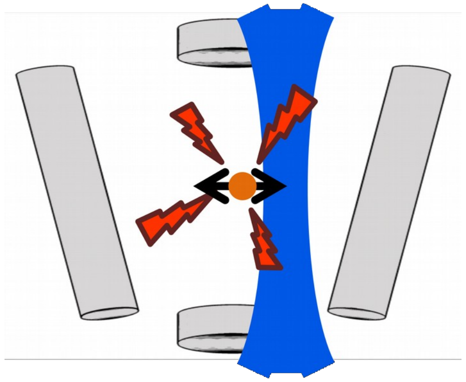
Fully working Heat Engine



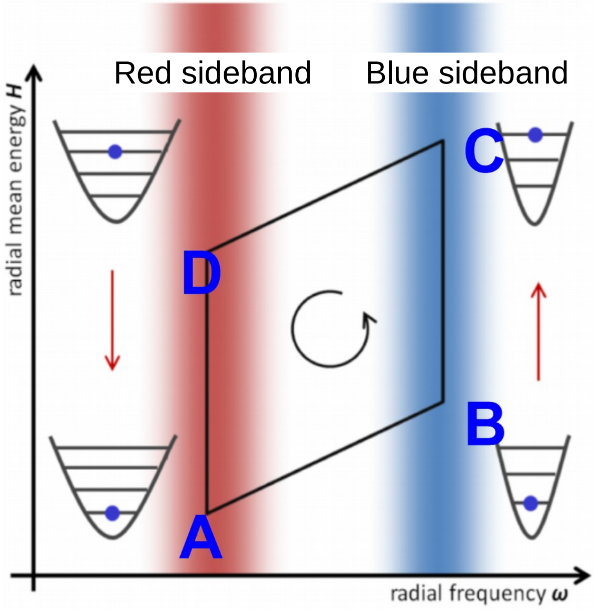
Heat Pump/Refrigerator



Autonomous Heat Engine



Quantum Heat Engine



Broad Spectrum of Approaches

Optomechanical System

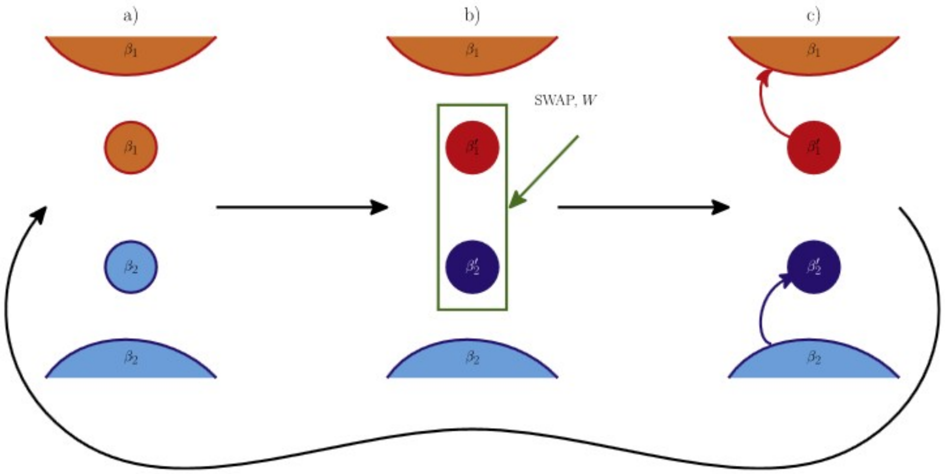
Quantum Dots/Solid State

Trapped Ions

Cicuit QED

Cold
Atoms/BEC

The Swap Engine

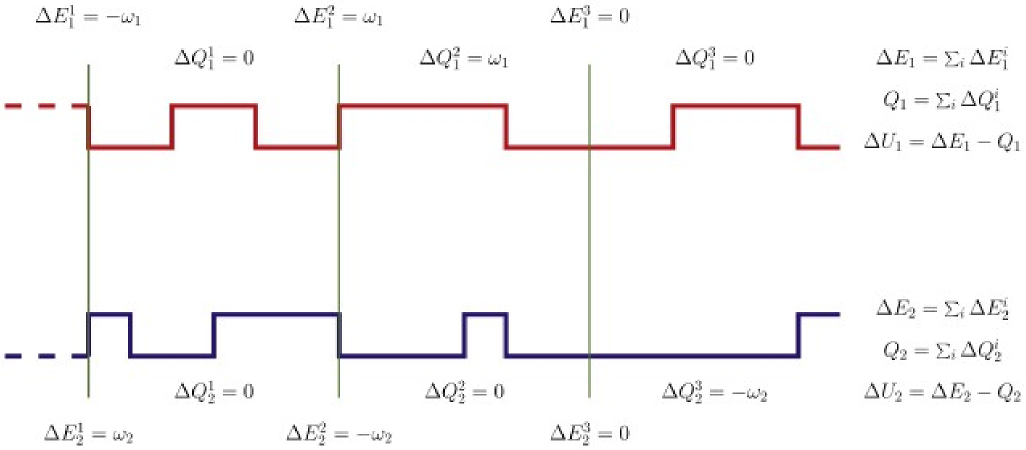


HEAT ENGINE: $\frac{\beta_1}{\beta_2} < \frac{\omega_2}{\omega_1} < 1$

REFRIGERATOR: $0 < \frac{\omega_2}{\omega_1} < \frac{\beta_1}{\beta_2}$

$$\beta_1' = \beta_2 \omega_2 / \omega_1$$

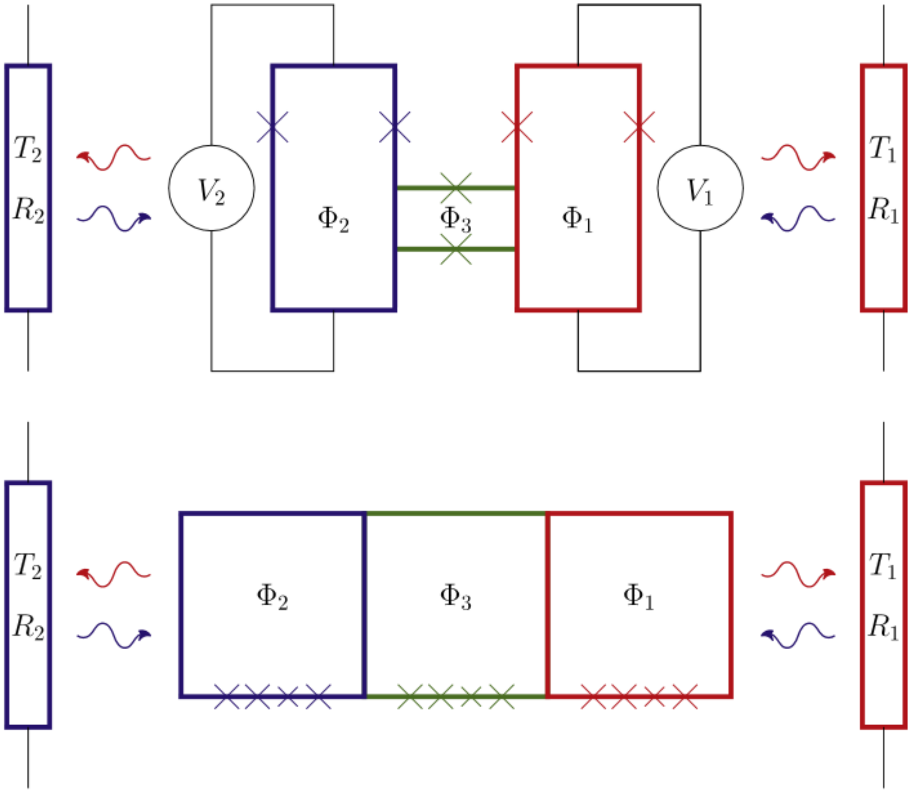
$$\beta_2' = \beta_1 \omega_1 / \omega_2$$



Campisi et al., NJP 17,035012(2015)

Uzdin et al., NJP 16,095003(2014)

The Swap Engine



Niskanen et al., PRB 76,174523(2007)

Campisi et al., NJP 17,035012(2015)

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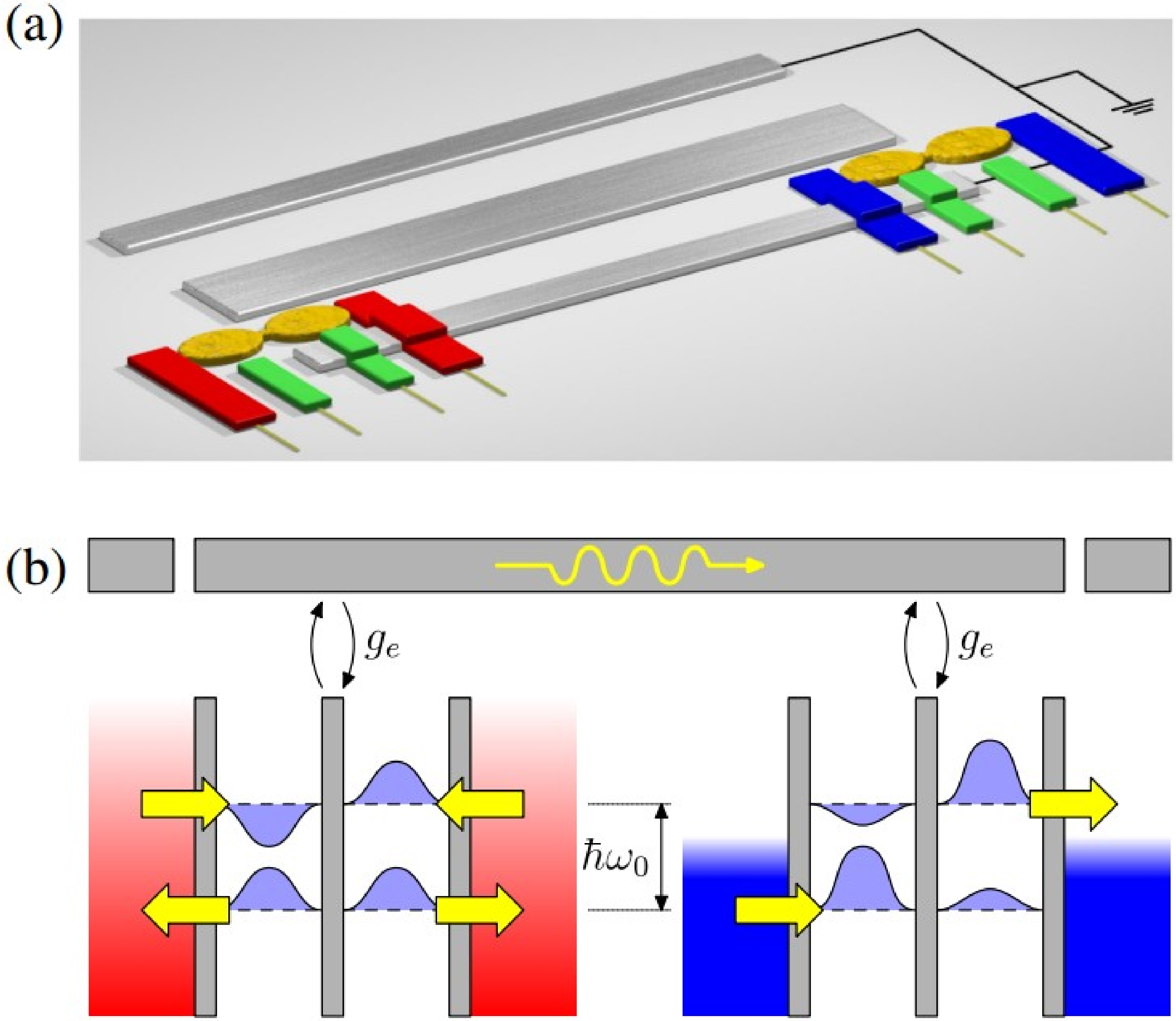
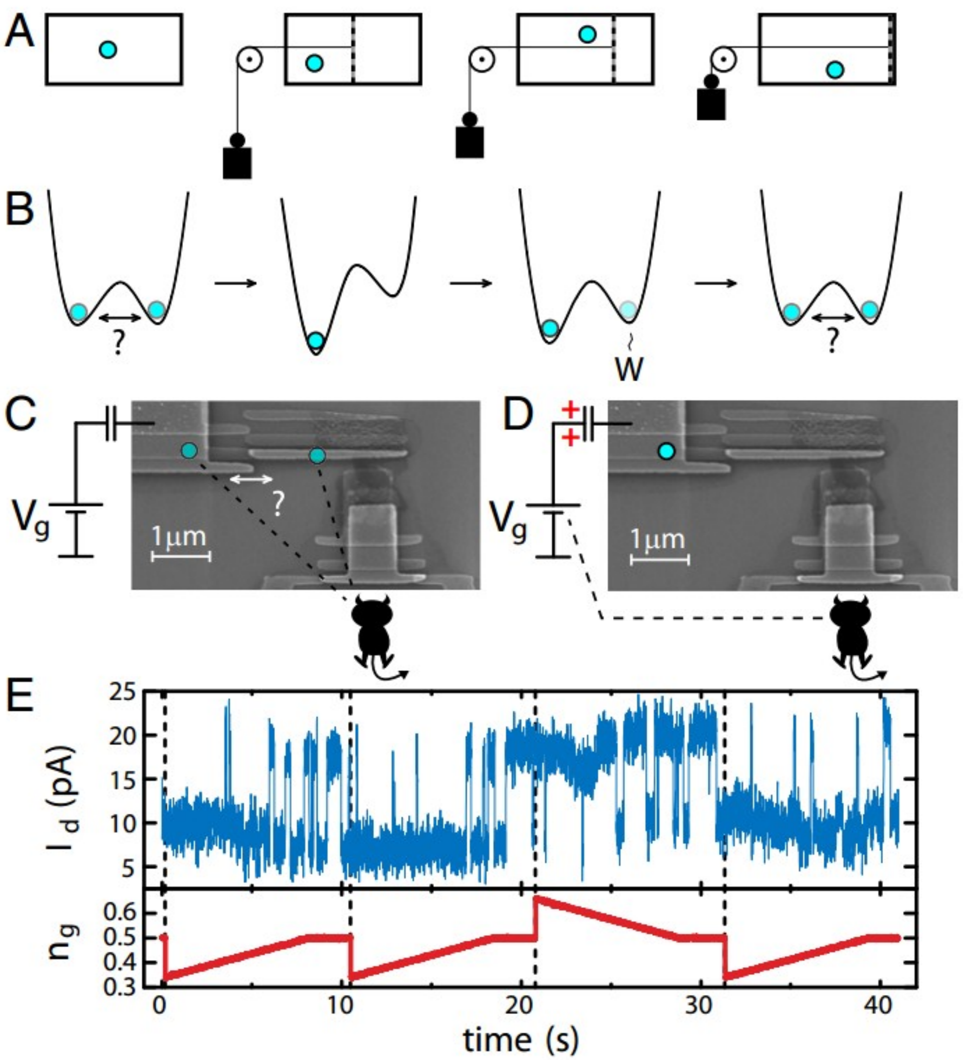
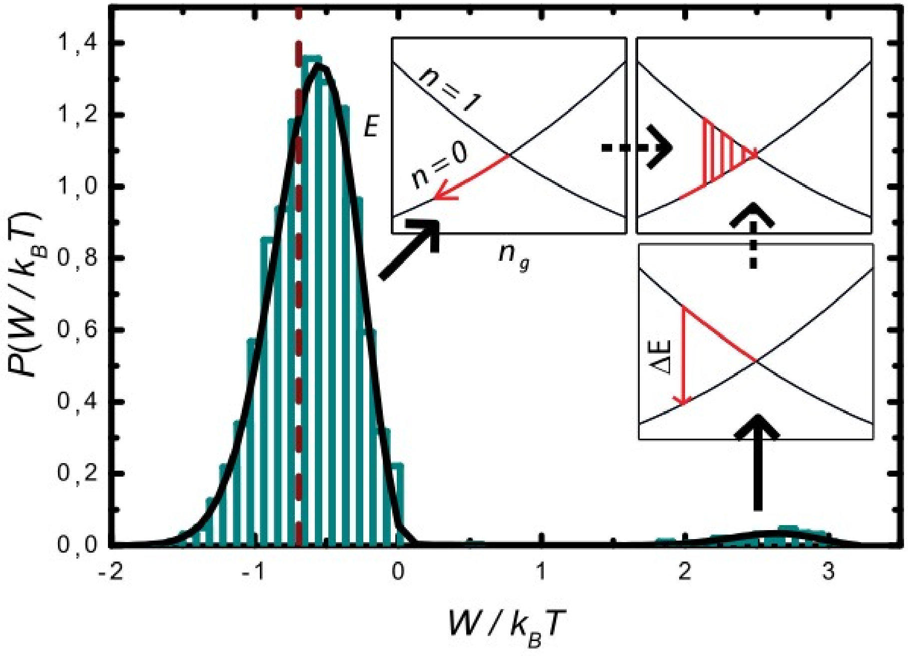
Quantum Dot Heat Engine



Bergenfeldt et al., PRL 112,076803 (2014)

Single Electron Szilard Engine





Koski et al., PNAS 111,38(2014)

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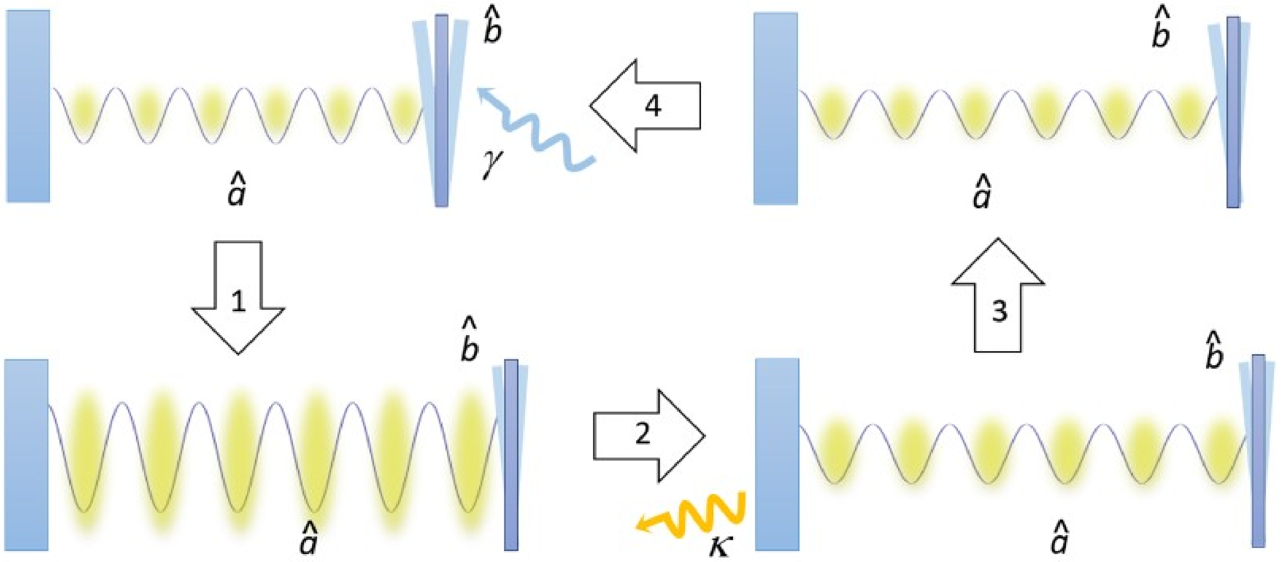
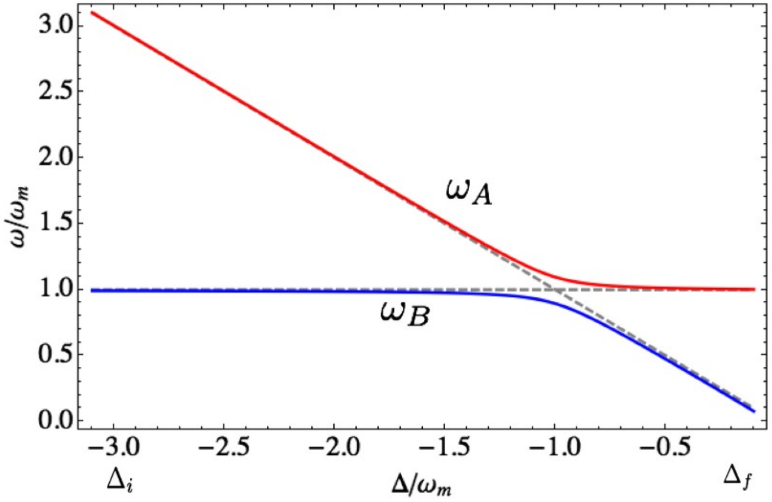
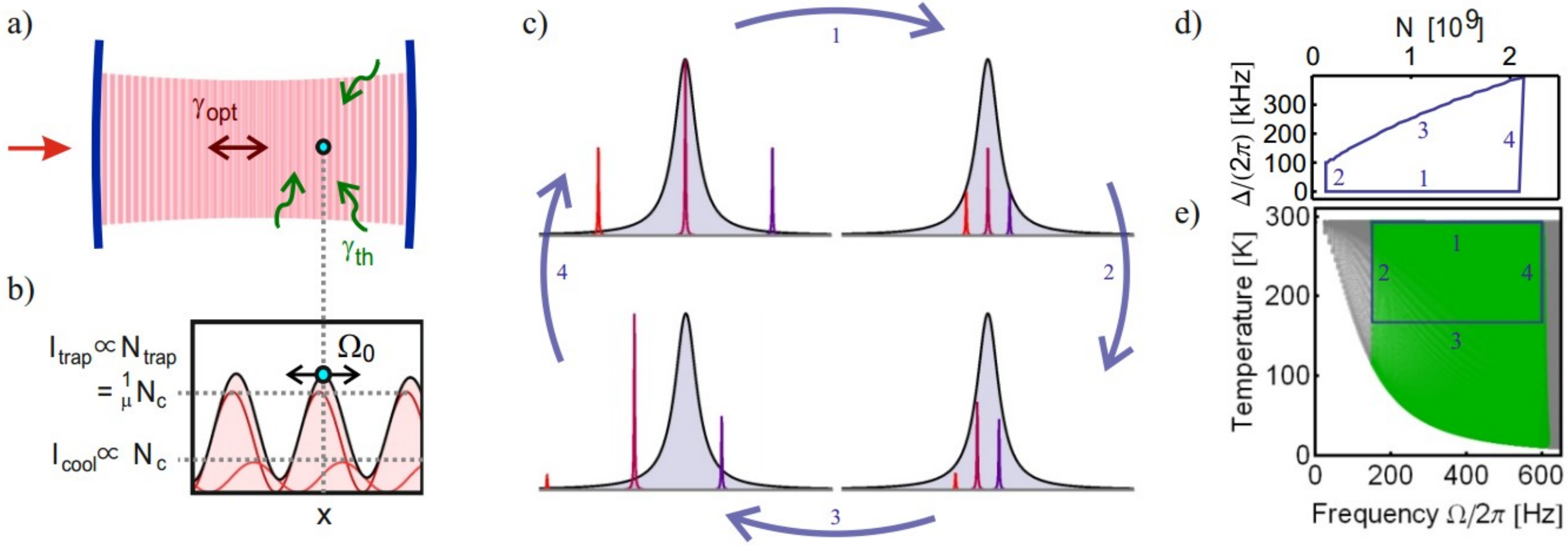
Optomechanical Heat Engine





Zhang et al., PRL 112,150602(2014)

Optomechanical Heat Engine



Dechant et al., arXiv 1408.4617v1(2014)

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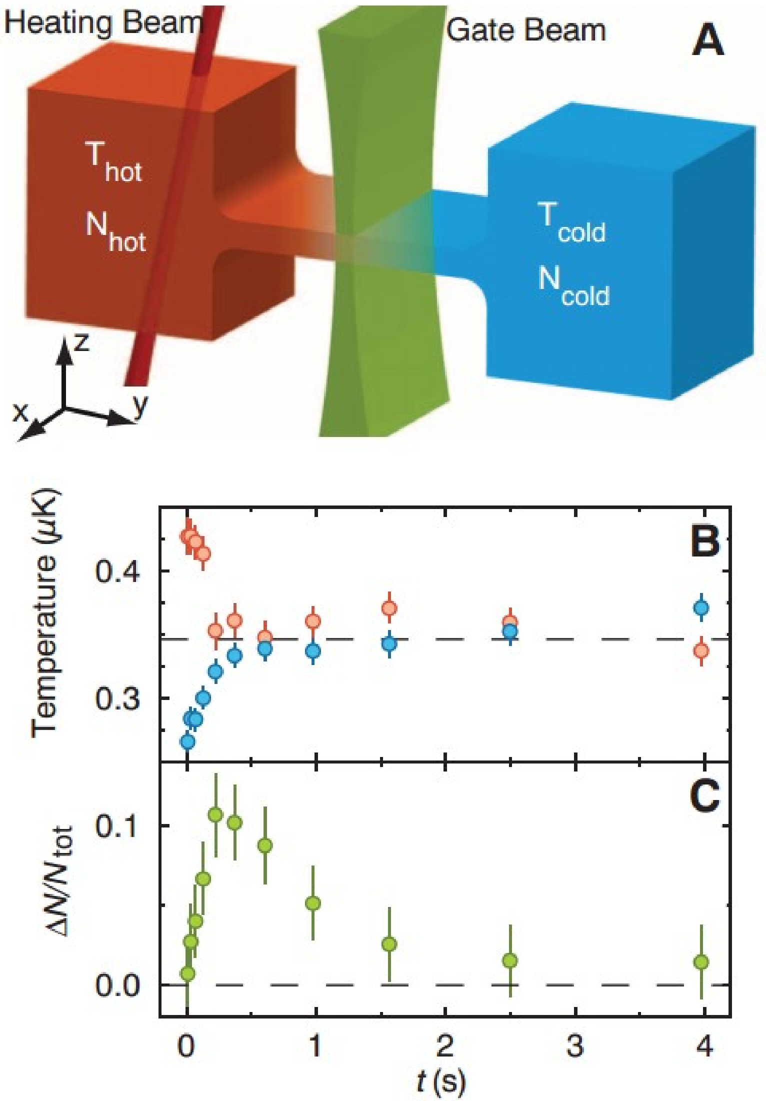
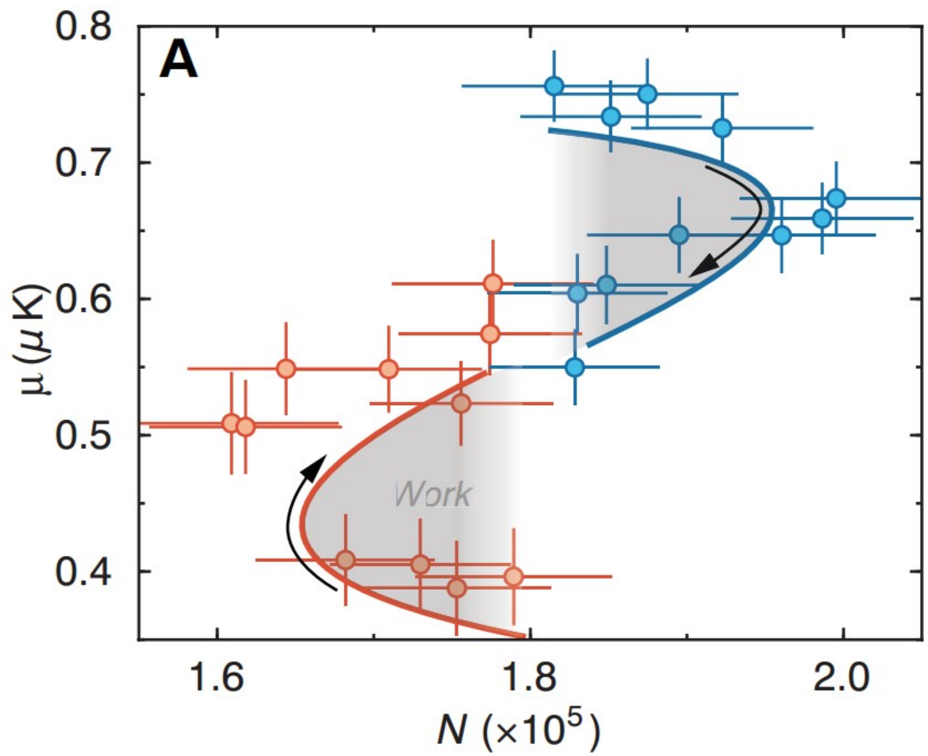
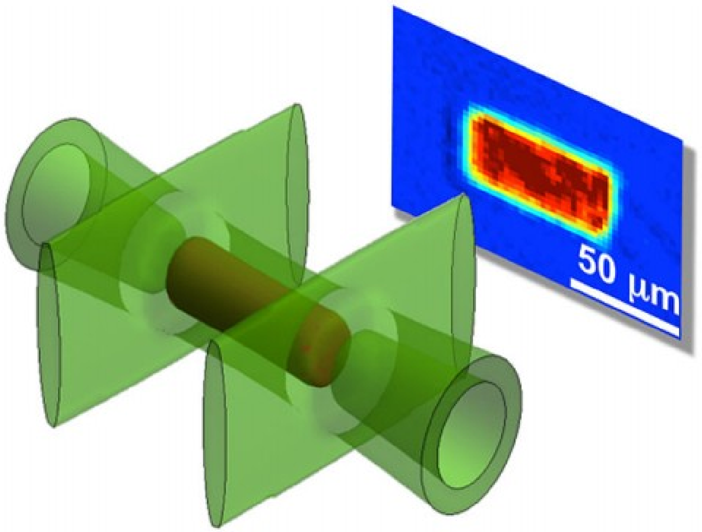
Thermoelectric HE with ultracold Atoms

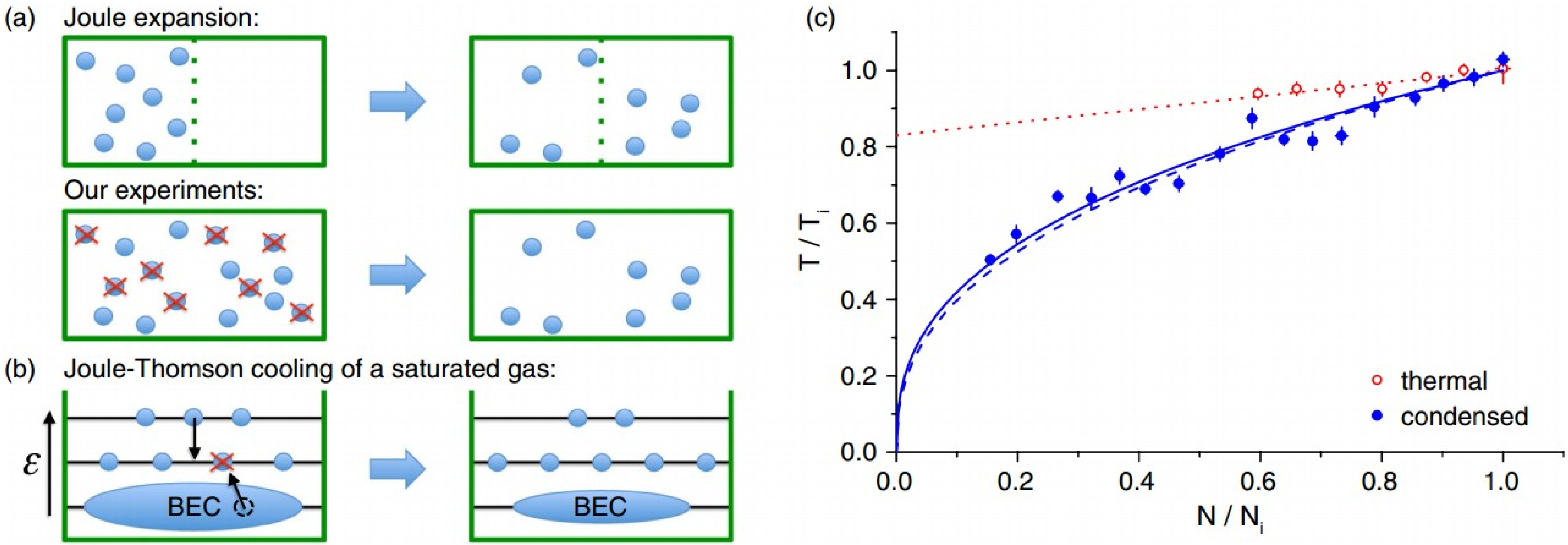




Brantut et al., Science 342 (2013)

Joule-Thompson Effect





Schmidutz et al., PRL 112,040403 (2014)

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Cicuit QED