Quantum absorption refrigerator with trapped ions

Dzmitry Matsukevich

Centre for Quantum Technologies
National University of Singapore

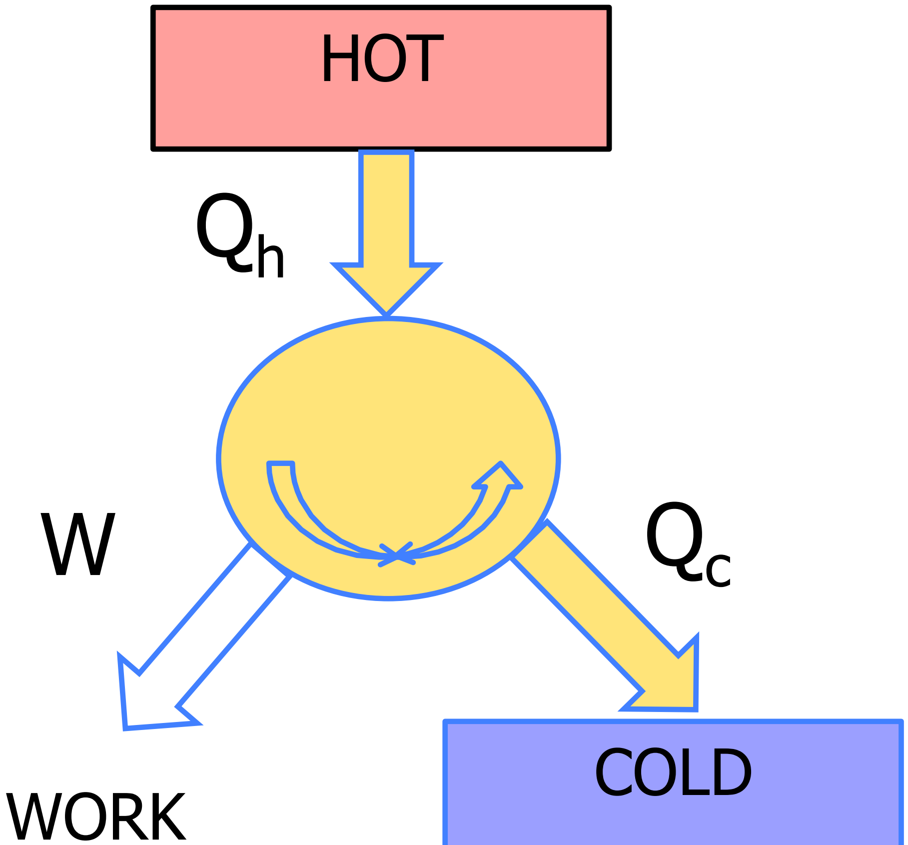
2018, KITP, UC Santa Barbara

Centre for Quantum Technologies

NUS National University of Singapore

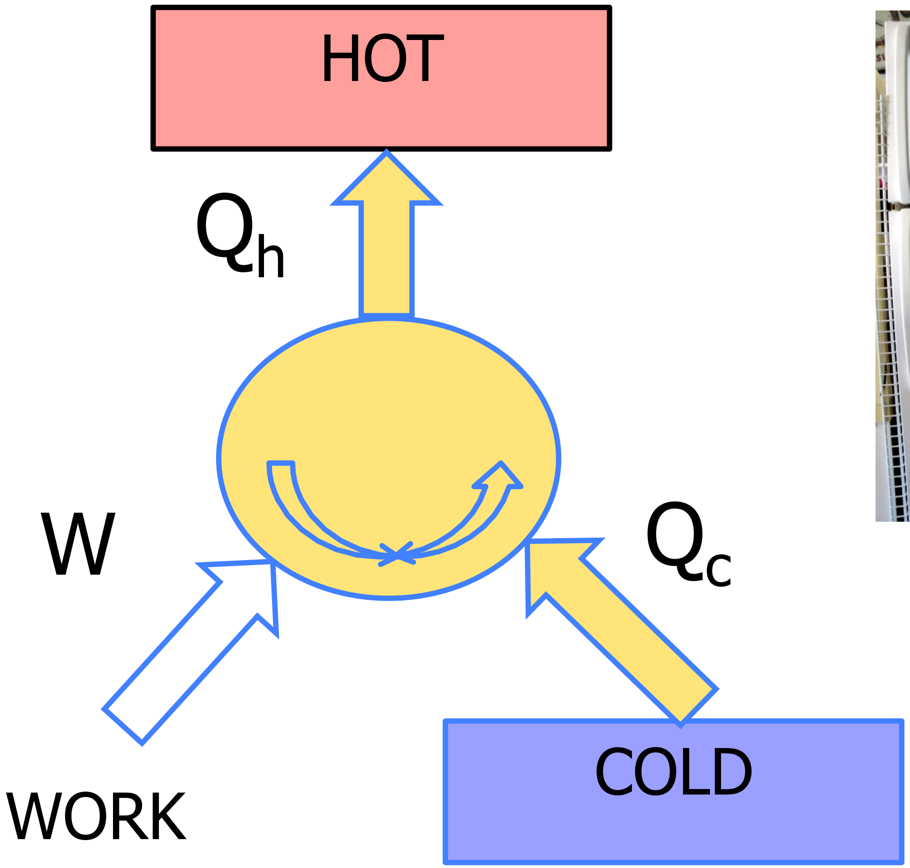
Types of heat machines: Engine

Engine: Uses heat to produce work



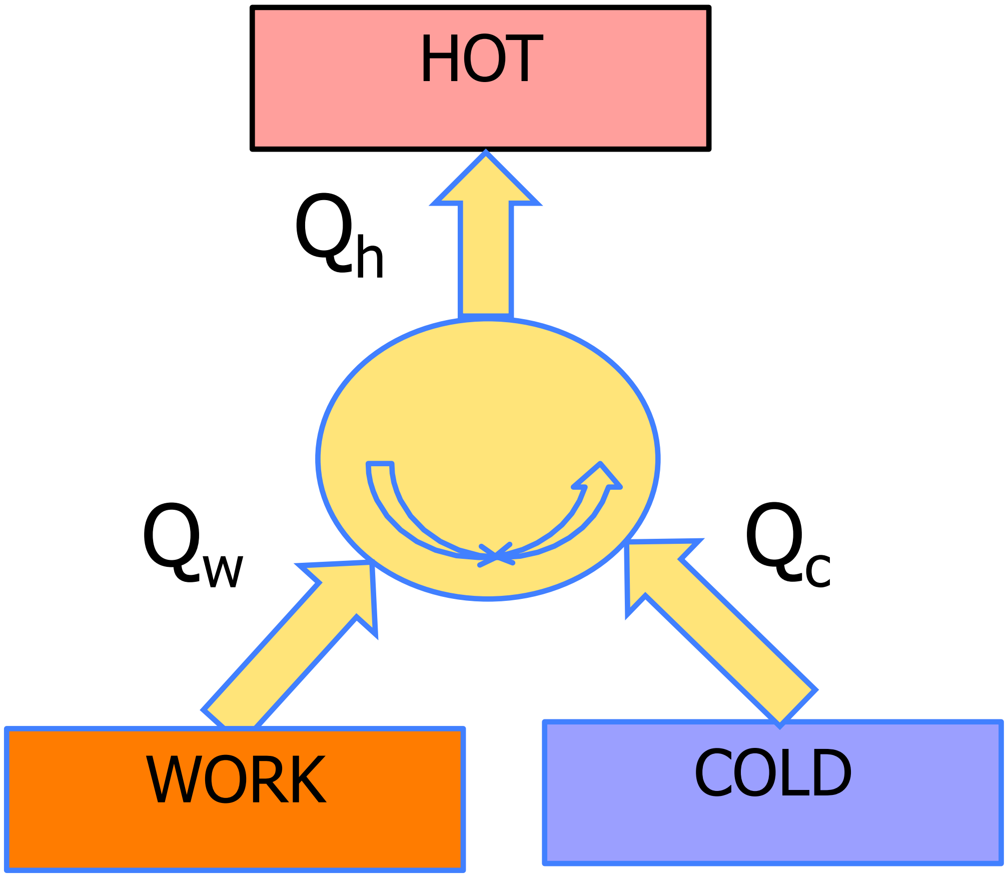
Types of heat machines: Refrigerator

Refrigerator: Uses work to refrigerate cold body



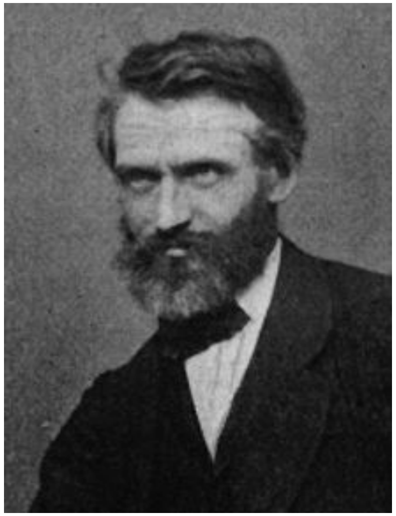
Absorption Refrigerator

Absorption Refrigerator: Driven by heat instead of work



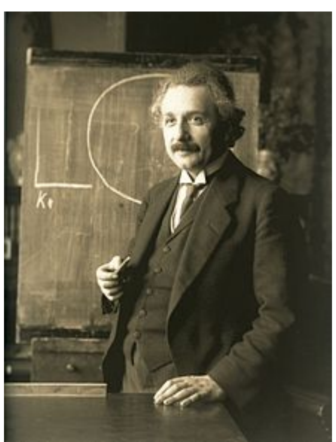
$T_w > T_h > T_c$

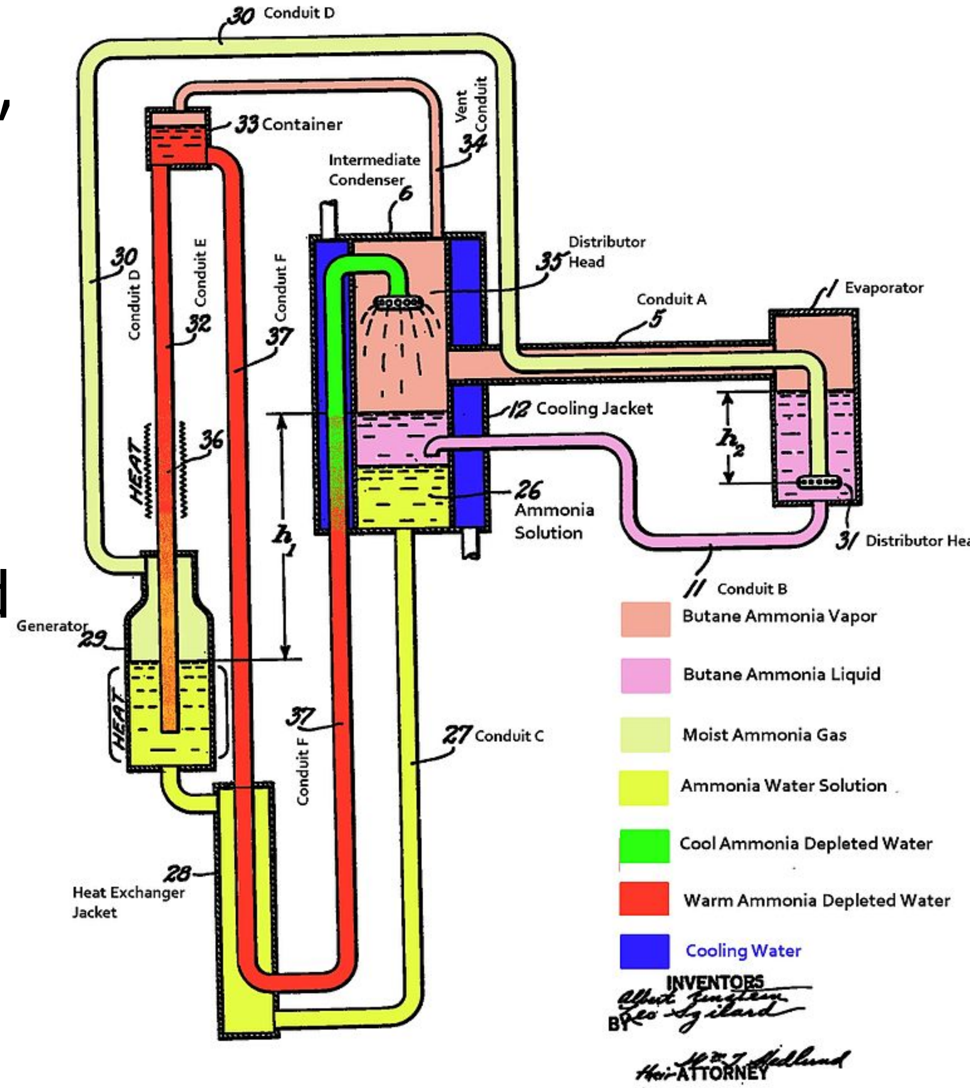
Absorption Refrigerator



Invented by:
Ferdinand Carre,
US Patent
30,201 (1860)

Improved design:
Albert Einstein and Leó Szilárd
US Patent 1,781,541 (1930)



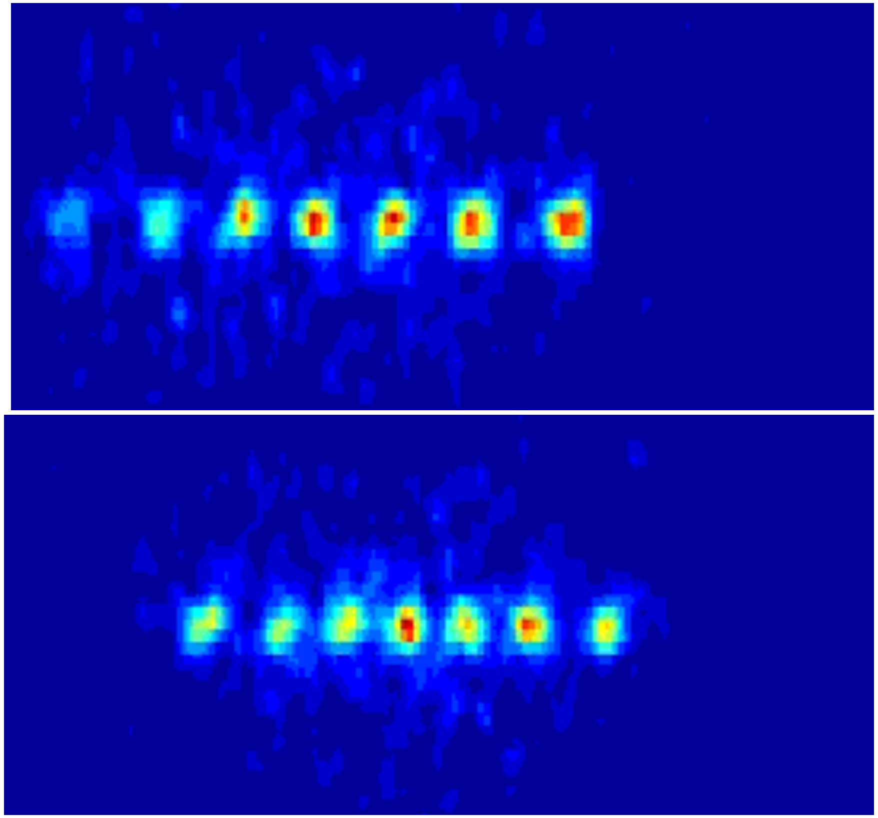


Quantum absorption refrigerator

What is the smallest refrigerator one can build?

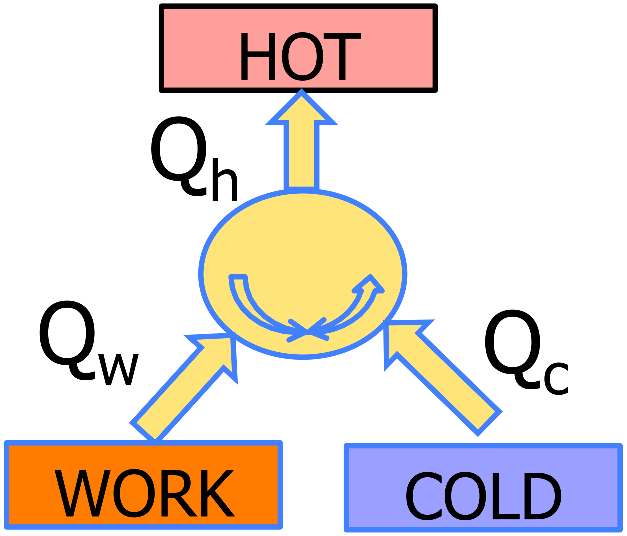
How does the quantum effects influence refrigerator performance?

Trapped Ions

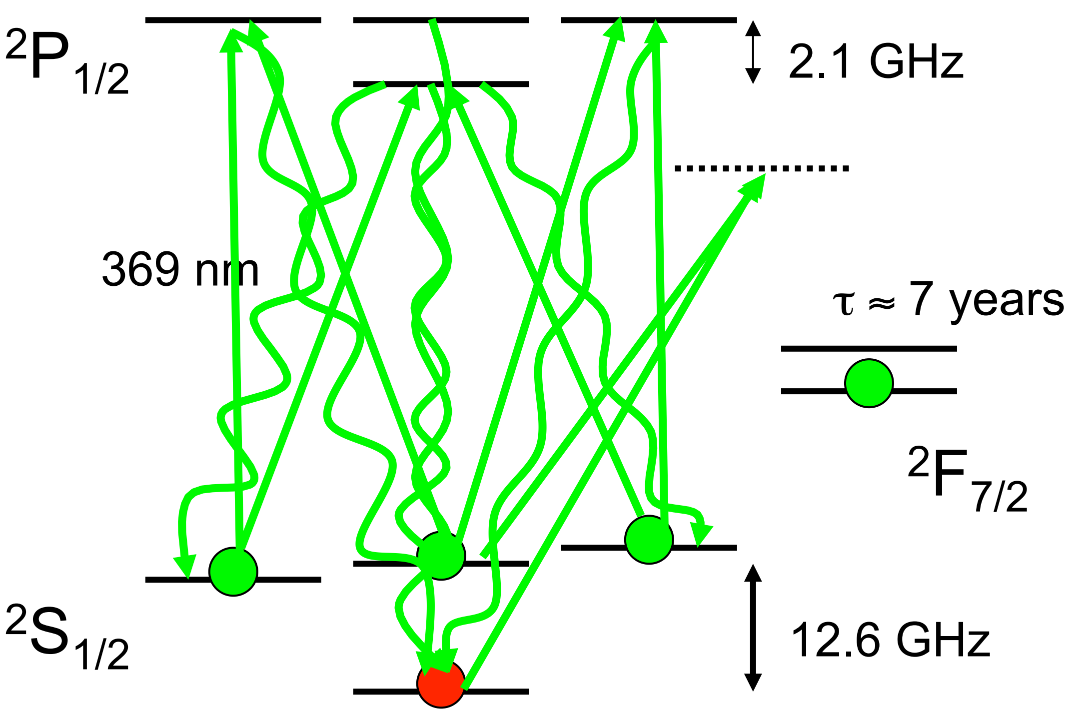


Thanks: R. Blatt, Univ. Innsbruck

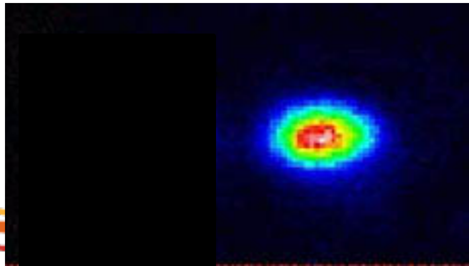
N ions, 3N modes of motion,
(Heat bodies)



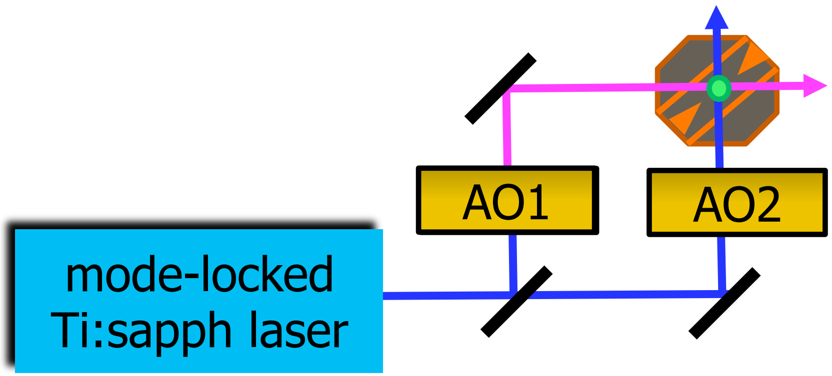
Experiment: Ytterbium ($^{171}Yb^{+}$) Ions



- Optical pumping for state initialization
- Resonance fluorescence for state detection
- Metastable $^2F_{7/2}$ state
- Raman transitions between hyperfine states



State preparation

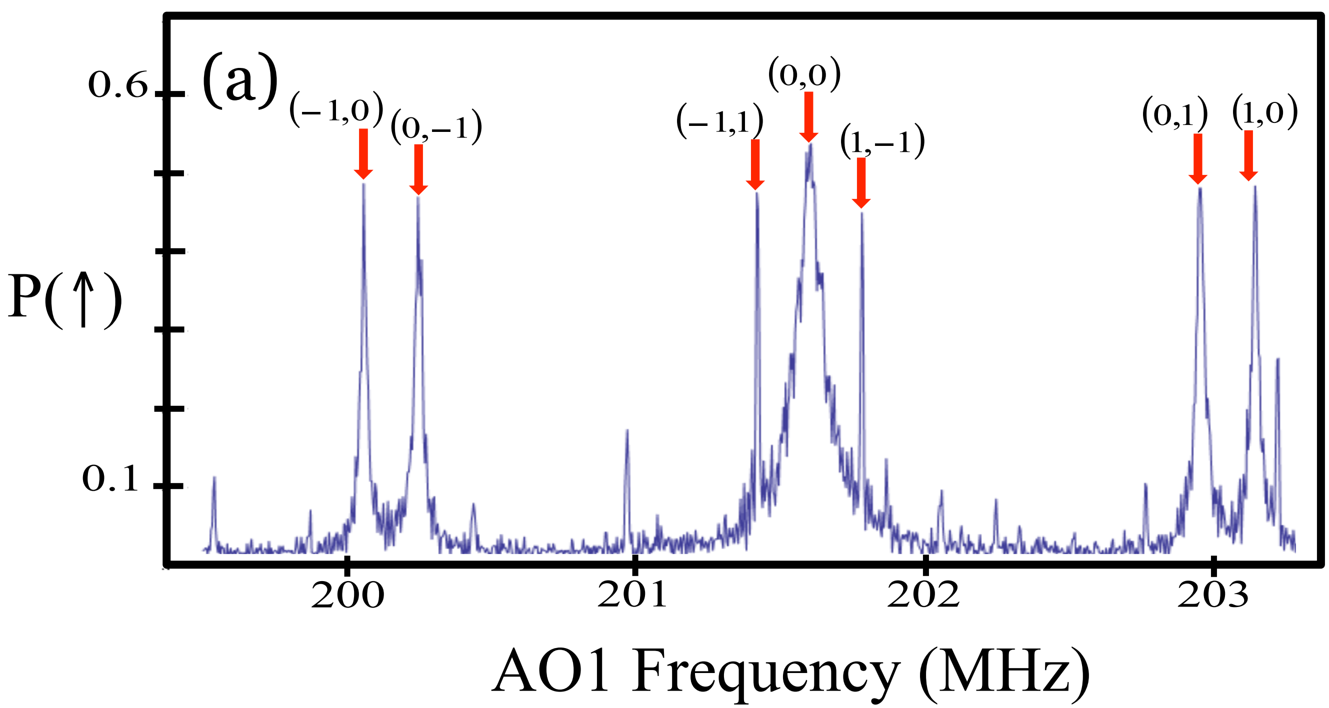


f_{rep}=76MHz

carrier $H_c = \hbar\Omega/2\ \sigma_+ + h.c.$

blue sideband $H_{bsb} = \hbar\eta\Omega/2\ \sigma_+ a^\dagger +$

red sideband $H_{rsb} = \hbar\eta\Omega/2\ \sigma_+ a +$



Sisyphus,
sideband cooling

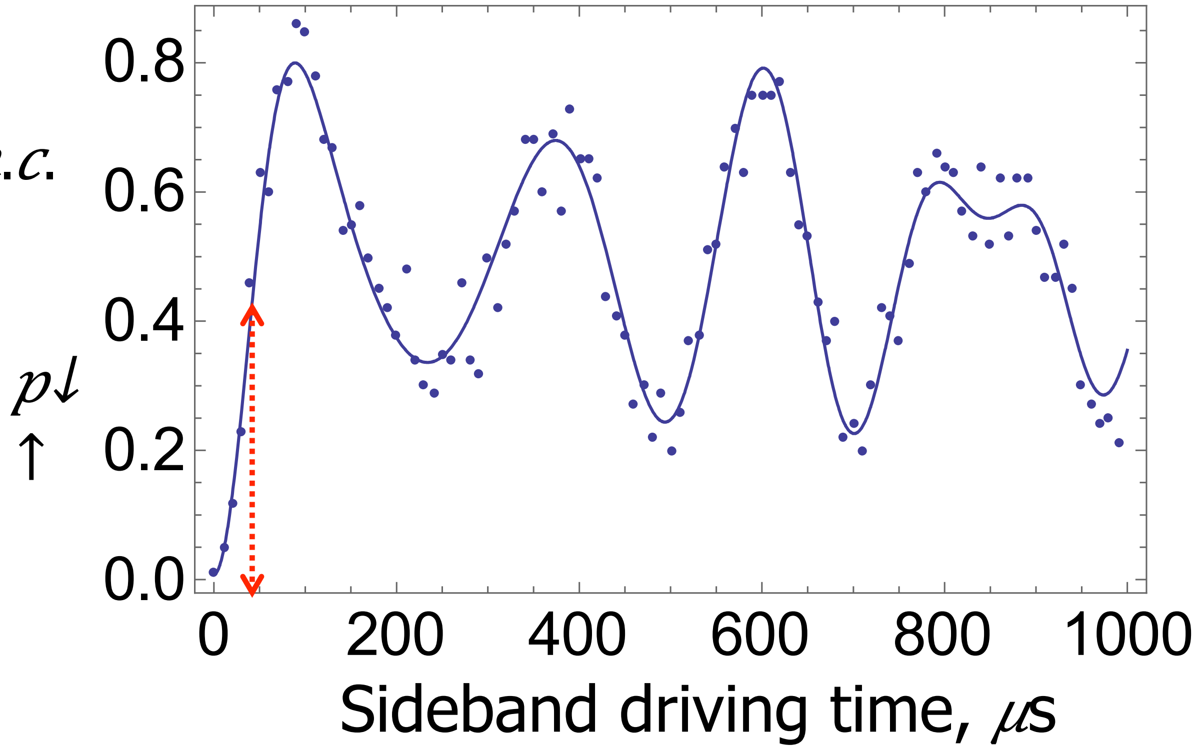
ground state

D. Hayes et. al,
Phys. Rev. Lett.
104, 140501 (2010).

How to probe ion motion

$H_{bsb}=\hbar\eta\Omega/2\ \sigma_{+}\, a^{\dagger} + h.c.$

$\Omega_{n,n+1}=\sqrt{n+1}\ \Omega_{0,1}$

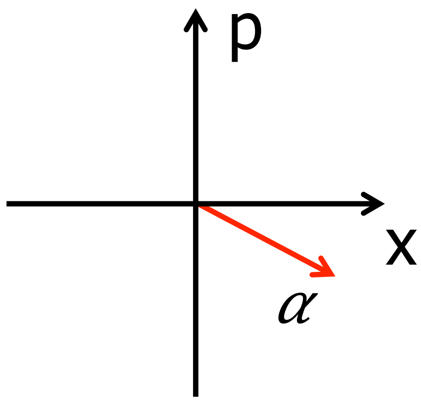


Measure $p_{\uparrow}$ as a function of time	Measure $p_{\uparrow}$ for fixed τ
Fourier transform gives p_{n} and n	Sensitive to small changes of n
Requires a lot of data	More assumptions

Coherent state

Force modulated at the mode frequency ω

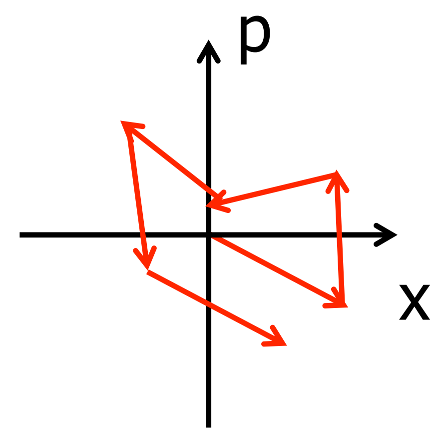
$$|\alpha\rangle = D(\alpha)\,|0\rangle$$



Thermal state

Random walk in phase space: Random ϕ for each step

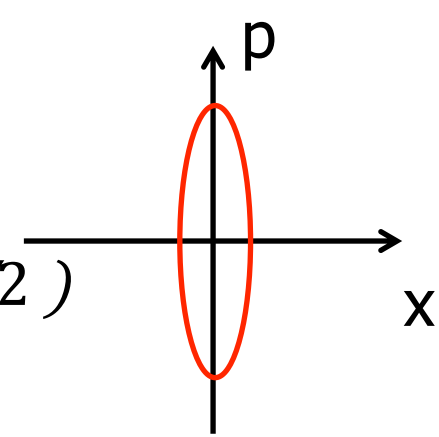
$$D(\alpha e^{i\phi_1})D(\alpha e^{i\phi_2})\ldots D(\alpha e^{i\phi_n})$$



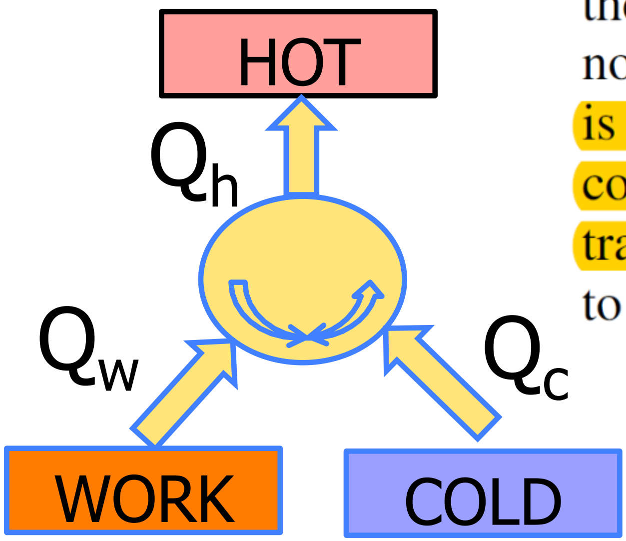
Squeezing operator

Force modulated at 2ω

$$S(r) = \exp\left(\left(r a^{\dagger 2} - r^{*} a^{2} \right)/2 \right)$$



Can we build refrigerator with ions?



no movable parts and induce the energy to flow away from a cold reservoir by coupling it with a system that is itself coupled with other (hot) reservoirs. In the quantum regime they were proposed by Kosloff and others [2] using a nonlinear model. Our work implies that, as nonlinearity is an essential resource, a quantum absorption refrigerator could never be built using harmonic systems such as trapped ions [11] or nanomechanical systems that are ideal to implement other quantum machines [14]. Finally, we

PRL **110**, 130406 (2013)

How can we make motional modes interact with each other ?

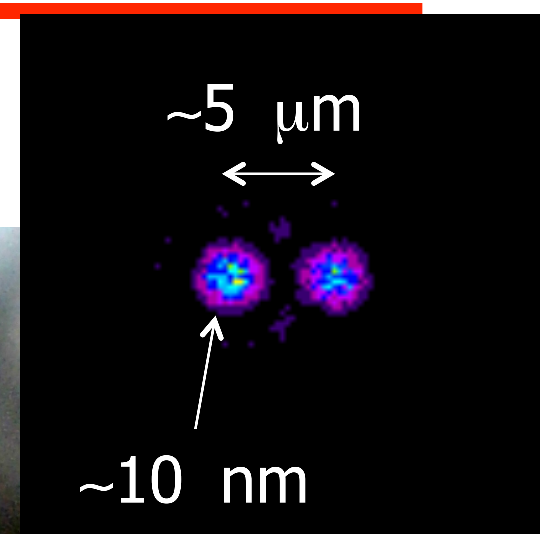
We need anharmonicity !!!

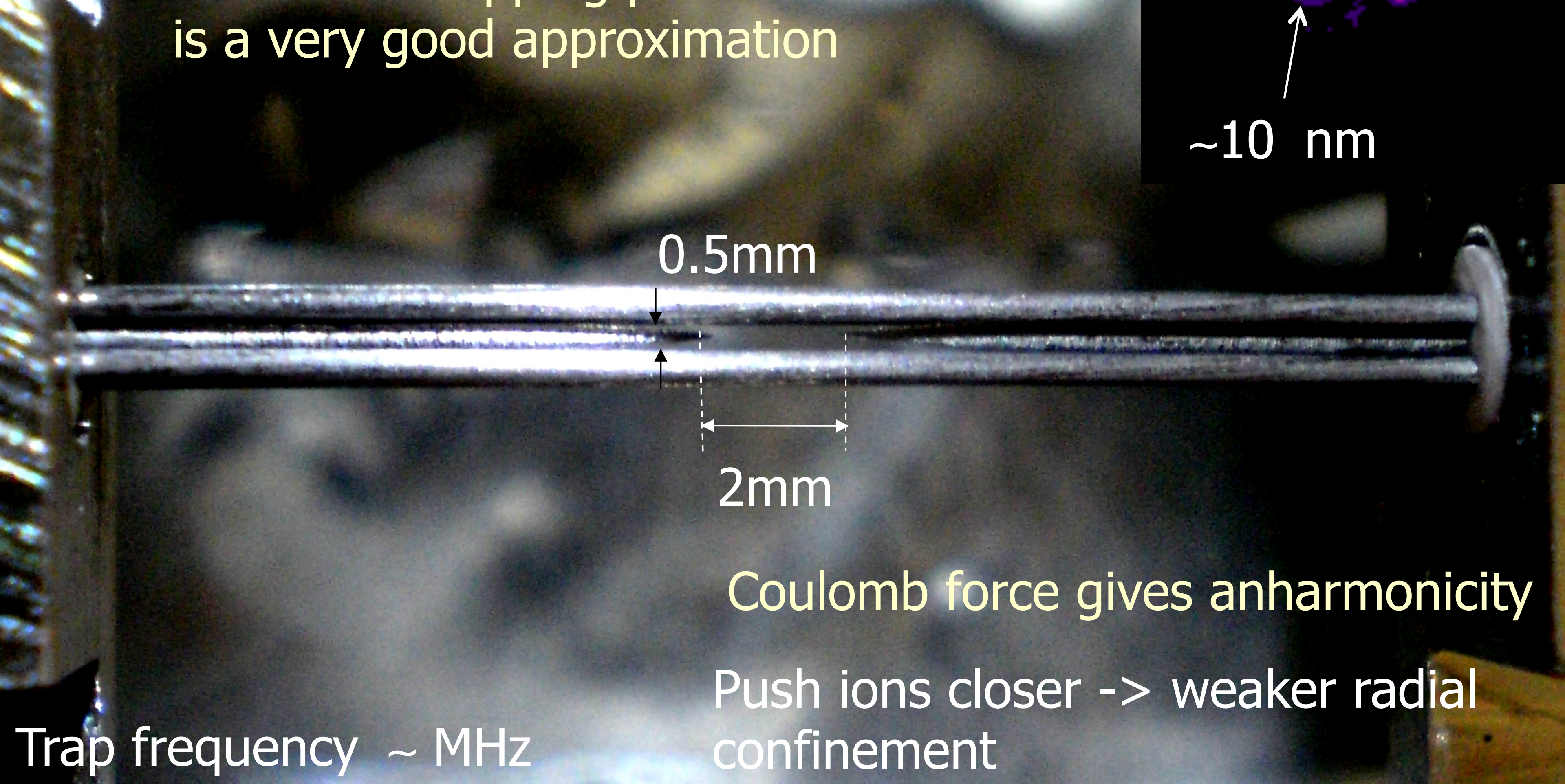
Centre for Quantum Technologies

Anharmonicity

National University of Singapore

Trap size ~ mm,
Amplitude of ion motion ~ 10 nm





Harmonic trapping potential is a very good approximation

Coulomb force gives anharmonicity

Push ions closer -> weaker radial confinement

Trap frequency ~ MHz

Anharmonicity

$$x_n^2 + \omega_y \Delta y_n^2 + \omega_z \Delta z_n^2) + e^2/8\pi\epsilon_0 \sum_{n,m=1,2,3\, n\neq m}$$

Harmonic terms

Anharmonicity

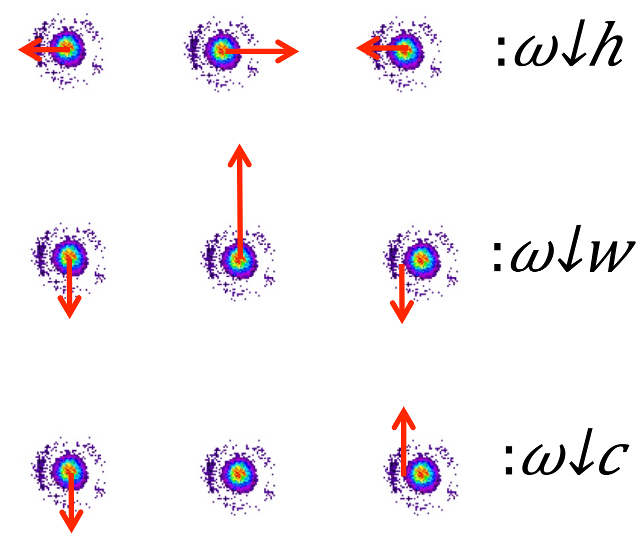
Normal mode coordinates -> Taylor expansion ->Quantization of motion

$$H_{int} = \hbar\xi(h^\dagger wc + hw^\dagger c^\dagger)$$

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

$$z^2/5x_0 \sqrt{\hbar/\omega_h \omega_w \omega_c}$$

For ω ≈1MHz,
ξ = 2-3 kHz



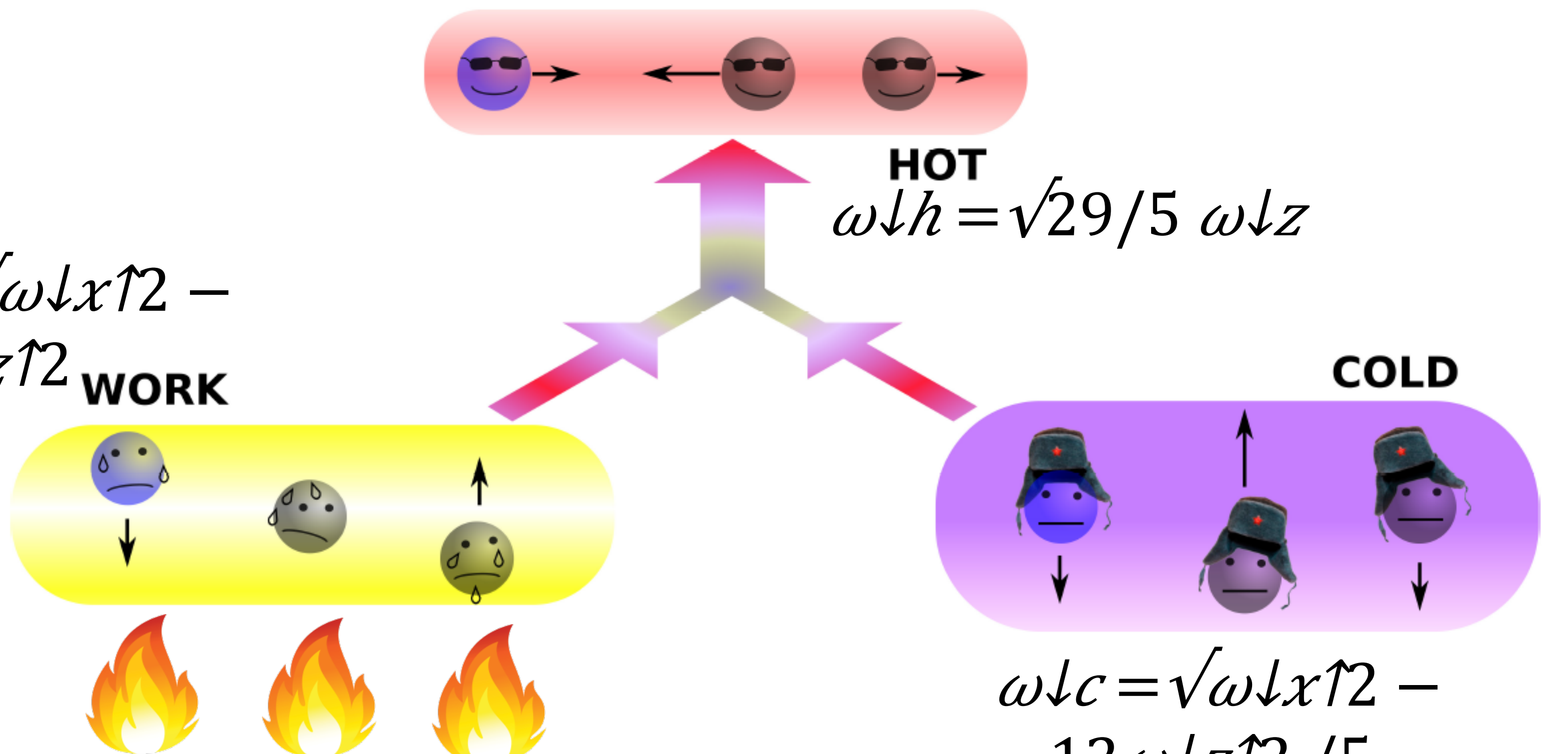
Marquet, C., et. al, Appl. Phys. B **76**, 199,

Refrigerator with trapped ions

Harmonic oscillators interacting via trilinear Hamiltonian

$$H_{int} = \hbar\xi(h^\dagger wc + hw^\dagger c^\dagger)$$

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



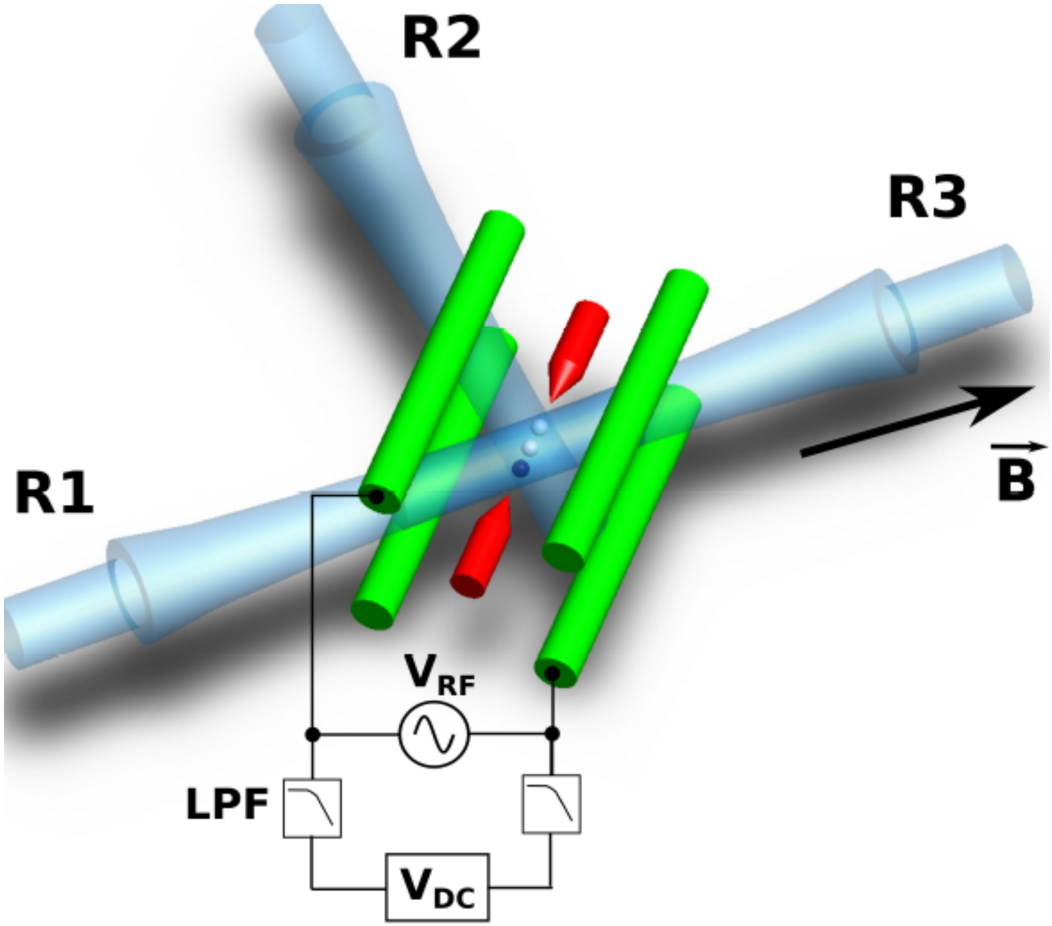
$$\omega_h = \sqrt{29/5}\,\omega_z$$

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

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

A. Levy, R. Kosloff, Phys. Rev. Lett. **108**, 070604 (2012)

Experimental setup



Three ^{171}Yb ions in the trap

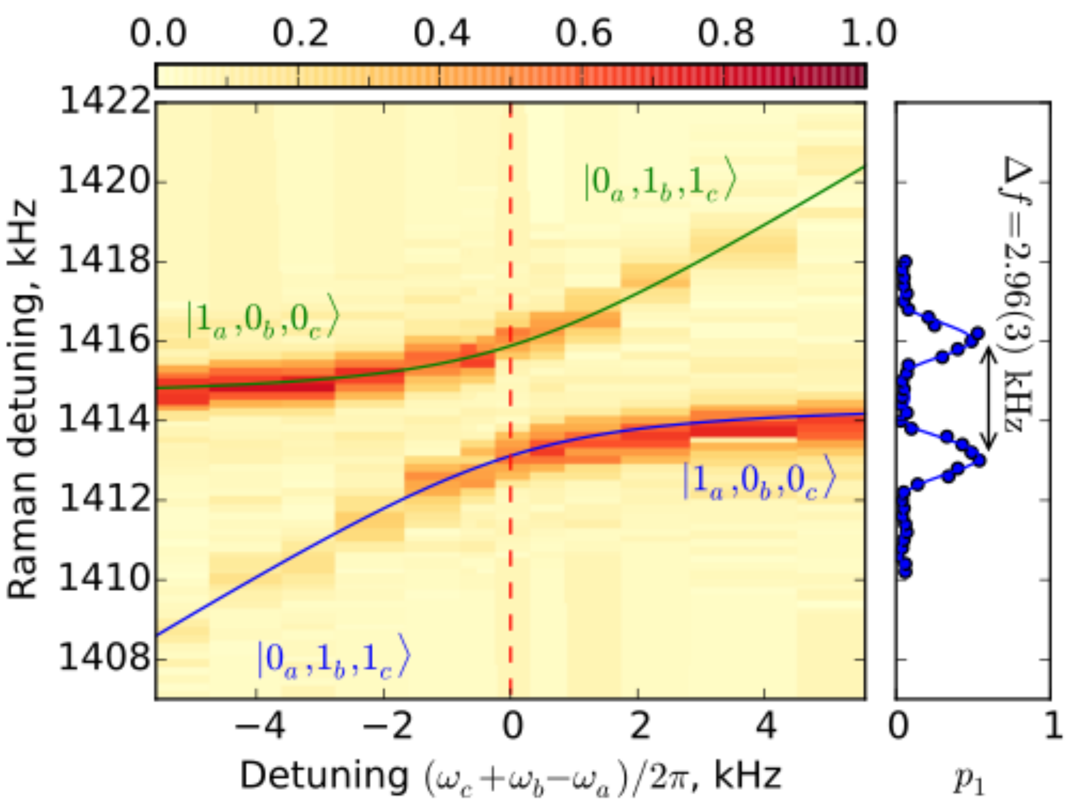
Two pairs of Raman beams to address motion from axial and radial directions

Two ions are pumped in the "dark" $^2F_{7/2}$ state

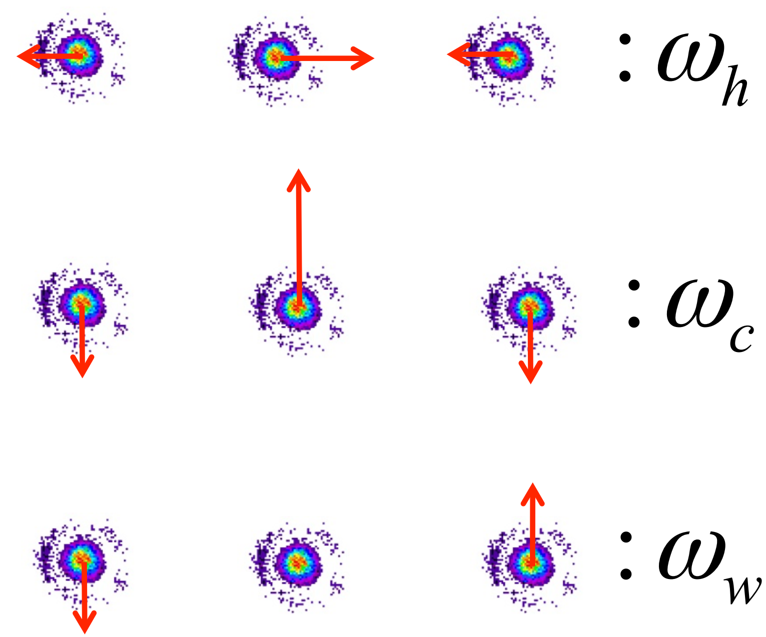
Offset voltages to tune the radial trap frequencies in and out of resonance

Coupling between three modes

$$H_{int} = \hbar\xi(h^\dagger wc + hw^\dagger c^\dagger)$$



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



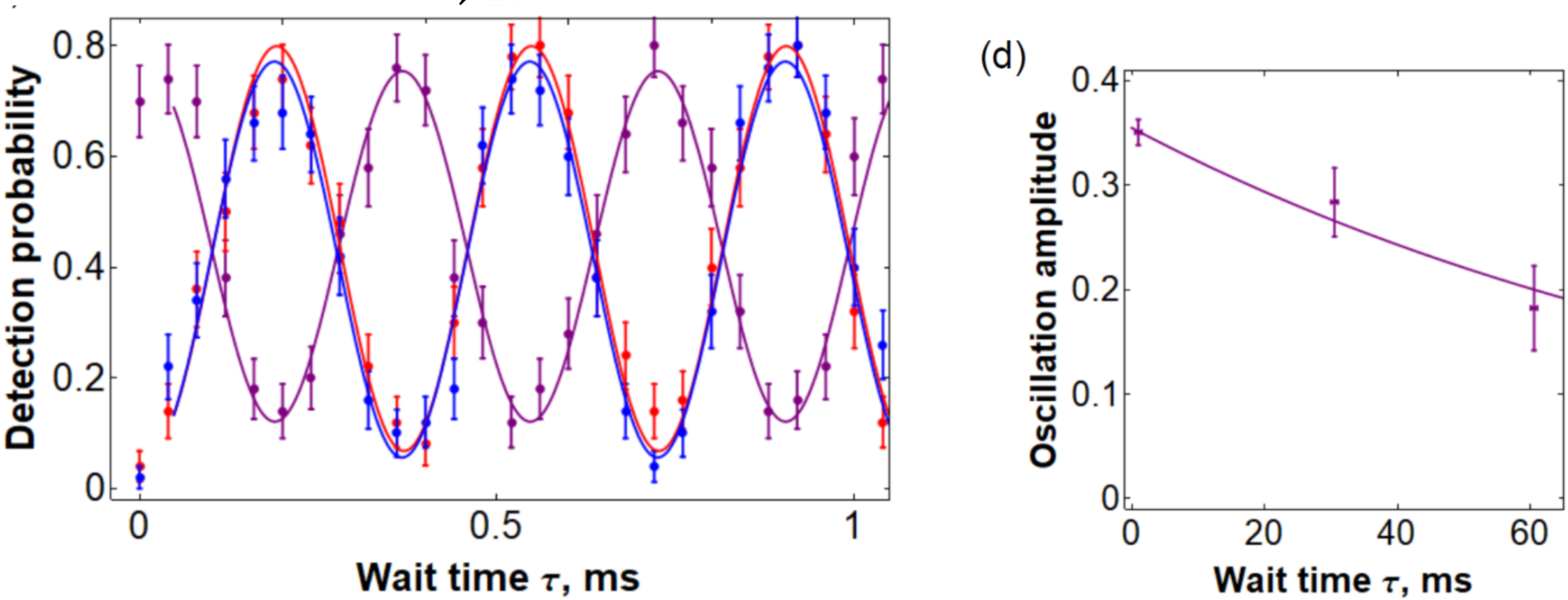
S. Ding et. al. arXiv:1805.11193

Coupling of 3 modes, state evolution

$$H_{int} = \hbar\xi(h^{\dagger} wc + hw^{\dagger} c^{\dagger})$$

$$|1_h 0_w 0_c\rangle \rightarrow |0_h 1_w 1_c\rangle \rightarrow |1_h 0_w 0_c\rangle$$

$$\rightarrow$$

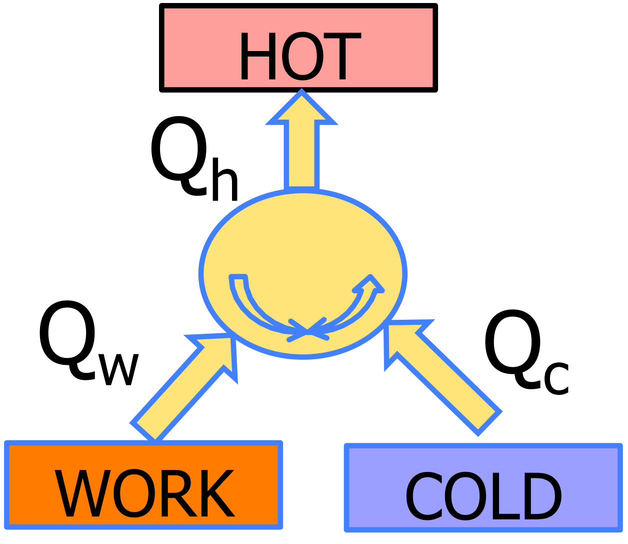


Coherence time > 8ms

S. Ding et. al. arXiv:1805.11193

Testing refrigerator

- Prepare initial states
- Tune the trap frequencies to resonance
- Let the modes interact for time τ
- Turn off interaction and measure mode energies



Equilibrium

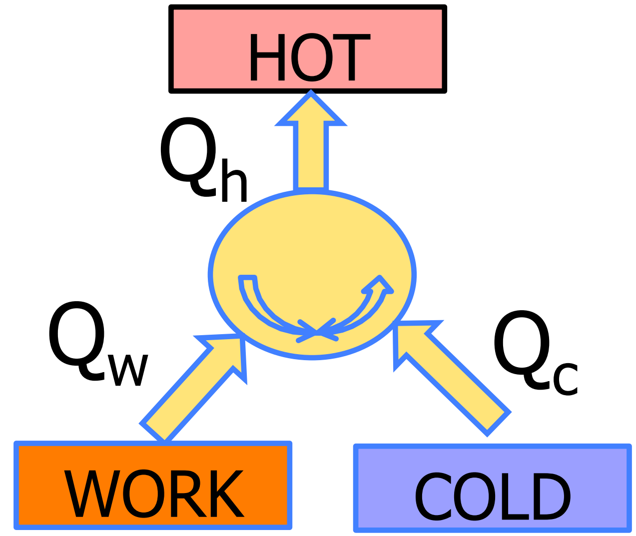
2nd law $\Delta S = Q_h/T_h + Q_w/T_w + Q_c/T_c = 0$

1st law $Q_i = \hbar\omega_i n_i$

Coupling Hamiltonian $n_h = -n_w = -n_c$

In Thermal Equilibrium

$$n_h^{(eq)})=(1+1/n_w^{(eq)})(1+1/n_c^{(eq)})$$



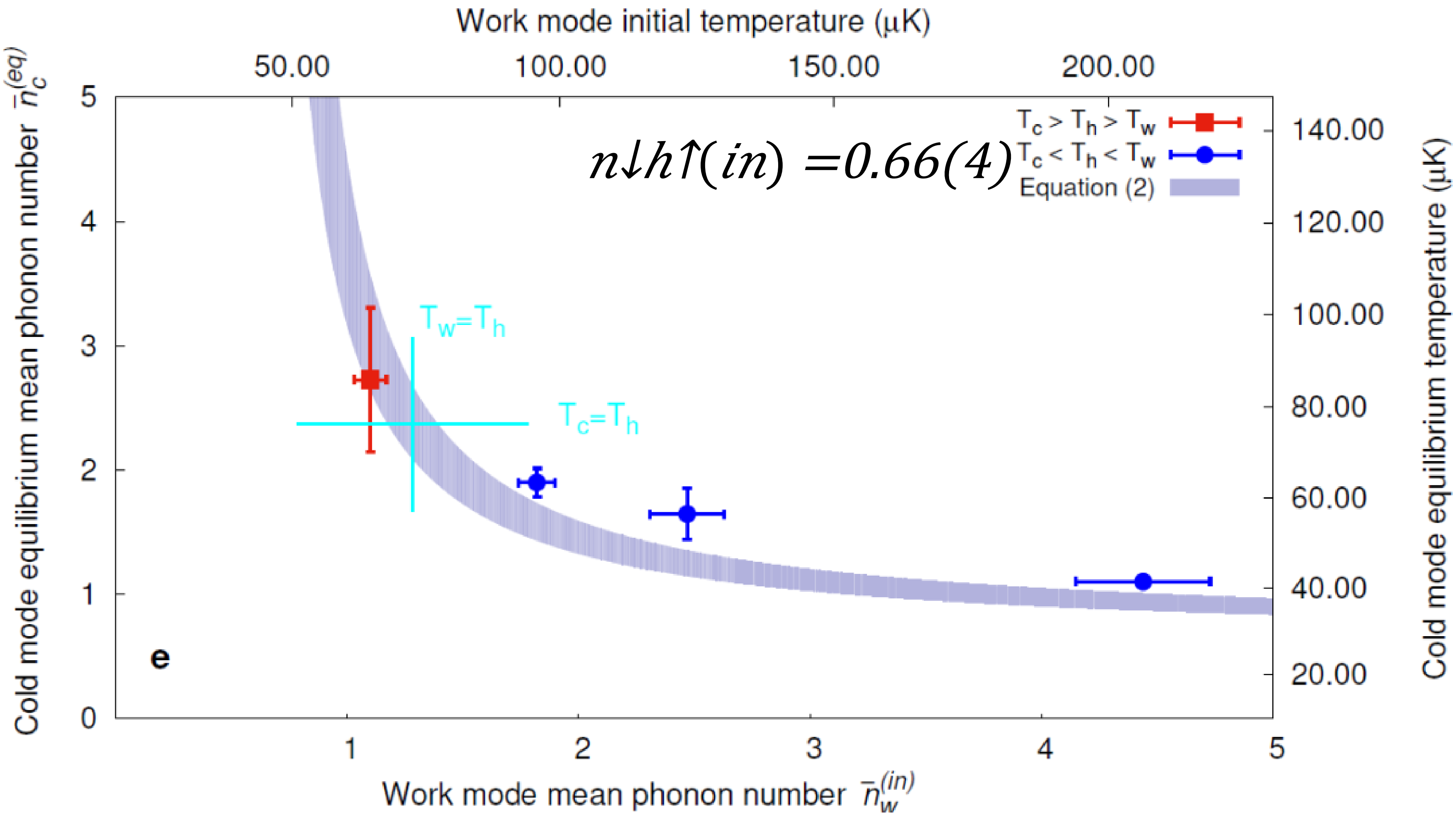
For Harmonic oscillator

$$n_i = 1/(\exp \hbar\omega_i/kT_i - 1$$

Quantum mechanics: $[H_{int}, \rho_h^{(eq)} \otimes \rho_w^{(eq)} \otimes \rho_c^{(eq)}]=0$

Equilibrium temperatures

Equilibrium conditions $(1+1/n_h^{(eq)})=(1+1/n_w^{(eq)})(1+1/n_c^{(eq)}$



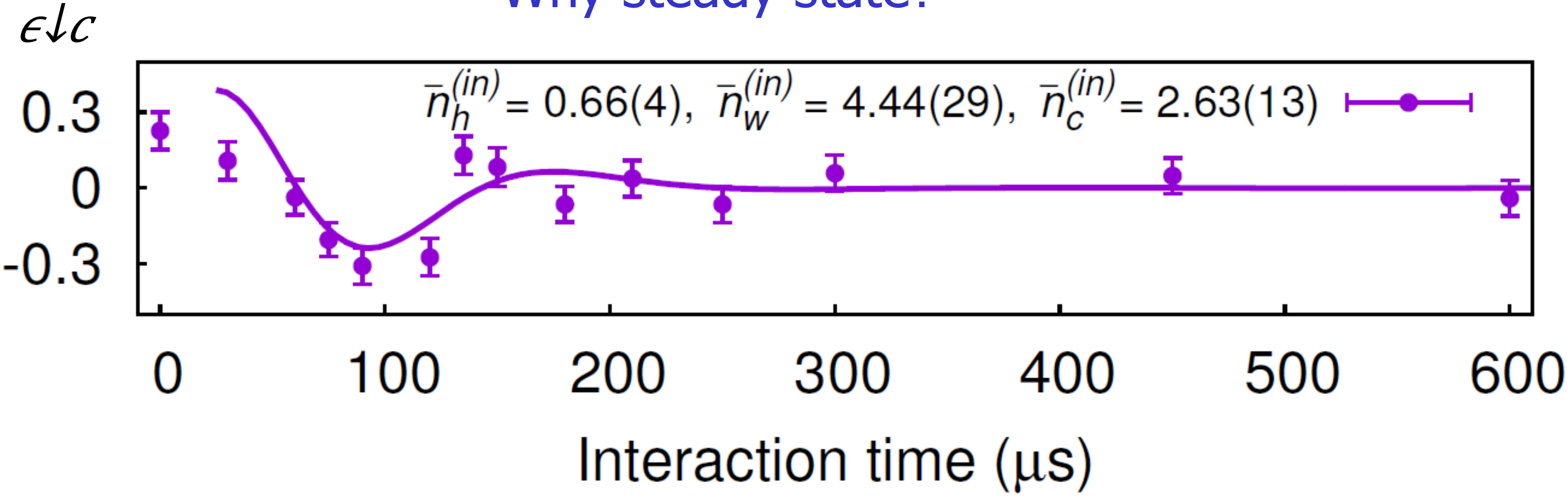
$n_h^{(in)}=0.66(4)$

G. Maslennikov, et. al, arXiv:1702.08672

Away from equilibrium

Start away from equilibrium. …. Evolution is unitary.

Why steady state?



Effective equilibration:

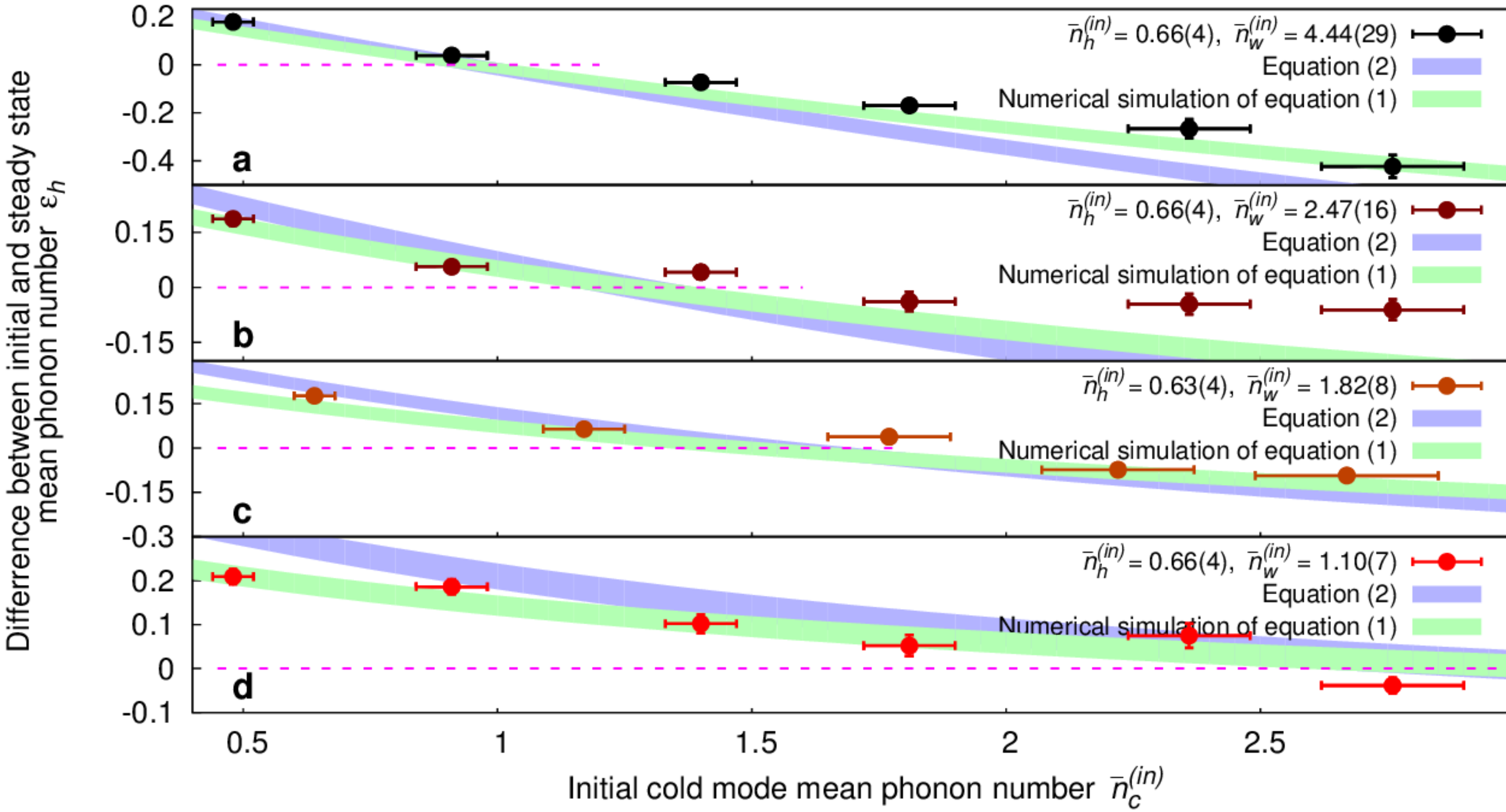
- Large "effective" Hilbert space
- Many Rabi frequencies which are incommensurable

S. Nimmrichter, et. al. *Quantum* **1** 37 (2017).

Steady state

Blue: thermal equilibrium $(1+1/n_h^{(eq)}+\epsilon)=(1+1/n_w^{(eq)}-\epsilon)(1+1/n$

Green: "quantum" steady state

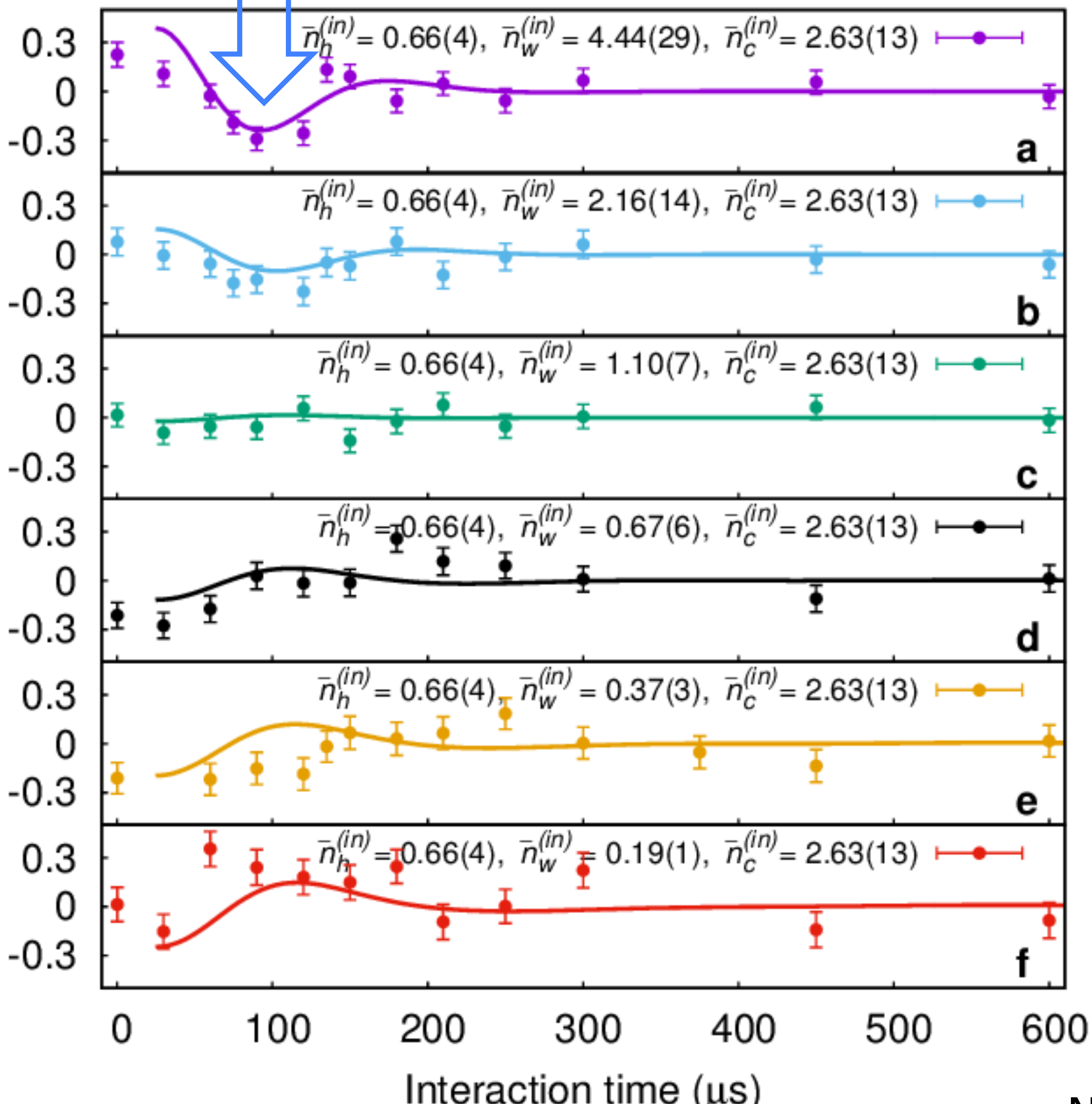


Final states are not thermal

G. Maslennikov, et. al, arXiv:1702.08672

Single shot cooling

It is cold here !!!

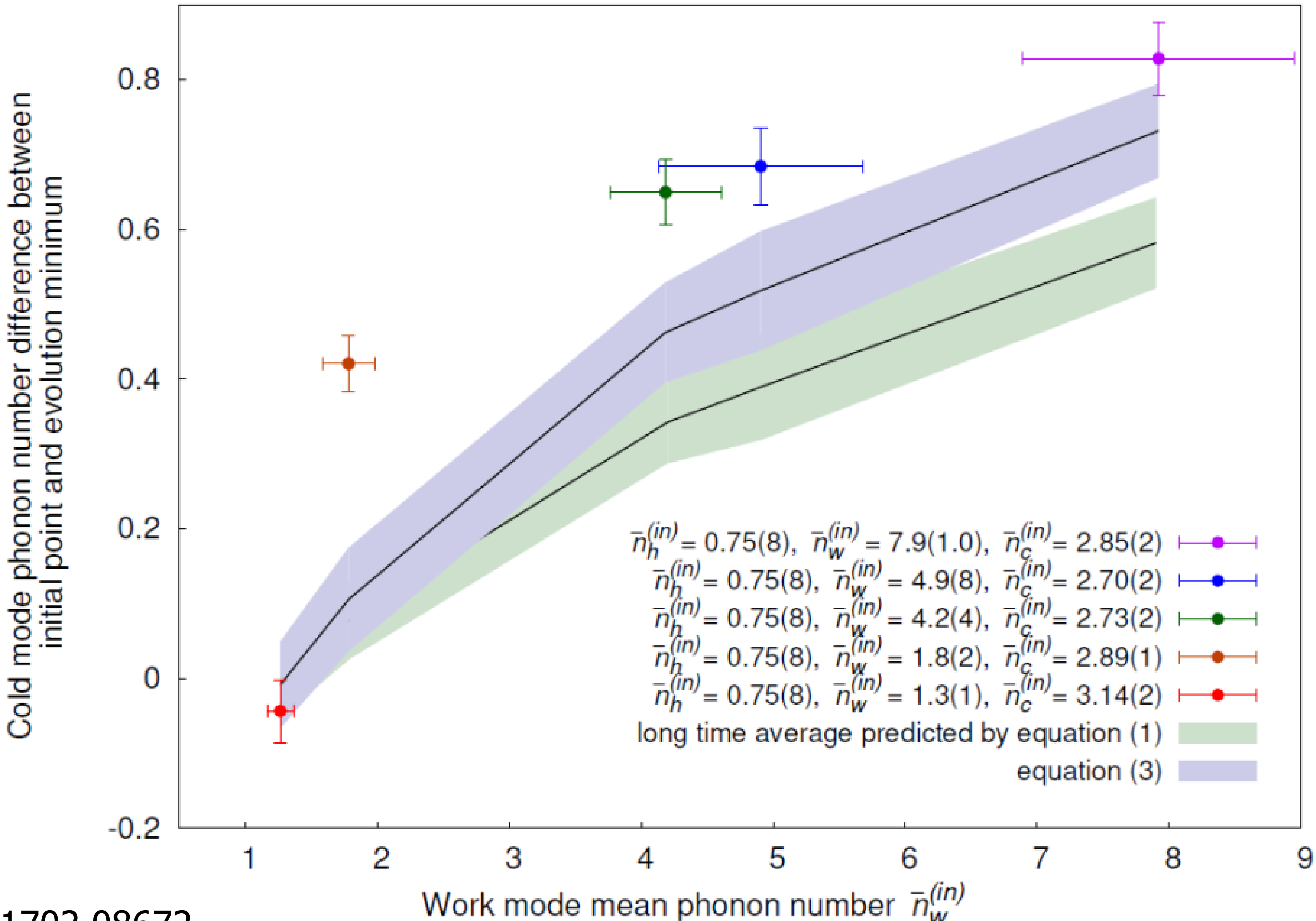


The cold mode "overshoots" before the steady state is reached.

Stop evolution when the mode is coldest !!!

M. Mitchison, et. al.
New J. Phys. 17 (2015) 115013

Single shot cooling



arXiv:1702.08672

Squeezing as a thermal resource

APS physics | Journals | Physics | PhysicsCentral | APS News

Physics ABOUT BROWSE PRESS COLLECTIO

Synopsis: “Squeezed” Engine Could Break Thermodynamic Limits

January 22, 2014

A theoretical analysis shows that nanoengines based on quantum squeezed states can perform several times more efficiently than classical engines.

Squeezed refrigerator also can ???

Prepare work mode in thermal state

Apply squeezing operation

$$S(r)=\exp\left(\tfrac{1}{2} r a^{\dagger 2} - \tfrac{1}{2} r^{*} a^{2}\right.$$

n increases to:

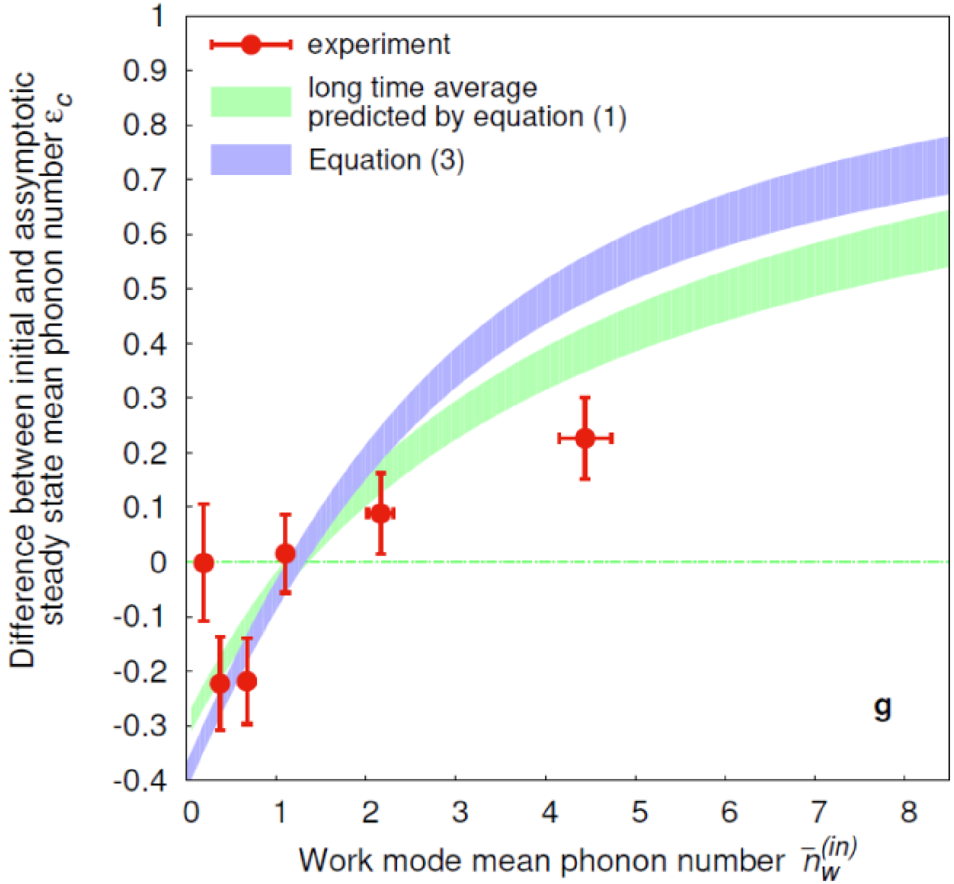
$$n^{(\mathrm{in,eq})} = n^{(\mathrm{in})} \cosh(2r) - \sinh^{2}$$

Compare to the thermal state with the same n

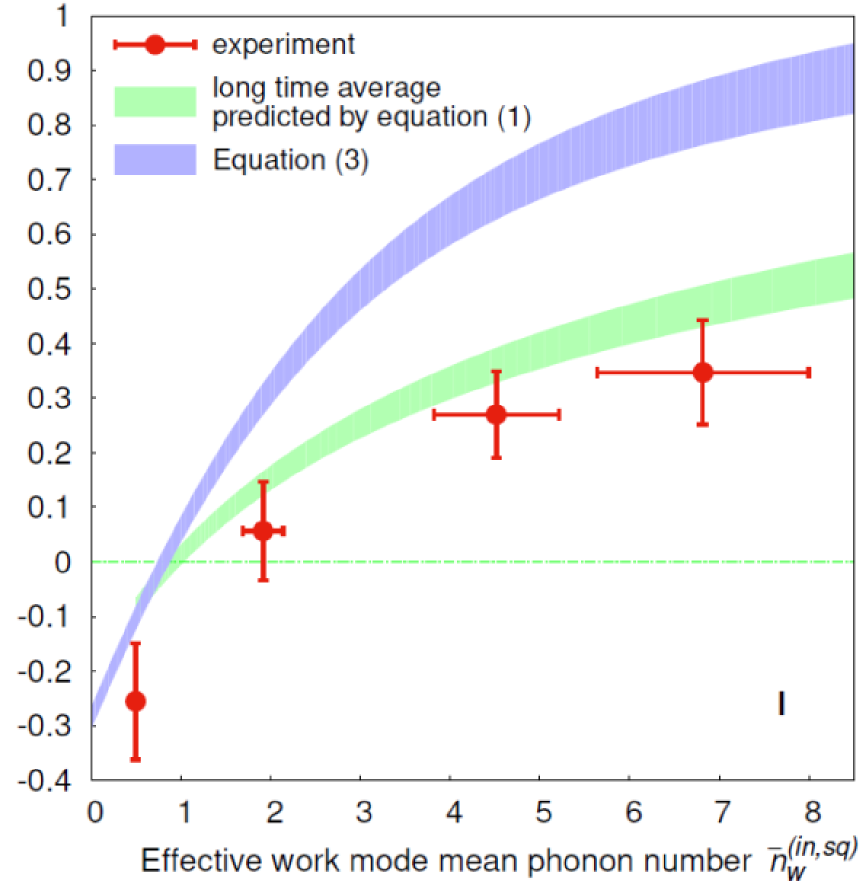
See also: *Scientific Reports* , **4**, 3949 (2014)

Which state of work mode is more efficient

Thermal



Squeezed thermal



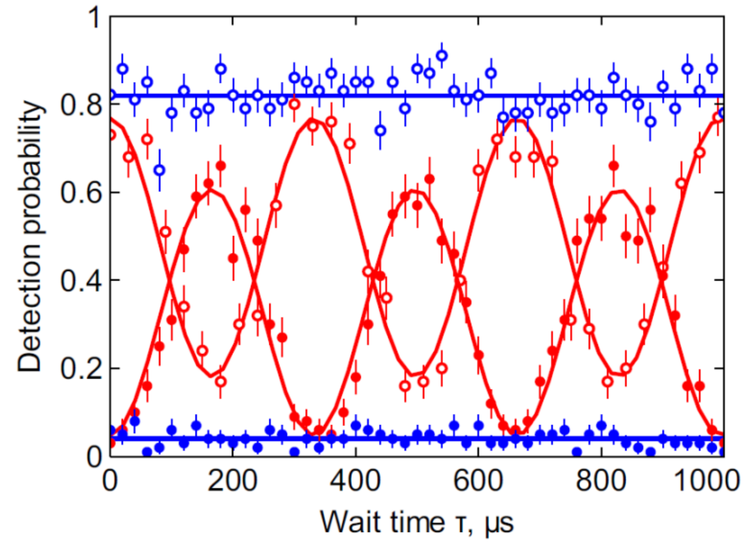
arXiv:1702.08672

Other types of nonlinear coupling

Parametric oscillator:

$$H_{int} = \hbar\xi(a^{\dagger 2} b + a^2 b^{\dagger})$$

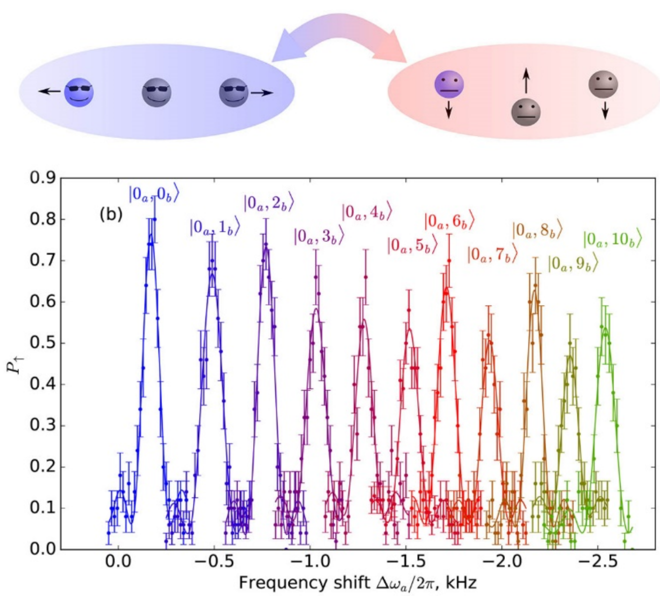
Phys. Rev. Lett. 119, 150404 (2017)



Cross Kerr interaction:

$$H_{int} = \hbar\xi n_a n_b$$

Phys. Rev. Lett. 119, 193602 (2017)



Any thermodynamic applications ??

Centre for Quantum Technologies

NUS National University of Singapore

Conclusion

- Implemented absorption refrigerator with trapped ions
  - Equilibrium properties of the refrigerator
  - Single shot cooling
  - Effects of squeezing on the fridge performance

Nonlinear coupling enables simulation of other systems

- Jaynes-Cummings model
- Parametric down conversion
- Hawking radiation

$$H_{int} = \hbar\xi(h^{\dagger} w c + h w^{\dagger} c^{\dagger})$$

Centre for Quantum Technologies

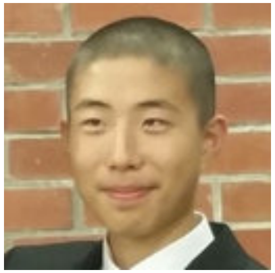
Group

NUS National University of Singapore

Jaren Gan

Gleb Maslennikov

Ko Wei Tseng



Beicheng Lou

Former members

Shiqian Ding (JILA)

Huanqian Loh (NUS)

Roland Hablutzel (Waterloo)

Theory : Alexandre Roulet, Stefan Nimmrichter, Jibo Dai, Valerio Scarani

Ministry of Education
moulding the future of our nation

National Research Foundation
Prime Minister's Office
Singapore

Singapore

We have atoms … ions … molecules …

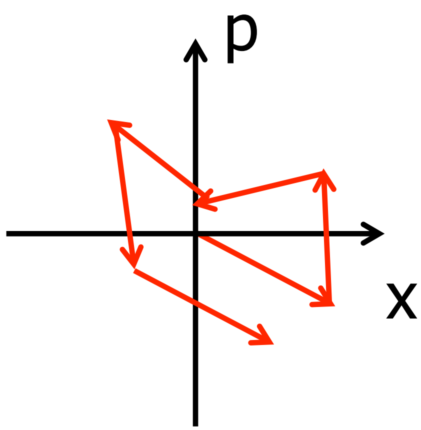
CQT Centre for Quantum Technologies

NUS National University of Singapore

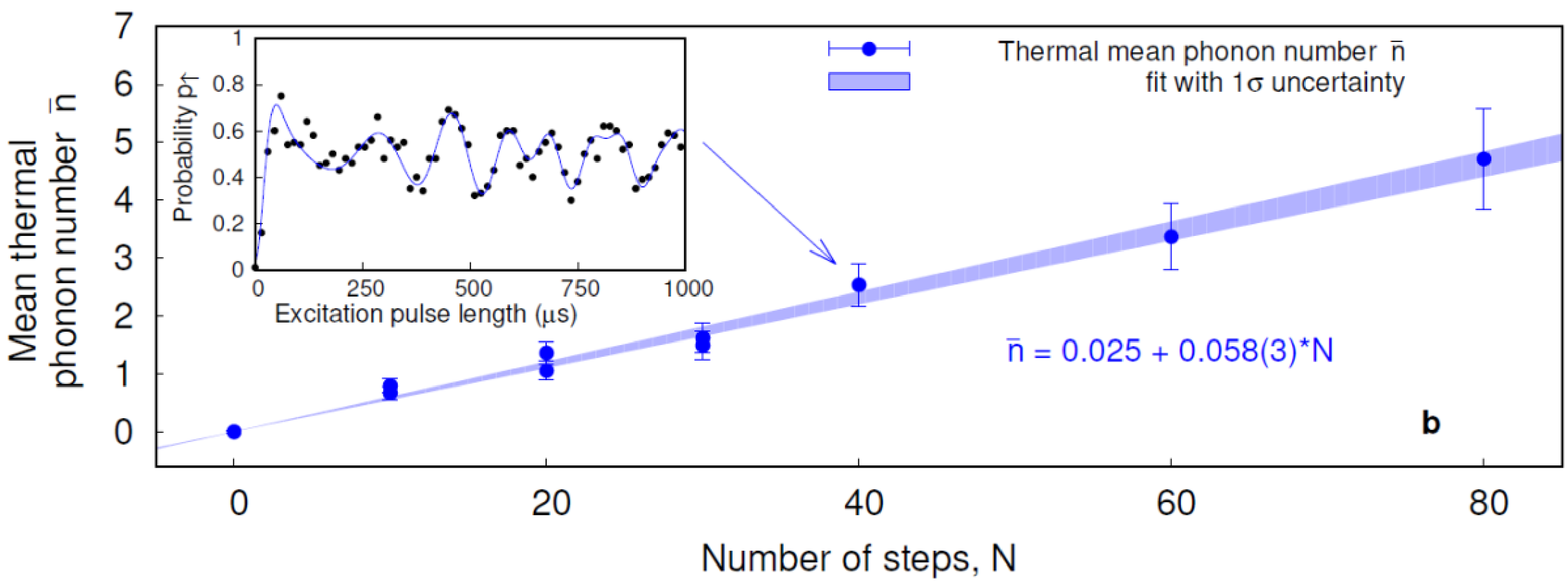
Thermal state

Random walk in phase space:

$$(\alpha e^{i\phi_1})D(\alpha e^{i\phi_2})\ldots D(\alpha e^{i\phi_n})|0\rangle$$



Phase chosen randomly for each step:



Thermal state preparation