Fast state preparation in trapped ion atomic clocks: **A fluctuation theorem perspective in the strong-coupling, non-Markovian regime**

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Theory: PRB 94, 214308 (2016).
Experiment: PRA 98, 023424 (2018).

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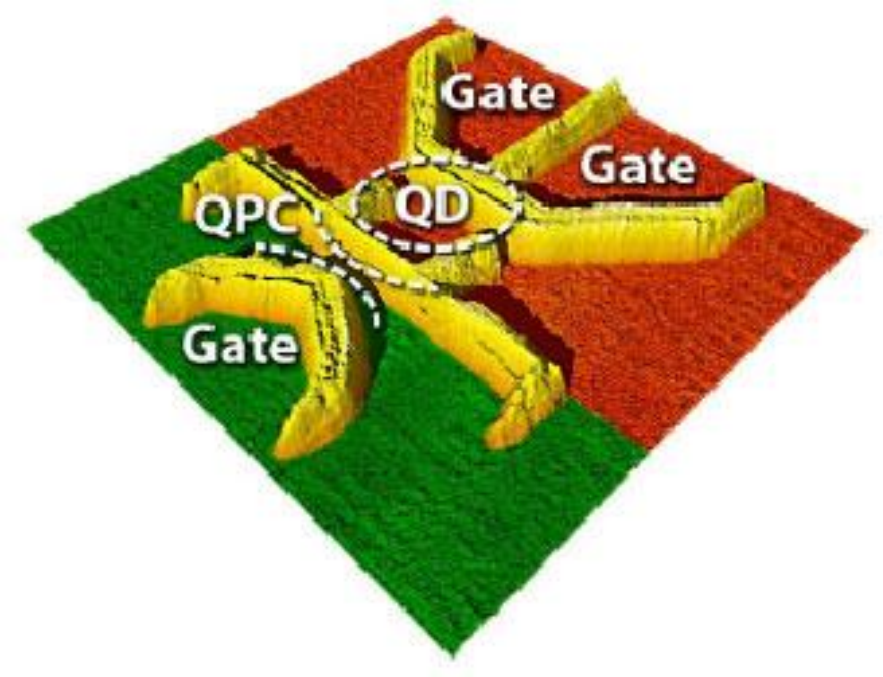
Full Counting Statistics

Electronic transport through a quantum dot



R. Haug, Hannover Univ.
J. Pekkola, Aalto Univ.
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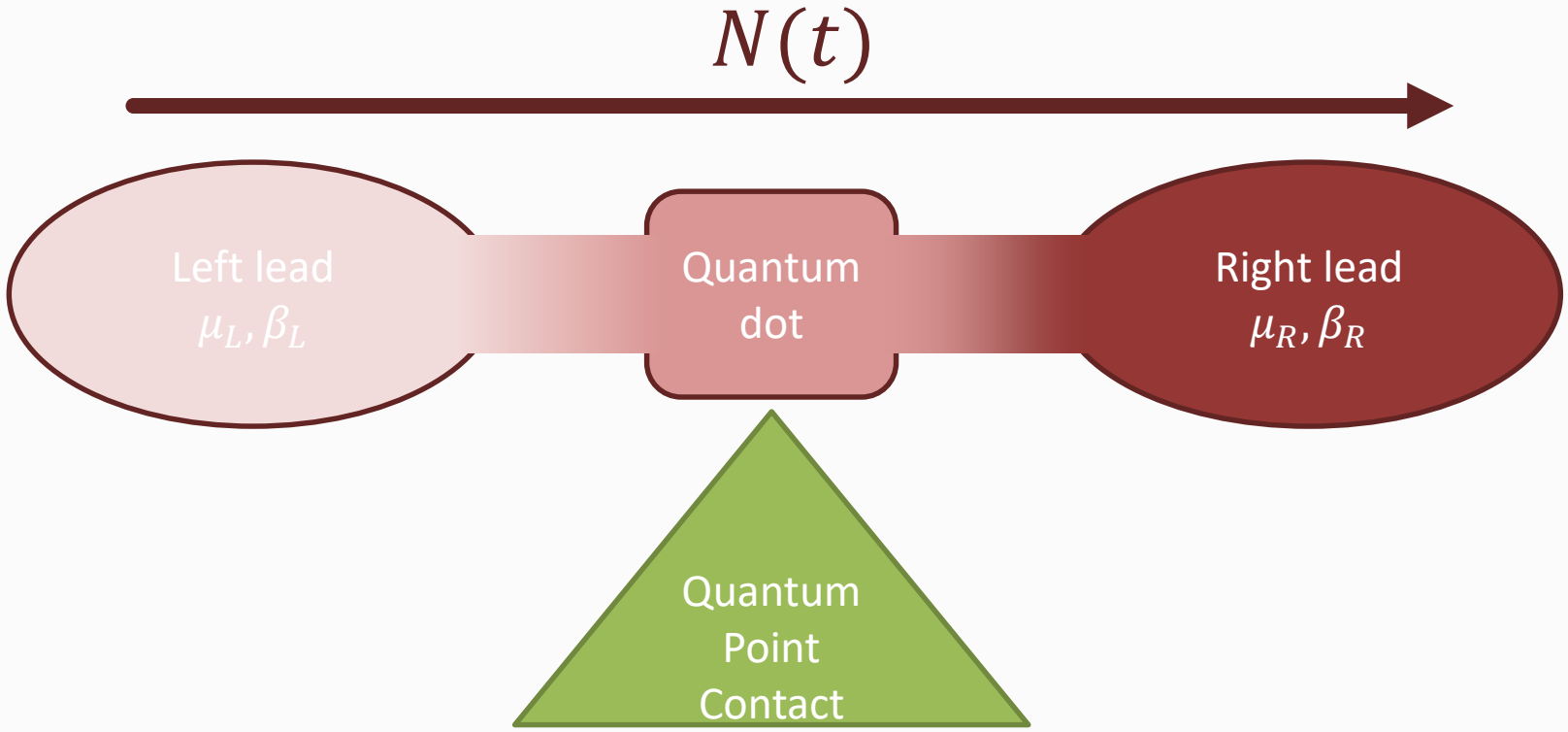


Cumulant generating function

$$C(\chi, t) = ln \sum_n e^{i\chi N(t)} p[N(t)]$$

Symmetries of Cumulant Generating Function

Shift of the counting field

$\chi \to -\chi + i\beta$

Forward / backward processes

- Fluctuation theorems

Free energy changes

- Jarzynski equality

Detailed balance

Correlation Functions: Absorption and Emission

$A(t) \propto E(-t + i\beta)$

THERMOMETRY

Strong coupling to non-Markovian baths

Redefinition of system-environment boundaries

Polaron transformation

L. Nicolin and D. Segal, *PRB 84*, 161414(R) (2011).

L. Nicolin and D. Segal, *JCP 135*, 164106 (2011). ✓

Consider environment part of the system

M. Campisi, P. Talkner and P. Hänggi, *PRL 102*, 210401 (2009). ✓

Chain Mappings / Reaction coordinate

R. Rosenbach, J. Cerrillo, S. Huelga, J. Cao, M. Plenio, NJP 18, 23035 (2016).

S. Restrepo, J. Cerrillo, P. Strasberg, G. Schaller, NJP 20, 053063 (2017).

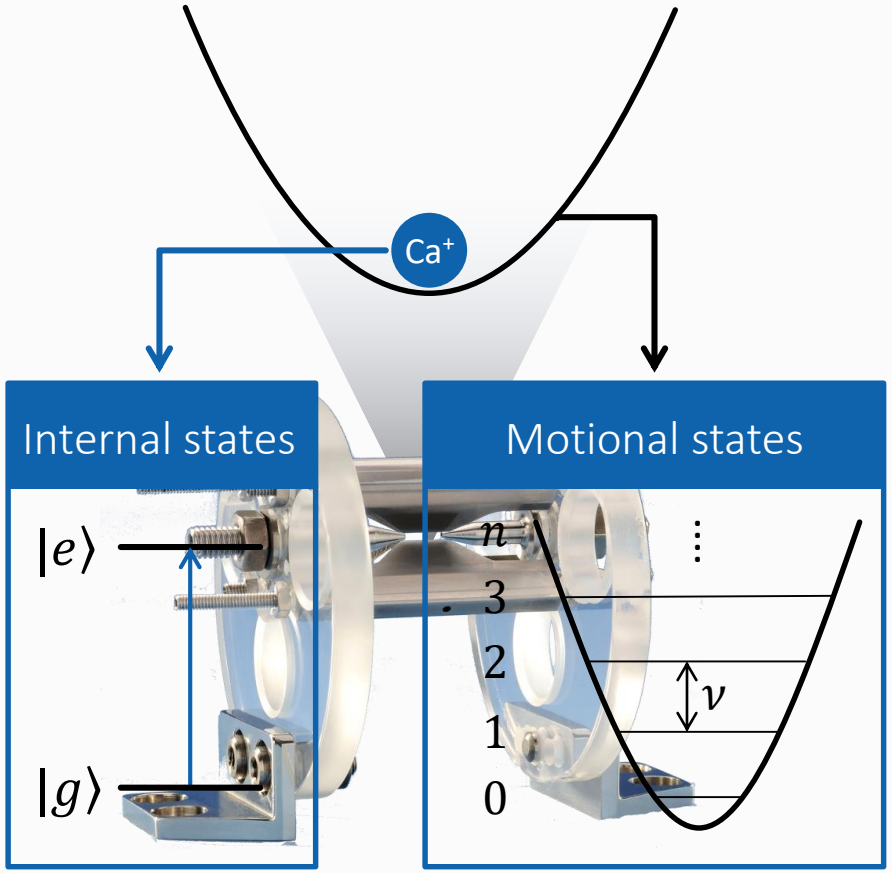
S. Restrepo, S. Böhling, J. Cerrillo, G. Schaller, accepted PRB (2019).

System-environment **correlations are essential for thermometry**

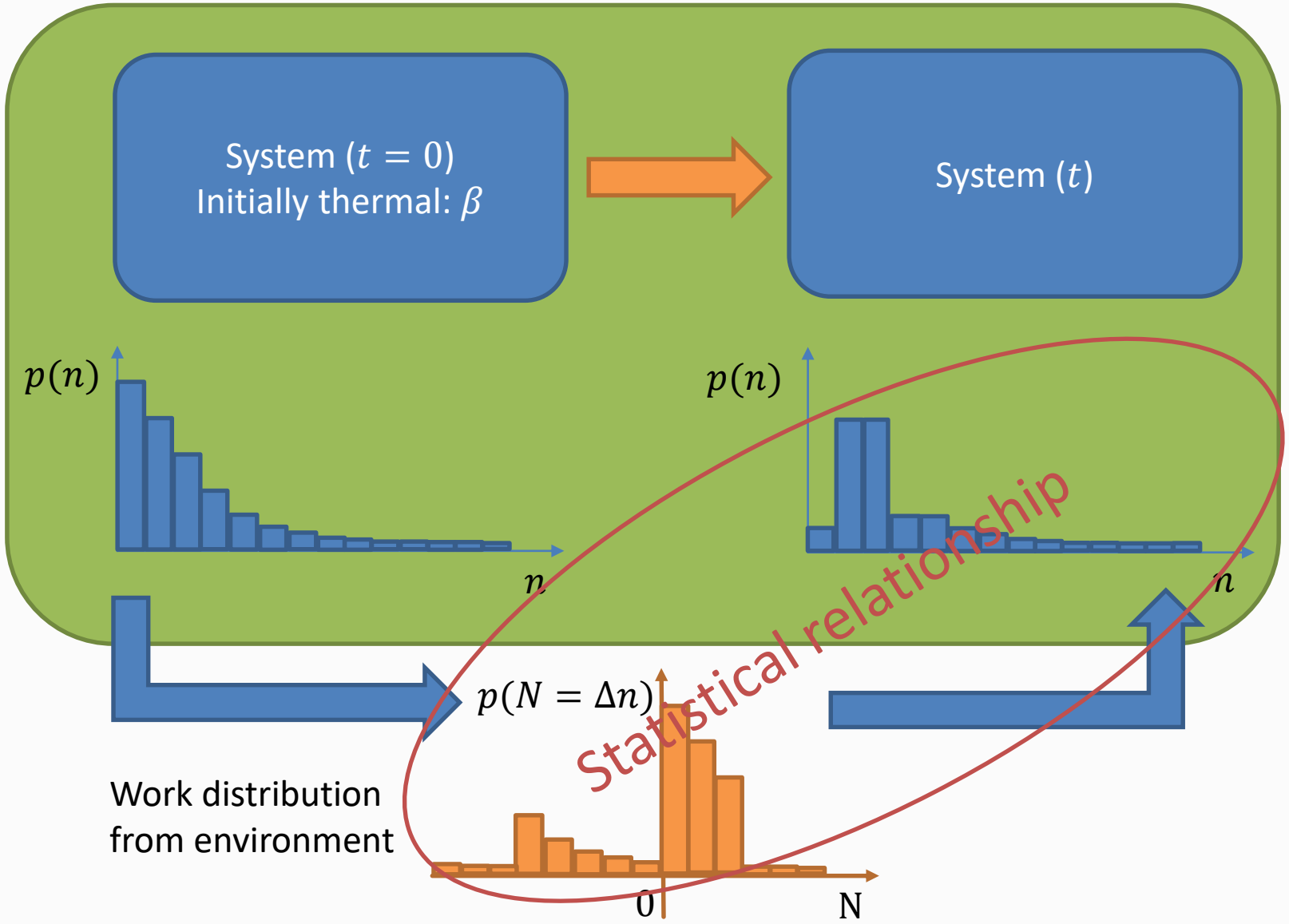
M. Buser, J. Cerrillo, G. Schaller, J. Cao, PRA 96, 062122 (2017).

M. Esposito, U. Harbola and S. Mukamel, *RMP 81*, 1665–1702 (2009).

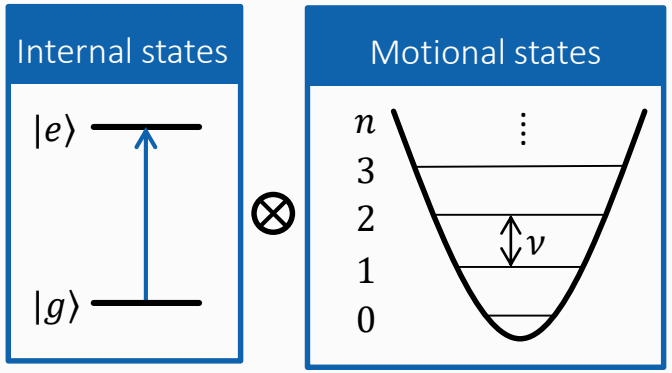
Atomic clock preparation

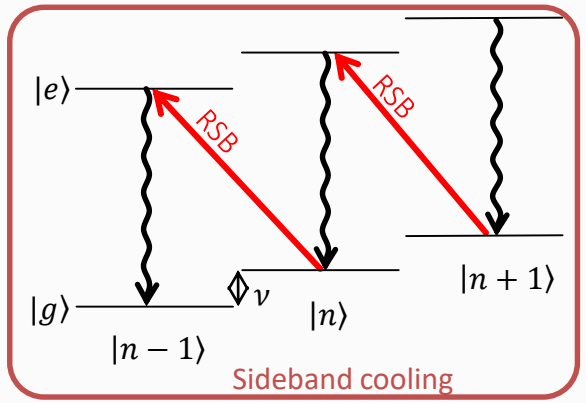


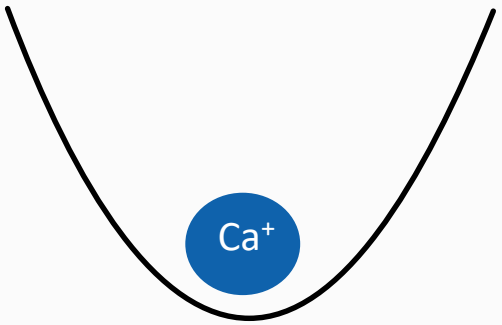
State preparation

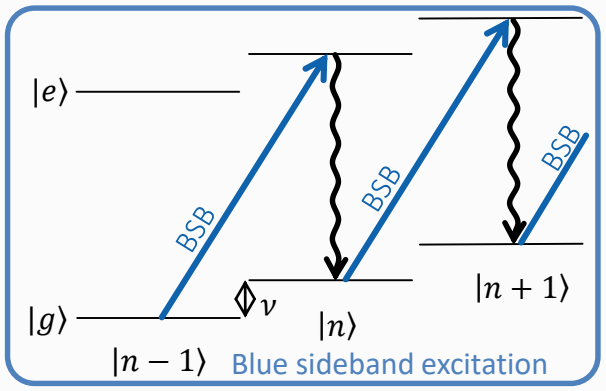


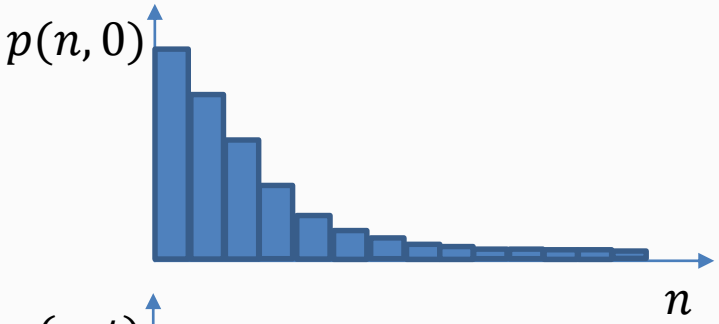
Atomic clock preparation

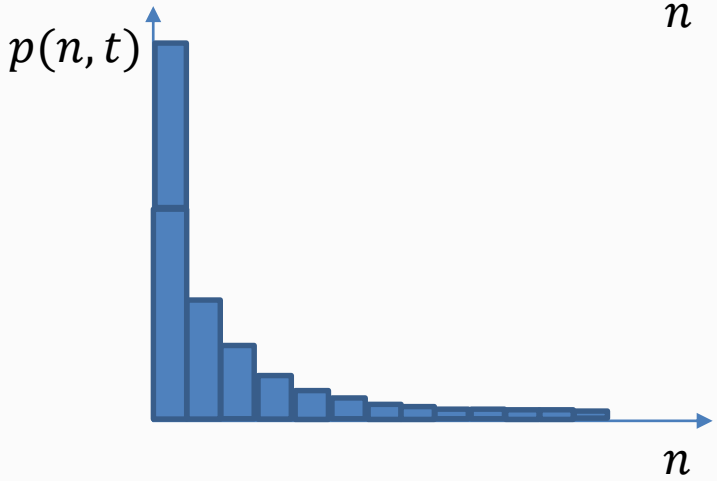


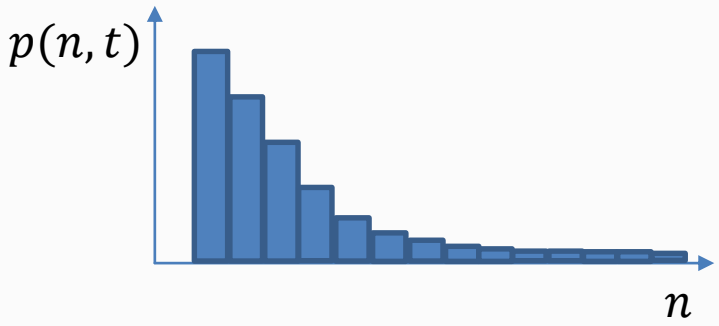




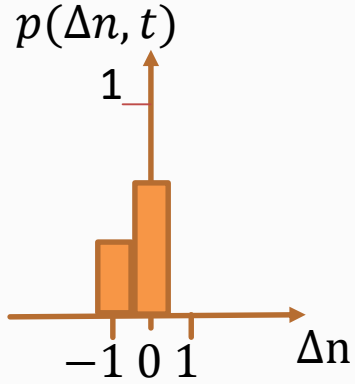


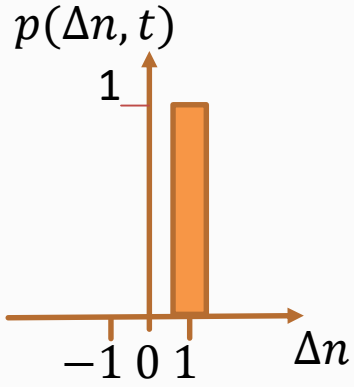




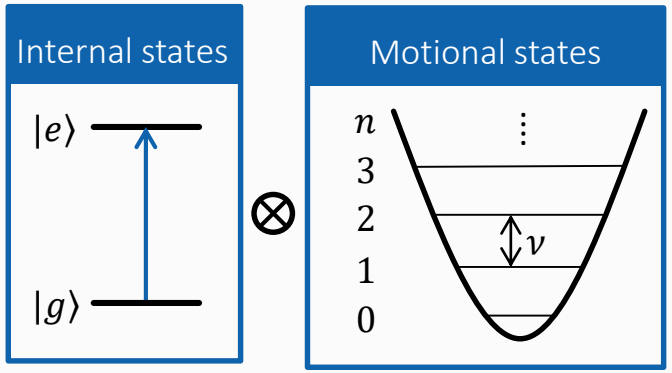


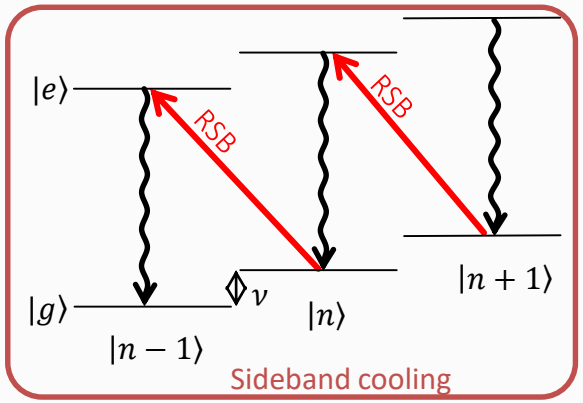
Transferred environmental energy (Work distribution)

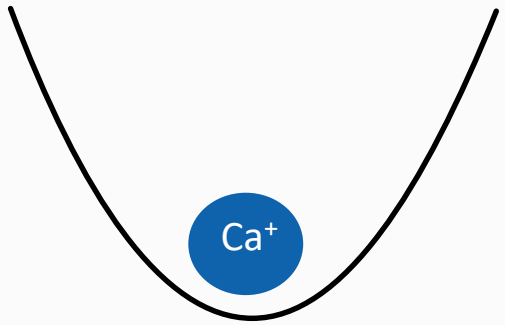


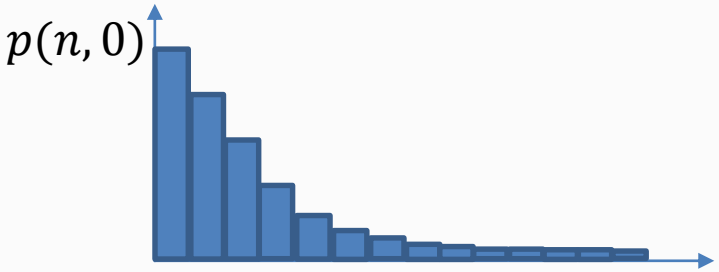


Atomic clock preparation

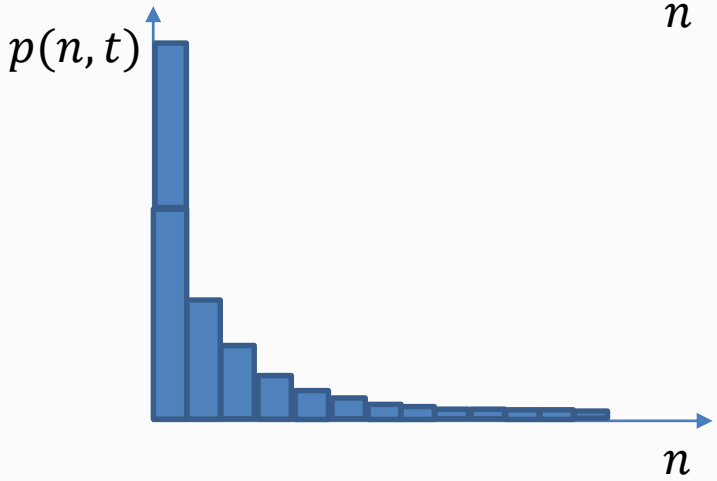


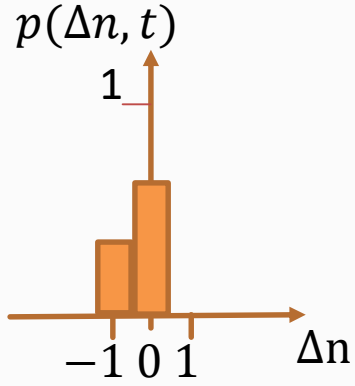






Transferred environmental energy (Work distribution)





$$\frac{\int e^{i\chi n} p(n,t)\,dn}{\int e^{i\chi n} p(n,0)\,dn} = \int e^{i\chi\Delta n}\, p(\Delta n,t)\,d\Delta n\Big|_{\beta=\beta-i\chi}$$

In terms of cumulant generating functions $C(\chi,t,\beta)$:

$$c(\chi,t,\beta) + F(\beta) - F(\beta - i\chi) = C(\chi,t,\beta - i\chi)$$

Symmetries in Full Counting Statistics

Shift of the counting field

$\chi \to -\chi + i\beta$

Forward / backward processes

- Fluctuation theorems

Free energy changes

- Jarzynski equality

Detailed balance

Correlation Functions:
Absorption and emission
$A(t) \propto E(-t + i\beta)$

Shift of the thermodynamic constraint

$\beta \to \beta - i\chi$

$$c(\chi, t, \beta) + F(\beta) - F(\beta - i\chi) = C(\chi, t, \beta - i\chi)$$

C - Transport cumulants

F - Free energy

c – State cumulants

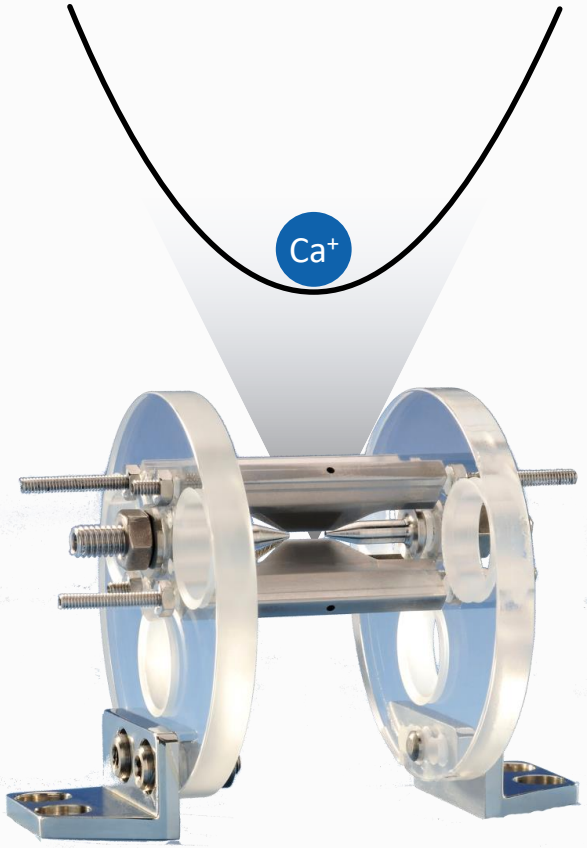
Valid under

- Strong-coupling
- Non-Markovianity
- Non-thermal environments

J. Cerrillo, M. Buser and T. Brandes, PRB 94, 214308 (2016).

Fast state preparation in trapped ion atomic clocks

- Attempt to go **beyond** the cooling speed limits of **sideband cooling.**
- Implementation of a double **electromagnetically-induced transparency** cooling scheme.
- The larger the **detuning** of the laser, the higher laser intensity can be used.



Rate as a figure of merit

$$R = \frac{\partial}{\partial\langle n\rangle}\langle\dot{n}\rangle$$

$$c(\chi,t,\beta) + F(\beta) - F(\beta - i\chi) = C(\chi,t,\beta - i\chi)$$

Fluctuation-dissipation like relation

$$R = \frac{-1}{2Cdt}\left[\Delta\langle\langle n^2(dt)\rangle\rangle - \langle\langle\Delta n^2(dt)\rangle\rangle\right]$$

Heat capacity of oscillator

Increase in state variance over dt

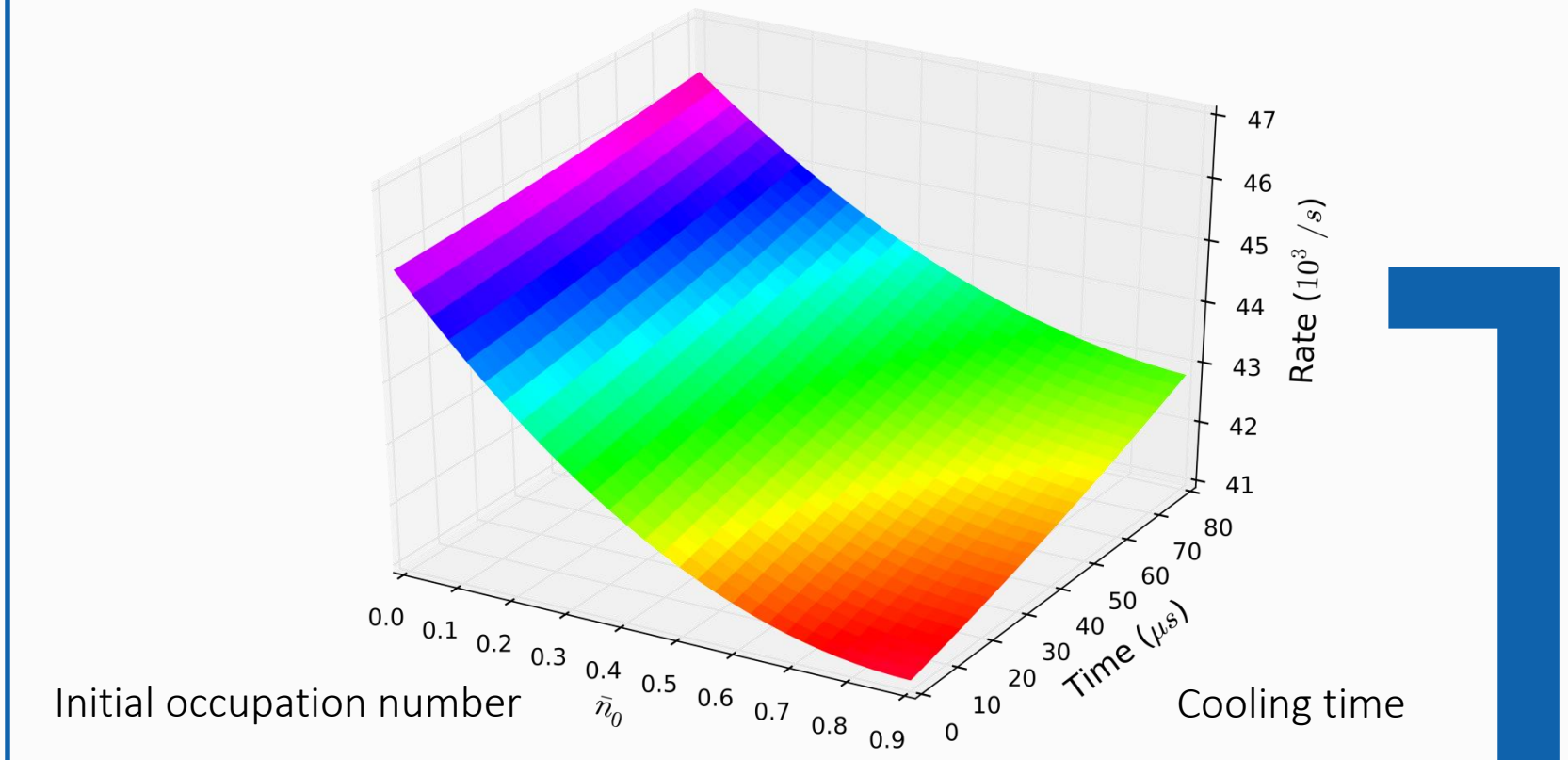
Variance of transferred phonons over dt

1. Weak coupling limit: Rate is independent of initial temperature
2. Increasing laser intensity: contribution to rate increase is detrimental and temperature dependent

N. Scharnhorst, J. Cerrillo et al., PRA 98, 023424 (2018).

Full master prediction for cooling rate

Time dependent axial single EIT cooling rate R(t, n_0) at $\Delta = 3\Gamma$



Initial occupation number

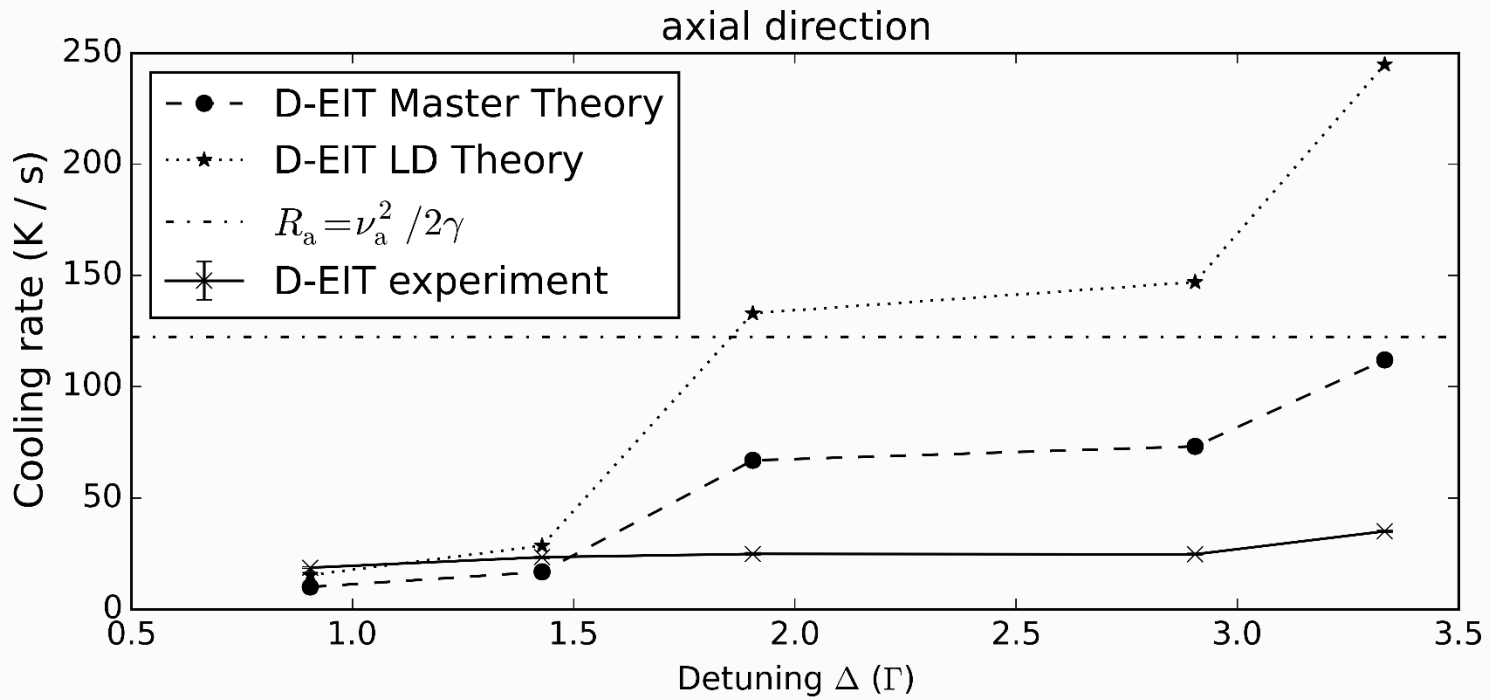
Cooling time

Lamb-Dicke theory: $52.2 \times 10^3\ s^{-1}$
Measured: $38.2 \times 10^3\ s^{-1}$

N. Scharnhorst, J. Cerrillo et al., PRA 98, 023424 (2018).

Full master prediction for cooling rate

Lamb Dicke, Master equation and Experimental cooling rates



- Contrary to the prediction of the weak coupling theory, the cooling rate does not increase with detuning/laser intensity.
- There exists an upper bound to the cooling rate **imposed by the initial temperature** of the ion.

N. Scharnhorst, J. Cerrillo et al., PRA 98, 023424 (2018).

Summary

$$c(\chi, t, \beta) + F(\beta) - F(\beta - i\chi) = C(\chi, t, \beta - i\chi)$$

- The preparation of a specific state involves an **exchange of an energy** distribution **with the environment**.
- Both distributions are non-trivially **related** through the expression above.
- The initial temperature of the system **imposes constraints** on state preparation
- These have been confirmed in **experiment** on atomic clock preparation.

J. Cerrillo, M. Buser and T. Brandes, PRB 94, 214308 (2016).
N. Scharnhorst, J. Cerrillo et al., PRA 98, 023424 (2018).

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Thank you for your attention!