SUPPLEMENTARY INFORMATION

For cavity cooling in the weak coupling regime $\eta \ll 1$, coherences [S1, S2] decay rapidly, and rate equations are sufficient to describe the cooling [S3]. For one-dimensional cooling along the cavity axis z, the rate of transitions from motional state $|n\rangle$ to $|n-1\rangle$ is

$$\frac{\Gamma_{sc}\eta\eta_{LD}^2 n}{1+4\left(\delta_{lc}+\omega\right)^2/\kappa^2} \equiv R^- n, \tag{S1}$$

and the rate of transitions from motional state $|n\rangle$ to $|n+1\rangle$ is

$$\frac{\Gamma_{sc}\eta\eta_{LD}^2(n+1)}{1+4(\delta_{lc}-\omega)^2/\kappa^2} + \Gamma_{sc}C\eta_{LD}^2 + \dot{n}_{ext} \equiv R^+(n+1) + N^+, \tag{S2}$$

where Γ_{sc} is the photon scattering rate into free space, the number C is defined such that $C\eta_{LD}^2\hbar\omega$ is the average recoil heating along the z direction per free space scattering event, and $\dot{n}_{ext}$ is the heating rate along the z direction due to environmental electric field fluctuations in quanta per second. Here, $\eta_{LD}^2 = E_{rec}/(\hbar\omega)$ is the Lamb-Dicke parameter, as determined by the ratio of recoil energy E_{rec} and trap vibration frequency ω. Note that these transition rates are only valid in the Lamb-Dicke regime $\eta_{LD}^2 \langle n\rangle \ll 1$, which limits the applicability of this model to $\langle n\rangle \ll 70$ for our experimental parameters. The expectation value of the mean vibrational quantum number $\langle n\rangle_t$ evolves according to

$$\langle n\rangle_t = n_0 e^{-Wt} + n_\infty\left(1-e^{-Wt}\right) \tag{S3}$$

for $\delta_{lc} = -\omega$ (cooling),

$$\langle n\rangle_t = n_0 + \left(R^+ + N^+\right)t \tag{S4}$$

for $\delta_{lc} = 0$, and

$$\langle n\rangle_t = \left(n_0 + n_\infty + 1\right)e^{Wt} - \left(n_\infty + 1\right) \tag{S5}$$

for $\delta_{lc} = +\omega$ (heating), where $n_0 \equiv \langle n\rangle_{t=0}$ and $n_\infty \equiv \langle n\rangle_{t\to\infty}$ are the initial and steady-state value of $\langle n\rangle_t$, respectively. The cavity cooling rate constant W is given by

$$W = \frac{\Gamma_{sc}\eta\eta_{LD}^2}{1+\kappa^2/\left(2\omega\right)^2}, \tag{S6}$$

and the steady state average occupation number n_∞ is given by

$$n_\infty = \left(\frac{\kappa}{4\omega}\right)^2 + \left[\frac{C}{\eta} + \frac{\dot{n}_{ext}}{\Gamma_{sc}\eta\eta_{LD}^2}\right]\left[1+\left(\frac{\kappa}{4\omega}\right)^2\right]. \tag{S7}$$

For cavity cooling of the z motional mode in our experiment, we calculate $C = 1/3$ (photons are scattered isotropically for a $J = 1/2 \leftrightarrow J' = 1/2$ transition), and measure independently $\dot{n}_{ext} = 17(2)\ \mathrm{s}^{-1}$. Thus, for our experimental parameters, the heating due to environmental field fluctuations is negligible ($\dot{n}_{ext} \ll \Gamma_{sc}\eta\eta_{LD}^2$) and the expression for the steady-state occupation number reduces to Eq. (1).

[S1] S. Zippilli and G. Morigi, Phys. Rev. Lett. **95**, 143001 (2005).
[S2] S. Zippilli and G. Morigi, Phys. Rev. A **72**, 053408 (2005).
[S3] V. Vuletić, H. W. Chan, and A. T. Black, Phys. Rev. A **64**, 033405 (2001).