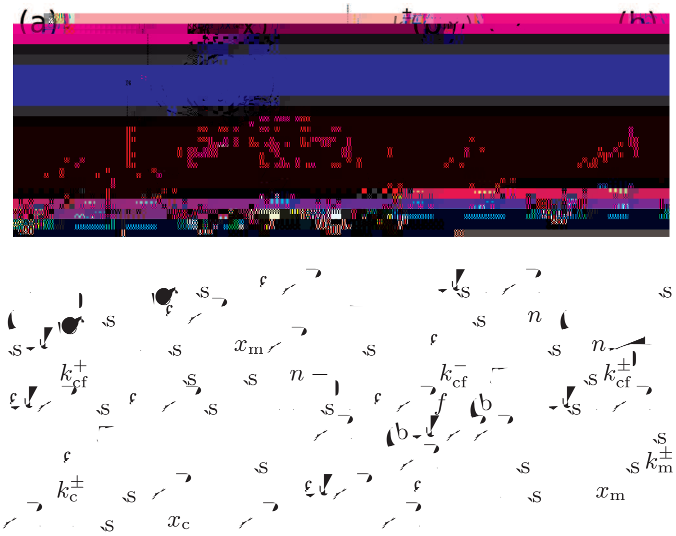
motors have been studied for decades [3], with recent experimental work observing their operation with improving resolution [4].

An important aspect of motor dynamics is the response to external forces, as the primary role of many in vivo motors is to tow cargoes, which impose drag forces. External forces are frequently modeled as constant across all motor cycles and cycle stages [5–13], recapitulating sophisticated experiments which use feedback to maintain near-constant resisting forces on the forward motion of molecular motors [14–17].

Molecular motors are also excellent systems in which to investigate statistical fluctuations at the nanoscale. Fluctuations in molecular motor progress have been related to the number of stages [6,18–20] and energy dissipation budget [21,22] for each motor cycle.

In this letter we investigate simple theoretical models of molecular motors towing cargo, with cargo represented either implicitly as a constant force or explicitly with diffusive dynamics. We find that constant-force models for cargo do not in general reproduce the step-number distributions of explicit diffusive-cargo models. The step-number Fano factor for diffusive cargo is also substantially less than when predicted solely from motor characteristics [6,18–22]. We demonstrate that diffusing cargo introduces a large number of effective stages to each motor cycle, allowing motors to increase the precision of their progress by pulling cargo, and often rendering the number of motor states irrelevant to the precision of motor progress. Our new, more permissive bound on the precision of motor progress, expressed in eq. (12), only depends on the energy dissipation budget per cycle.

**Model.** – Molecular motor dynamics are commonly described as stochastic transitions between discrete states. For a simple one-state unicyclic model, every forward cycle results in a forward step of the motor and consumption of the free-energy budget per cycle. For "constant-force" motor dynamics (shown schematically in fig. 1(a)), we use static transition rate constants



energies to units of $_{\rm B}T$, for Boltzmann's constant $_{\rm B}$ and temperature $T$.

The transition rate constants in eq. (1) (as well as all other model variations in this work) satisfy microscopic reversibility, quantified by the general detailed balance condition $^{+}_{\rm cf}\ \ ^{-}_{\rm cf}$ = exp($\Delta G$) for free-energy difference $\Delta G$, reducing at equilibrium to detailed balance and no net flux. This condition is a standard constraint on rate constants in thermodynamically consistent models of molecular motors [5,9,12,23–26].

The forward transition rate constant in eq. (1) is affected by the load $\Delta G_{\rm cf}$, while the reverse rate constant is unaffected. This is a specific limiting case of how load can impact rate constants, as the influence of the load can generally be split between the forward and reverse rate constants [12,23,25]. In the Supplementary Material (SM) ("Reverse-labile motor dynamics"), we show that the opposite extreme, where the load only increases the reverse rate constant and leaves the forward rate constant unchanged, does not change our conclusions.

The motor diffusivity is

$$D_{\rm cf} \quad d_{\rm m} \frac{n \qquad n}{2t} \tag{2}$$

where $n$ is the net number of forward motor steps over time $t$. In terms of rate constants [13],

$$D_{\rm cf} = \frac{1}{2}( \ ^{+}_{\rm cf} + \ ^{-}_{\rm cf}) d_{\rm m} \tag{3}$$

We also consider a similar "diffusing-cargo" kinetic model of a motor taking forward and reverse steps while coupled by a Hookean spring (with spring constant $_{\rm spring}$) to a cargo also taking discrete steps (fig. 1(b)). The motor has transition rate constants

$$^{+}_{\rm m} = \ _{\rm m} e^{\omega \ G^{+}_{\rm sm}(x_{\rm m}-x_{\rm c})} \quad \text{and} \quad ^{-}_{\rm m} = \ _{\rm m} \tag{4}$$

and the cargo has transition rate constants

$$^{\pm}_{\rm c} = \begin{cases} _{\rm c} & \text{if } \Delta G^{\pm}_{\rm sc}(x_{\rm m} \quad x_{\rm c}) \leq 0 \\ _{\rm c}\, e^{\ G^{\pm}_{\rm sc}(x_{\rm m}-x_{\rm c})} & \text{if } \Delta G^{\pm}_{\rm sc}(x_{\rm m} \quad x_{\rm c}) > 0 \end{cases} \tag{5}$$

which provide the standard Hookean response to an applied force in an overdamped medium [27], as derived in the SM ("Overdamped cargo dynamics under force"). $x_{\rm m}$ is the motor position and $x_{\rm c}$ is the cargo position. $_{\rm m}$ and $_{\rm c}$ are the bare rate constants for the motor and cargo, respectively; we choose a timescale such that $_{\rm m}$ = 1. $G_{\rm s}$ = $-\ _{\rm spring}(x_{\rm m} \quad x_{\rm c})$

For low cargo di□usivity, the cargo moves very slowly,

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