Long-time Correlations in Atom-Surface Dispersion Forces

D. Reiche, K. Busch, F. Intravaia
reiche@physik.hu-berlin.de
Max Born Institute

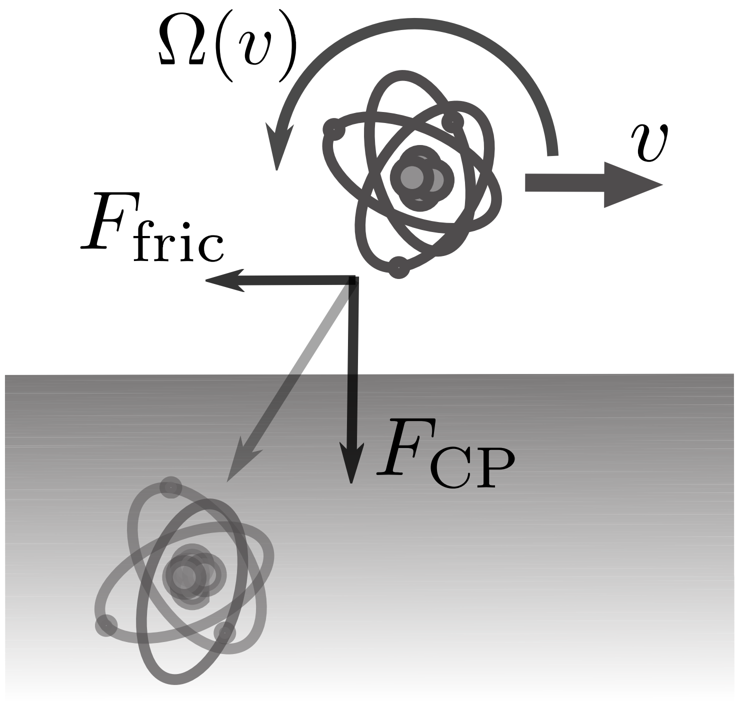
Nonequilibrium | Model | Fluctuations | Rolling Friction | Non-additivity

Neutral particles or bodies separated by nothing but vacuum can interact due to the quantum and thermal fluctuations of the electromagnetic field. Vacuum fluctuations, in particular, do not discriminate between different length scales and hence the corresponding dispersion forces acting on the constituents of the system derive from a broad range of frequencies.

In practice, however, realistic materials as well as external parameters of the experiment effectively constrain the range of frequencies that are relevant to the interaction. Approximate descriptions around possible resonances of the system are oftentimes justifiable which inevitably means that low-frequency fluctuations, or equivalently long-time correlations between the subsystems, are more or less neglected.

Focusing on the interaction between a microscopic particle and the material-modified vacuum, we argue that taking off-resonant long-time correlations properly into account can be crucial for understanding the dynamics of open quantum systems in certain situations. We analyze the spectral fluctuations of the electromagnetic field as well as the atomic dipole fluctuations and highlight their implications on the quantum friction experienced by an atom moving in the vicinity of a vacuum-material interface.

$$\mathrm{F}=\sum_j \left\langle \hat{d}_j \nabla \hat{E}_j \right\rangle \neq \sum_j \left\langle \hat{d}_j \right\rangle \left\langle \nabla \hat{E}_j \right\rangle$$



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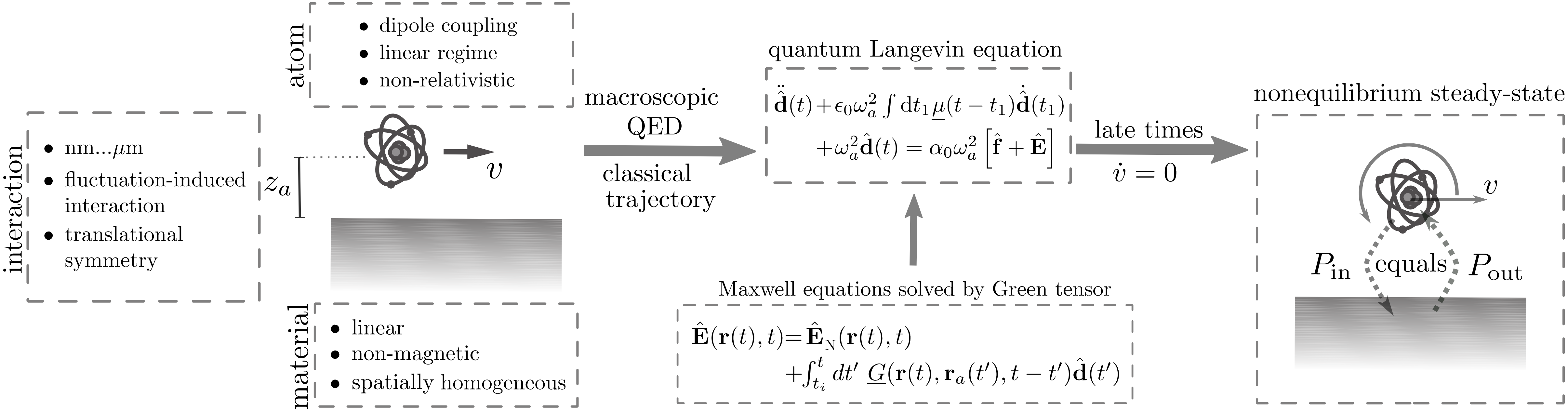

D. Reiche, PhD thesis (2020).

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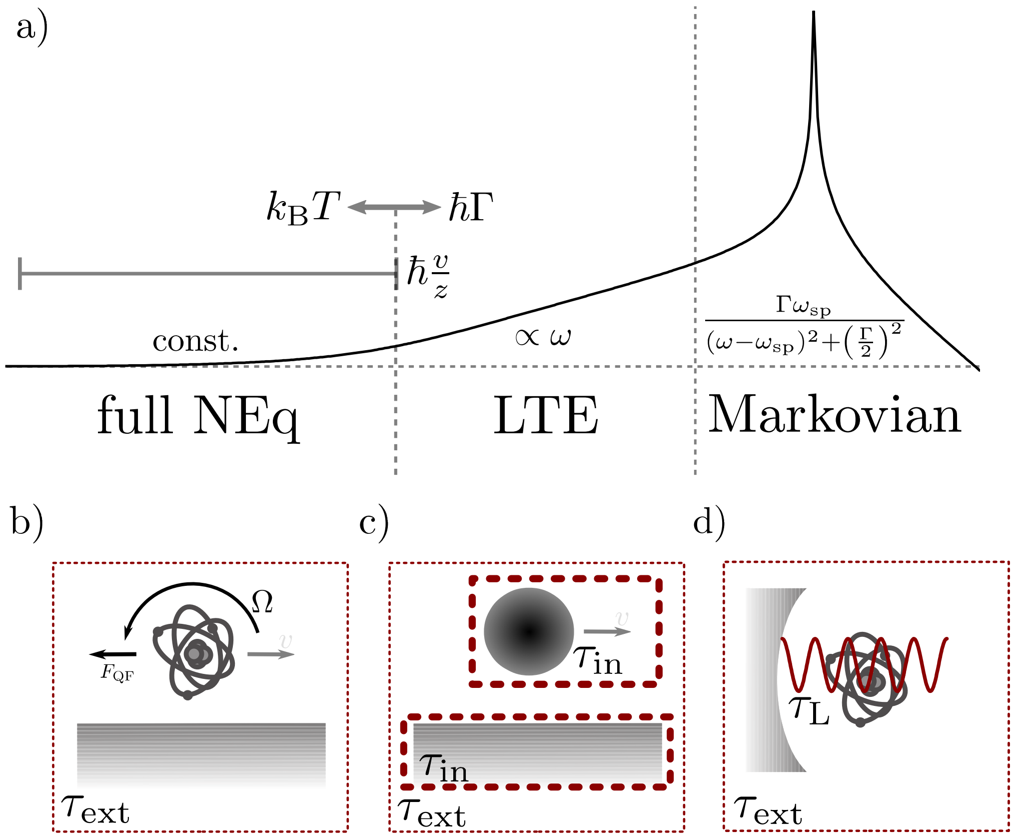
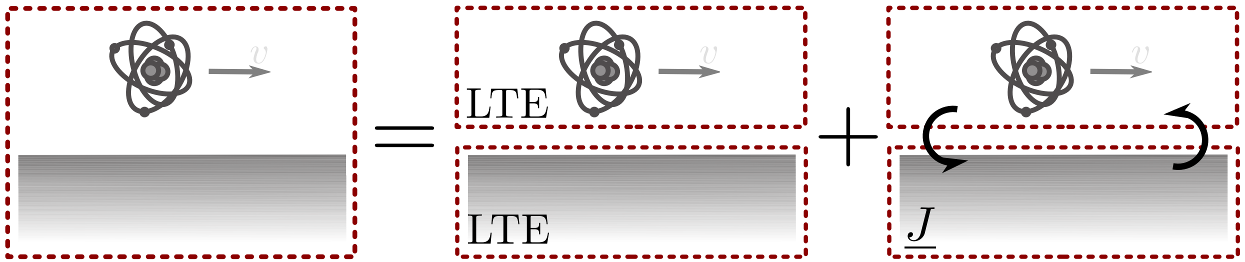
The fluctuations of the atomic dipole operator, given by its power spectrum $\underline{S}$, are self-consistently determined by the fluctuations of the material-modified vacuum field. In addition to the conventional fluctuation-dissipation theorem, since the system is in nonequilibrium, we find another contribution $\underline{J}$ to the statistics. It describes the impact of long-time correlations on the nonequilibrium statistics.

Quantum friction is particularly sensitive to small frequencies in the power spectrum. Here, commonly applied simplifications such as the Born-Markov approximation or the assumption of local thermal equilibrium (LTE) fail completely and we need to employ a full nonequilibrium formalism.



$$\underline{S}(\omega, v) = \frac{\hbar}{\pi}\theta(\omega)\underline{\alpha}_{\Im}(\omega, v) + \underline{J}(\omega, v)$$



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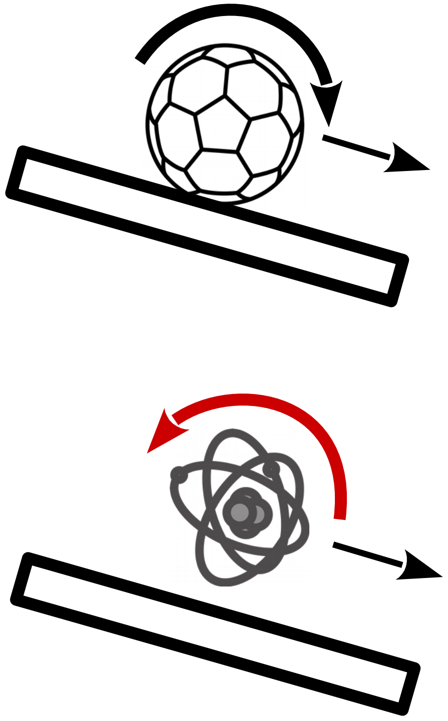
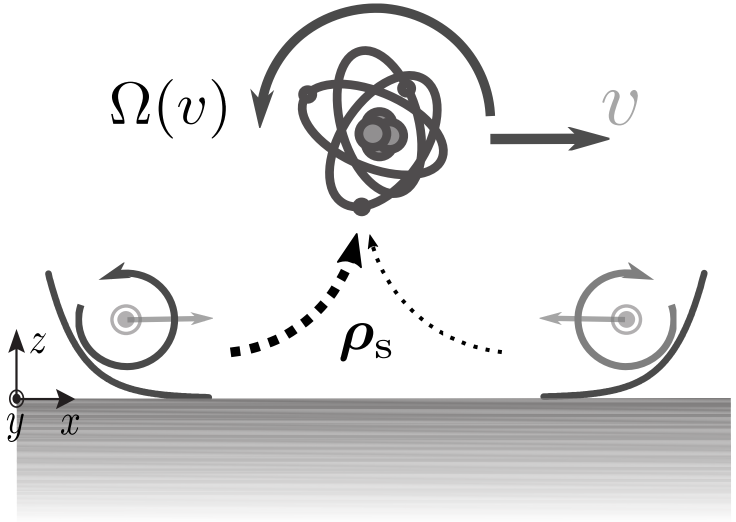
Humboldt-Universität zu Berlin





$$\Omega \sim -\frac{v}{z_a}\left[1+\left(\frac{1}{3}\frac{r_R(\omega_a)}{r_I(\omega_a)}\right)\right]^{-1}$$

Counter-intuitive sense of rotation

$$F \sim -\frac{63-45}{\pi^3}\hbar\alpha_0^2\rho^2\frac{v^3}{(2z_a)^{10}}$$

Reduction of force
due to angular momentum

Intravaia *et al.*, PRL **122**, 120401 (2019). | Football by Shakeel Ch. from the Noun Project.

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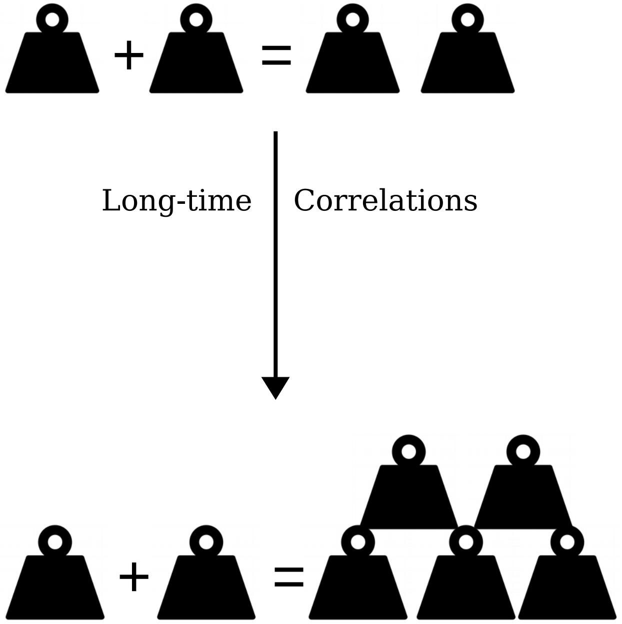
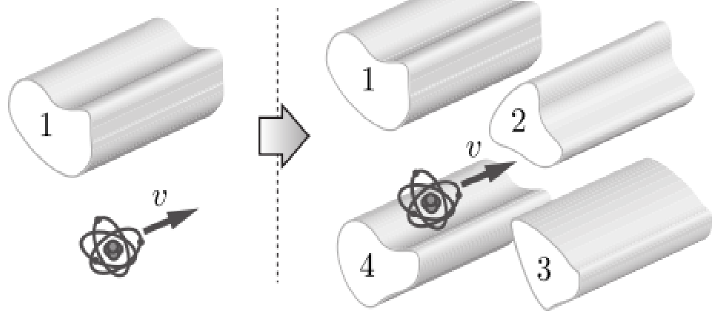
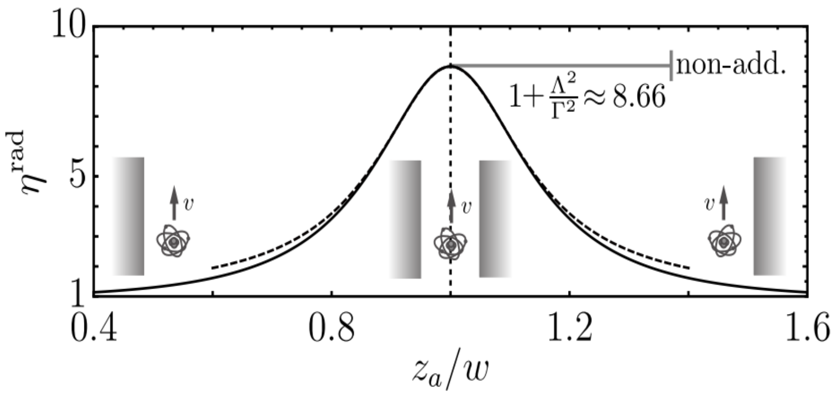
Nonequilibrium | Model | Fluctuations | Rolling Friction | **Non-additivity**







$$F \neq F_{\mathrm{add}} \sim N F_1$$

Long-time | Correlations

$$F \sim \phi N^2 F_1$$

Suppression of angular momentum transfer

Reiche *et al.*, PRL **124**, 193603 (2020). | Weight by styleku from the Noun Project.