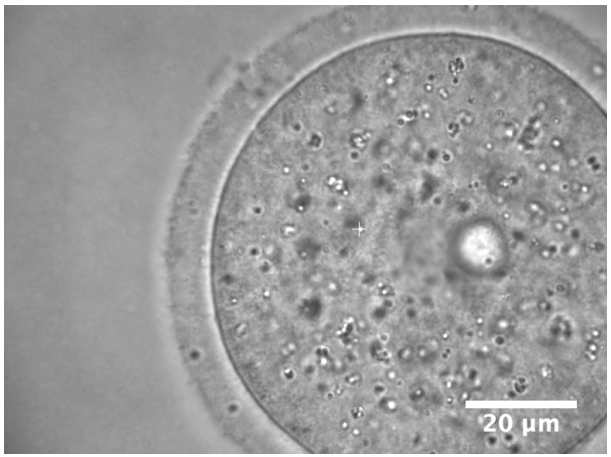
Modeling Active Fluctuations in Living Matter

Étienne Fodor[1], Wylie W. Ahmed[2], Timo Betz[2], Matthias Bussonnier[2], Nir S. Gov[3], Ming Guo[4], Vishwajeet Mehandia[5], Daniel Riveline[5], Paolo Visco[1], David A. Weitz[4], Frédéric van Wijland[1]



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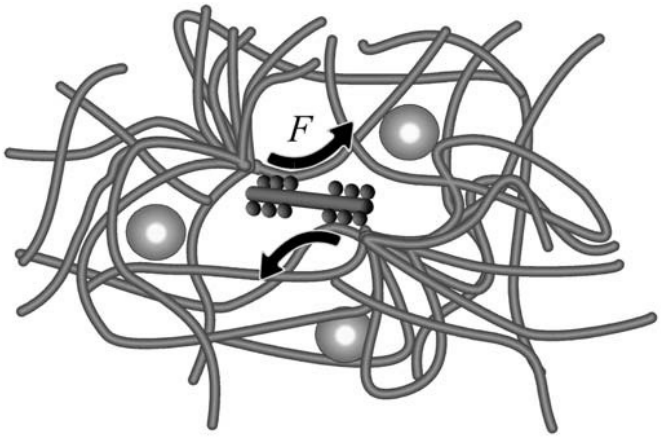
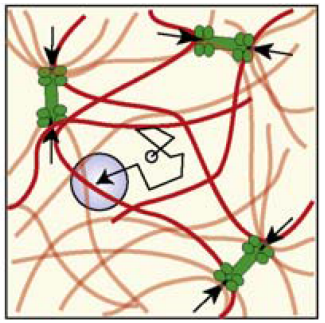
5. Laboratoire de Physique Cellulaire, Université de Strasbourg

Statistical challenges in Single-Particle Tracking

Introduction





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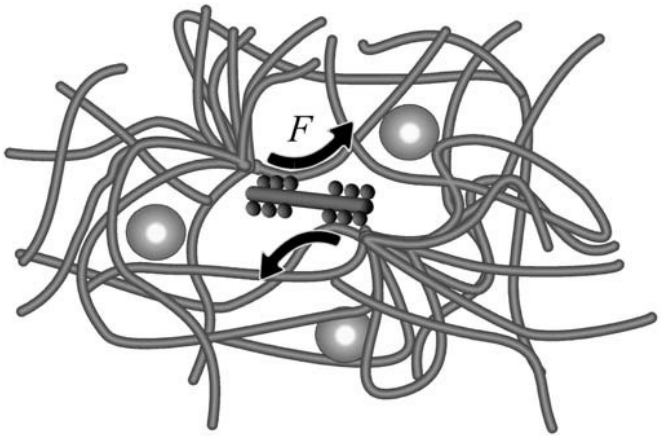
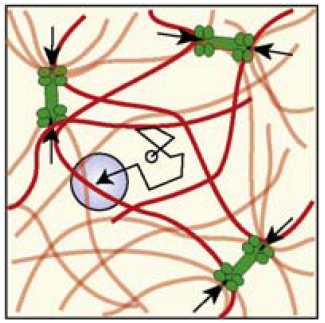
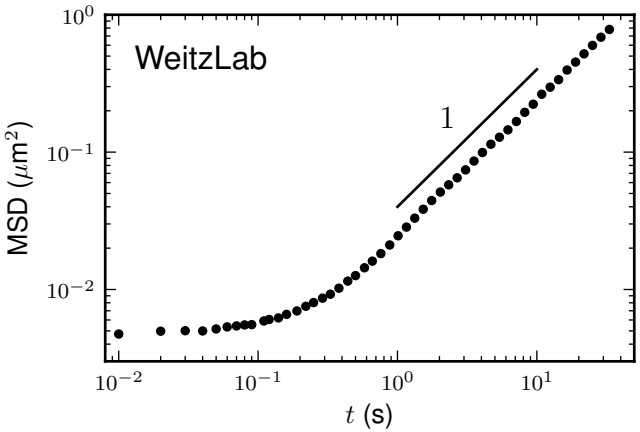




Mean square displacement



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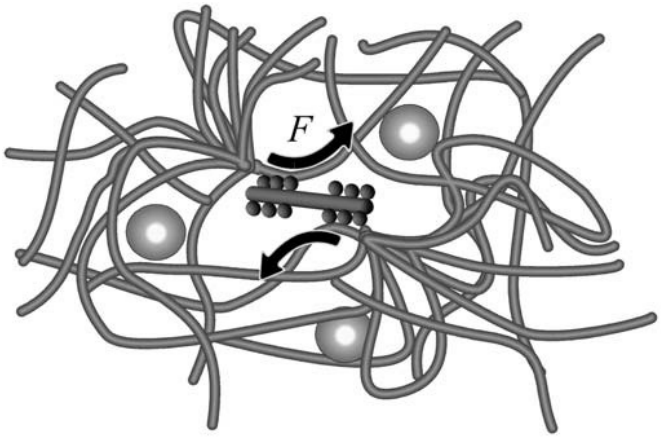

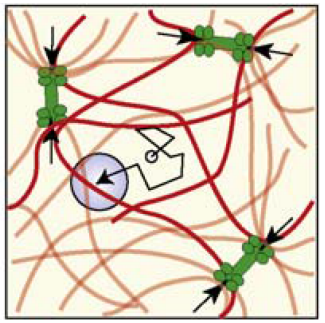

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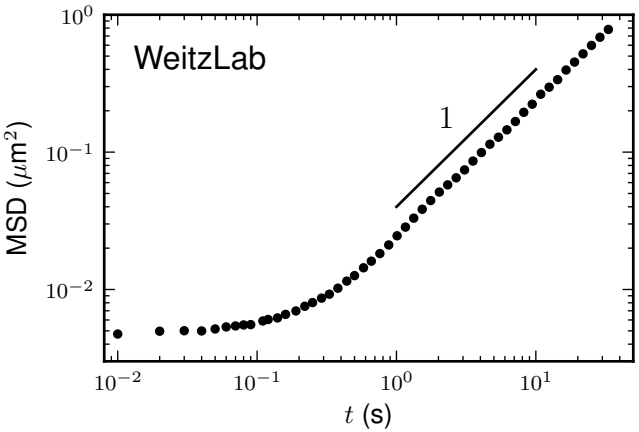
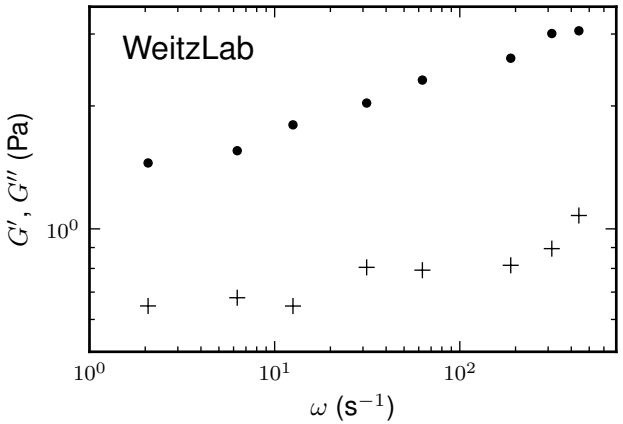


Complex modulus



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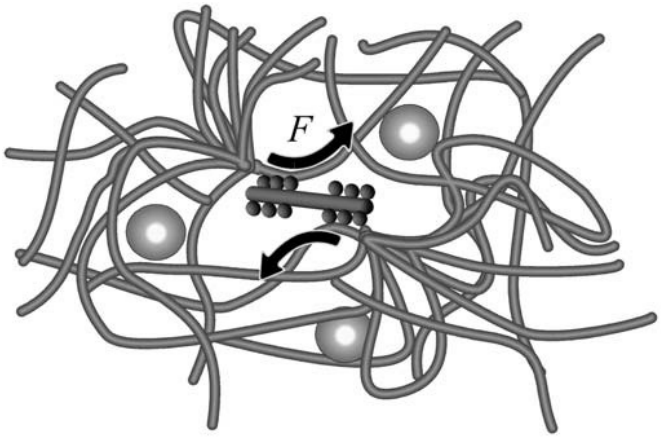

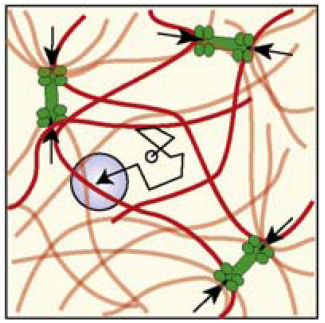

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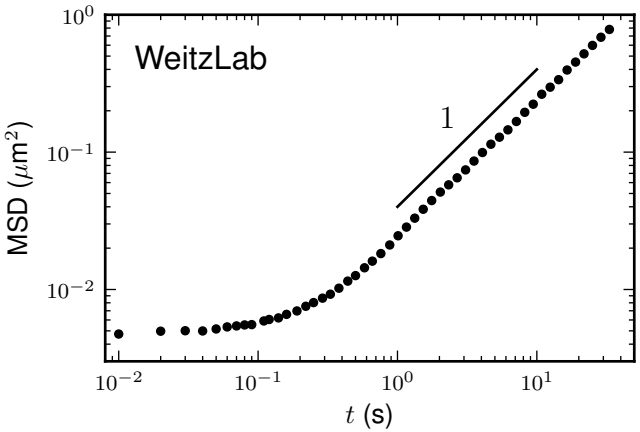

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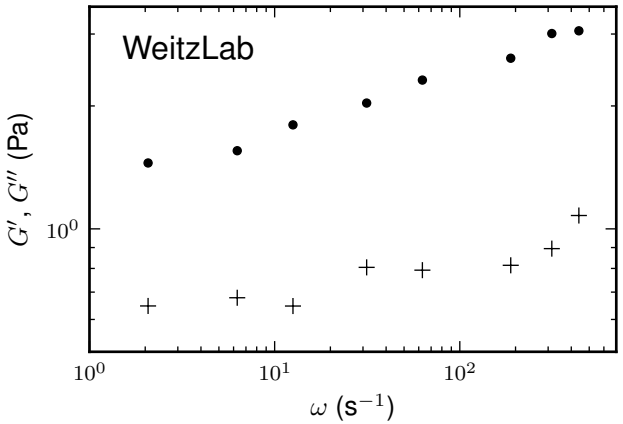
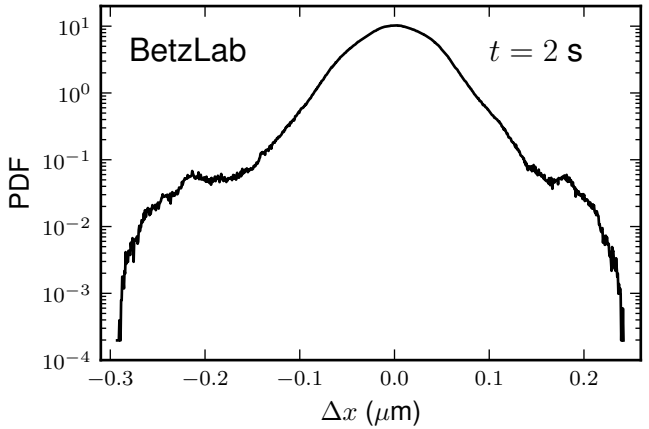


PDF of displacement



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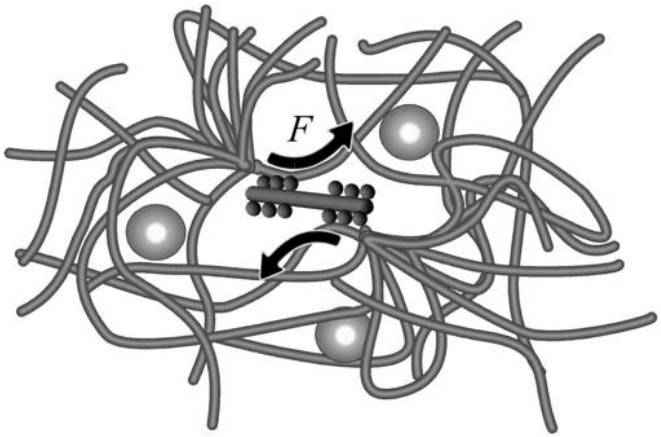

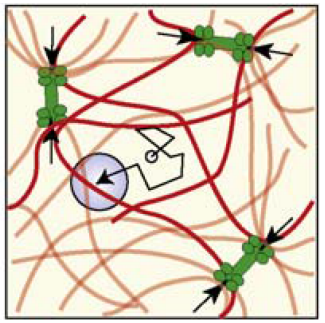

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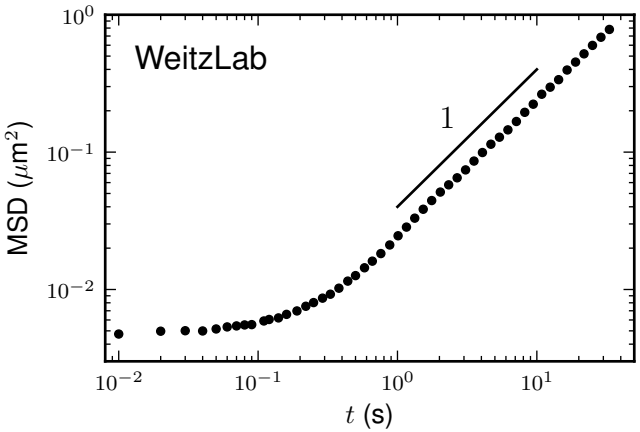

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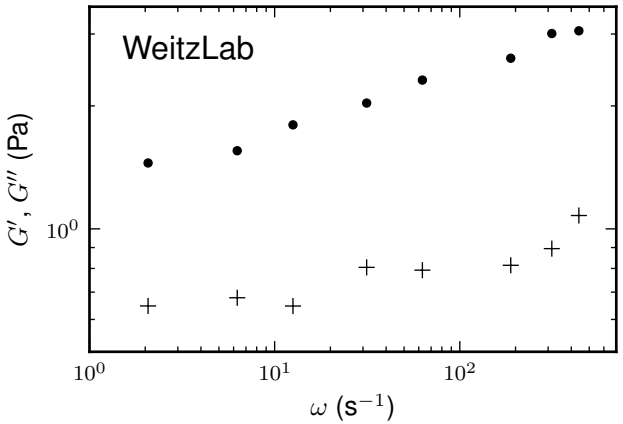

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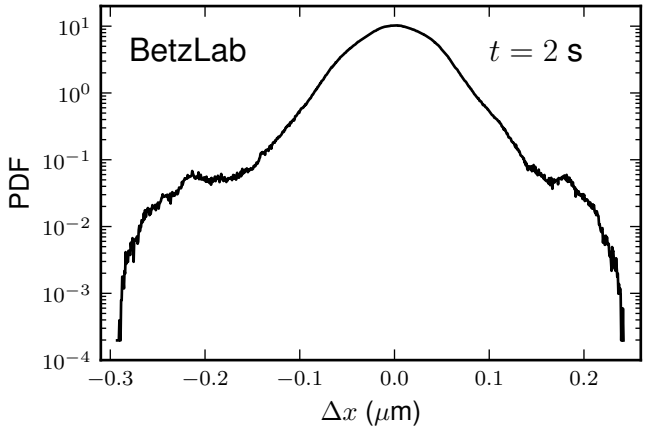

Is it possible to extract information about molecular motor activity?

Propose a model for the tracers' dynamics

Outline

Activity driven fluctuations in living cells

Ming Guo, David A. Weitz

Outline

Activity driven fluctuations in living cells

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1. Modeling tracer's dynamics

Outline

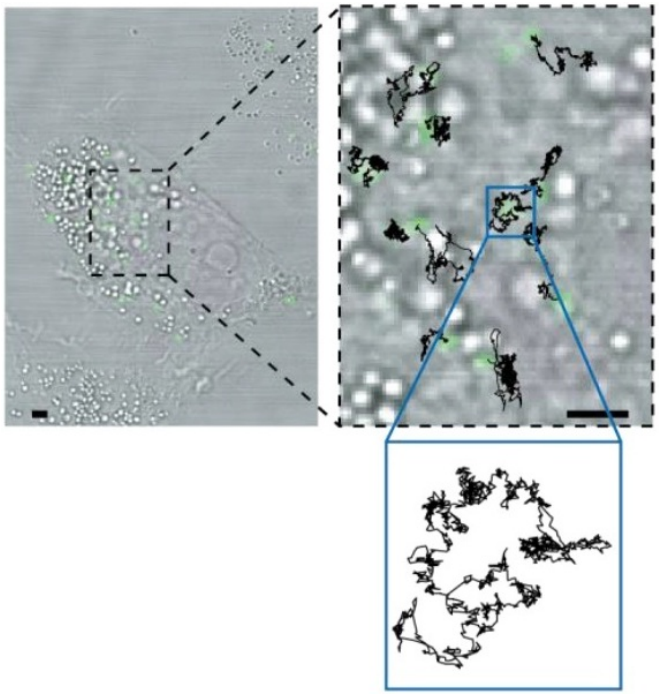
Activity driven fluctuations in living cells

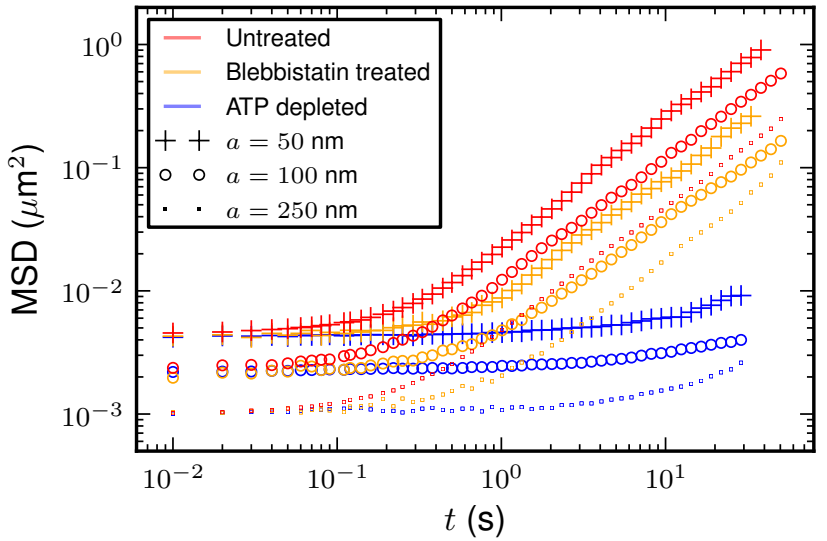
Ming Guo, David A. Weitz

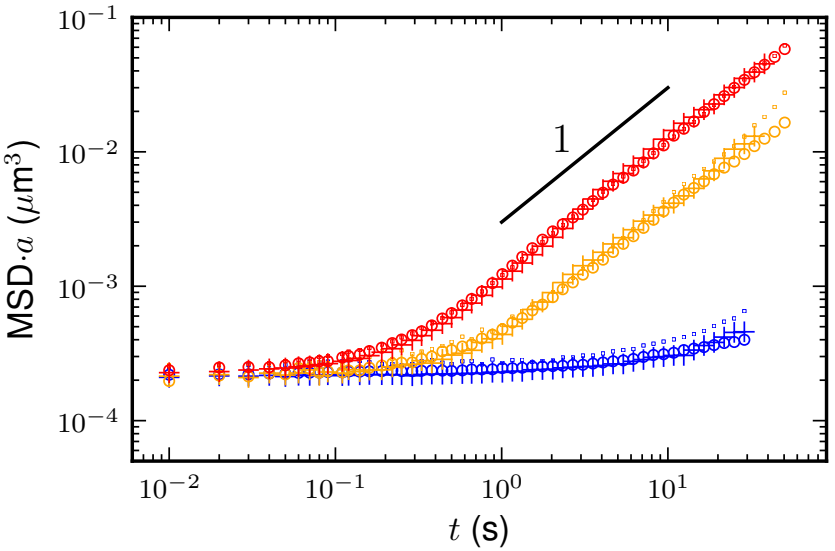
1. Modeling tracer's dynamics
2. Characterizing active force

Modeling tracer's dynamics

Experimental results

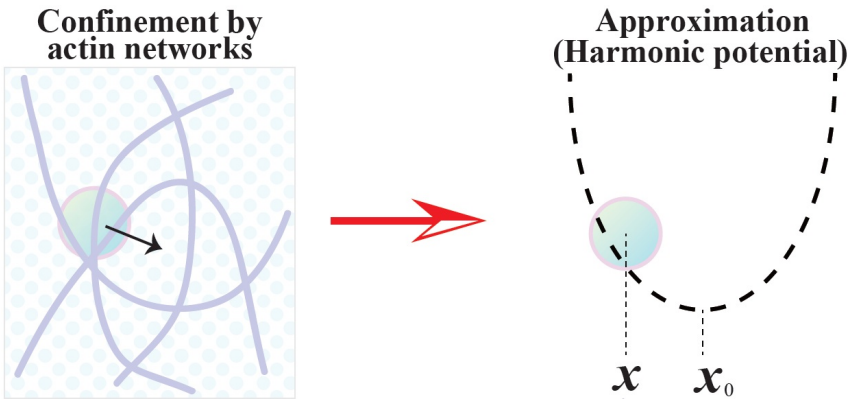






Modeling tracer's dynamics

Equation of motion



Modeling tracer's dynamics

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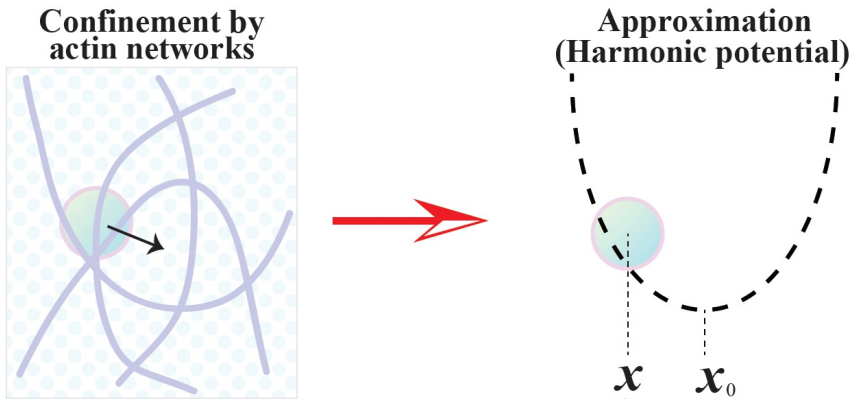


Tracer's dynamics

$$m\frac{\mathrm{d}^2\mathbf{r}}{\mathrm{d}t^2} = -\boldsymbol{\nabla} U + \mathbf{F}_\mathrm{S} + \mathbf{F}_\mathrm{th}$$

Harmonic potential: $U = \frac{k}{2}(\mathbf{r} - \mathbf{r_0})^2$

Stokes force: $\mathbf{F}_\mathrm{S} = -\gamma\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t}$

Gaussian white noise: $\mathbf{F}_\mathrm{th}$

Modeling tracer's dynamics

Equation of motion

Tracer's dynamics

$$\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t} = -\frac{1}{\tau_\mathrm{d}}(\mathbf{r} - \mathbf{r_0}) + \sqrt{2D_\mathrm{T}}\boldsymbol{\xi}$$

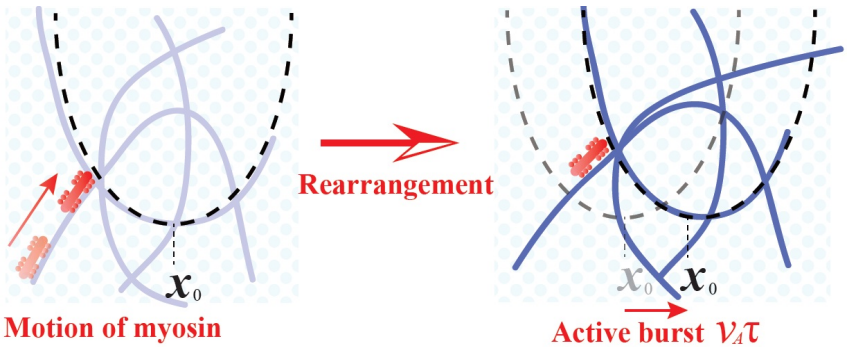
Modeling tracer's dynamics

Equation of motion

Tracer's dynamics

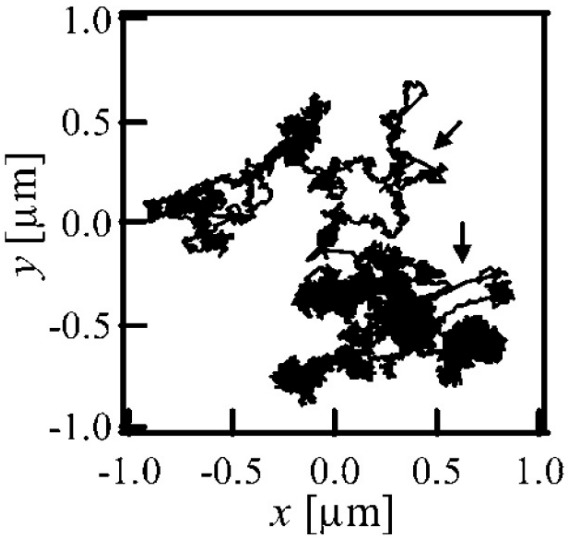
$$\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t} = -\frac{1}{\tau_\mathrm{d}}(\mathbf{r} - \mathbf{r_0}) + \sqrt{2D_\mathrm{T}}\boldsymbol{\xi}\ , \qquad \frac{\mathrm{d}\mathbf{r_0}}{\mathrm{d}t} = \mathbf{v}_\mathrm{A}$$

Active motion of local minimum



Modeling tracer's dynamics

Active burst's statistics



Modeling tracer's dynamics

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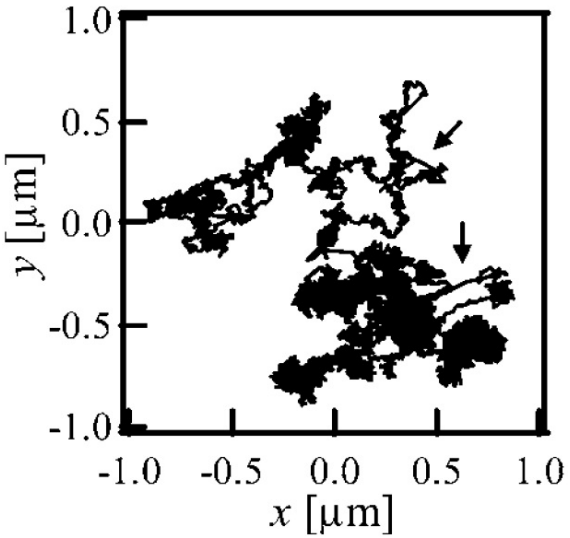

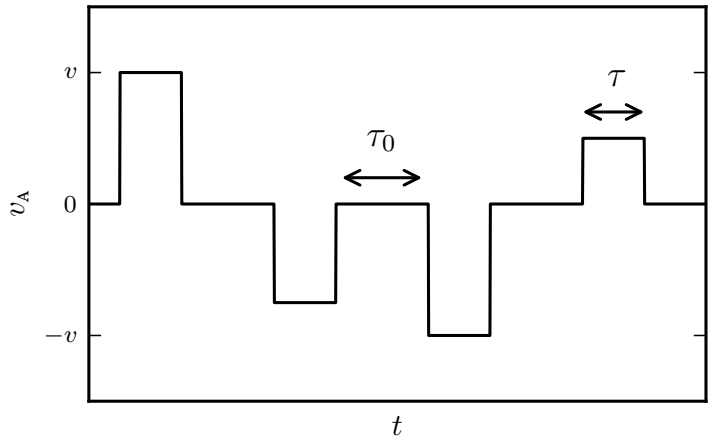

Modeling tracer's dynamics

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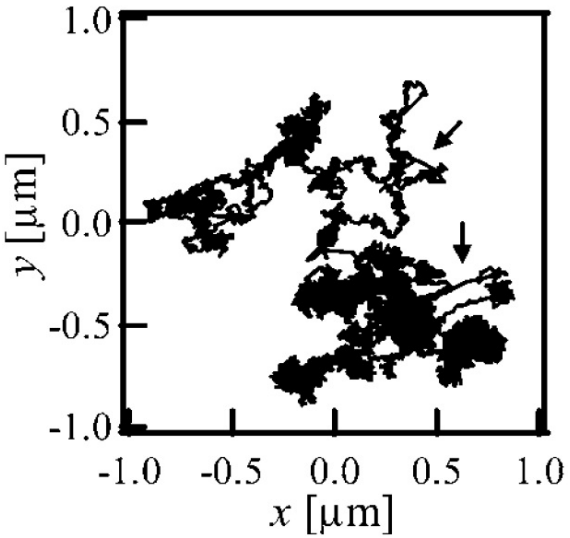
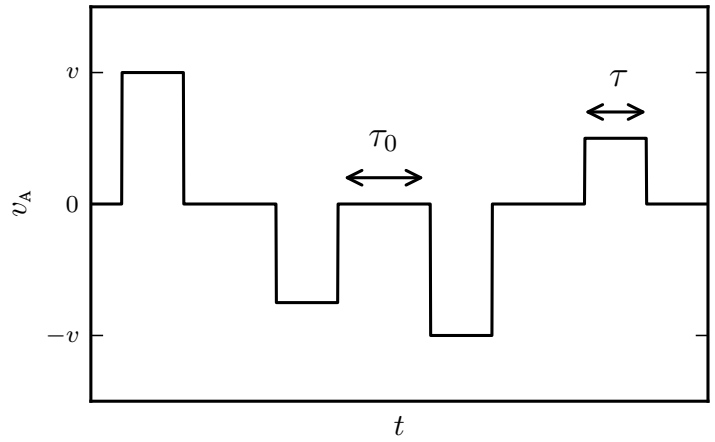




2–time correlation function

$$\langle v_A(t) v_A(0) \rangle = \frac{D_A}{\tau} e^{-|t|/\tau} \quad , \quad D_A = \frac{(v\tau)^2}{3(\tau + \tau_0)}$$

Modeling tracer's dynamics

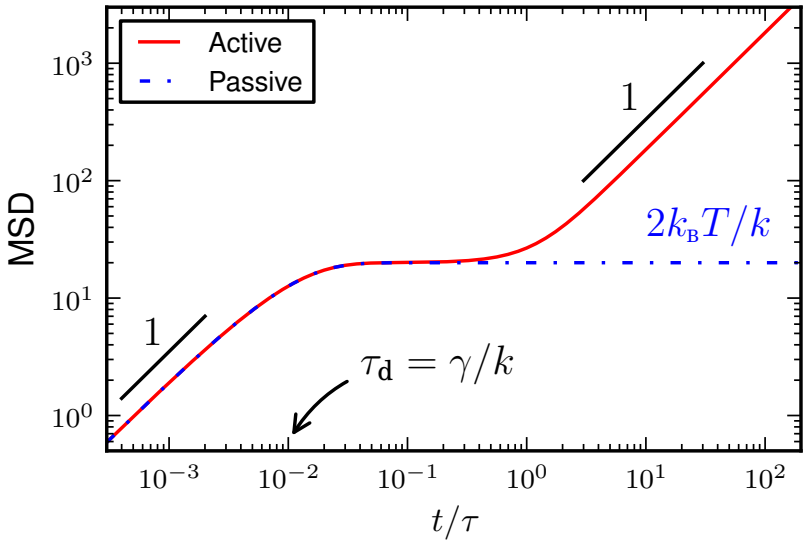
Tracer's statistics

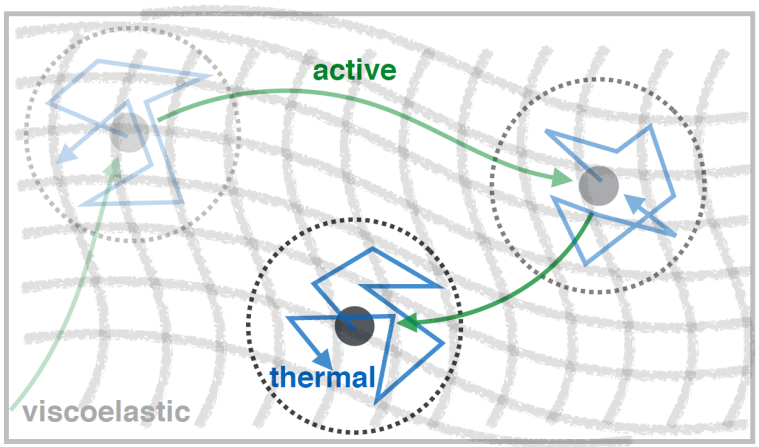
Short time Diffusion + Confinement

$\text{MSD} \sim 2D_{\text{T}}t$

Large time Free diffusion

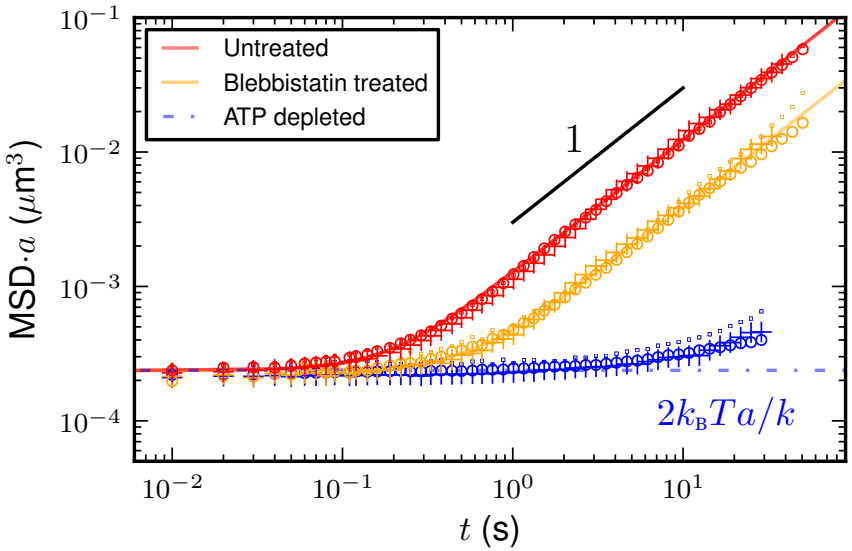
$\text{MSD} \sim 2D_{\text{A}}t$





Modeling tracer's dynamics

Fitting experimental results



Microscopic features

- Typical time of activity

  Untreated: $\tau = 0.16 \pm 0.03$ s, Bleb. treated: $\tau = 0.39 \pm 0.09$ s

- Amplitude of active fluctuations

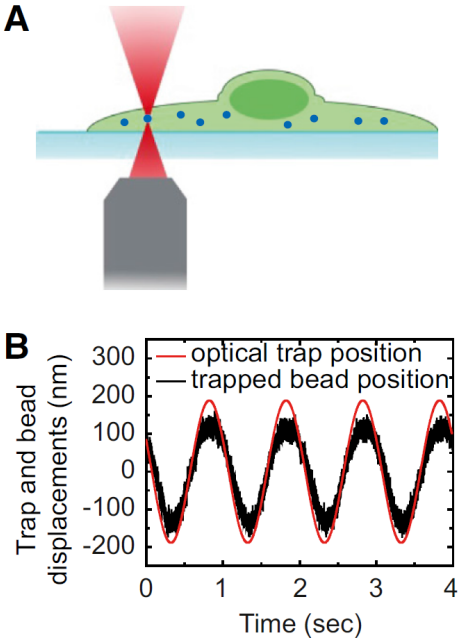
  Untreated: $D_A \simeq 2.8 \cdot 10^{-3} D_T$, Bleb. treated: $D_A \simeq 9.0 \cdot 10^{-4} D_T$

Characterizing active force

Nonequilibrium properties

Fluctuation dissipation

$$\chi''(\omega) = \frac{\omega C(\omega)}{2k_B T}$$



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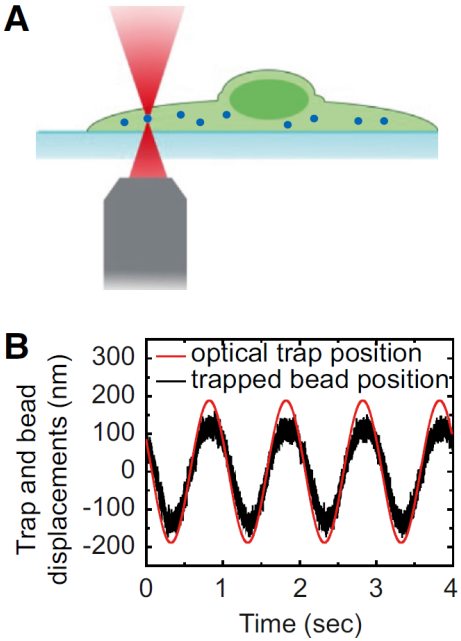
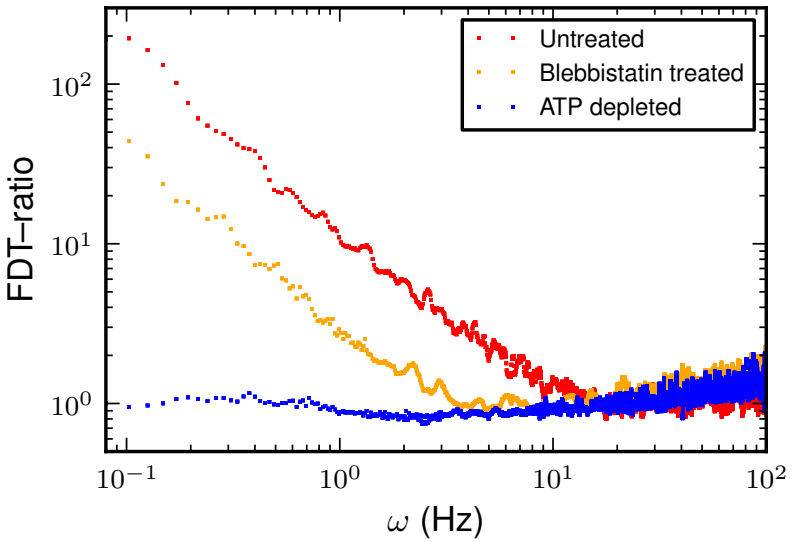




$$\text{FDT-ratio} = \frac{\omega C(\omega)}{2\chi''(\omega) k_B T}$$

Characterizing active force

Active force spectrum

Spectrum of stochastic forces

$$S_{\text{tot}}(\omega) = \frac{C(\omega)}{|\chi(\omega)|^2}$$

Characterizing active force

Active force spectrum

Spectrum of stochastic forces

$$S_{\text{tot}}(\omega) = \frac{C(\omega)}{|\chi(\omega)|^2}$$

Tracer's dynamics

$$\gamma \frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t} = -k\mathbf{r} + \mathbf{F}_{\text{th}} + \underbrace{\mathbf{F}_{\text{A}}}_{k\mathbf{r_0}} \quad \rightarrow \quad S_{\text{tot}} = S_{\text{th}} + S_{\text{A}}$$

Characterizing active force

Active force spectrum

Spectrum of stochastic forces

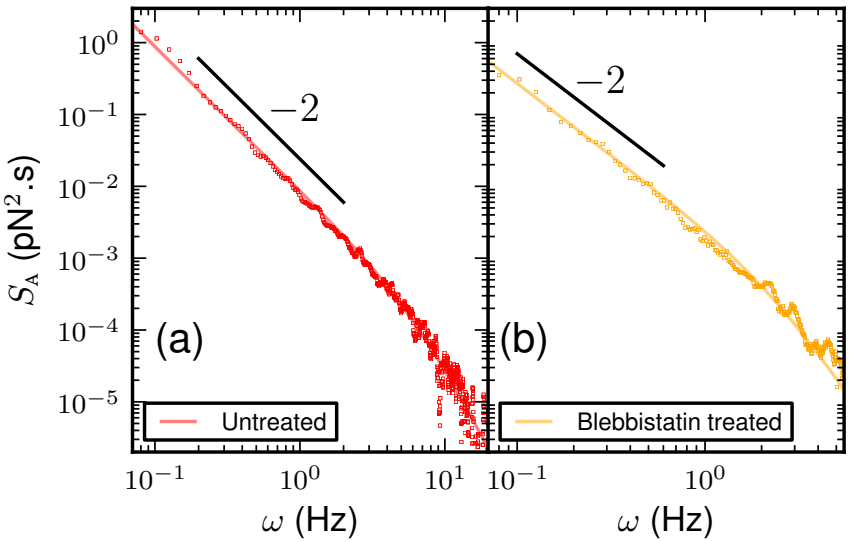
$$S_{\mathrm{tot}}(\omega) = \frac{C(\omega)}{|\chi(\omega)|^2}$$

Tracer's dynamics

$$\gamma \frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t} = -k\mathbf{r} + \mathbf{F}_{\mathrm{th}} + \cancel{\mathbf{F}_{\mathrm{A}}} \quad \rightarrow \quad \underbrace{S_{\mathrm{tot}} = S_{\mathrm{th}}}_{\text{ATP depleted}} + \cancel{S_{\mathrm{A}}}$$

Characterizing active force

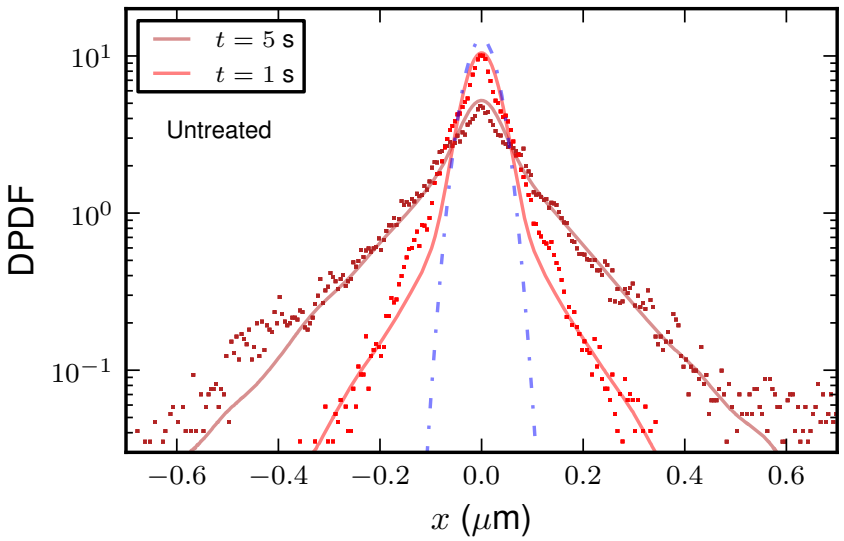
Active force spectrum

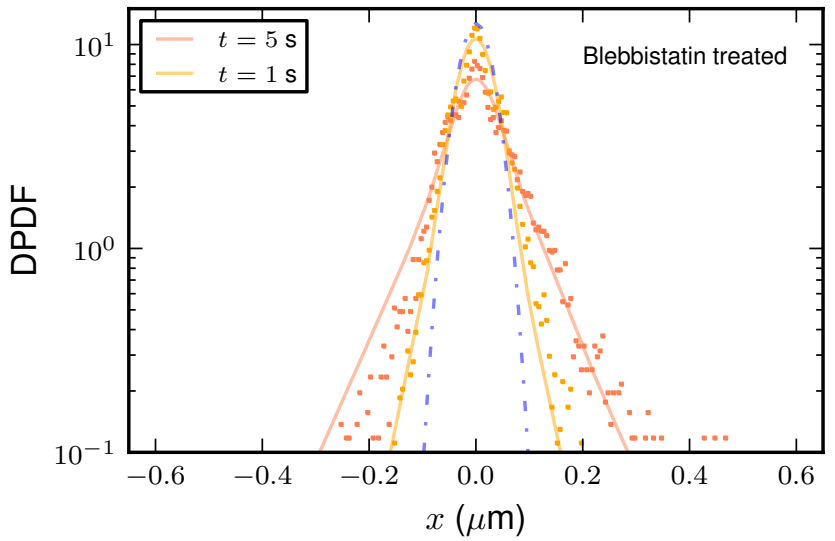


$$S_A(\omega) = \left(\frac{k}{\omega}\right)^2 \frac{2D_A}{1+(\omega\tau)^2}$$

Characterizing active force

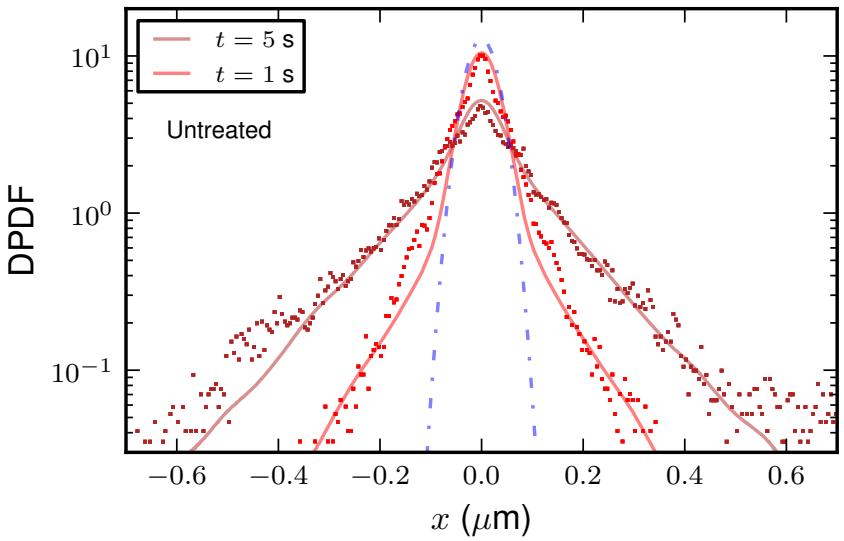
Probability distribution function of displacement

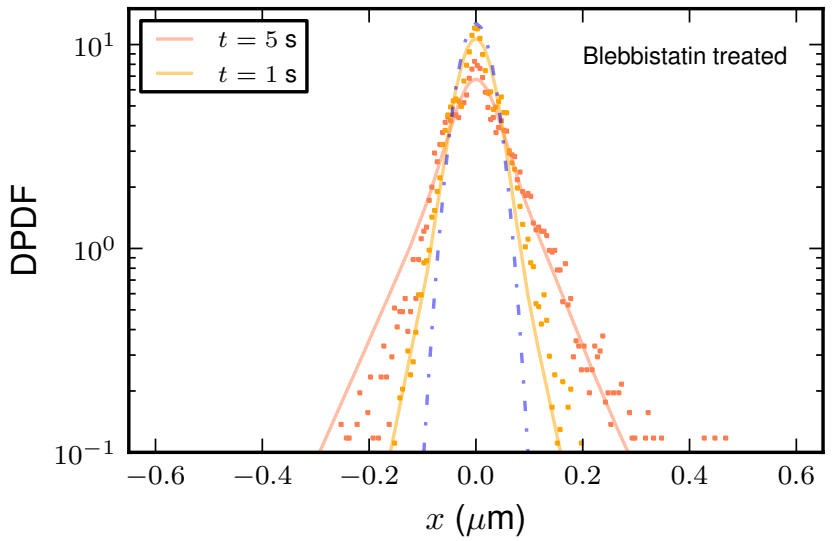




Characterizing active force

Probability distribution function of displacement





Numerical simulations $\rightarrow$ Duty ratio: $p_{\text{on}} = \dfrac{\tau}{\tau + \tau_0}$

Microscopic features

- Untreated: $p_{\text{on}} \simeq 6$ %, $\tau_0 \simeq 2.5$ s
- Blebbistatin treated: $p_{\text{on}} \simeq 15$ %, $\tau_0 \simeq 2.8$ s

Conclusion

New model tracer's dynamics

Two driving forces

1. Passive, purely thermal, equilibrium
2. Active, out-of-equilibrium

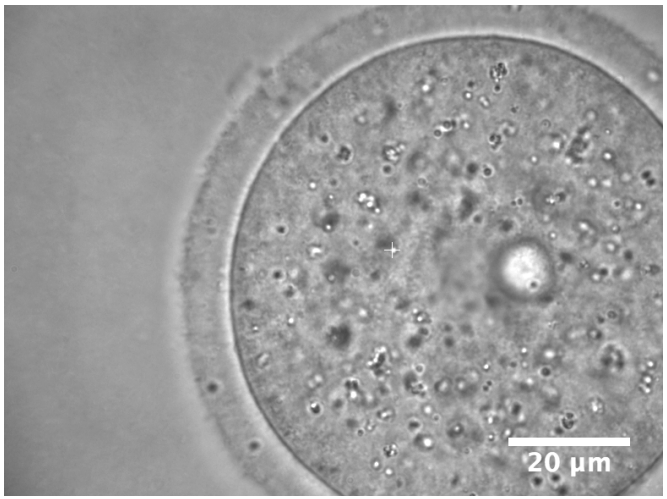
Quantify active features $\{\tau, \tau_0, D_A\}$

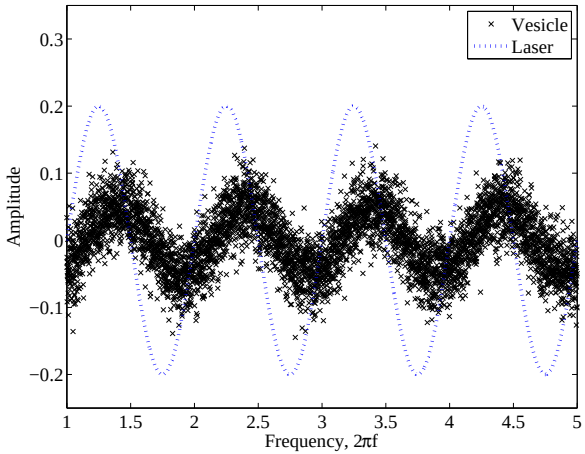
Check consistency with other measurements

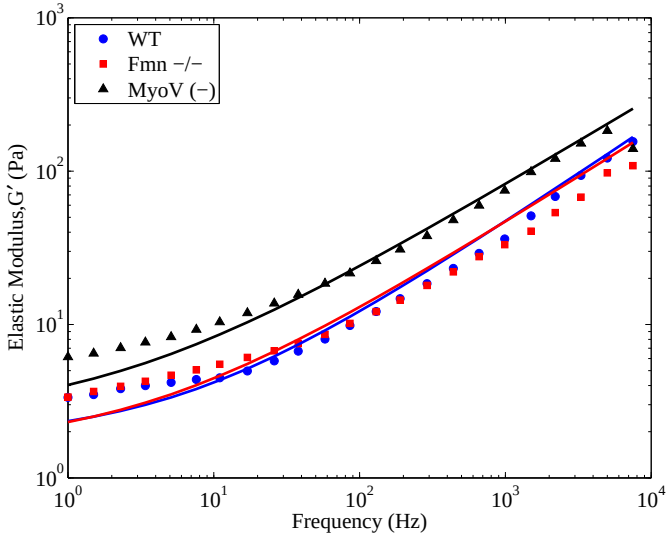
- Active force spectrum
- Tracers' distribution

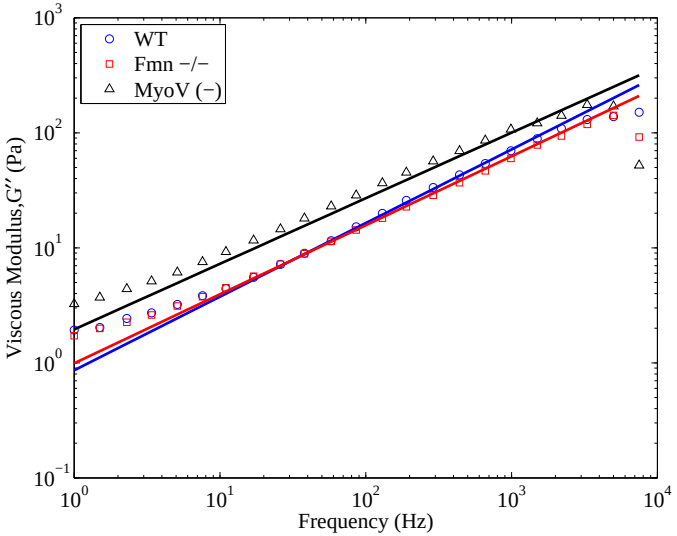
Nonequilibrium mechanics in living oocytes

Wylie W. Ahmed, Timo Betz, Matthias Bussonnier





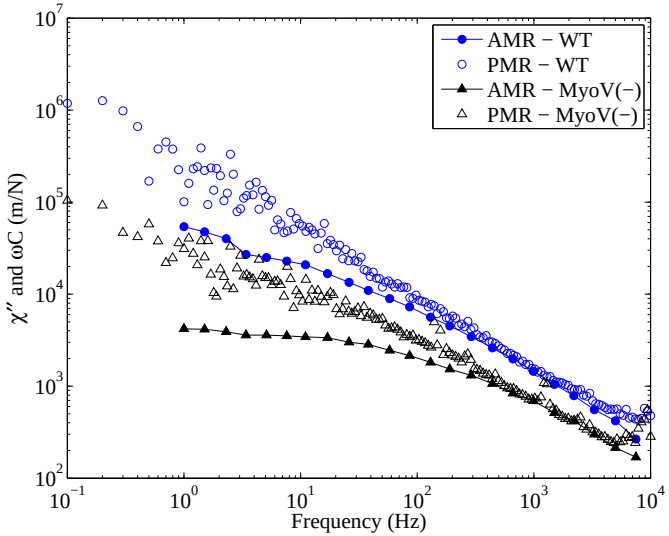


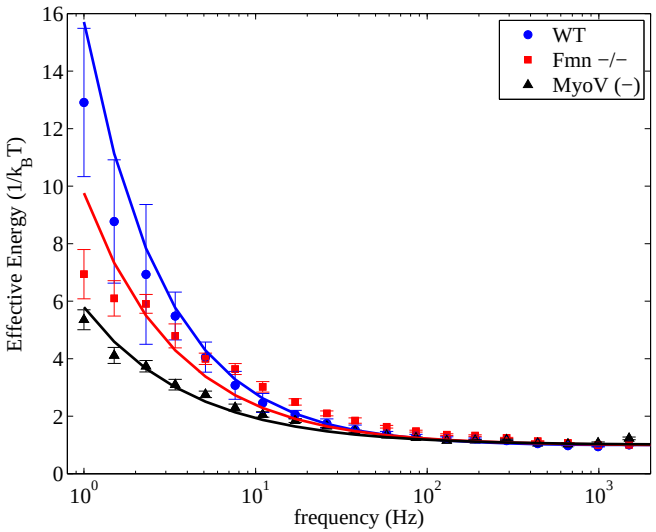


Complex modulus: $G^*(\omega) = G_0\left(1 + (i\omega\tau_\alpha)^\alpha\right)$, $\alpha \simeq 0.6$

Nonequilibrium mechanics in living oocytes

Wylie W. Ahmed, Timo Betz, Matthias Bussonnier





Fluctuation dissipation

$$\chi''(\omega) = \frac{\omega C(\omega)}{2k_B T}$$

$$T_A = 5.5\,T$$

$$T_A = 5\,T$$

$$T_A = 3.8\,T$$

Epithelial tissues as fluctuating active foams

Vishwajeet Mehandia, Daniel Riveline

Fluctuations of tricellular junctions