Swimming-induced non-Fickian transport of bacteria in porous media

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Summary

Progress in experimental techniques and imaging methods have led to a leap in the understanding of microscopic transport and swimming mechanisms of motile particles in porous media. This is very different for the understanding and characterization of large scale transport behaviors, which result from the interaction of motility with flow and medium heterogeneity, and the upscaling of microscale behaviors. Only few works have investigated large scale dispersion of active particles in porous media, which mainly operate in the framework of Brownian dynamics and effective dispersion or are completely data driven. In this work, we use the particle tracking data of Creppy et al. [1] to derive the stochastic dynamics of small scale particle motion due to hydrodynamic flow variability and the swimming activity of bacteria. These stochastic rules are used to derive a continous time random walk (CTRW) based model for bacteria motion. The CTRW naturally accounts for persistent advective motion along streamlines [2]. In this framework, particle motility is modeled through a subordinated Ornstein-Uhlenbeck process that accounts for the impact of rotational diffusion on particle motion in the fluid, and a compound Poisson process that accounts for the motion toward and around grains. The upscaled transport framework can be parameterized by the distribution of the Eulerian pore velocities, and the motility rules of the bacteria. The model predicts the propagators of the ensemble of bacteria as well as their center of mass position and dispersion for bacteria transport under different flow rates.

Experiment

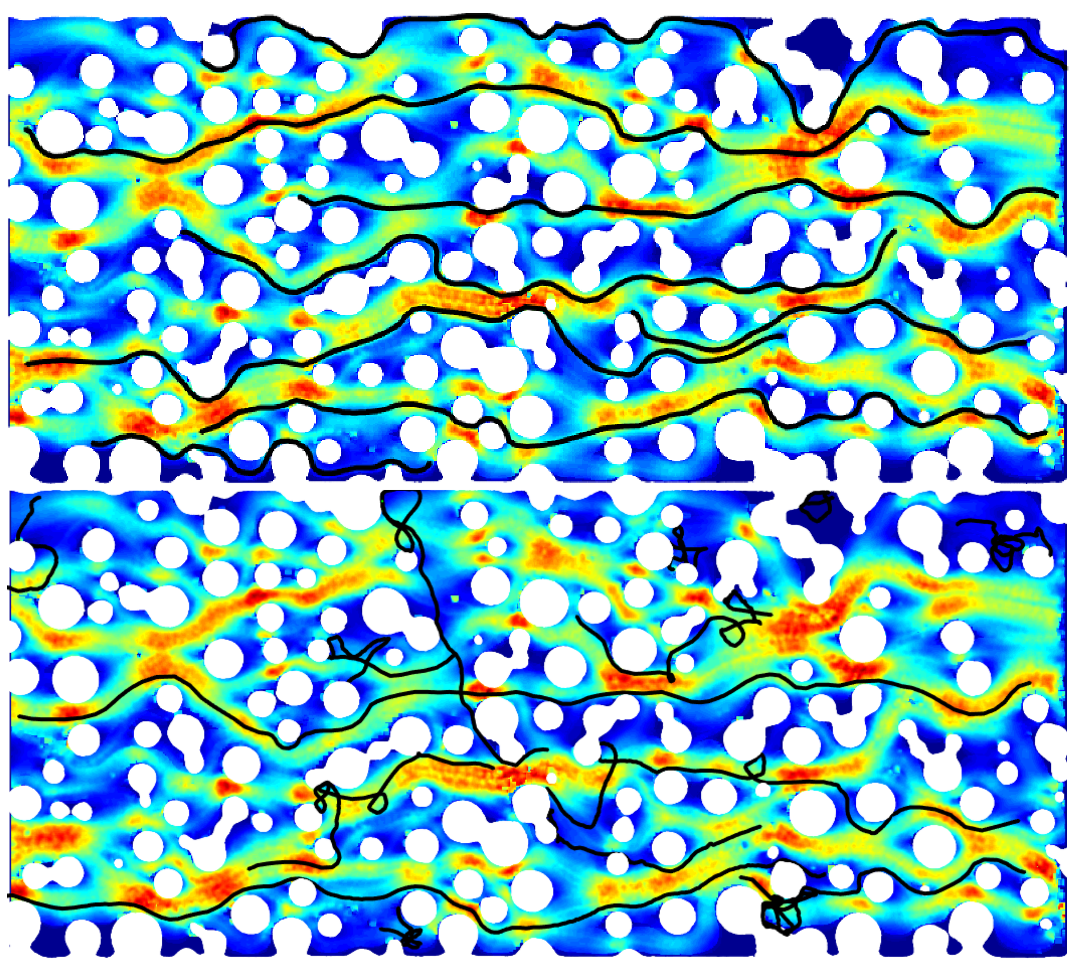
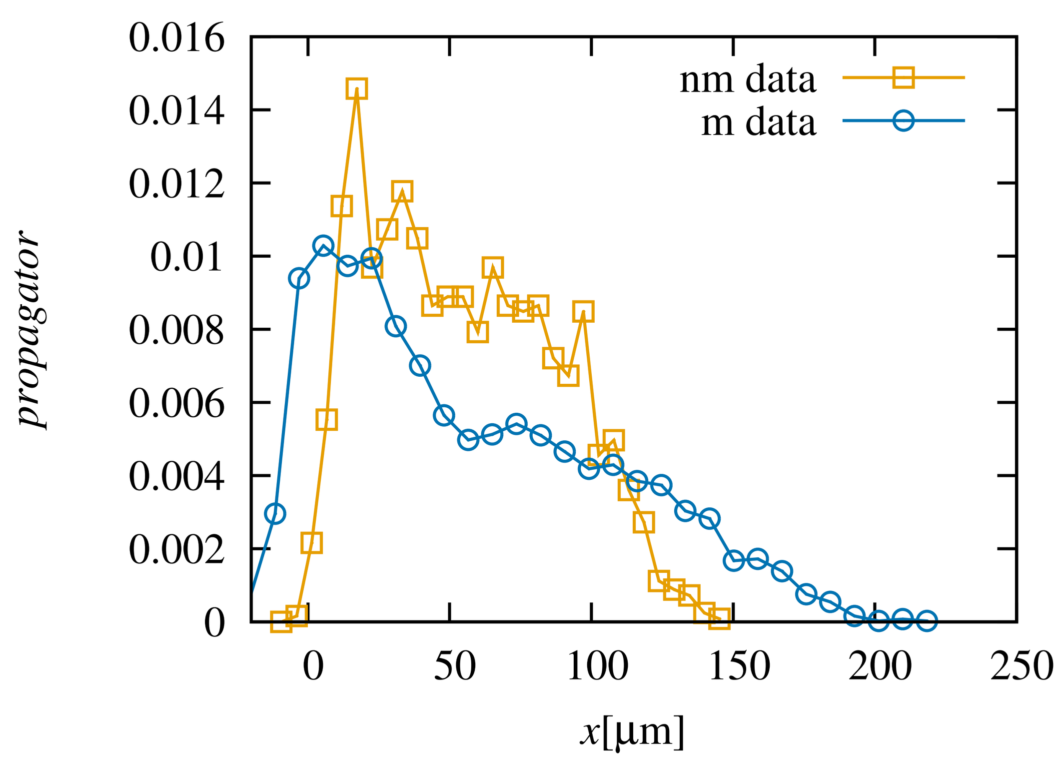


Figure 1: Experimental setup, and particle trajectories of (top) non-motile and (bottom) motile bacteria [1].

- Mean flow rate of $Q = 50$ μm/s
- Average pillar diameter 35 μm

Propagators



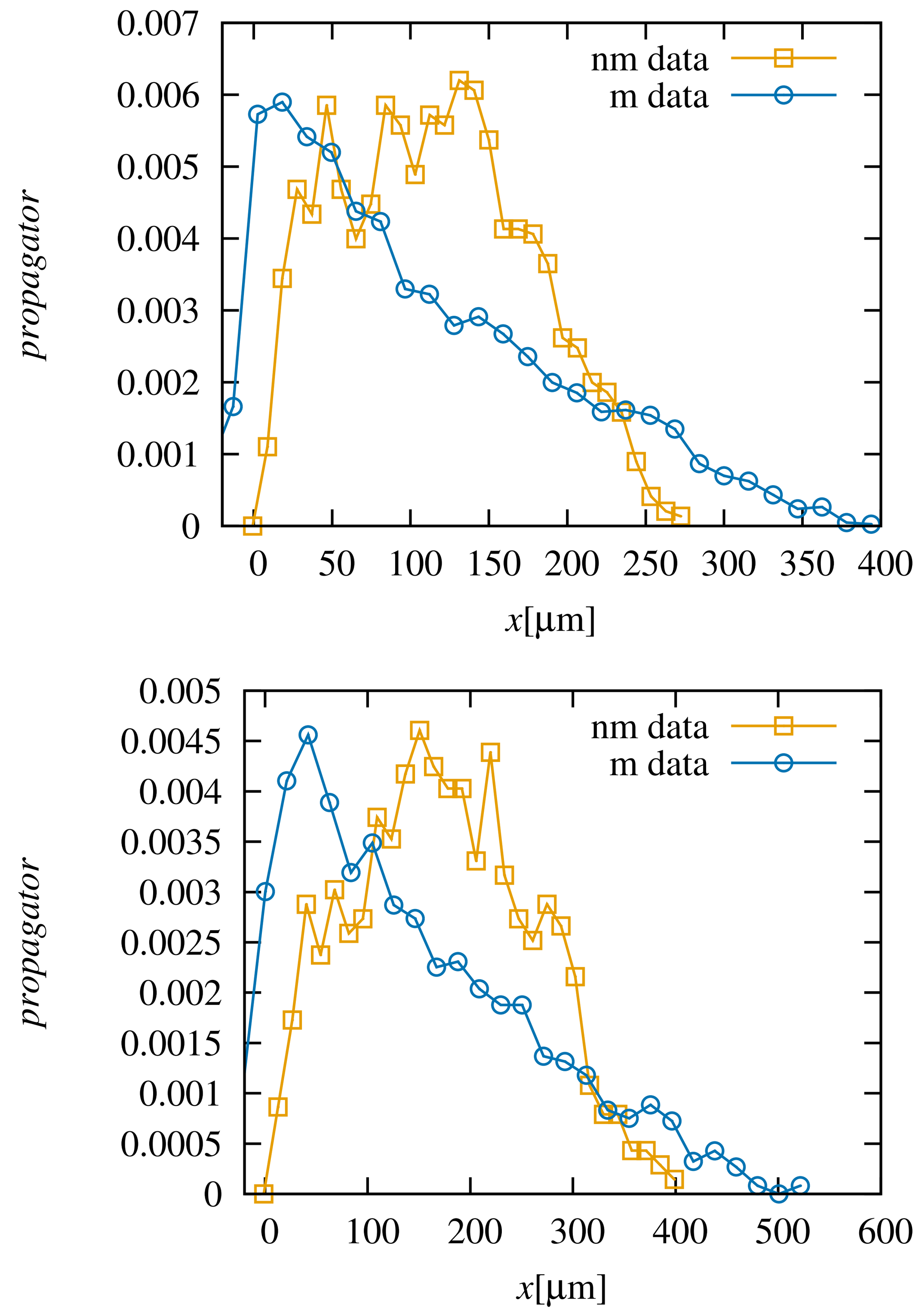


Figure 2: Propagators of non-motile and motile bacteria at $t = 1, 2, 3$ seconds.

- No resampling of increments along trajectories.
- Non-motile propagator compact.
- Motile propagator characterized by localized peak and forward tail.
- Motile particles move toward pillars and are immobilized.
- Forward tail due to fast particles that do not get immobilized.

Upscaling

- Seek predictive upscaled model reflecting the microscopic transport mechanisms, medium and flow properties.
- Characterize hydrodynamic motion in the fluid flow.
- Characterize own motion of bacteria.

Particle motion

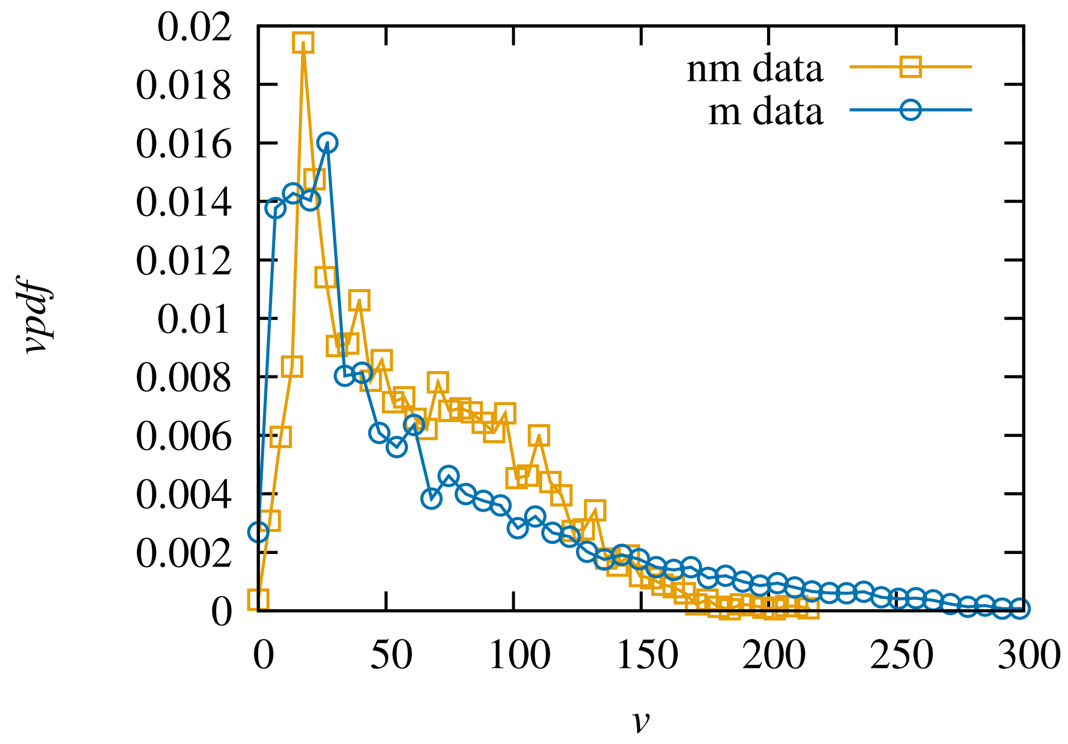


Figure 4: Velocity distributions of non-motile and motile bacteria.

- Velocity distribution of non-motile particles reflects flow distribution.
- Velocity distribution of motile particles is peaked at zero and skewed toward high velocities indicating trapping at pillars and fast motion in pores.
- The trapping and release processes occur at constant rate related to the inverse tumbling time, and depend on the particle velocity.

Continuous time random walk

- Non-motile particles

$$x_{n+1} = x_n + \ell_c, \qquad t_{n+1} = t_n + \frac{\ell_c}{v_n}, \qquad p(v) = \frac{v p_e(v)}{\langle v_e \rangle}$$

- Motile particles
  - CTRW based on $p_e(v)$.
  - Own motion represented by Ornstein-Uhlenbeck process.
  - Trapping modeled through compound Poisson process.
  - Trapping rate equal to the inverse tumbling time for particles whose velocity is smaller than the average maximum pore velocity and zero else.

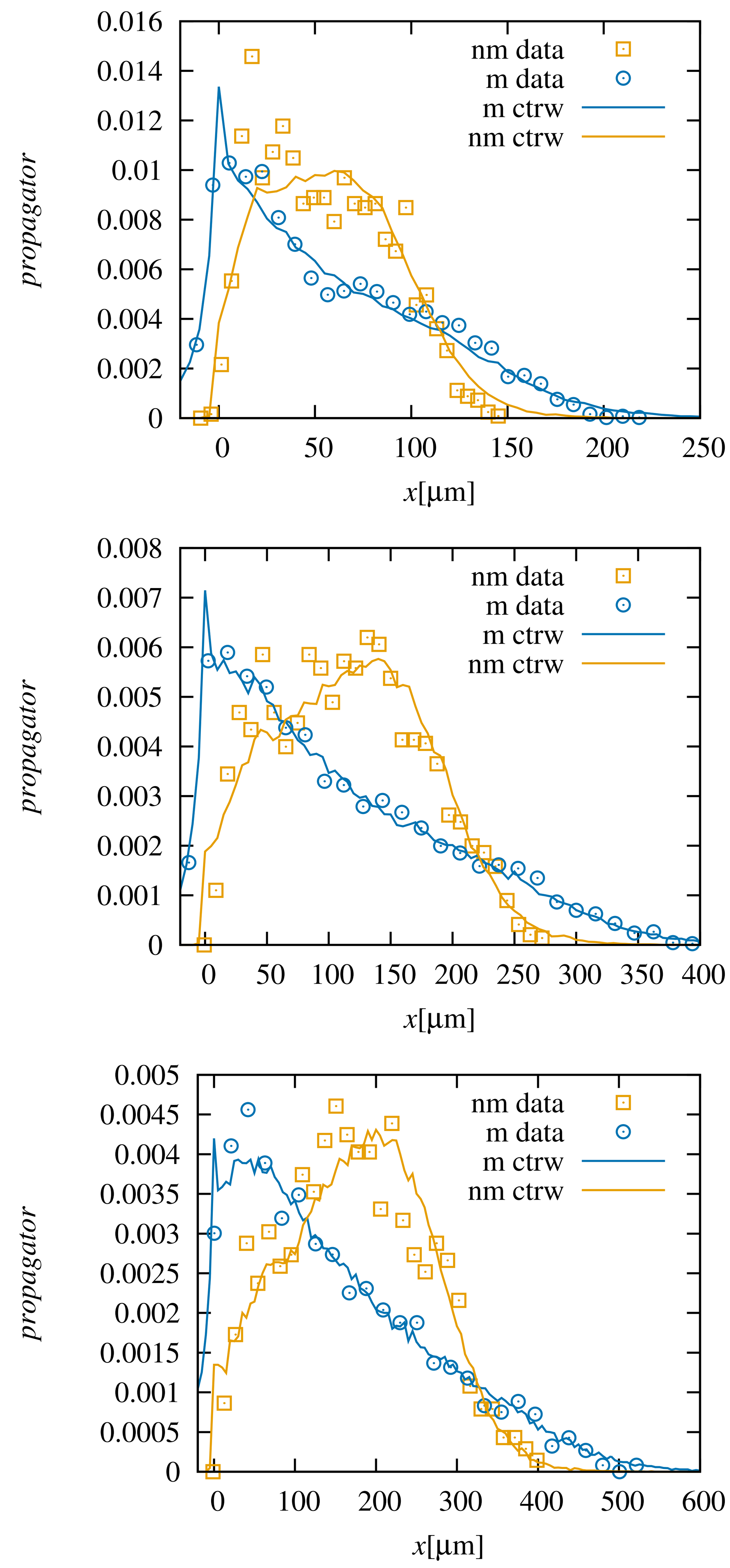


Figure 5: Propagators of non-motile and motile bacteria at $t = 1, 2, 3$ seconds compared to the CTRW model predictions.

References:

[1] Creppy et al., Effect of motility on the transport of bacteria populations through a porous medium, Phys. Rev. Fluids, 4, 013102, 2019.

[2] Dentz, M. et al., Continuous time random walks for the evolution of Lagrangian velocities. Phys. Rev. Fluids, 1(7), 74004, 2016.

Acknowledgements:

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