Solvent hydrodynamics alter the collective diffusion of quasi two-dimensional systems: From trapped colloids to membrane lipids

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In many instances, molecules and colloidal particles move confined to a two-dimensional (2D) manifold which is embedded in a 3D solvent. The confined domain could be a perfectly flat plane, like colloids moving in a fluid-fluid interface or trapped by acoustic or optical forces, it could be a fluctuating plane, like in membrane lipids (also spherical vesicles), or maybe just softly confined, like colloids near a charged wall, etc. These dynamics are usually called quasi two-dimensional (q2D) and the situation can be even extended to 1D (kinesines walking along microtubules).

The hydrodynamic interaction with the solvent makes these q2D dynamics particularly surprising. For instance, if we follow a single Brownian q2D particle it would be hard to notice any change with respect the 3D (bulk) diffusion. However, looking at a collection of them (a stain) yields a radically different view. Unlike standard Brownian dynamics, in q2D their displacements become highly correlated and the collective diffusion coefficient D_c (of a stain of wavelength λ) increases without bound with the wavelength! (in particular, like $D_c \sim \lambda$).

This anomalous behavior has been theoretically predicted and experimentally measured (see Ref. [1]). We have recently shown that the same effect is observed in softly confined colloids, provided λ is larger than the confinement width [2]. This enhancement of coherent motions arises from the hydrodynamic propagation of the confinement forces, which act on the particles in normal-to-plane direction. These normal forces are immediately transmitted to the plane via the Oseen solvent hydrodynamics and create a mutual drag which is long-ranged and repulsive, like a "electrostatic" force between the particles [1, 3] (see Fig. 1).

This q2D effect also radically changes the non-equilibrium spectra of density fluctuations so it modifies the way two species mix in the plane [3]. Even more surprisingly, using MD (Martini) and CG dynamics with hydrodynamics, we found that q2D dynamics also rule the short-time collective motion of lipids in membranes [4]. Most probably this q2D dynamics will be also relevant for membrane proteins. Interestingly, the time-lag dependent mutual-mobility indicates a cross-over from q2D to the intrinsic membrane (2D) collective dynamics, where the Saffmann dynamics takes over at long times. However, lipid displacements correlations persist over quite long times!

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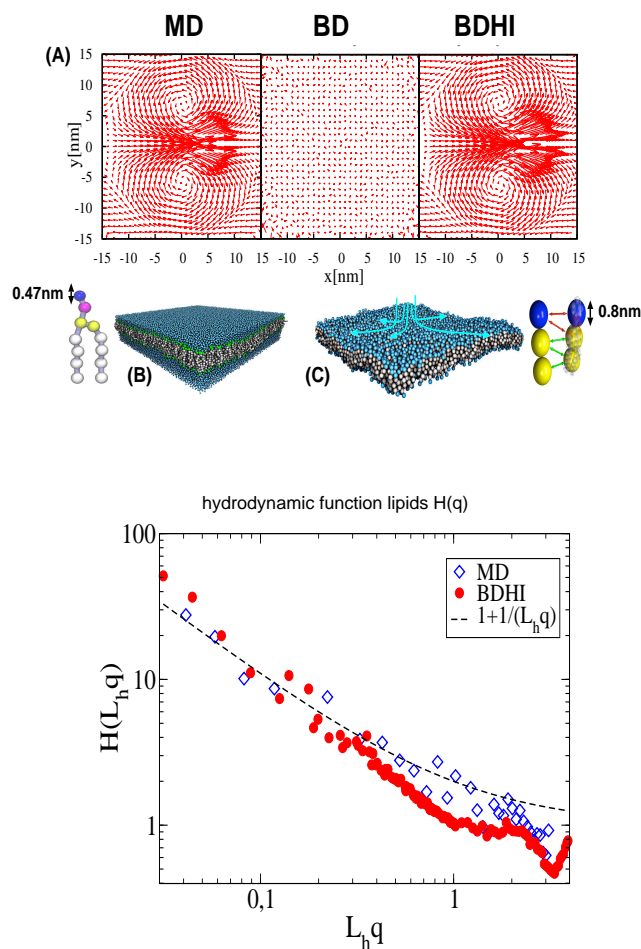[4] S. Panzuela and R. Delgado-Buscalioni, Phys. Rev. Lett. (in press) [arXiv:1803.03961].

Fig. 1. (Top) Velocity field obtained from the relative displacement of lipids in the membrane. Results from molecular dynamics (Martini model) with explicit water (MD); Brownian dynamics without hydrodynamics (BD) and Immersed boundary method in the Stokes regime (i.e., with implicit solvent hydrodynamics, BDHI). In BD and BDHI, we use the Deserno membrane model. (Bottom) Comparison of the hydrodynamic function $H(q)$ (proportional to the collective diffusion coefficient) for MD and BDHI. The dashed line comes from the theory of q2D.