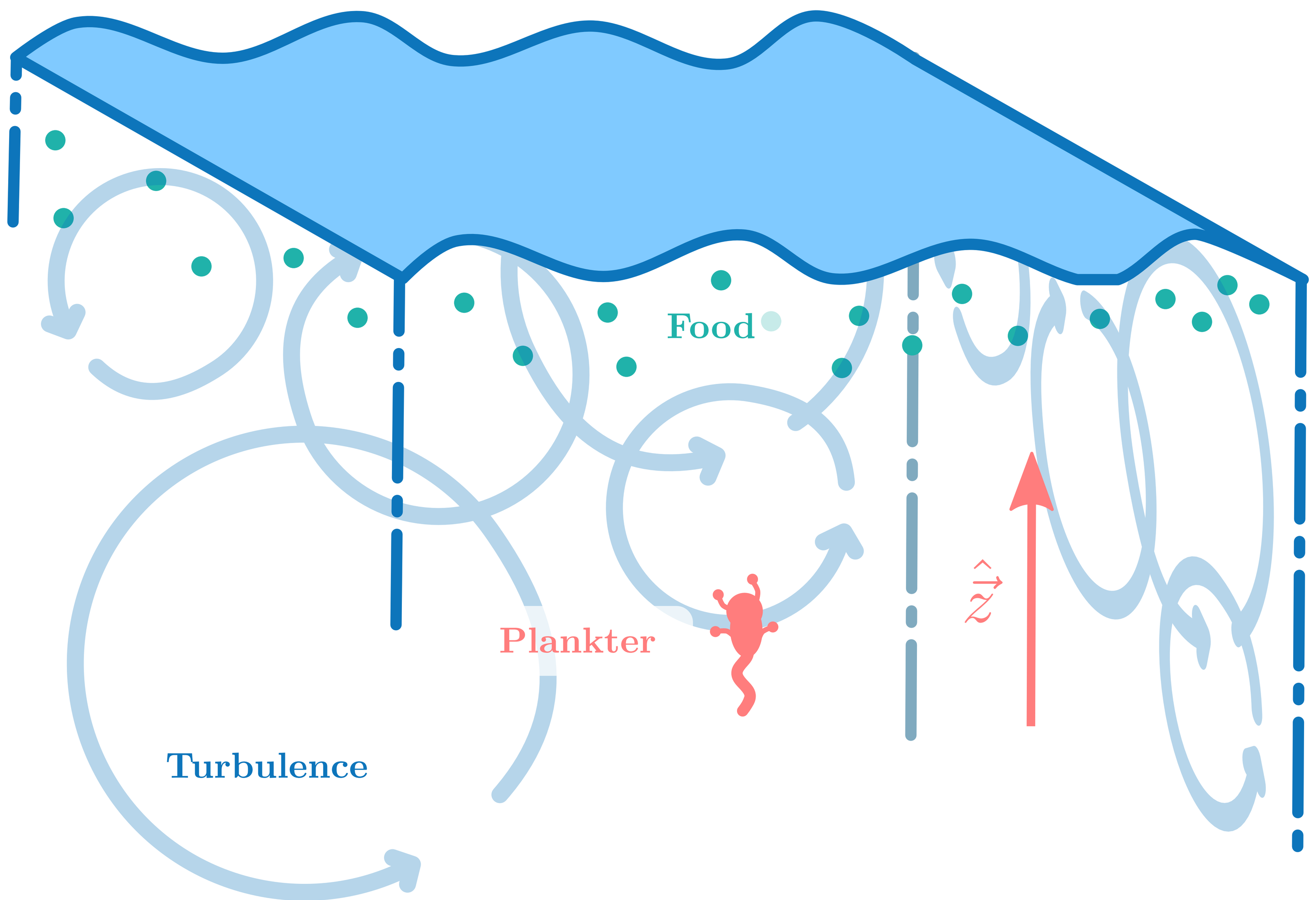
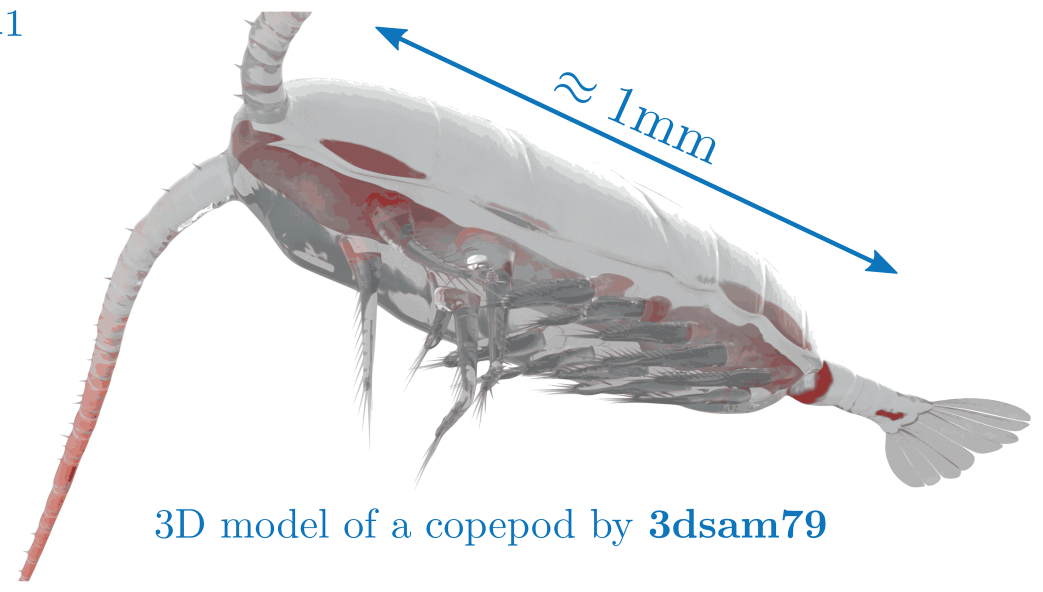
Surfing on turbulence
a strategy for plankton navigation.

Rémi Monthiller[1], Aurore Loisy[1], Mimi A. R. Koehl[2], Benjamin Favier[1], and Christophe Eloy[1]

[1]Aix Marseille Univ, CNRS, Centrale Marseille, IRPHE, Marseille, France
[2]Department of Integrative Biology, University of California, Berkeley, CA 94720-3140, USA





3D model of a copepod by **3dsam79**

Motivation

Living in a **turbulent environment**, **navigation** is a challenging task for motile planktonic organisms (plankters). Yet **vertical migration** is essential to many of them.

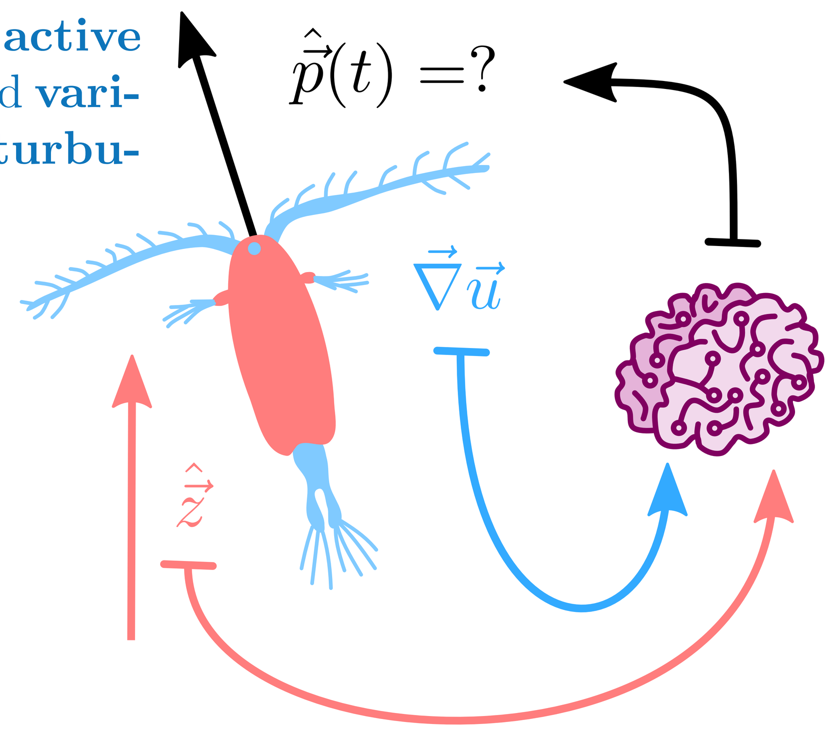
For example, copepods (crustaceans that are a critical link in aquatic food webs) move upwards at night to feed in surface waters, and downwards during the day to escape visual predators [1], [2].

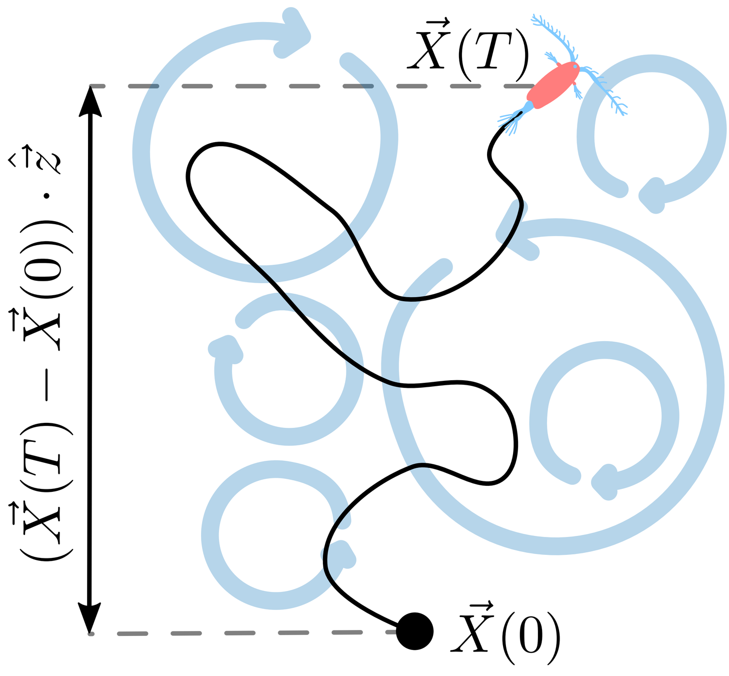
Being equipped with **flow sensors**, can these plankters use local hydrodynamic cues to **migrate faster through turbulence?**

Model and Problem

Plankters are modelled as **inertialess active particles** at **constant speed** V_{swim} and **variable swimming direction** $\hat{p}(t)$ in a **turbulent flow** $\vec{u}(\vec{x}, t)$.

$$\frac{d\vec{X}}{dt} = \vec{u}(\vec{X}, t) + V_{\text{swim}}\,\hat{p}(t)$$

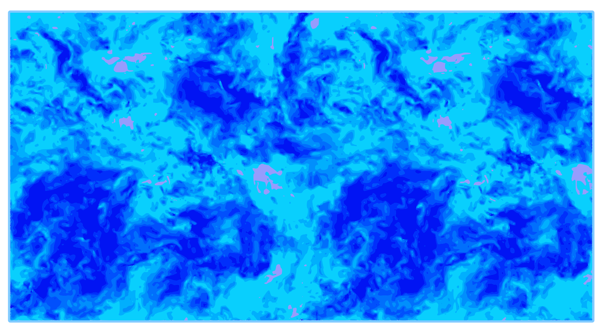




How to control their swimming direction $\hat{p}(t)$ to maximize their **effective vertical speed** given they can only measure gravity and their **local** velocity gradients $\vec{\nabla}\vec{u}$?

$$V_{\text{eff.}} = \lim_{T\to\infty} \frac{\vec{X}(T) - \vec{X}(0)}{T} \cdot \hat{\vec{z}}$$

Numerical methods



Velocity magnitude.
Rendering by **Gudmundur Adalsteinsson**.

- Johns Hopkins Turbulence Databases [3]
- 3D forced homogeneous isotropic turbulence, $Re_\lambda = 418$
- Runge-Kutta 4 integrator
- open source code **SHELD0N**
  https://github.com/C0PEP0D/sheld0n

Surfing strategy

Using a **Taylor expansion** of $\vec{u}(\vec{x}, t)$ in the neighborhood of the current time t_0 and position $\vec{X}_0 = \vec{X}(t_0)$, the **velocity field can be approximated**.

$$\vec{u}(\vec{x}, \tau) \approx \vec{u}_0 + (\vec{\nabla}\vec{u})_0 \cdot (\vec{x} - \vec{X}_0) + \left(\frac{\partial \vec{u}}{\partial t}\right)_0 (\tau - t_0)$$

Leading to a solvable local optimization problem of solution:

$$\hat{p}_{\text{surf}} = \frac{\vec{p}_{\text{surf}}}{|\vec{p}_{\text{surf}}|}, \quad \text{with} \quad \vec{p}_{\text{surf}} = \left[\exp\left(\tau(\vec{\nabla}\vec{u})\right)\right]^T \cdot \hat{\vec{z}}$$

The **sole free parameter** of the surfing strategy is τ corresponds to the time when the **linearization starts to break down**.
It is linked to the **flow velocity gradients correlation times**.

Results

Flow sensing is beneficial for planktonic navigation!

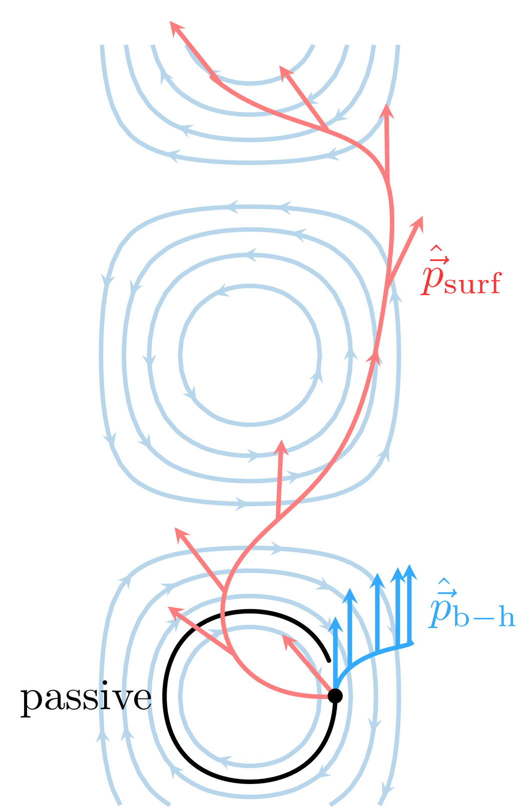


Illustration of the surfing strategy in Taylor Green Vortices.

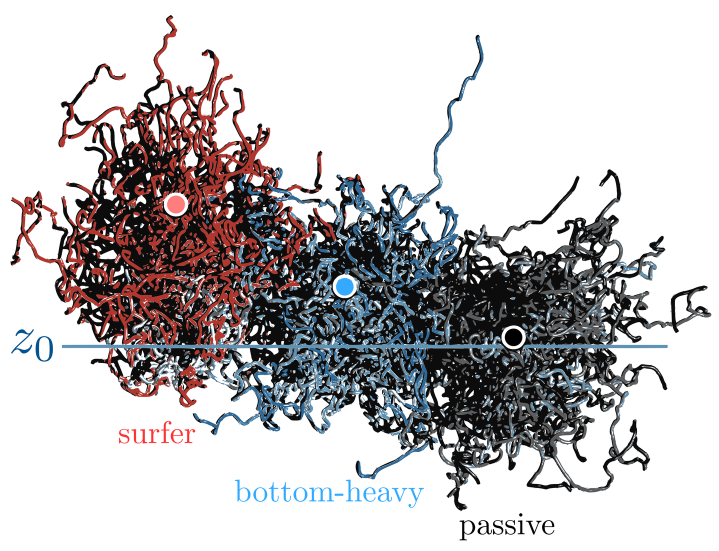
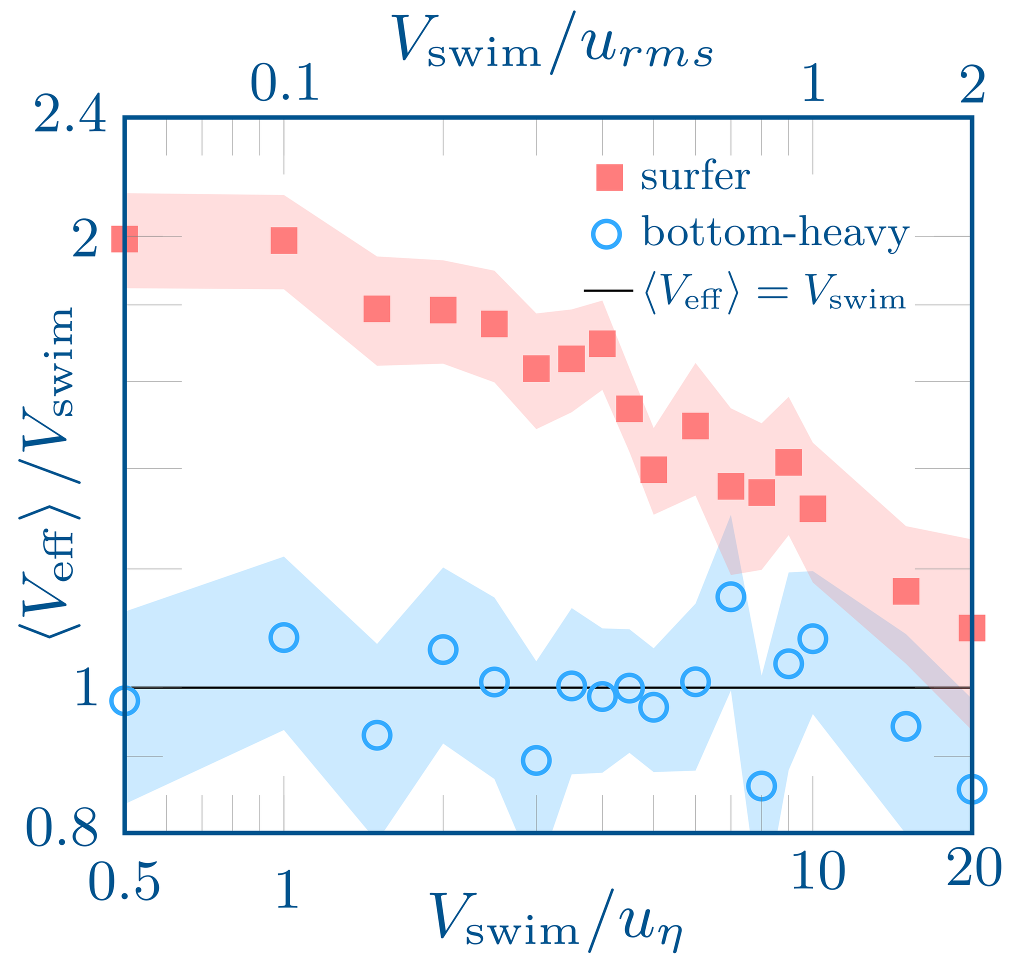
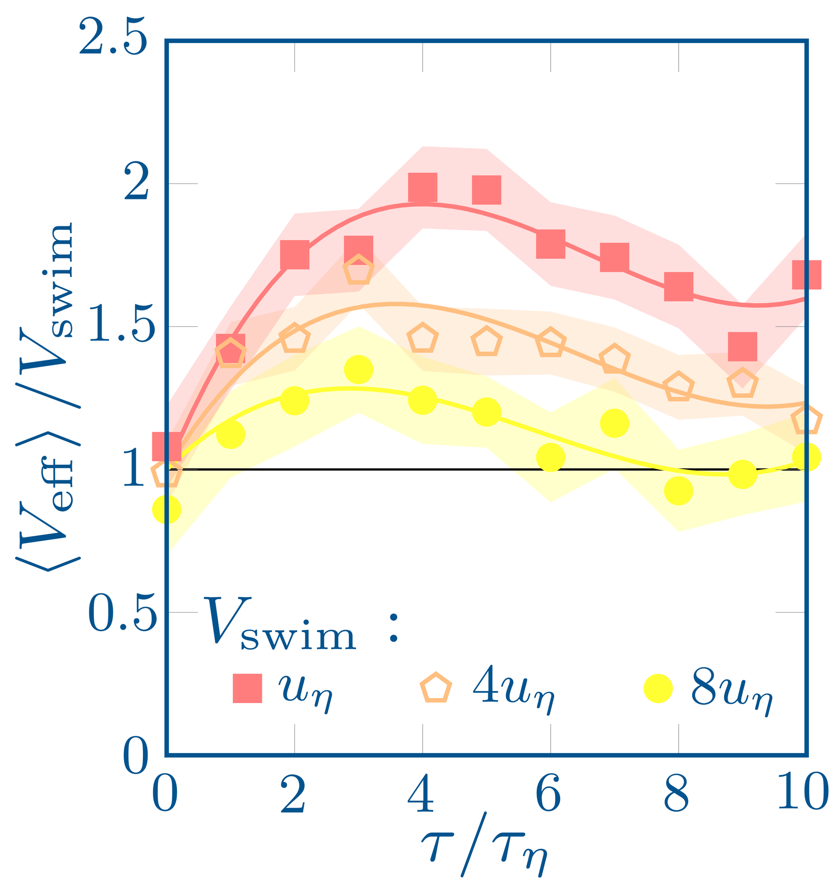


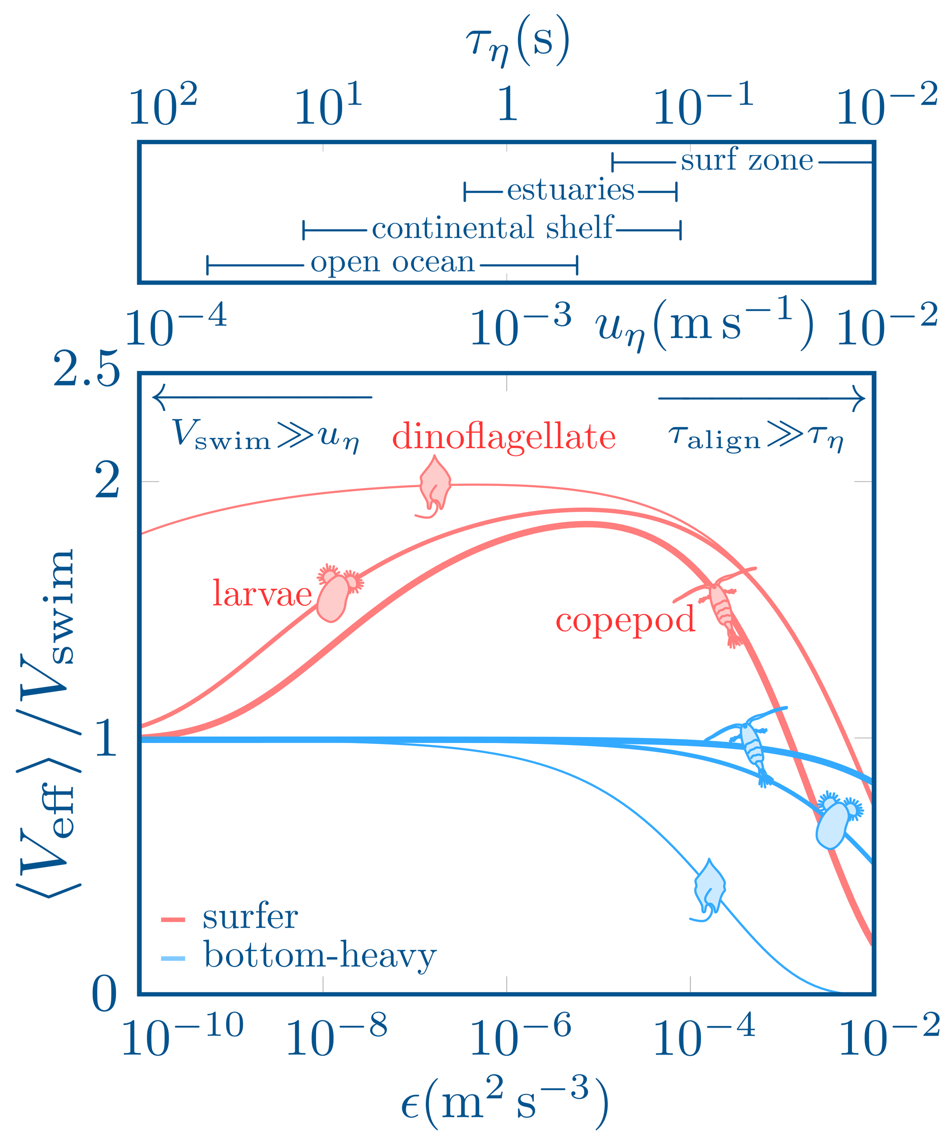
Illustration of the surfing strategy in 3D turbulence.





We show that surfers:

- systematically **outperform bottom-heavy swimmers** that always swim upwards.
- can reach effective speeds, $V_{\text{eff.}}$, as large as **twice their swimming speed**.
- are **competitive** with **reinforcement learning swimmers** [4].



Moreover:

- The decrease of performance with V_{swim} is related to **shorter decorrelation times** of the **flow sampled** by surfers.
- Surfing would be **beneficial** for the range of parameters corresponding to **actual plankton habitats**.

Perspectives

- turbulent channel flow: **inhomogeneous anisotropic flow**
- **generalization**: memory, odour tracking, energetic constraints ...
- investigation of the properties of the **flow sampled** by microswimmers

[1] Richards et al., J. Plankton Res. (1996)
[2] Hadfield et al., Biol. Bull. (2004)
[3] Y. Li et al., J. Turb. (2008)
[4] Alageshan et al., Phys. Rev. E (2020)