Active particles in free decaying quantum turbulence at zero temperature

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Motivations and objectives

- In superfluid helium experiments, particles like hydrogen flakes are the main tool used to sample quantum turbulence. [1,2]
- We study numerically:

A. Whether the presence of particles modify the development of superfluid turbulence.

B. What is the actual dynamics of particles immersed in a tangle of quantized vortex filaments.

Model → Gross-Pitaevskii with particles [3,4,5]

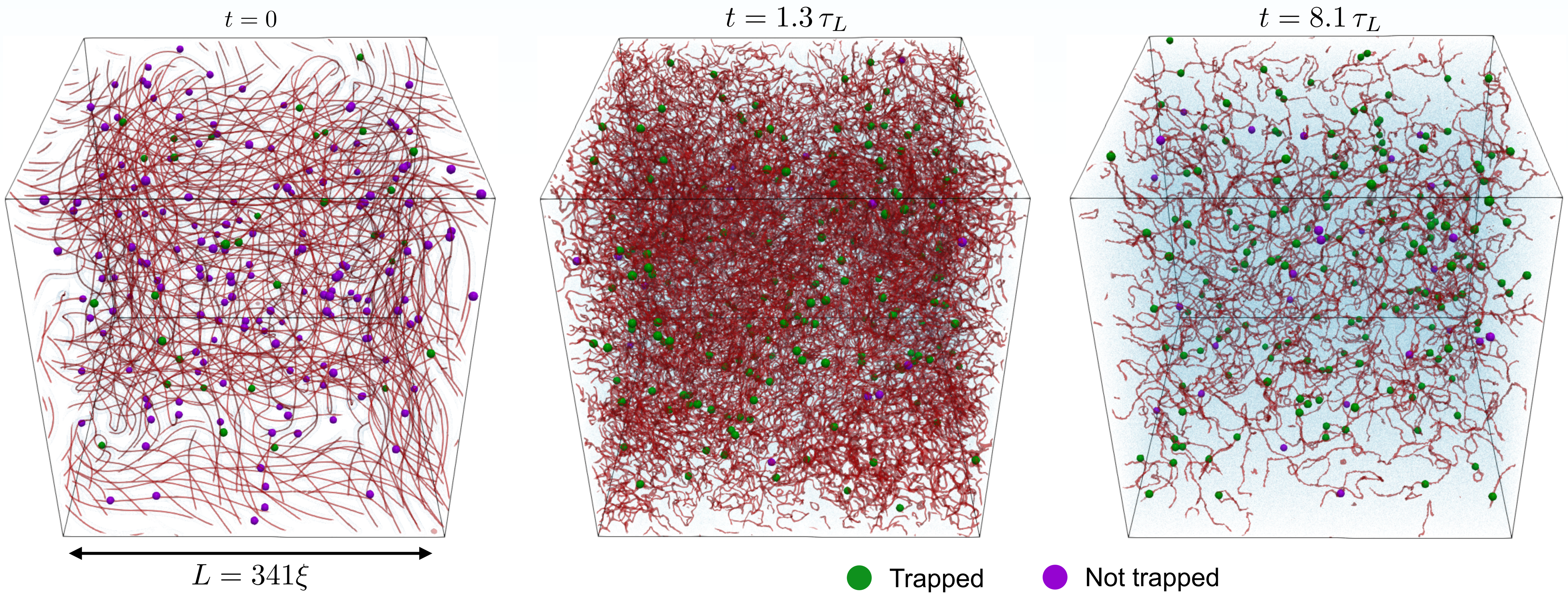
$$H = \int \left(\frac{\hbar^2}{2m}|\nabla\psi|^2 + \frac{1}{2}\left(g|\psi|^2 - \mu\right)^2 + \sum_{j=1}^{N_\mathrm{p}} V_\mathrm{p}(\mathbf{r}-\mathbf{q}_j)|\psi|^2 \right) \mathrm{d}\mathbf{r} + \sum_{j=1}^{N_\mathrm{p}} \frac{\mathbf{p}_j^2}{2M_\mathrm{p}} + \sum_{j<i}^{N_\mathrm{p}} V_\mathrm{rep}^{ij}$$

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + \left(g|\psi|^2 - \mu\right)\psi + \sum_{j=1}^{N_\mathrm{p}} V_\mathrm{p}(\mathbf{r}-\mathbf{q}_j)\psi$$

Superfluid dynamics

$$M_\mathrm{p}\frac{\partial^2\mathbf{q}_j}{\partial t^2} = -\int V_\mathrm{p}(\mathbf{r}-\mathbf{q}_j)\nabla|\psi|^2\,\mathrm{d}\mathbf{r} - \sum_{j<i}^{N_\mathrm{p}} \nabla V_\mathrm{rep}^{ij}$$

Particle dynamics



- The initial condition is an **ABC flow** with 200 particles immersed in it.
- We use particles of different masses and **different sizes**:

$$a_\mathrm{p} = 4\xi, \qquad a_\mathrm{p} = 10\xi$$

- We define the **large "eddy turnover" timescale**:

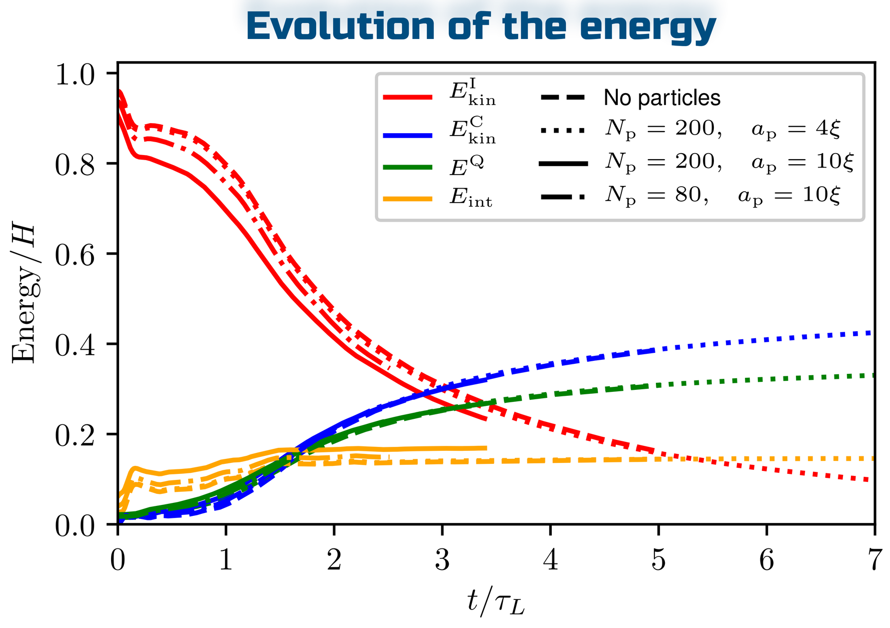
$$\tau_L = \frac{L/2}{v_\mathrm{rms}}, \qquad v_\mathrm{rms} = \sqrt{\frac{2E_\mathrm{kin}^\mathrm{I}(t=0)}{3}}$$

- We define the analogous of the classical **dissipative timescale**, where the inter-vortex distance plays the role of the Kolmogorov length:

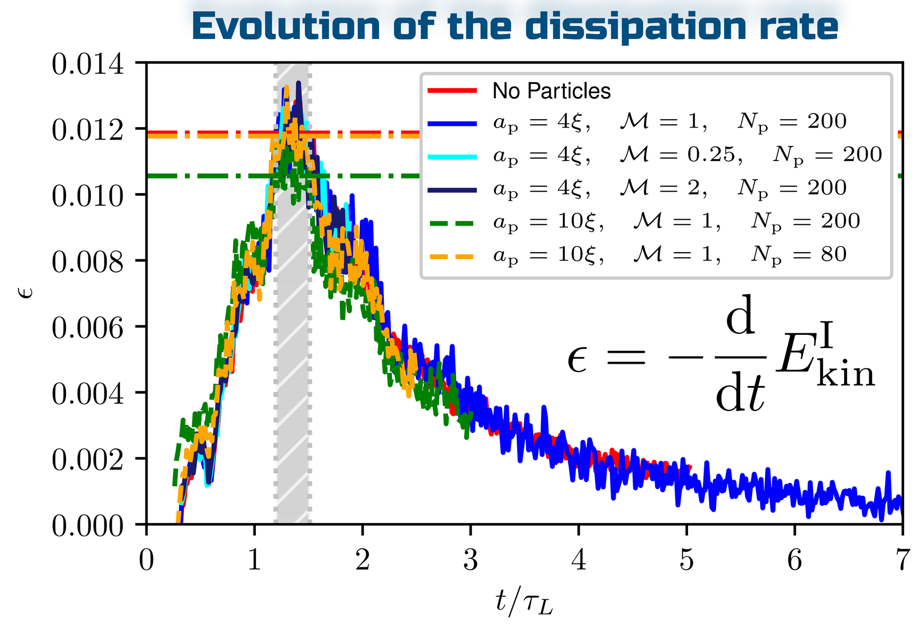
$$\tau_\ell = \left(\ell^2/\epsilon\right)^{1/3}$$

Particles don't disturb superfluid turbulence

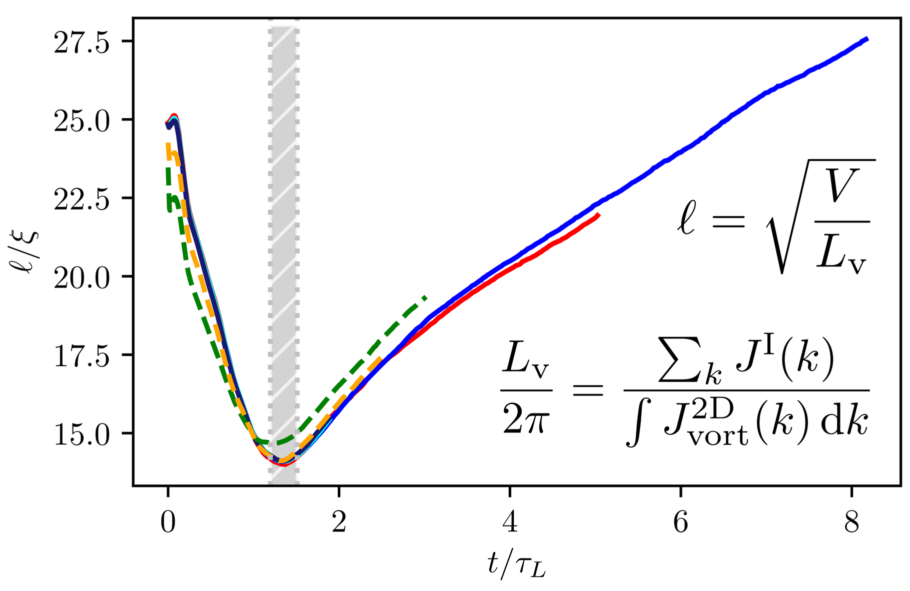
Evolution of the energy



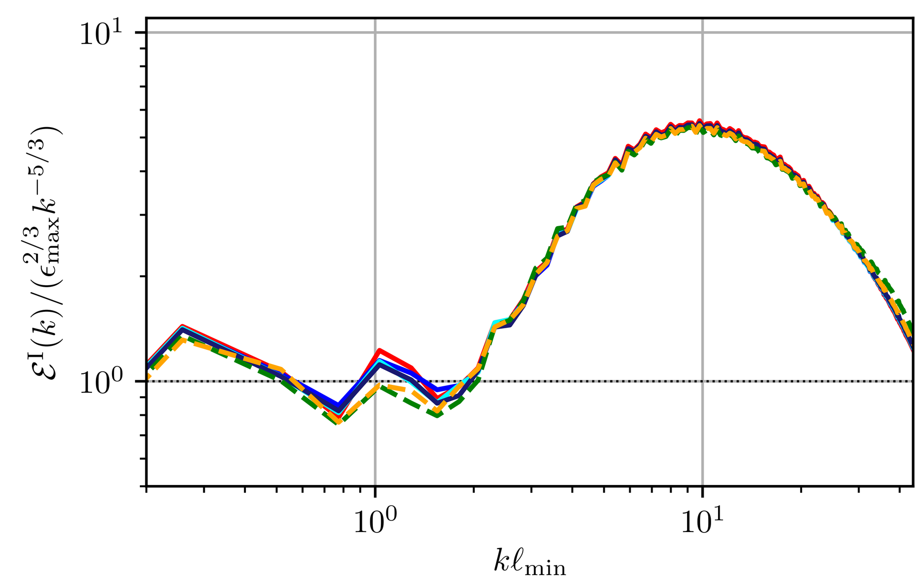
Evolution of the dissipation rate



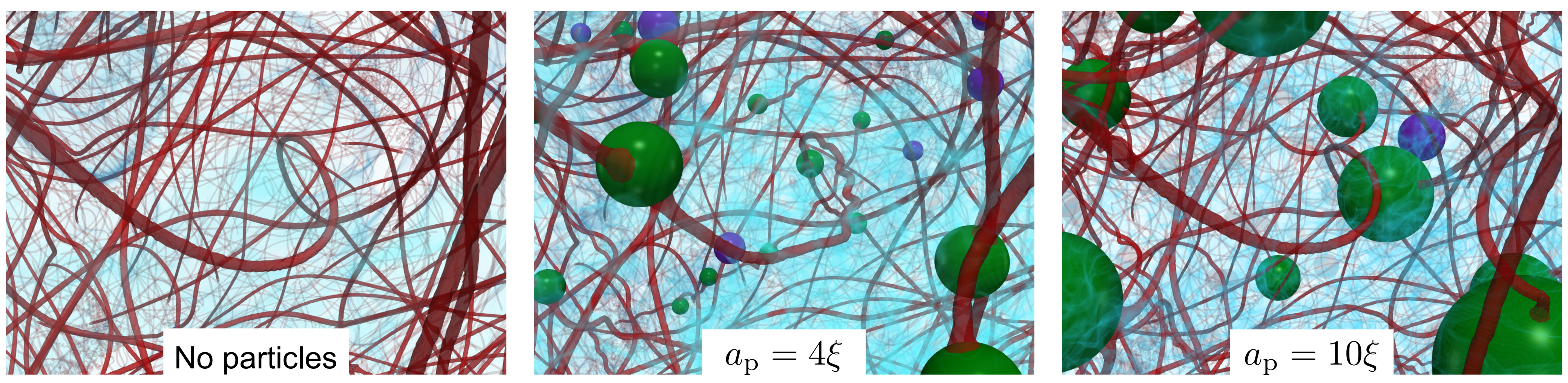
Inter-vortex distance



Incompressible energy spectrum

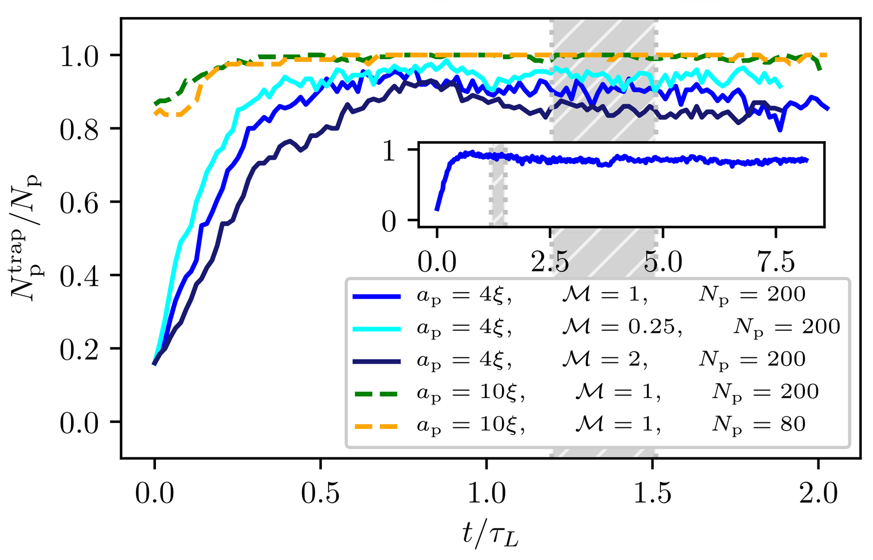


- The presence of particles **does not** affect dramatically the building-up and decay of **quantum turbulence**.
- The typical picture[6] in which the **incompressible energy** is dissipated into compressible and quantum energy is preserved. At the maximum of dissipation the inter-vortex distance is minimum and at large scales the vortex tangle is in a **classical turbulence** regime.
- Particles trapped by vortices excite more **Kelvin waves**, but this does not affect the statistical observables.

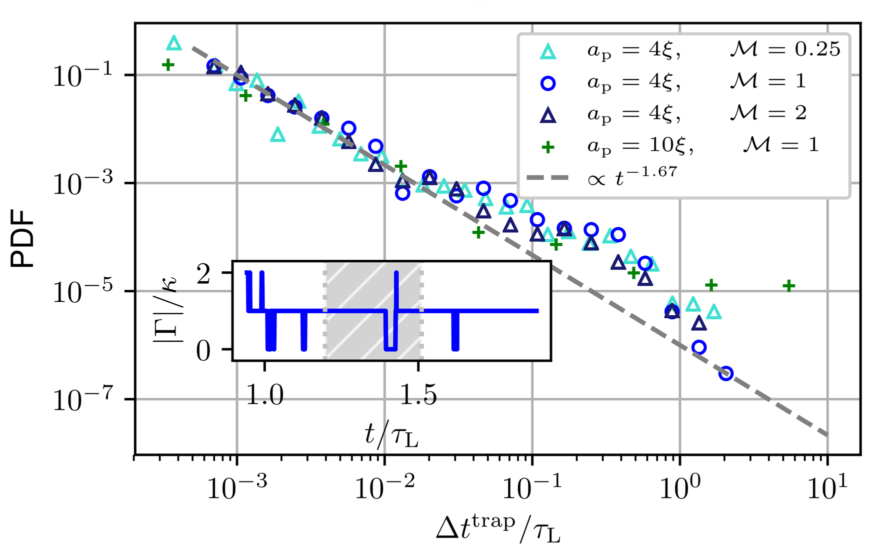


Motion of particles immersed in a turbulent tangle

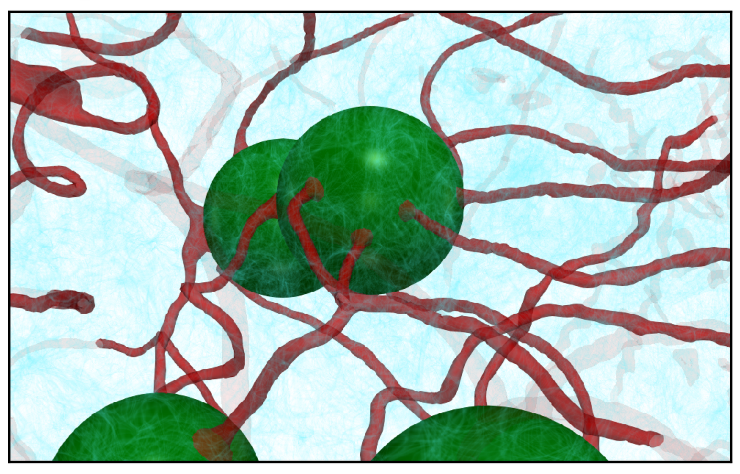
Fraction of particles trapped



PDF of the time spent inside vortices



Large particles are multiply trapped



- The majority of particles **gets trapped** and remains trapped inside the vortex filaments.
- At large timescales the velocity spectrum is compatible with **classical lagrangian turbulence**[7]:

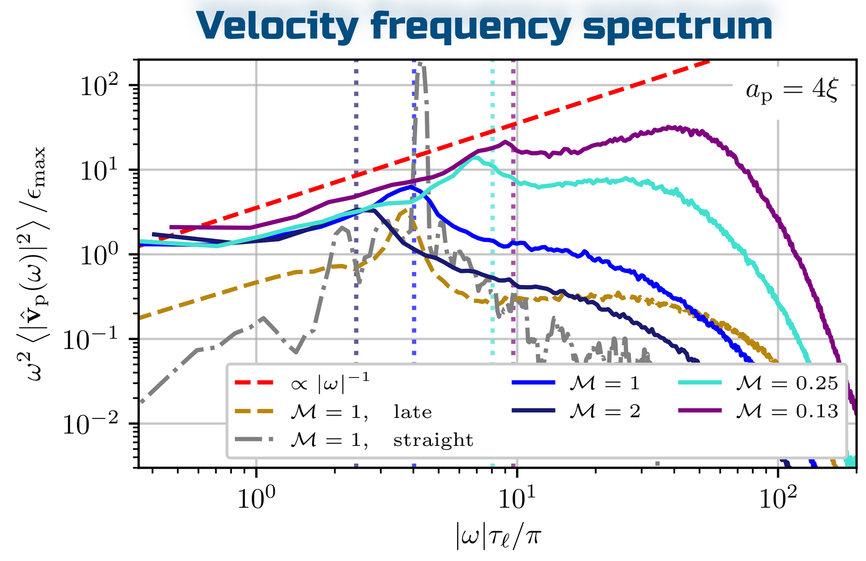
$$\left\langle |\hat{\mathbf{v}}_\mathrm{p}(\omega)|^2 \right\rangle = B\epsilon\omega^{-2}, \qquad B = \mathcal{O}(1)$$

- At small timescales the velocity spectrum shows a peak due to **Magnus effect**[5] and a scaling compatible with **vortex reconnections** ($v_\mathrm{rec} \propto \sqrt{\kappa/|t-t_0|}$):

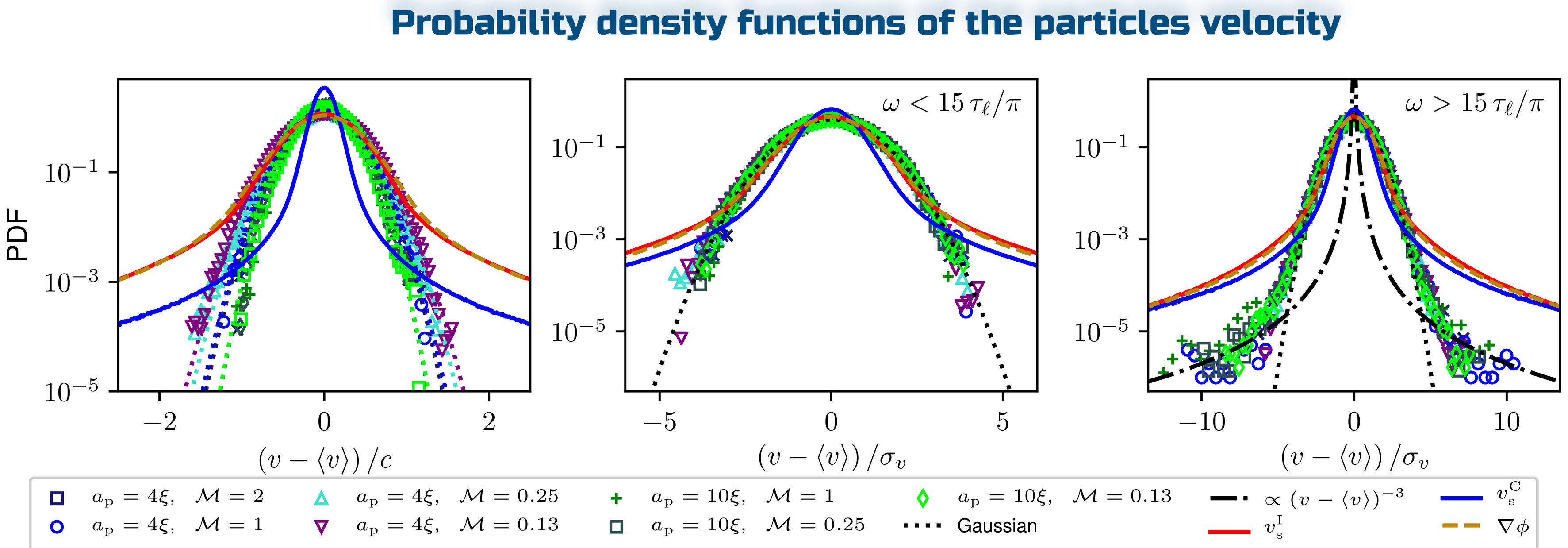
$$\left\langle |\hat{\mathbf{v}}_\mathrm{p}(\omega)|^2 \right\rangle \propto \kappa|\omega|^{-1}, \qquad \omega_\mathrm{Magnus} = \frac{3}{2}\frac{\rho_\infty a_\mathrm{p}}{M_\mathrm{p}^\mathrm{eff}}\Gamma$$

- The PDF of particle velocity, filtered at high frequencies, show non-classical **power-law tails**.

Velocity frequency spectrum



Probability density functions of the particles velocity



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