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Coalescence and breakup of droplets in a viscoelastic turbulent fluid

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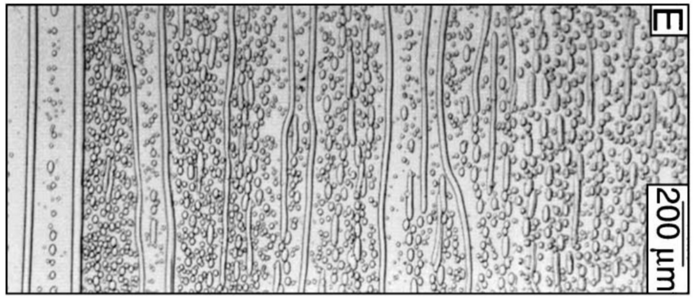
Droplets in viscoelastic flows

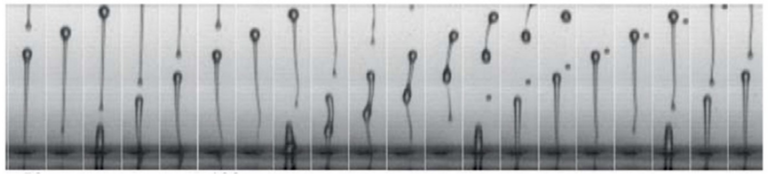
- Ubiquitous industry and nature

Polymer production



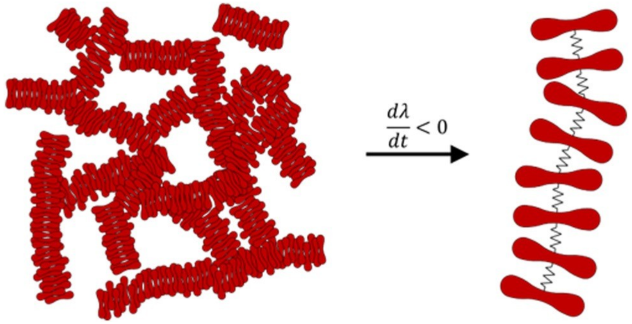
K. B. Migler, 'String Formation in Sheared Polymer Blends: Coalescence, Breakup, and Finite Size Effects', *Phys. Rev. Lett.* 2001

Inkjet printing



H. Wijshoff, 'Drop dynamics in the inkjet printing process' *Curr. Opin. Colloid Interface Sci.* 2018

Blood

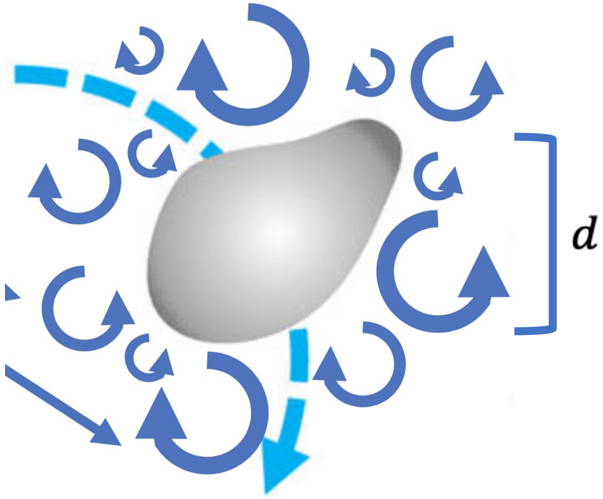


J. S. Horner et al. 'Measurements of human blood viscoelasticity and thixotropy…'. *J. Rheol* 2019

Drop size spectrum in Newtonian flows

- Deane & Stokes (*Nature* 2002) and Crialesi-Esposito et al. (*Commun Phys* 2023) observed a $N{\sim}d^{-10/3}$ dependence on drop diameter d in the drop size spectrum for droplets in turbulence.
- Garrett et al (*J. Phys. Oceanogr* 2000) proposed a mechanism;
- Drops of diameter d experience velocity fluctuations of order $(\varepsilon d)^{1/3}$, causing breakup in time $d(\varepsilon d)^{-1/3}{\sim}d^{2/3}$.
- We suppose that it is broken into two drops of equal diameter $2^{-1/3}d$
- These persist for a time $(2^{-1/3}d)^{2/3}$.
- Given the reduced lifetime, we expect $2(2^{-1/3})^{2/3} = 2^{7/9}$ times as many drops of this size.
- Divide by the ratio of the drop diameters to get the number per unit radius; $N(2^{-1/3}d) = 2^{1/3}2^{7/9}N(d) = 2^{10/9}N(d)$.
- This gives the observed scaling $N(d) = d^{-10/3}$.

$$d_H = 0.725\left(\frac{\sigma^2}{\rho^2\epsilon^3}\right)^{1/5}$$

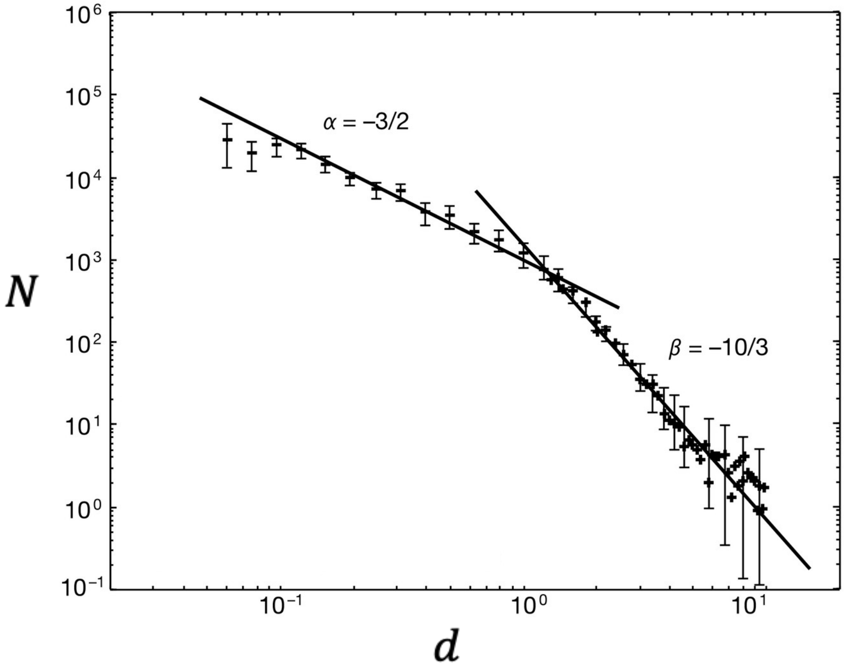


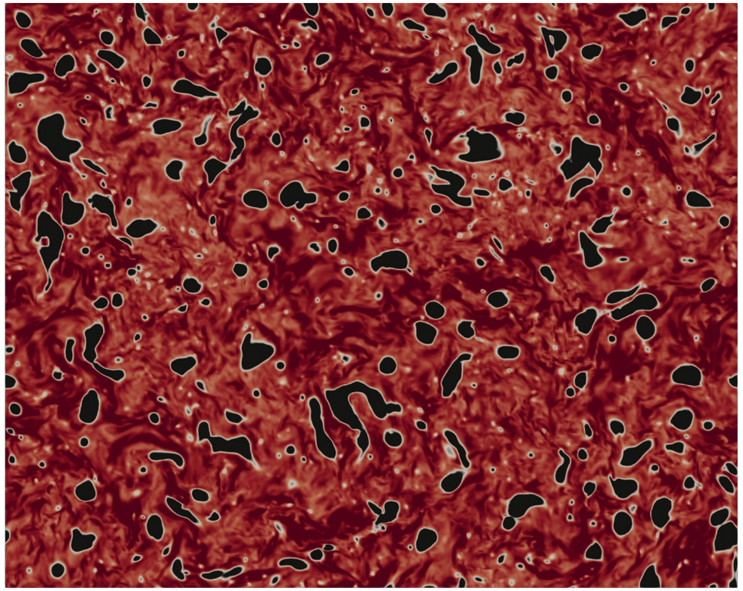
Qi *et al*. Fragmentation in turbulence by small eddies. *Nat Commun* (2022).

Goal of the work

- Previous investigations of drop breakup have been carried out in the classical Kolmogorov cascade.

How is droplet breakup affected by non-classical turbulence?





Deane & Stokes. Scale dependence of bubble creation mechanisms in breaking waves. *Nature* (2002).

Numerical method

Flow equations are solved on a 500^3 grid with **triperiodic boundary conditions**.
Turbulence is sustained by stochastic forcing (Eswaran & Pope, *Comput. Fluids*, 1988)

$$\rho_f\left(\frac{\partial u_\alpha}{\partial t}+\frac{\partial u_\alpha u_\beta}{\partial x_\beta}\right)=-\frac{\partial p}{\partial x_\alpha}+\frac{\partial}{\partial x_\beta}\left(2\mu_f S_{\alpha\beta}+\frac{\mu_p}{\tau_p}C_{\alpha\beta}\right)+F_\alpha \qquad \frac{\partial u_\alpha}{\partial x_\alpha}=0$$

Oldroyd-B model

$$\frac{\partial C_{\alpha\beta}}{\partial t}+u_\gamma\frac{\partial C_{\alpha\beta}}{\partial x_\gamma}=C_{\alpha\gamma}\frac{\partial u_\beta}{\partial x_\gamma}+C_{\gamma\beta}\frac{\partial u_\gamma}{\partial x_\alpha}-\frac{C_{\alpha\beta}-\delta_{\alpha\beta}}{\tau_p}$$

Volume-of-fluid model (Ii et al. *J. Comput. Phys.* 2012)

$$\partial_t\phi+\partial_i u_i\mathcal{H}=\phi\,\partial_i u_i, \qquad F_\alpha=\sigma\xi\delta_s n_\alpha$$

Dimesionless groups

$$Re_\lambda\equiv\rho u_{rms}/\mu_f\approx 200,$$

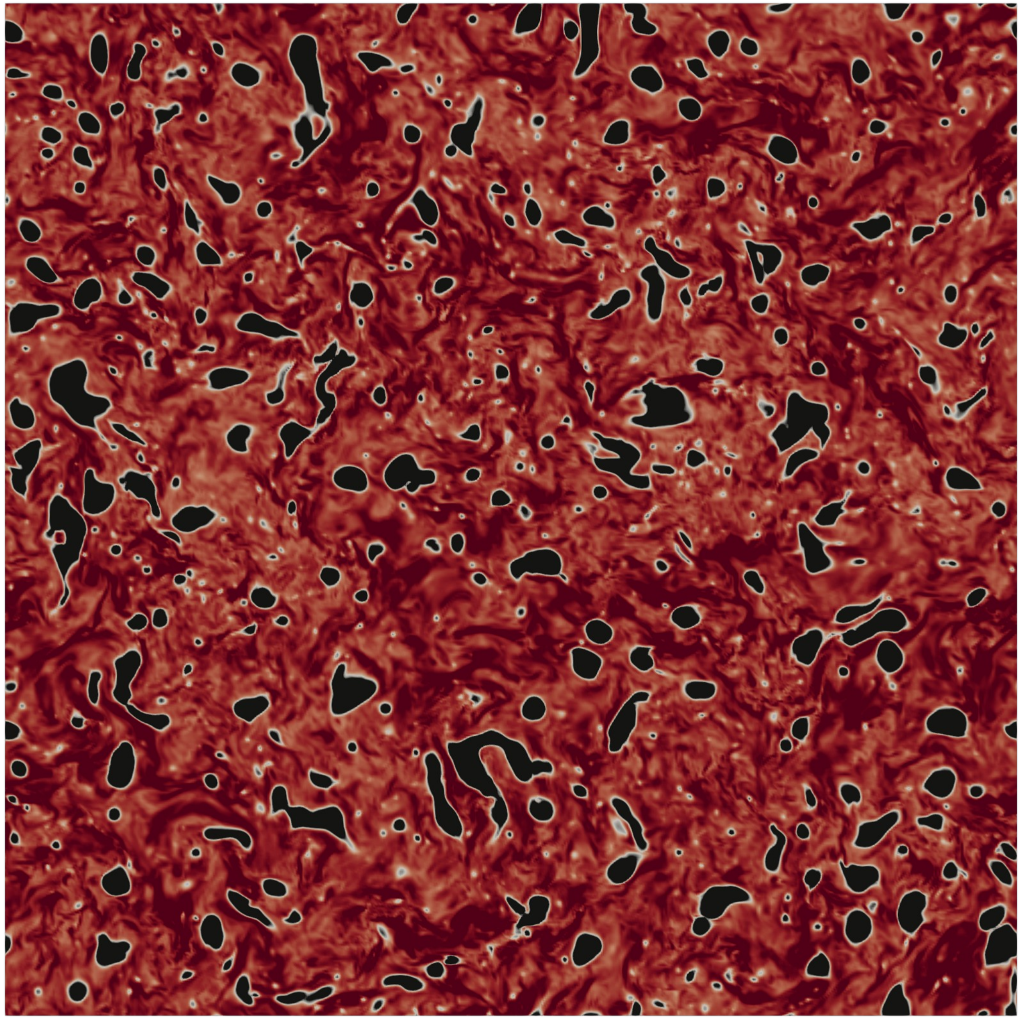
$$0<\mathrm{De}\equiv\tau_p/\tau_L<3$$

$$\tau_L=L/u_{rms}$$

$$\Phi=\{0,0.1\}$$

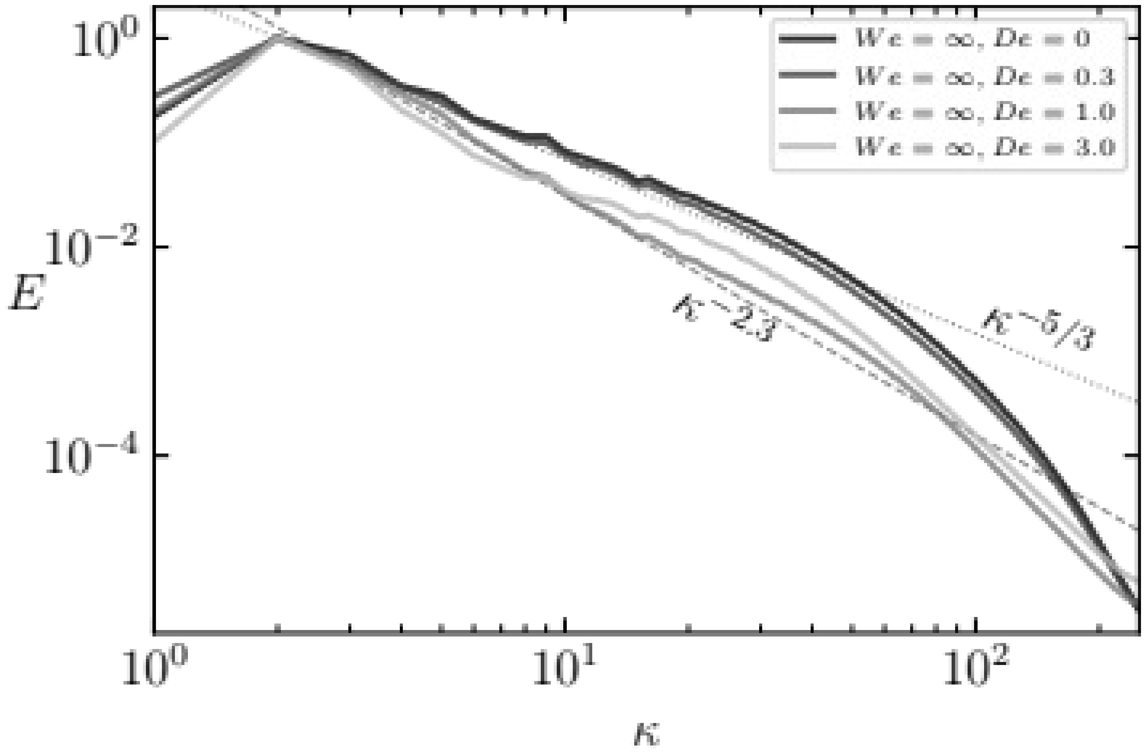
$$We_{\mathcal{L}}=\rho_c\mathcal{L}u_{rms}^2/\sigma=\{20,40\}$$

Droplets in a viscoelastic carrier fluid



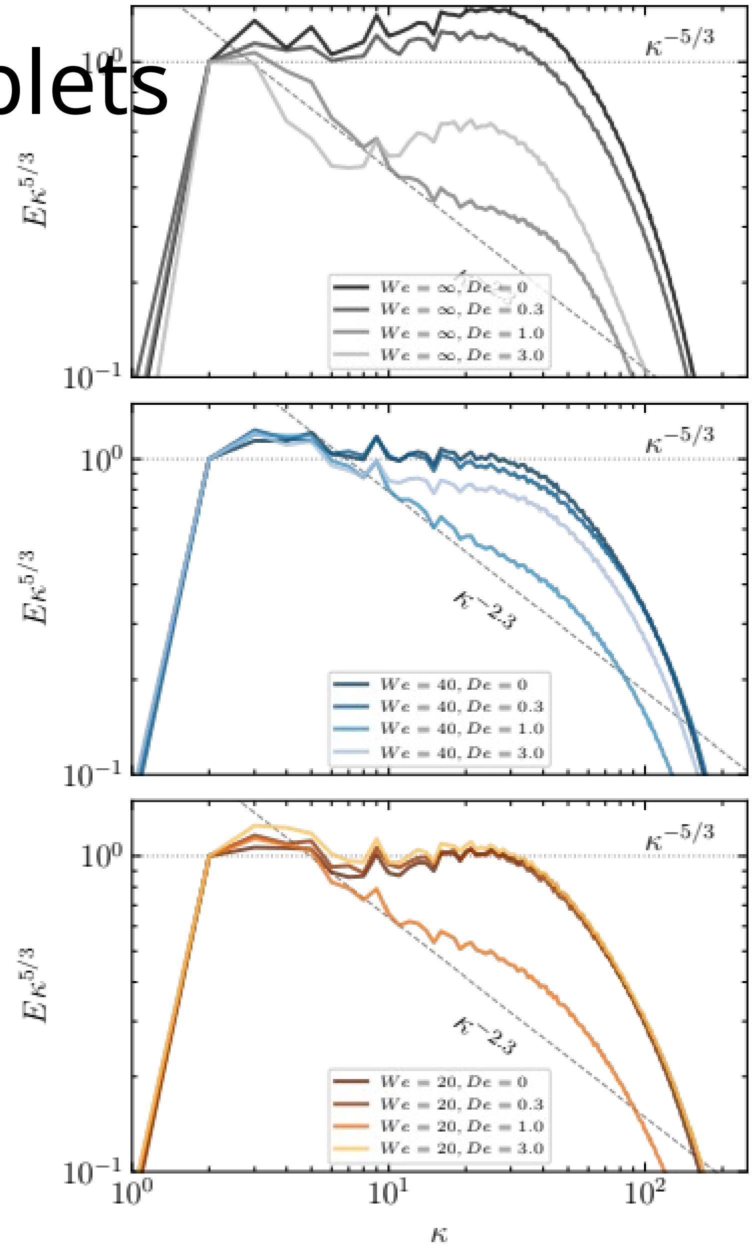
Turbulence modulation due to the viscoelastic fluid

- For the Newtonian single phase flow we observe the classical $E \sim \kappa^{-5/3}$ scaling
- In the case of $De = 1$, the viscoelastic fluid introduces a new scaling $E \sim \kappa^{-2.3}$
- This has been previously observed by Rosti Perlekar & Mitra. (Large is different.... *Science Advances* 2023).



Turbulence in the presence of droplets

- The droplets have little effect on the kinetic energy spectrum of the fluid.
- As before, $E \sim \kappa^{-2.3}$ for the $De = 1$ cases.



Spectral energy balance

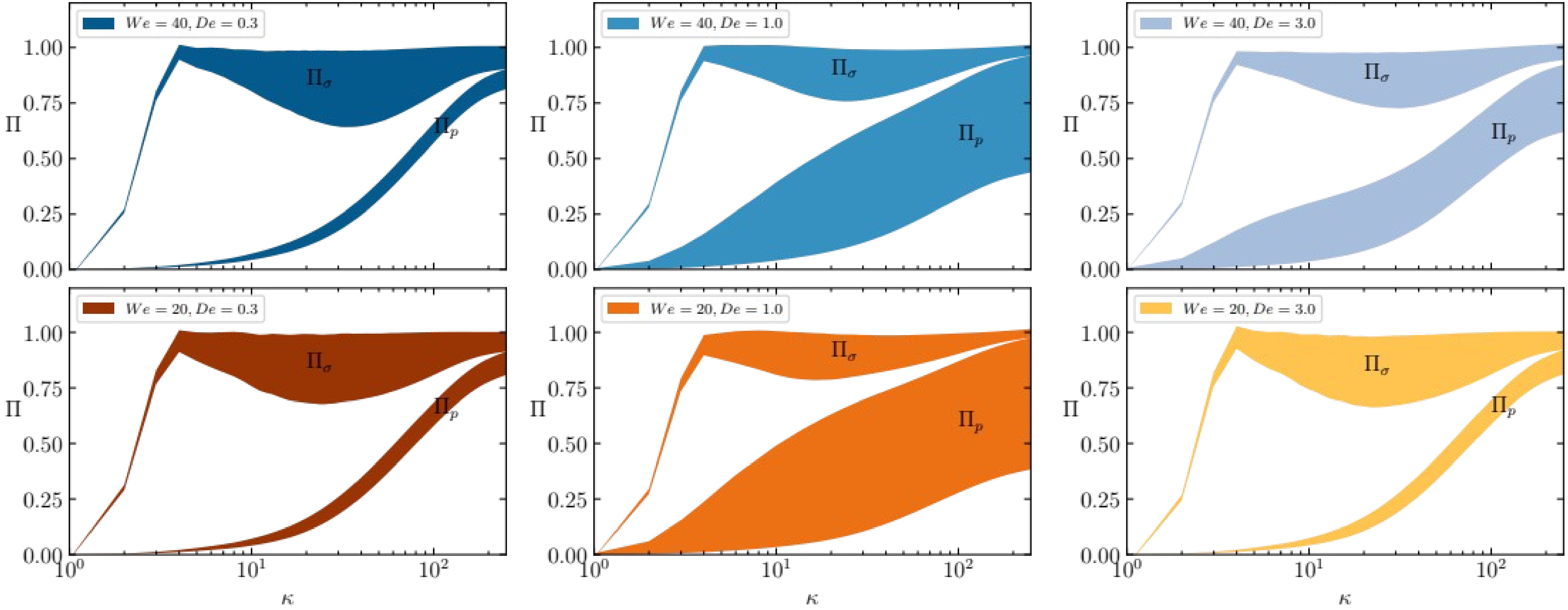
interface polymers

$$\epsilon = P + \Pi_\sigma + \Pi + \Pi_p + D$$

injection convection dissipation

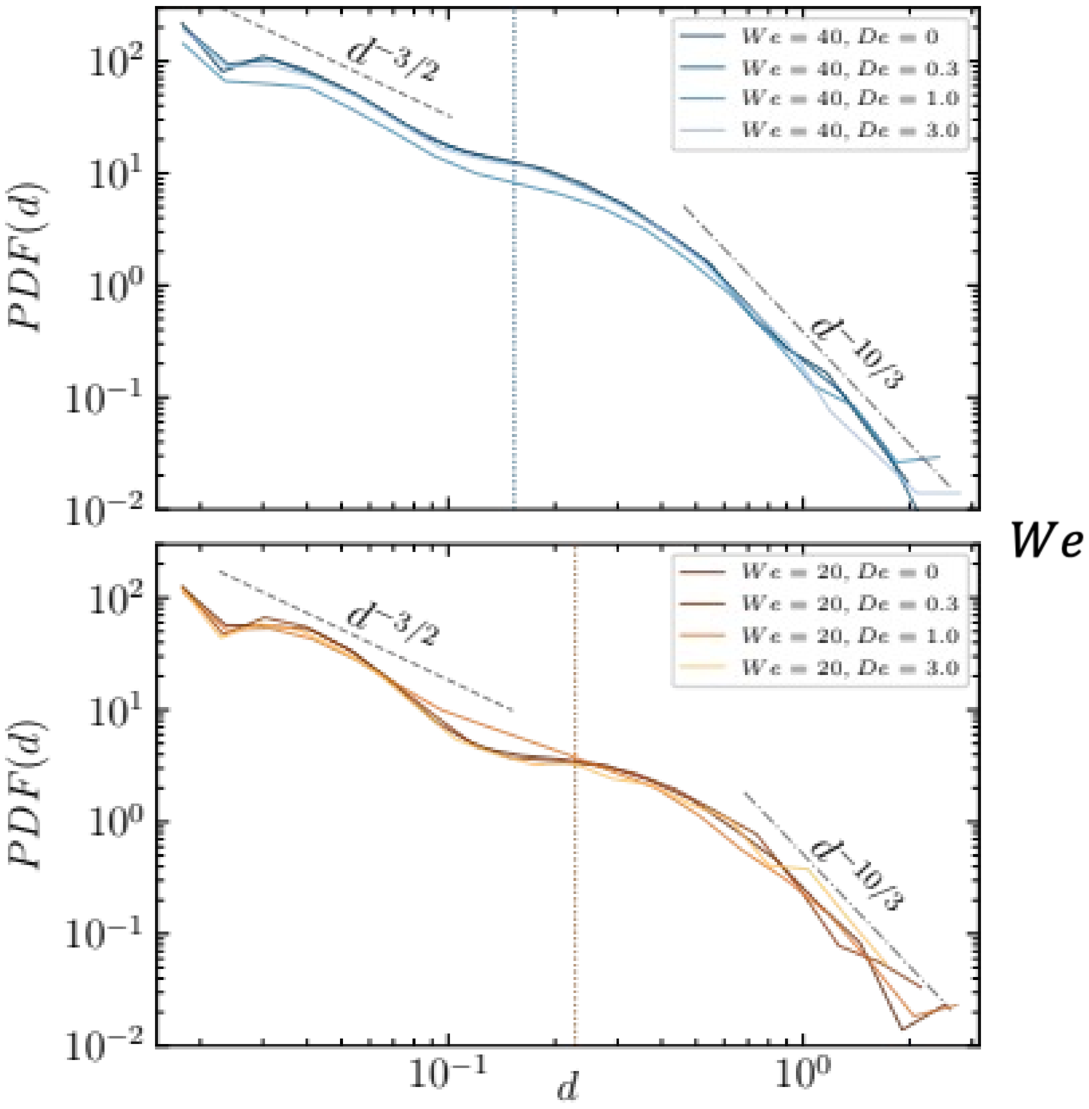
De

We



Drop size spectrum

- At larger Weber numbers, there more small drops, supporting the previous observation that Π_σ moves to larger wavenumbers.
- The mechanism of Garrett et al (*J. Phys. Oceanogr* 2000) with $E \sim \kappa^{-2.3}$ predicts a drop size scaling of $d^{-3.65}$ in the breakup region.
- However, we recover $d^{-3/2}$ and $d^{-10/3}$ scalings in the drop size spectra at all Deborah numbers.



Conclusions and further work

- We made DNS of droplet breakup in viscoelastic turbulence. We found:

→An energy scaling $E \sim \kappa^{-2.3}$ is seen at intermediate Deborah numbers

→Increasing the Weber number reduces the drop size, and the interface coupling acts at larger wavenumbers.

→The canonical droplet size scalings are recovered, even in the presence of a turbulent viscoelastic fluid.

→To better elucidate the breakup mechanism, we should measure drop size spectra in other flows, such as elastic turbulence, linear forcing, 2D turbulence, and bubble induced turbulence.