Droplet Spreading in a 2D Active Chiral Fluid

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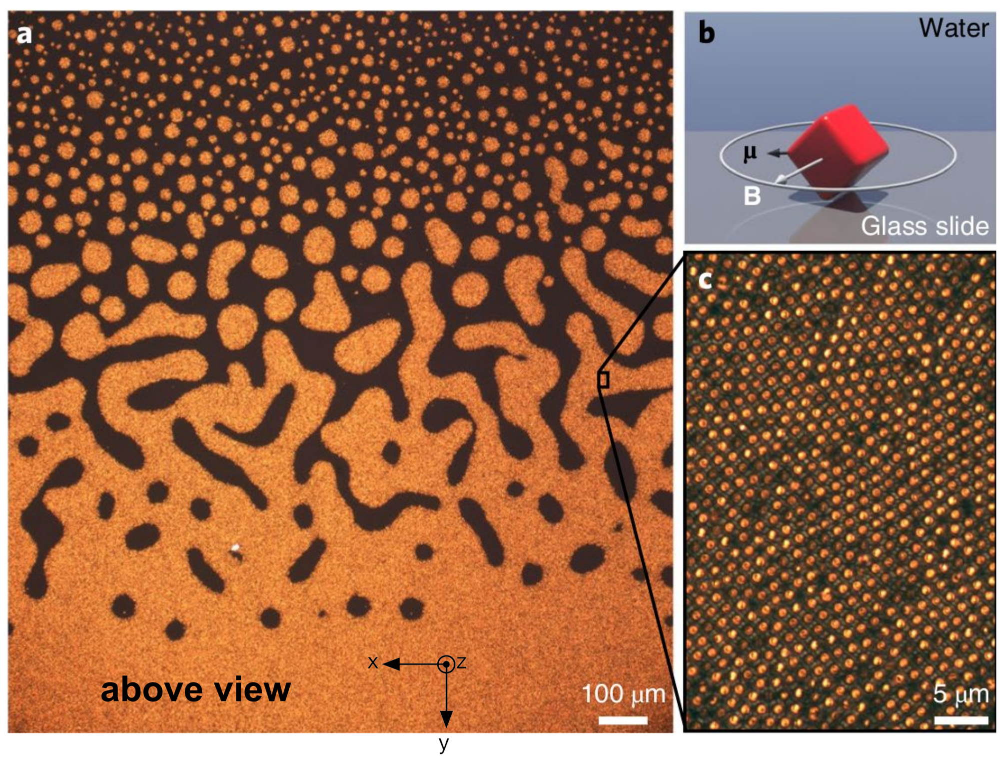
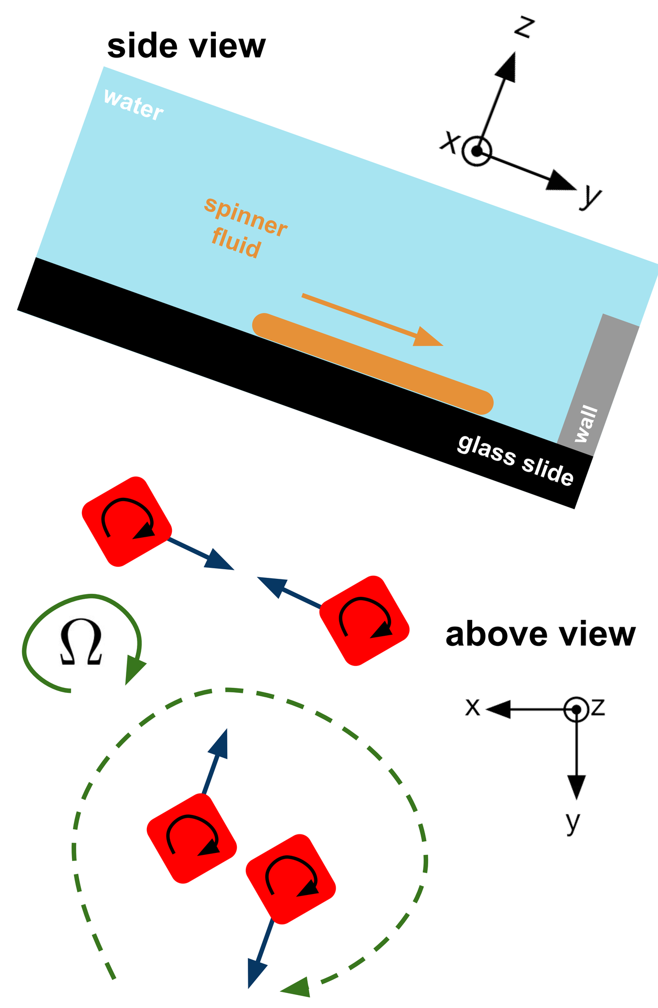
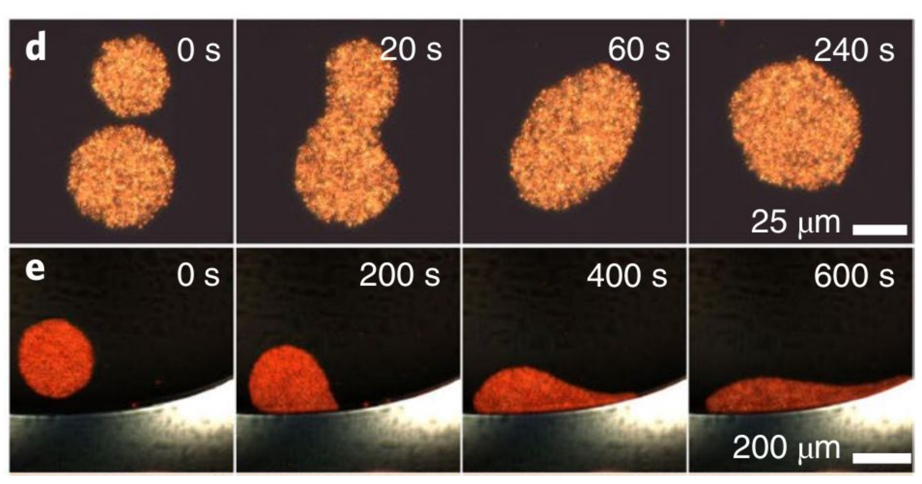
Introduction







- Our colloidal fluids consist of **magnetically spun** hematite particles in water, sedimented on a 2D glass substrate [1].
- The particles collide and frictionally repel each other in a direction tangential to the contact line, creating **odd interactions**.
- These fluids display an **edge current**, transport of fluid around the boundary.

viscosity η
surface tension γ
substrate drag Γ
odd viscosity η_O
rotational viscosity η_R

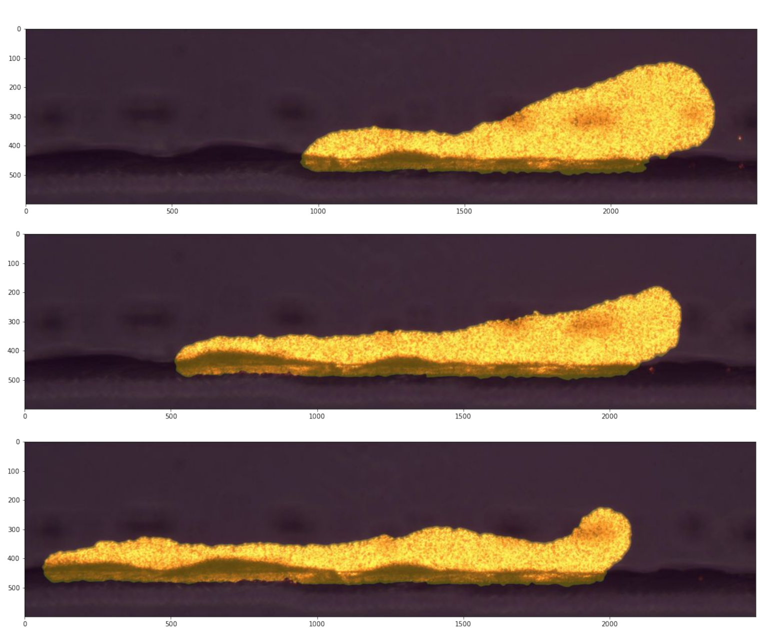
- We can describe our fluid with a hydrodynamic theory like any other fluid using parameters like viscosity and surface tension.
- However, the odd interactions add extra terms to the equations, with extra parameters like **odd viscosity** (see: **passive vs. active fluids**).

Goal: test + develop the hydrodynamic theory using classical scenarios like droplet spreading and thin films.

Thin film theory

- The long-term evolution of spreading chiral droplets is a crawling thin film [4]. (right)
- Lubrication theory is an technique to describe thin films where motion is primarily sideways.
- We can derive a **thin film equation**, a useful PDE for the film height.

$$\partial_t h = -\partial_x \left[\frac{h}{\Gamma} \partial_x (\gamma \partial_x^2 h - gh) \right]$$



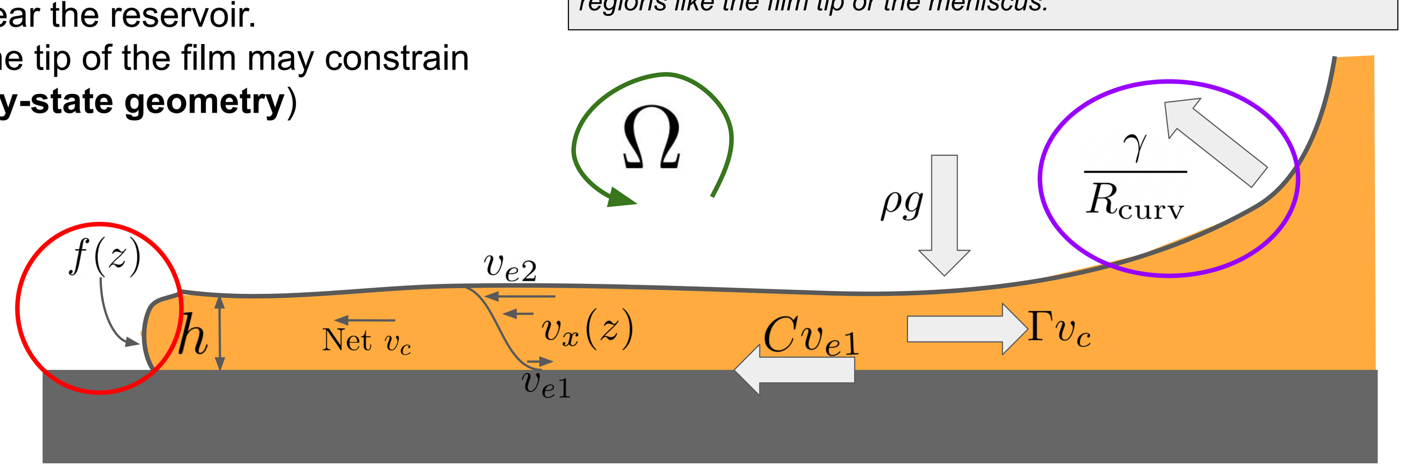
- Does this lubrication theory give us testable physical predictions (e.g. predicted droplet height)?
- **No:** there is nothing in the flat thin film system that constrains the height.
  - The only intrinsic quantity is the **crawling flux**.
- *The droplet is remembering a height constraint from a different regime.*

$$j = v_c h = \frac{2\Omega \eta_R \delta C}{(\eta + \eta_R + C\delta)\Gamma}$$

Where is the height set? 2 possibilities
1. **The meniscus**: similar to the Landau-Levich dip coating problem [5], the height may be constrained by matching lubrication theory in the thin regime with meniscus geometry near the reservoir.
2. **The tip**: forces near the tip of the film may constrain the height. (see **steady-state geometry**)

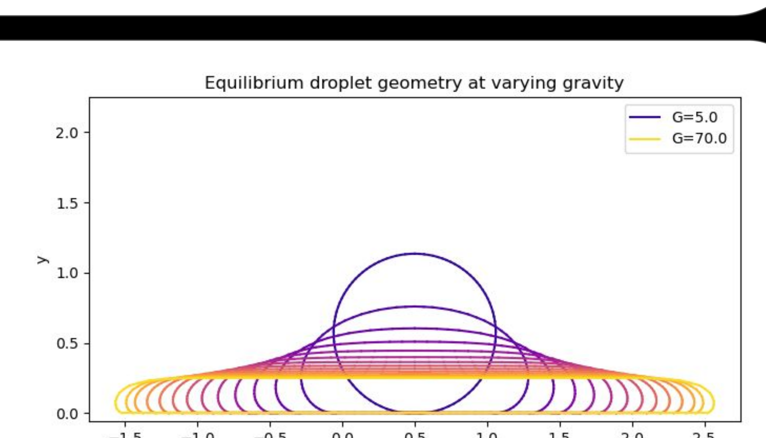
A schematic for our crawling thin film. It has some geometry and velocity profile that powers the crawl, but we can't predict this behavior from the thin film theory without also examining other regions like the film tip or the meniscus.

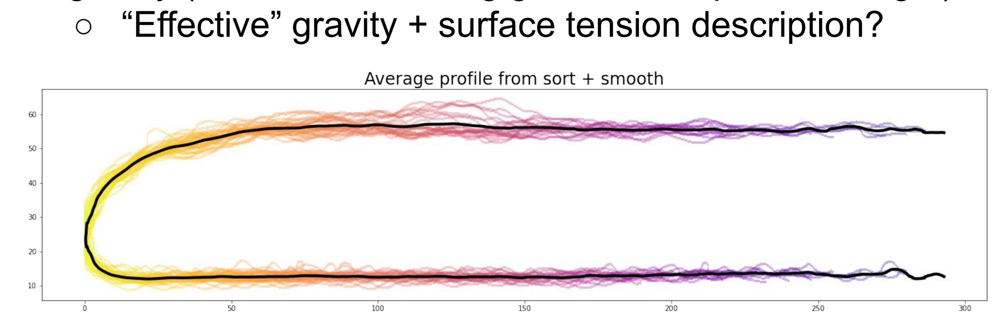
$$h = ??$$

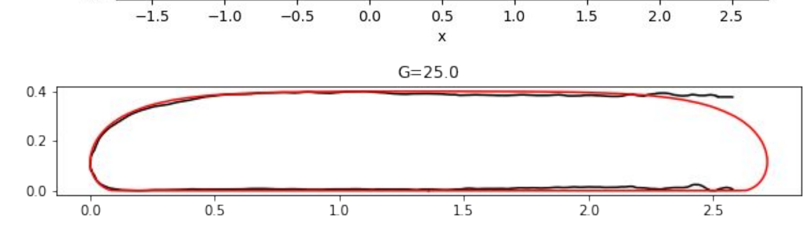


Steady-state geometry

- Understanding what determines the geometry of our film would provide another test of the hydrodynamic theory.
- We measured the average geometry of our film (below).
- It happened to match the geometry of an non-wetting droplet in gravity (curvature matching gravitational pressure; right).
  - "Effective" gravity + surface tension description?

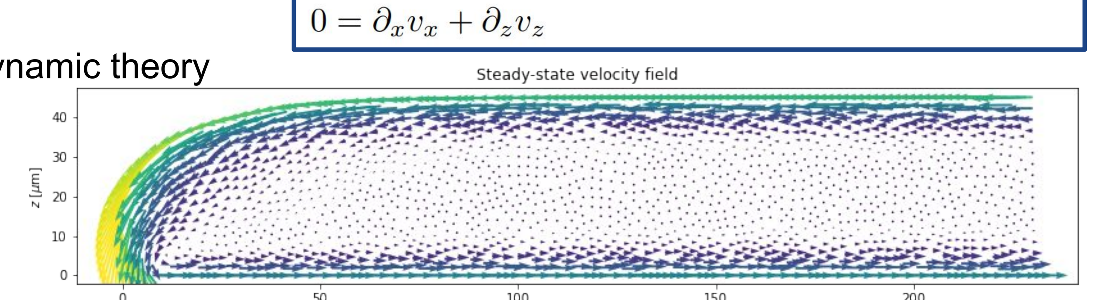






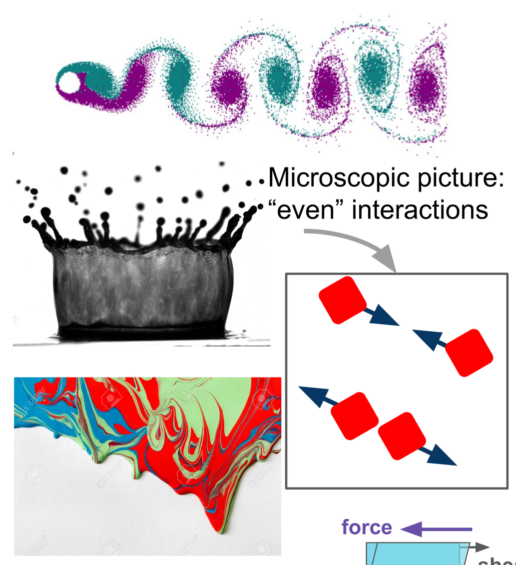
- We have begun solving the **equations of motion** on a domain of this geometry using FEniCS [6].
- Goal: determine if this velocity field matches observations, and for what combination of parameters.
  - This would give us a test of the hydrodynamic theory and parameters!

$$0 = -\partial_x (p + \eta_O \omega) + (\eta + \eta_R)(\partial_x^2 + \partial_z^2) v_x - \Gamma v_x$$
$$0 = -\partial_z (p + \eta_O \omega) + (\eta + \eta_R)(\partial_x^2 + \partial_z^2) v_z - \Gamma v_z - \rho g$$
$$0 = \partial_x v_x + \partial_z v_z$$



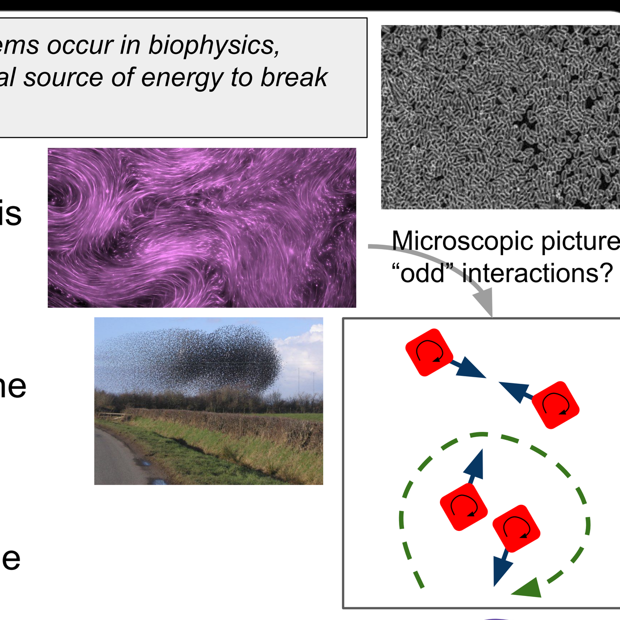
Passive vs. active fluids

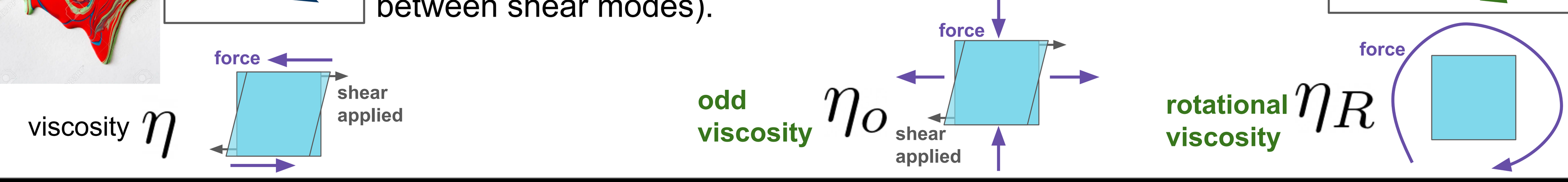
Many active matter systems occur in biophysics, where there is an external source of energy to break time-reversal symmetry.



Left: particles in everyday fluids have interactions parallel to line between them. This causes familiar notions of fluid flow and viscosity (resistance to shear).

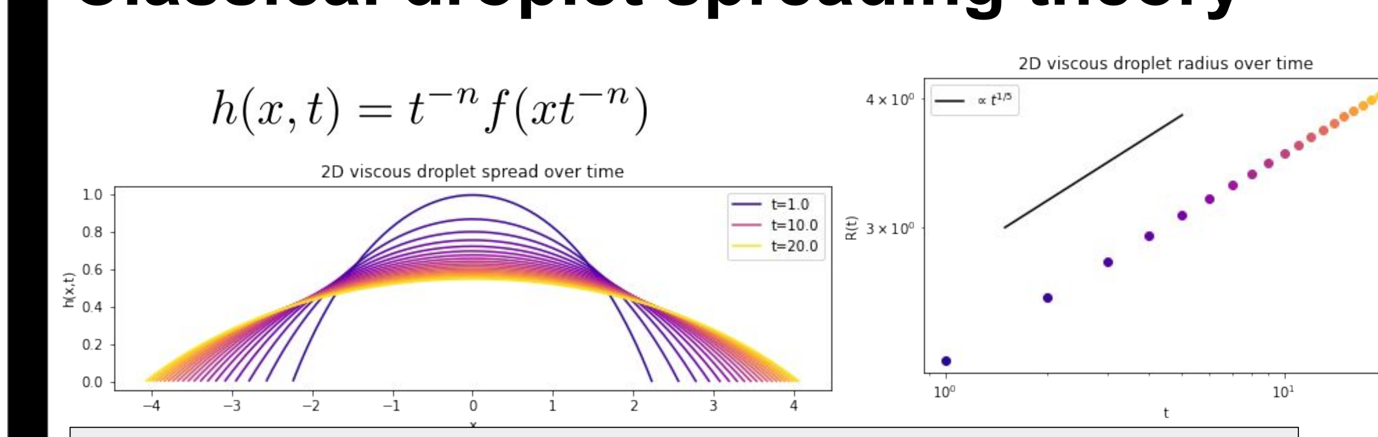
Right: allowing forces perpendicular to the line between fluids particles breaks time-reversal symmetry and enters the broader realm of **active matter**. These fluids can have nonintuitive flows and odd viscosity (exchange between shear modes).





Classical droplet spreading theory

$$h(x,t) = t^{-n} f(xt^{-n})$$



Left: the possible evolution of a droplet spreading under the competition of viscosity and gravity. Right: its radius over time, displaying the power law expansion.

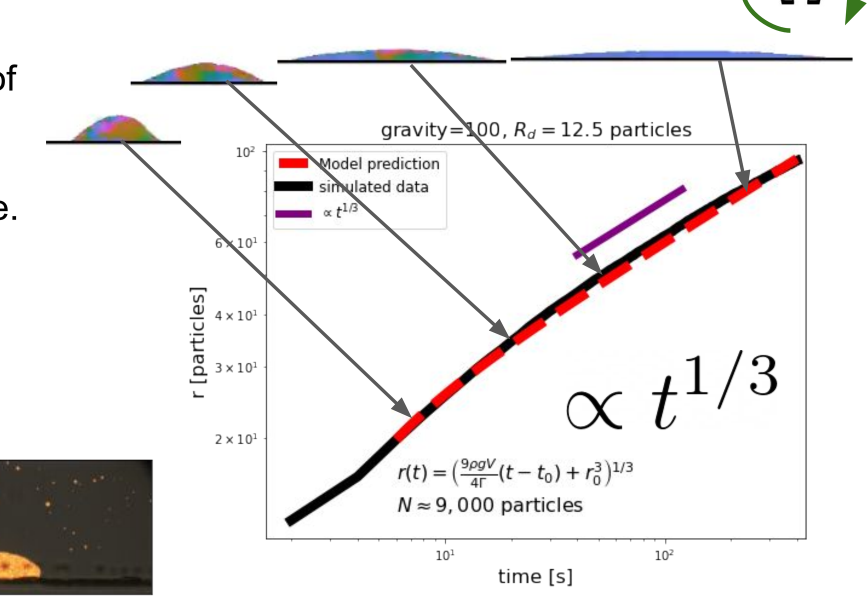
Driving Mechanism	Dissipation Mechanism	Expansion exponent *n*
gravity	substrate drag Γ	1/3
gravity	viscosity η	1/5
surface tension γ	substrate drag Γ	1/5
surface tension γ	viscosity η	1/7

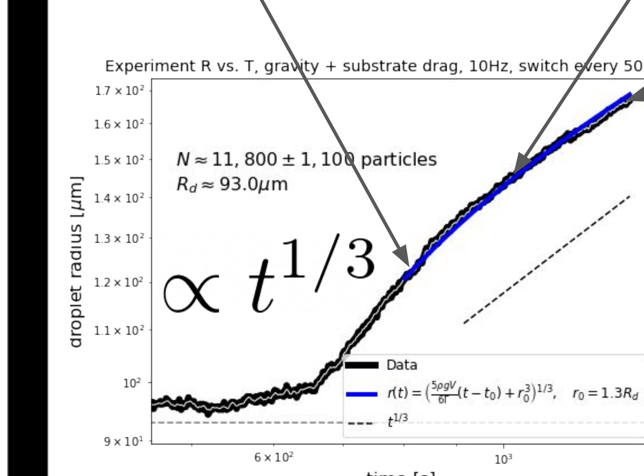
- Classical droplets typically spread "self-similarly," where the shape is maintained but stretched.
- The stretching typically follows a power law with time, with the exponent *n* determined by the dominant dissipation and driving mechanisms.

In our experiment, the dominant forces are gravity and substrate drag $\xrightarrow{\text{Classical prediction}}$ $r(t) \propto t^{1/3}$

Testing the droplet spreading theory

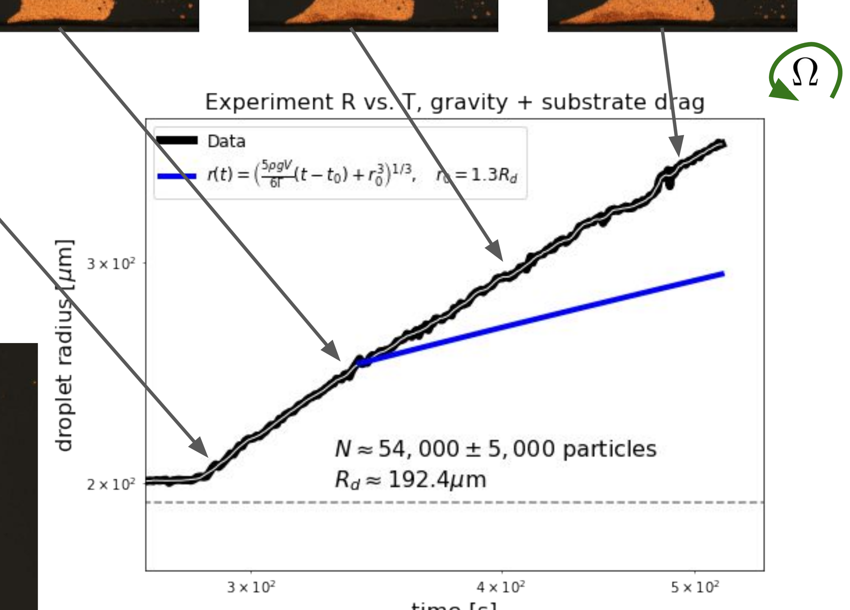
- First we tested the droplet spreading theory on a suite of realistic simulations of the chiral fluid [2,3]. (right)
- The theory agreed for high enough rotational frequencies Ω, where droplets were in a more fluid state.
- The parameters varied were droplet size, gravity strength, and rotational frequency Ω.
- There was no friction programmed into the fluid's interaction with the wall.

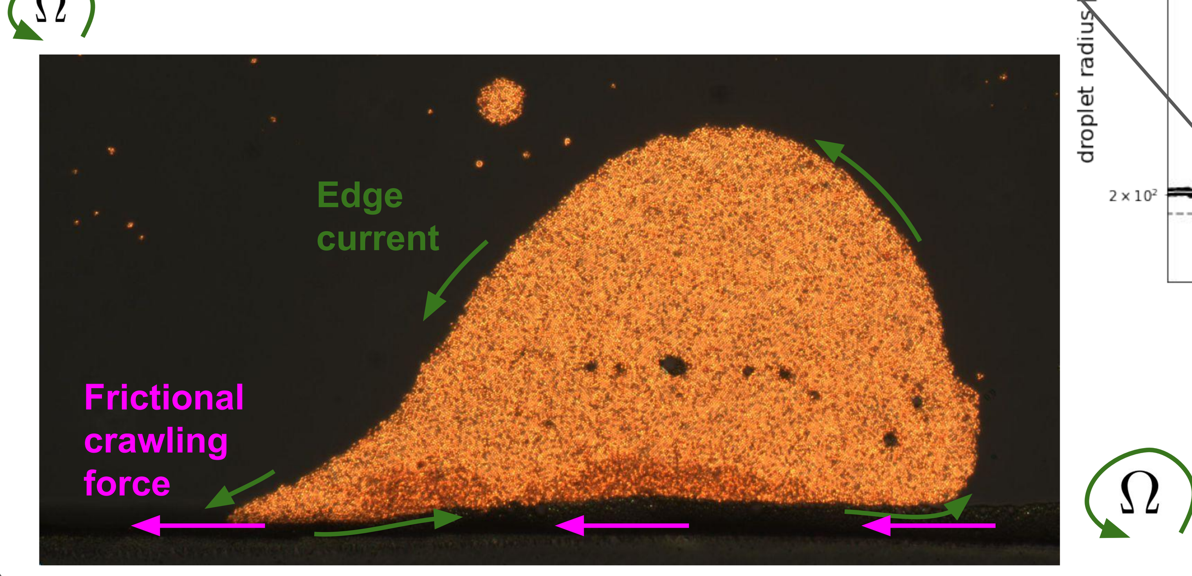




- Next we tested the droplet spreading theory on real droplets of our fluid with the chirality removed [4]. (left)
- The theory agreed for these droplets, when accounting for their friction with the wall.
- Chirality was removed by switching rotation direction every 10-50 cycles.

- Next we tested the droplet spreading theory on real droplets of our chiral fluid [4]. (right)
- The theory didn't agree for these droplets, because the spread was now powered by chiral friction between the droplet's **edge current** and the wall (not gravity).





Conclusions

- We have developed the hydrodynamic theory for our chiral active fluid in classic scenarios like droplet spreading and lubrication theory.
- Classical droplet spreading powered by gravity competing with substrate drag explains the spread of simulated chiral droplets and experimental achiral droplets.
- Experimental chiral droplet spreading is powered instead by friction from the edge current, which turns it into a crawling thin film.
- Lubrication theory may describe the behavior in this regime, but provides no testable physical predictions.
- A closer look through numerical simulations is necessary to test the theory in this regime.

References

[1] Soni, V., Bililign, E.S., Magkiriadou, S. et al. The odd free surface flows of a colloidal chiral fluid. *Nat. Phys.* 15, 1188–1194 (2019). https://doi.org/10.1038/s41567-019-0603-8

[2] Bililign, E.S., Balboa Usabiaga, F., Ganan, Y.A. et al. Motile dislocations knead odd crystals into whorls. *Nat. Phys.* 18, 212–218 (2022). https://doi.org/10.1038/s41567-021-01429-3

[3] Simulations were performed by Yehuda Ganan.

[4] Experiments were performed by Ephraim Bililign.

[5] Levich, B., & Landau, L. (1942). Dragging of a liquid by a moving plate. *Acta Physicochimica U.R.S.S.*, Vol. XVII, No. 1-2, 1942, pp. 42-54.

[6] https://fenicsproject.org/