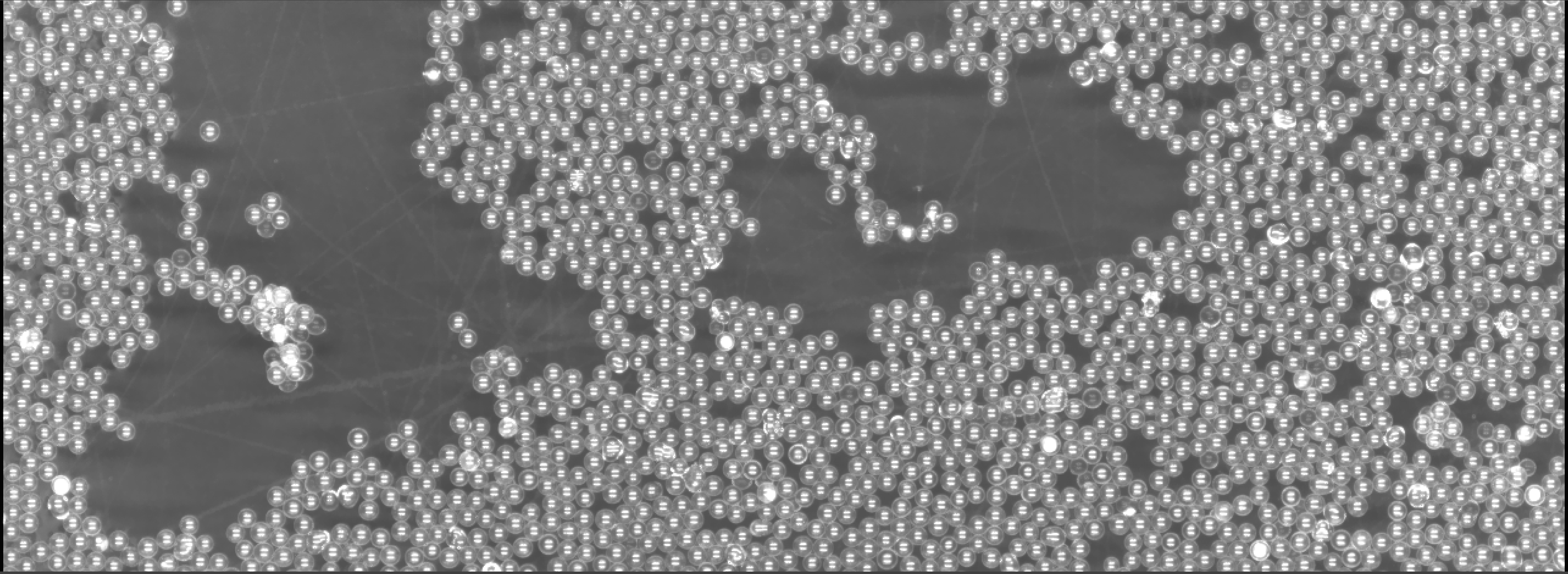


Stability of aggregates under 2D time-periodic flow

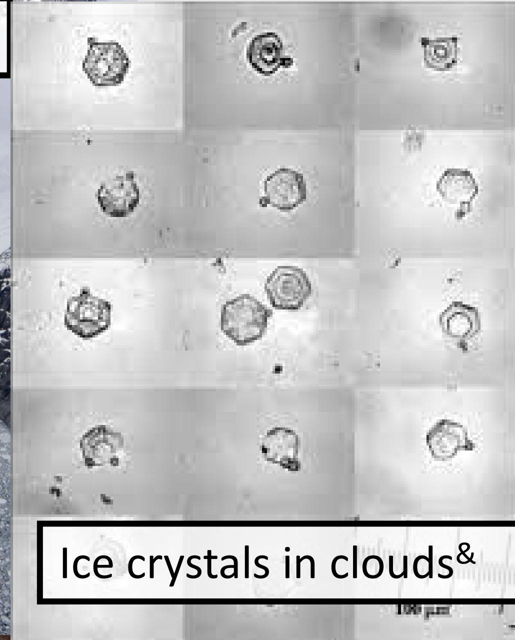
Cacey Bester, Swarthmore College

with

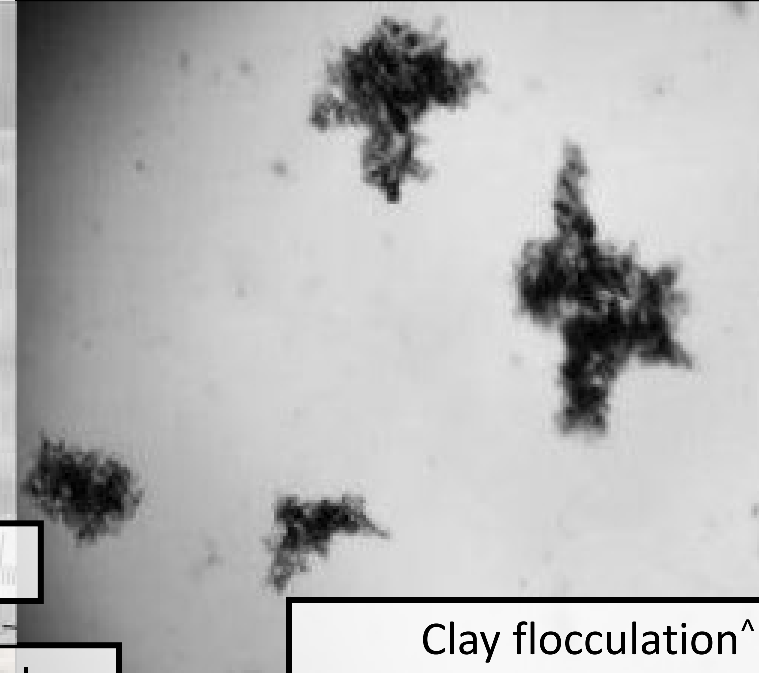
Paulo Arratia and Douglas Jerolmack

KITP Program on Multiphase Flows November 2022

Ice mélange[+]



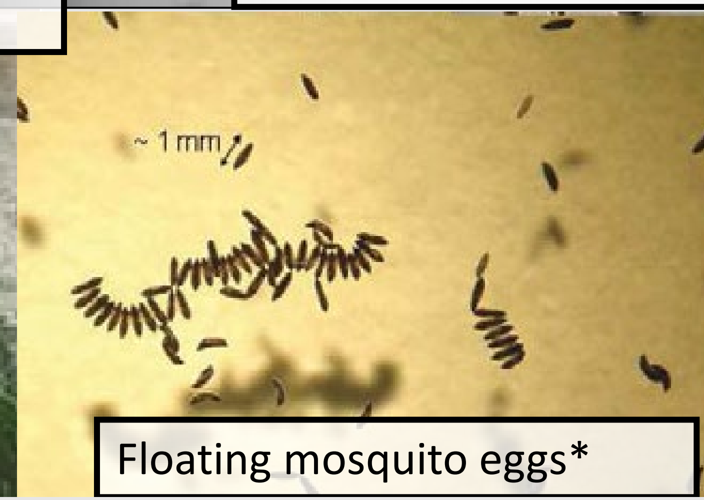
Ice crystals in clouds[&]



Clay flocculation[^]

Sediment along river delta[#]

Pollen floating on pond



Floating mosquito eggs*

Aggregation and flow at fluid interface

[#]From NASA Terra Satellite (2001)

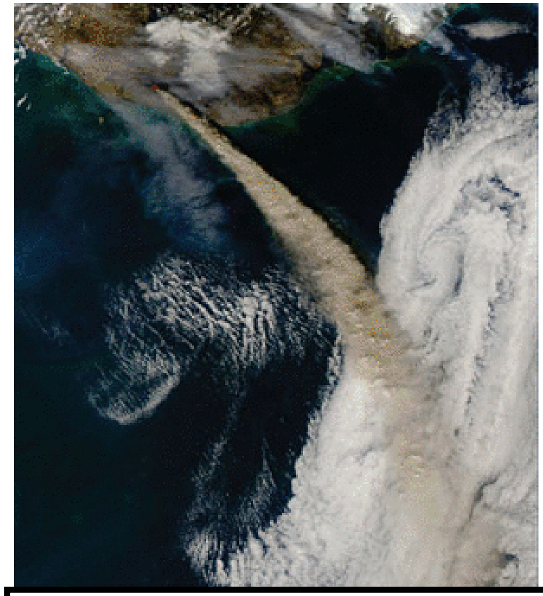
[+] J. Burton et. al. (2018)

* Loudet & Pouligny (2011)

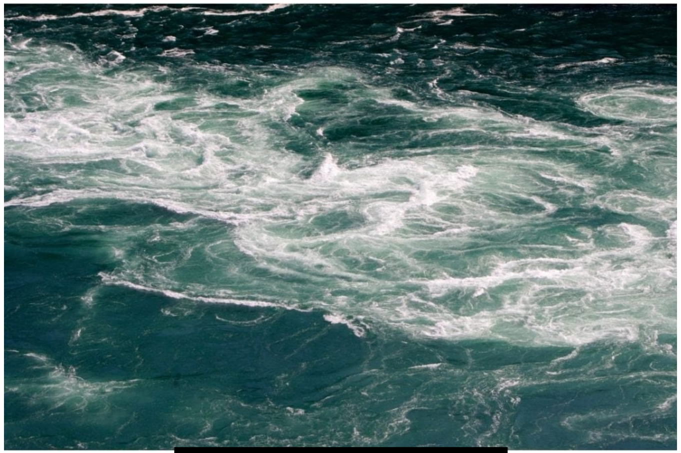
^ K Strom (2018)

[&]Pruppacher & Klett (1997)

Coherent structures in environmental fluid flows

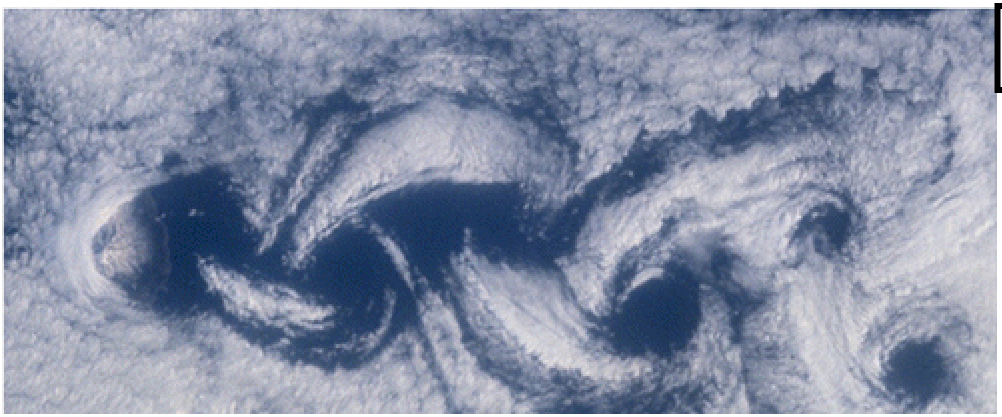


Volcanic eruption (NASA)



Ocean gyre

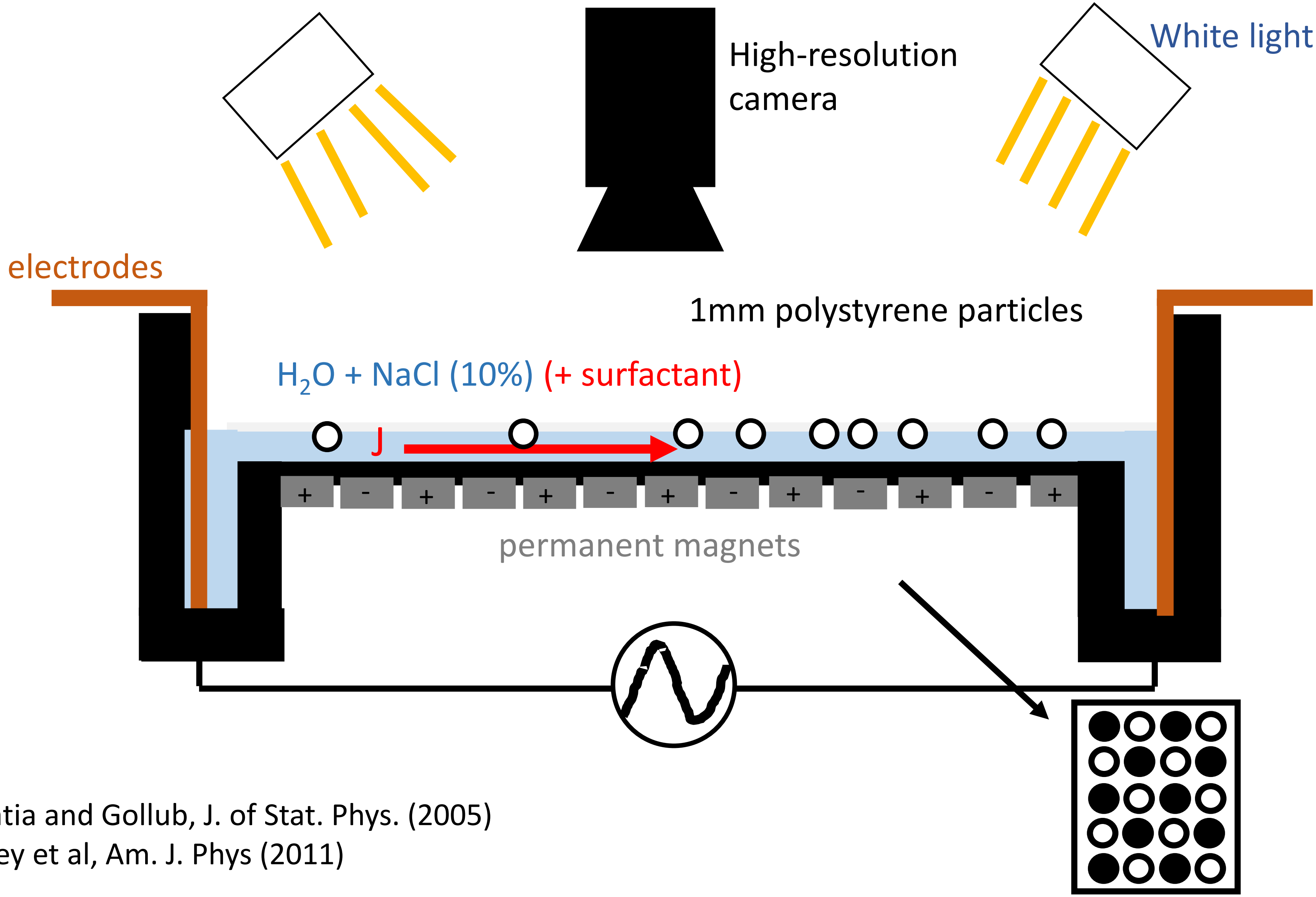
River plume



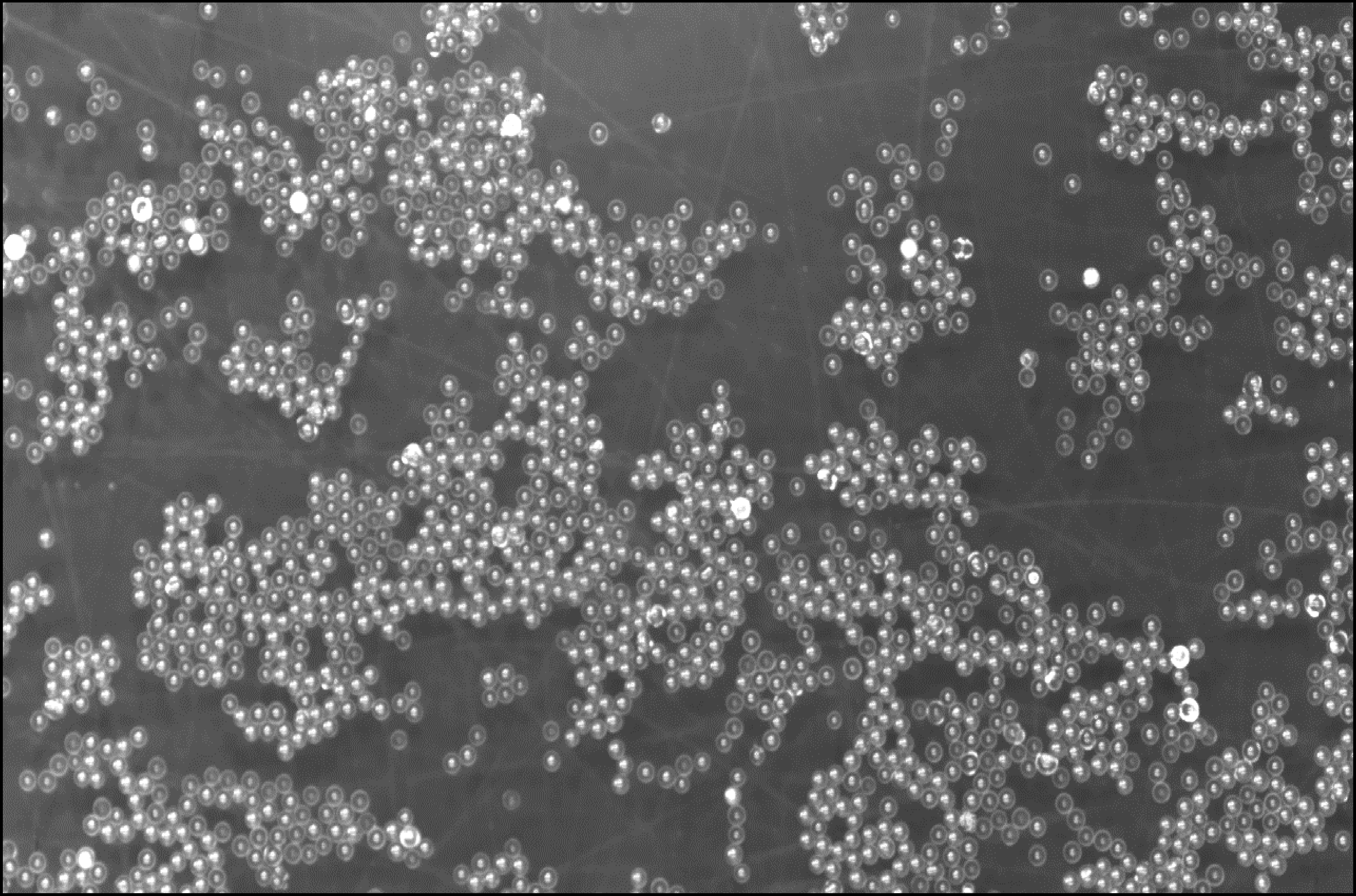
Clouds

Peacock and Haller, Phys. Today (2013)

2D fluid flow driven by Lorentz forcing

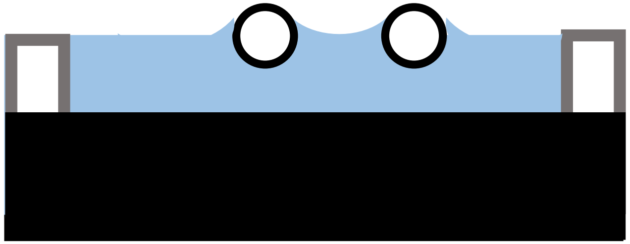


Arratia and Gollub, J. of Stat. Phys. (2005)
Kelley et al, Am. J. Phys (2011)

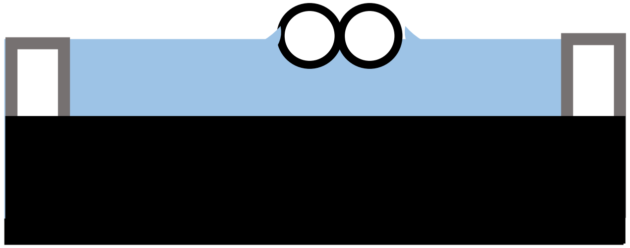


Recorded at 60 fps

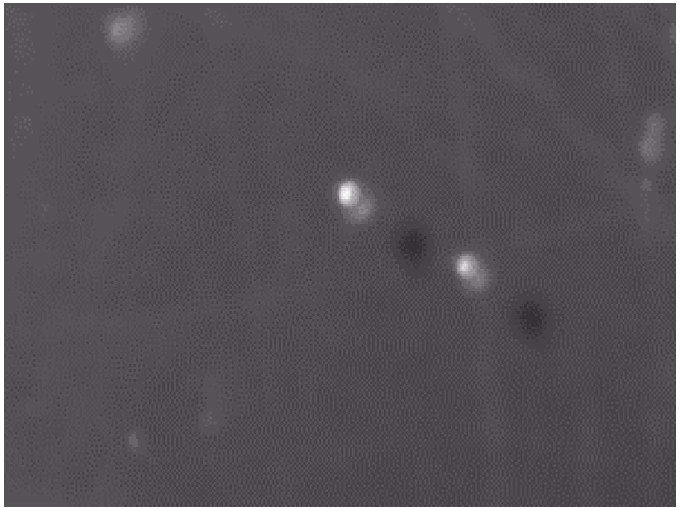
Particle attraction: The "Cheerios" Effect



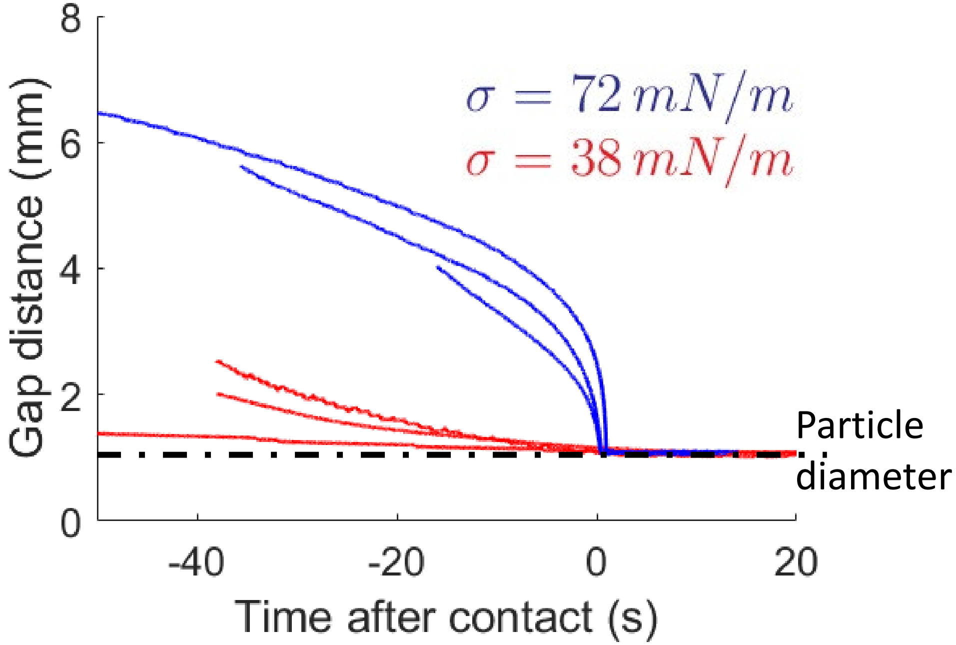
Particles cause interfacial deformation



When deformations overlap, attraction results

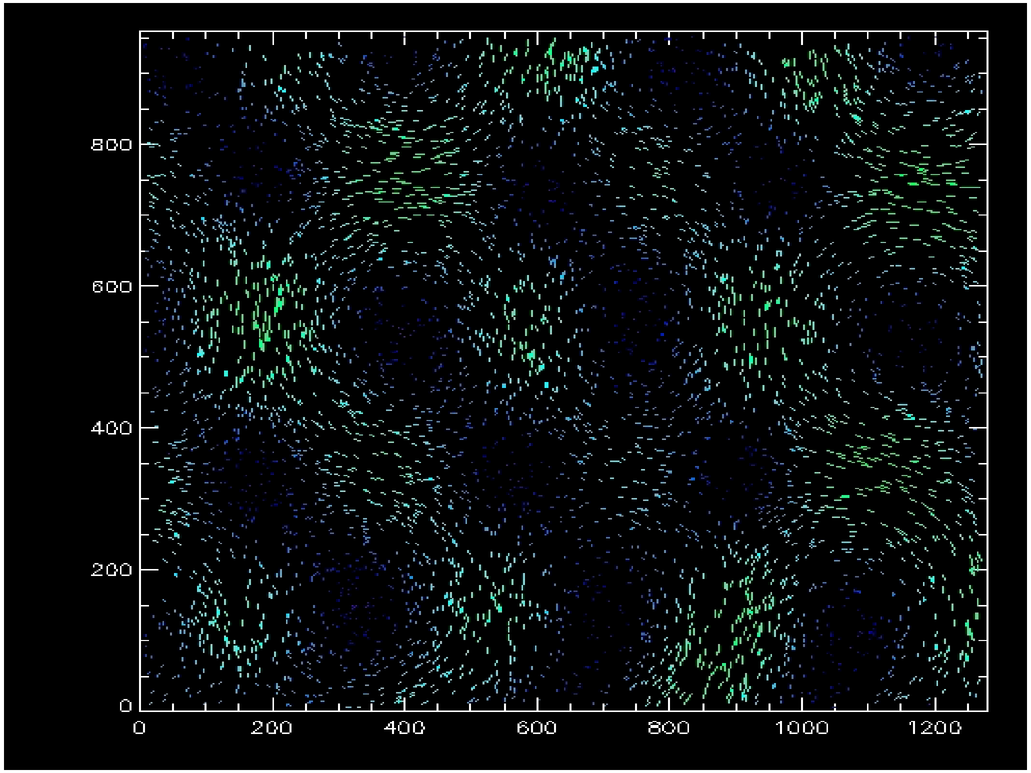


video of approach of two particles



D. Vella and L. Mahadevan, Am. J. Phys (2005)
Berhanu and Kudrolli PRL (2010)
M.J. Dalbe et. al., PRE (2011)
N. Rahman et. al., JMES (2017)
Ho et. al., PRL (2019)

Velocity field shows flow pattern in experimental cell



Re = 25 *p = 0.6*

Fluid tracers in flow

Flow described by:

Reynolds number *Re*

$$Re = \frac{Inertia}{viscosity}$$

Path length *p*

$$p = U/Lf$$

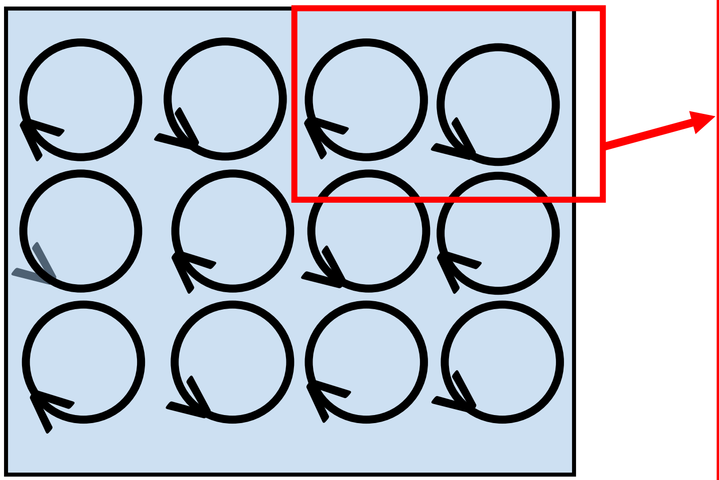
mean displacement of fluid element in one period

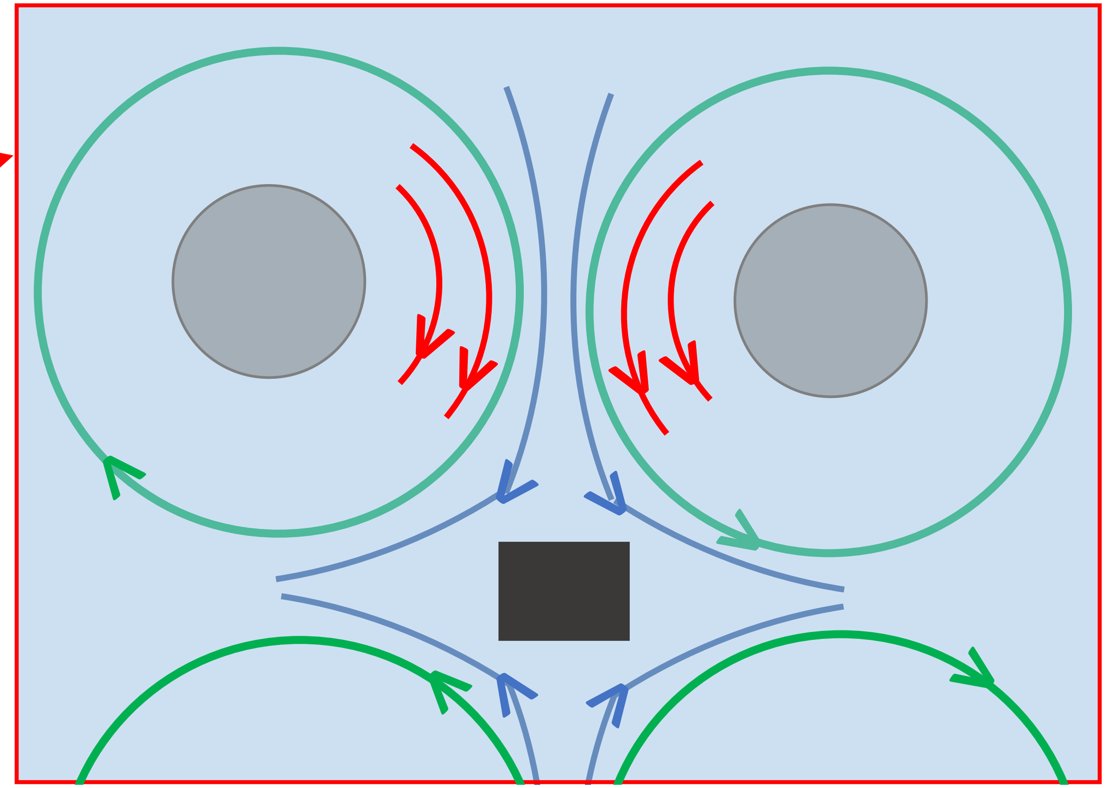
1 pixel = 70 micron

Faber, Fluid dynamics for physicists (1995)
Arratia and Gollub, J. of Stat. Phys. (2005)
Ouellette et al, PRL (2008)

Features of structured flow

spatial symmetry

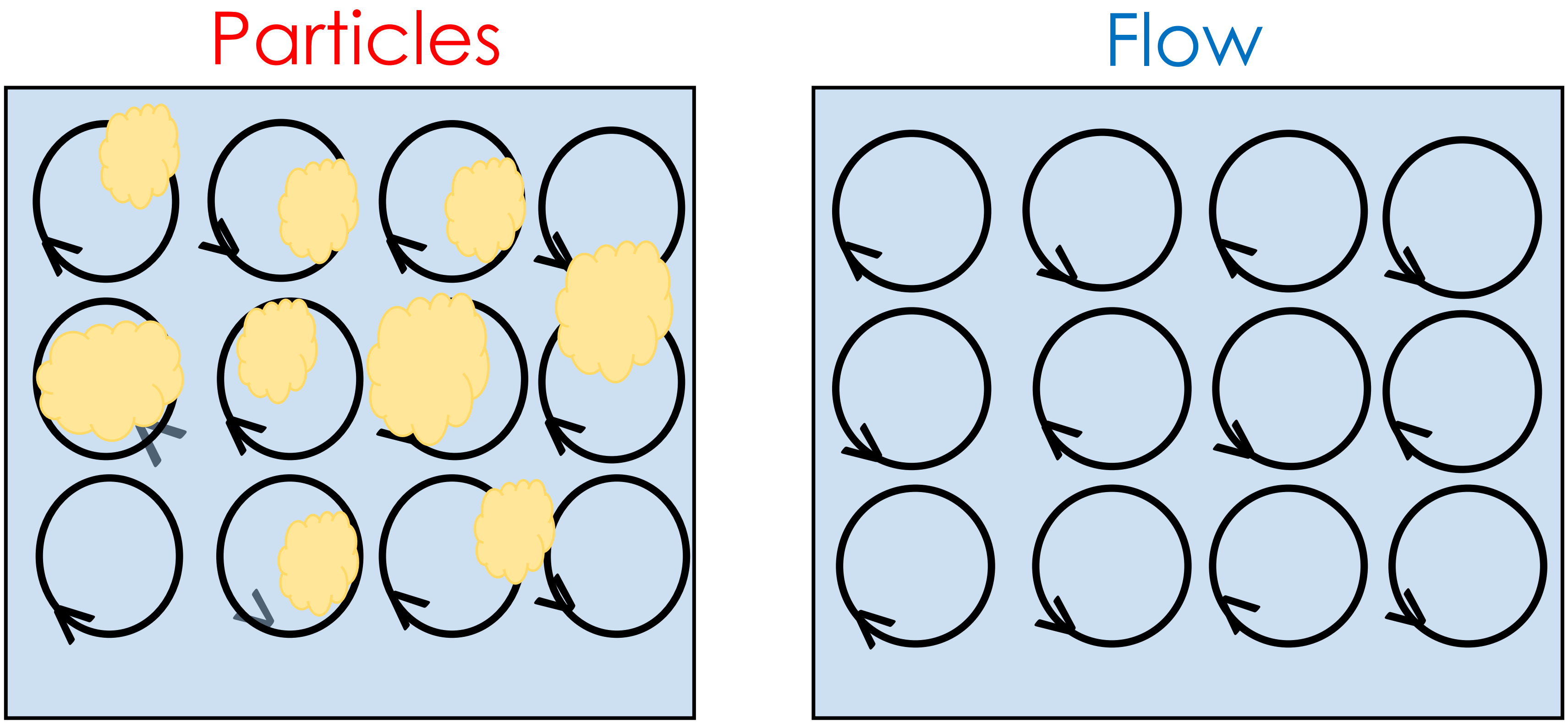




Shear layer in river

rotation
extension
shear
stagnant zones
compression

Ottino, Cambridge U. Press (1989)
Arratia and Gollub, J. of Stat. Phys. (2005)
J. Venditti et. al, Coherent flow structures (2013)

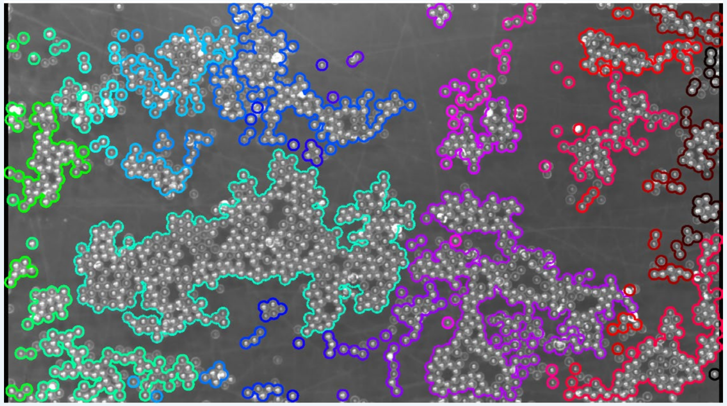


Particle attraction, concentration, polydispersity, shape

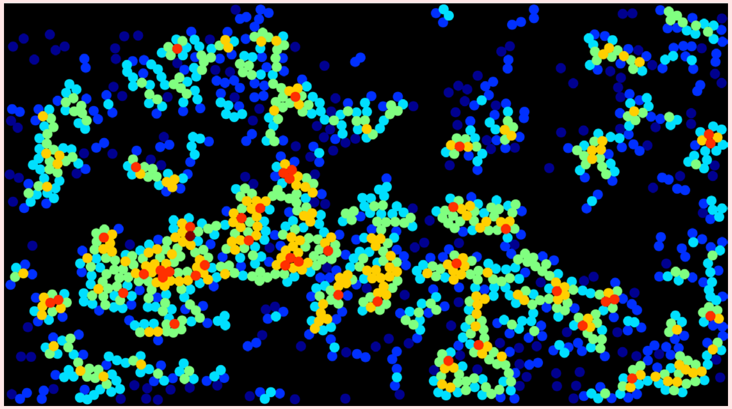
Spatial structure, flow speed, drag, ordered or nonperiodic flow, alternating or constant

Stability of aggregates depends on shear flow and particle interactions

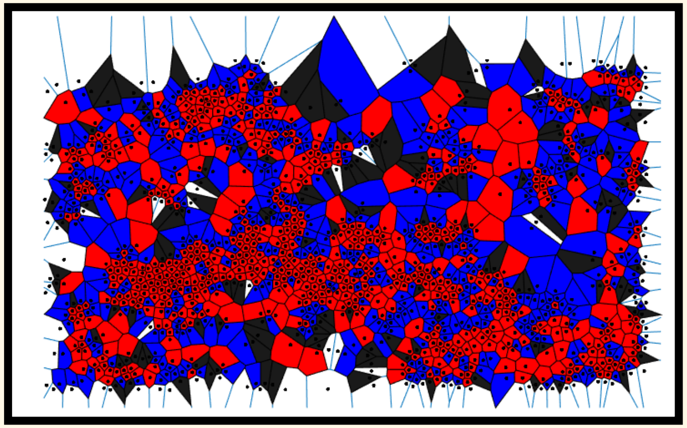
1. Aggregates



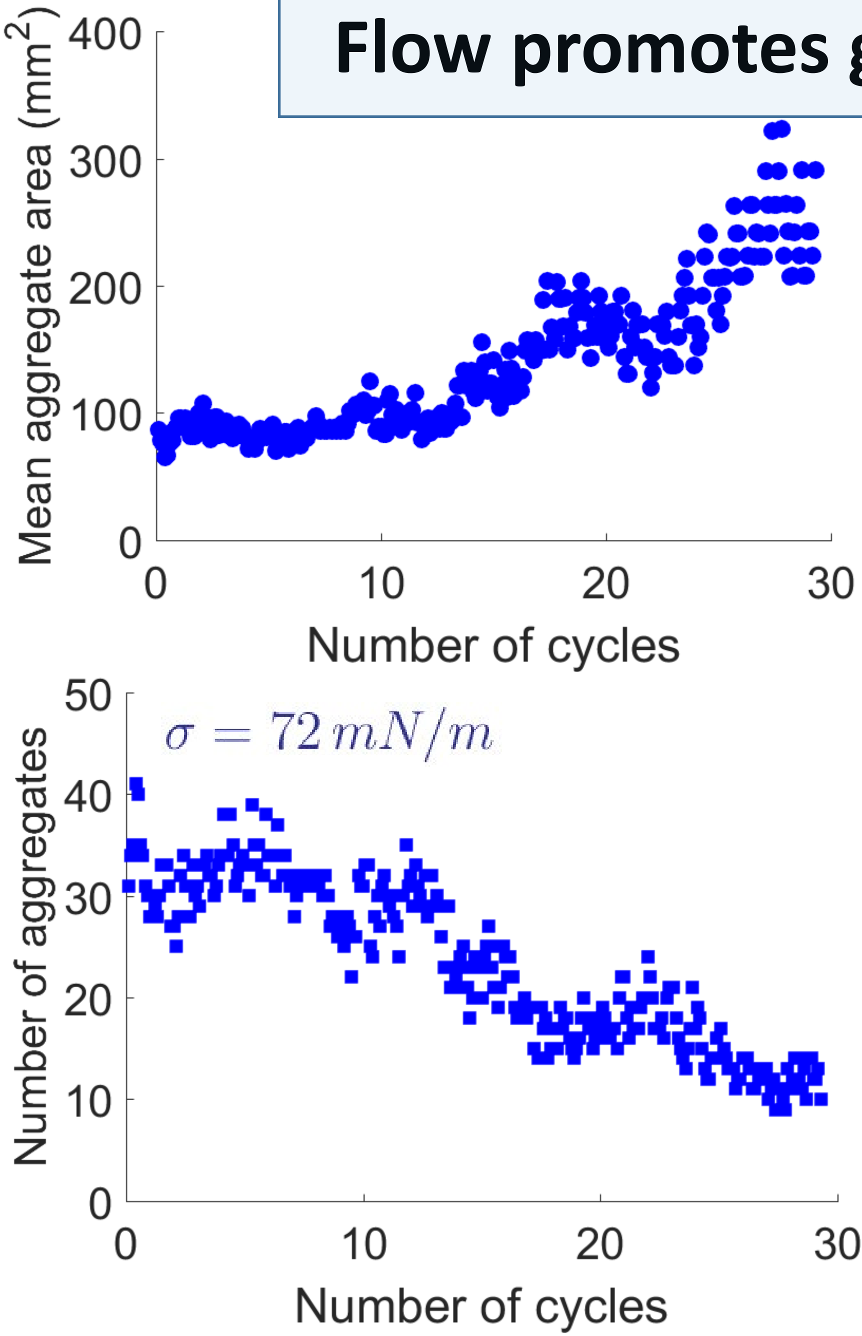
2. Particle contact distribution and mobility

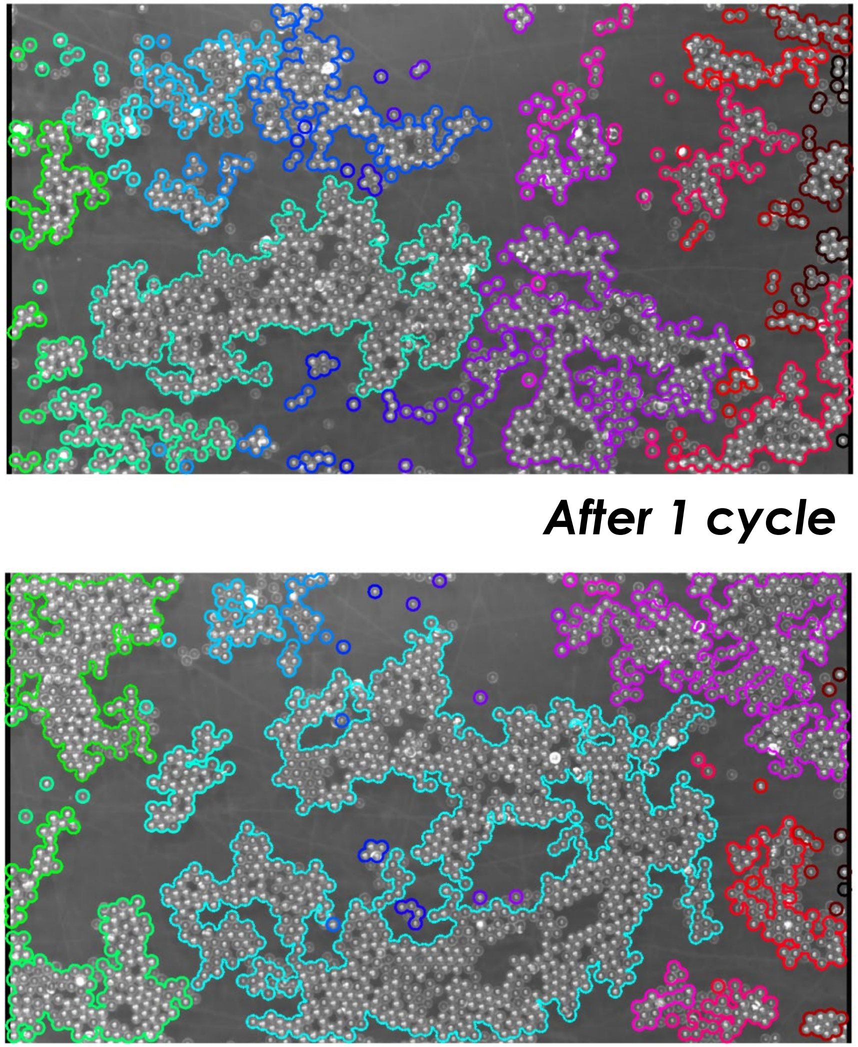


3. Granular phases



Flow promotes growth of aggregates





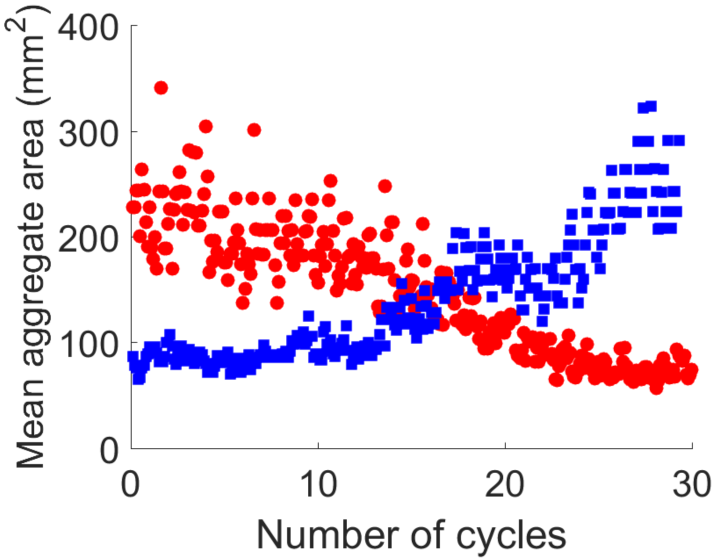
After 1 cycle

After 35 cycles

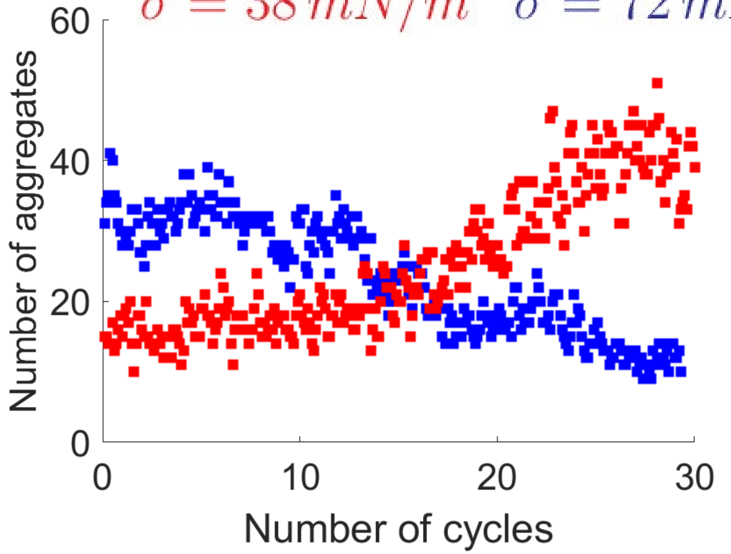
Aggregates

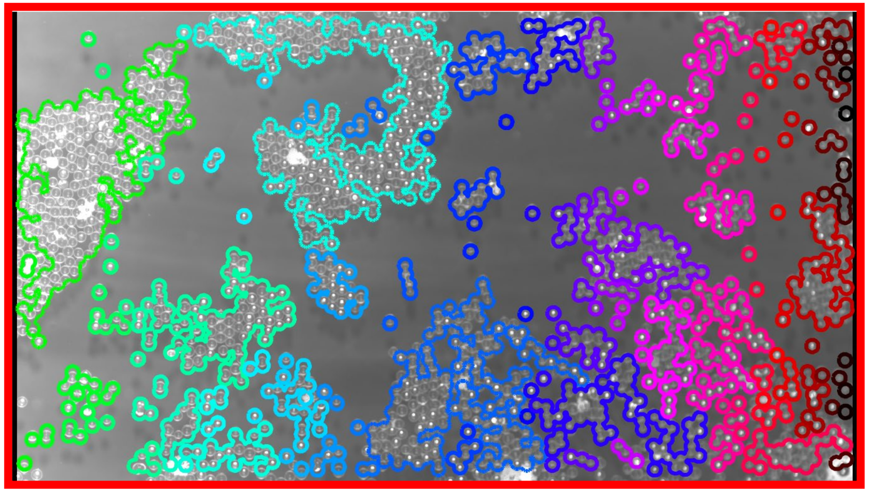
Breakup of aggregates

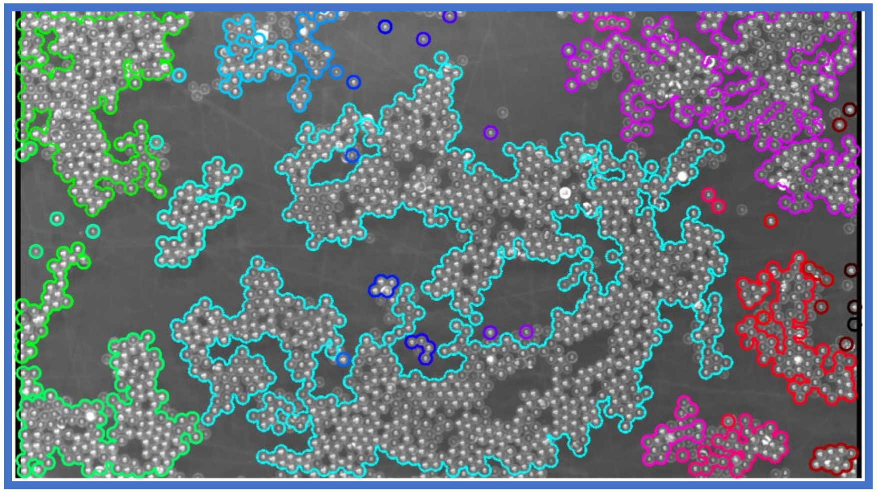
For weaker capillary attraction aggregates break due to shear flow



$\sigma = 38\, mN/m$ $\sigma = 72\, mN/m$





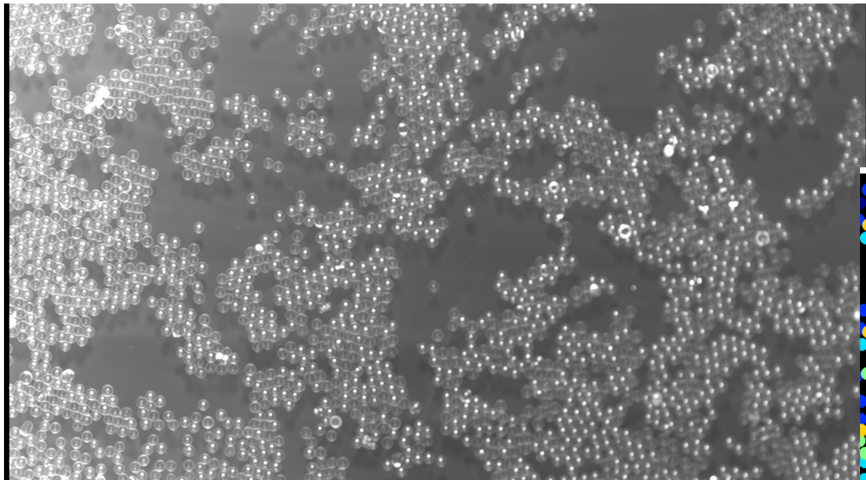


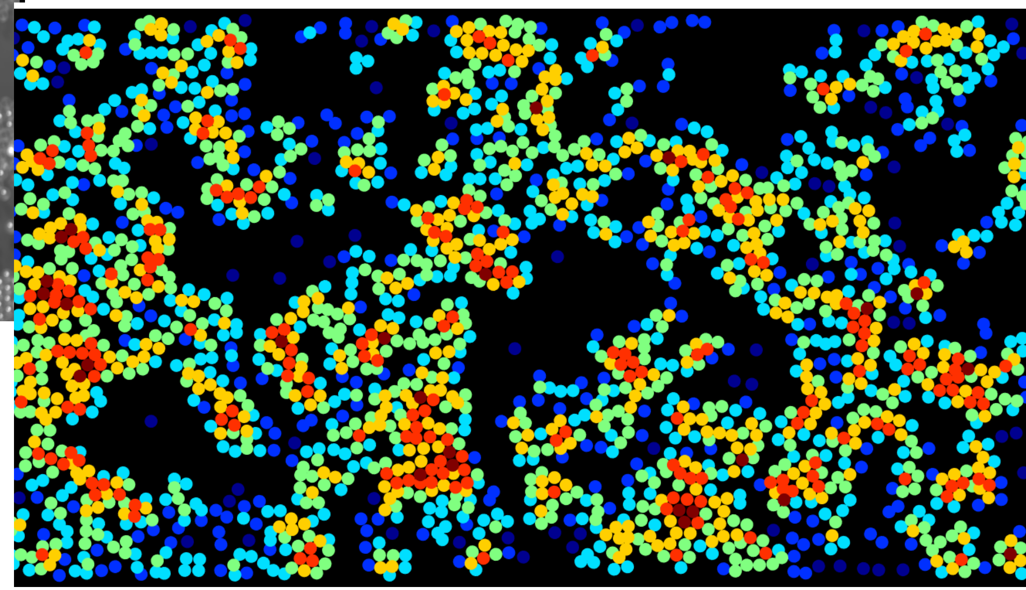
After 35 cycles

Aggregates

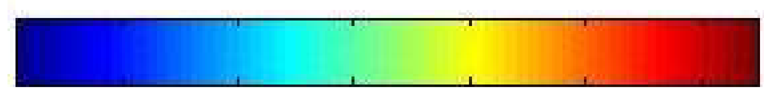
Tracking particle-level information

Particle contact defined by threshold distance of *1.2d*





Number of contacts

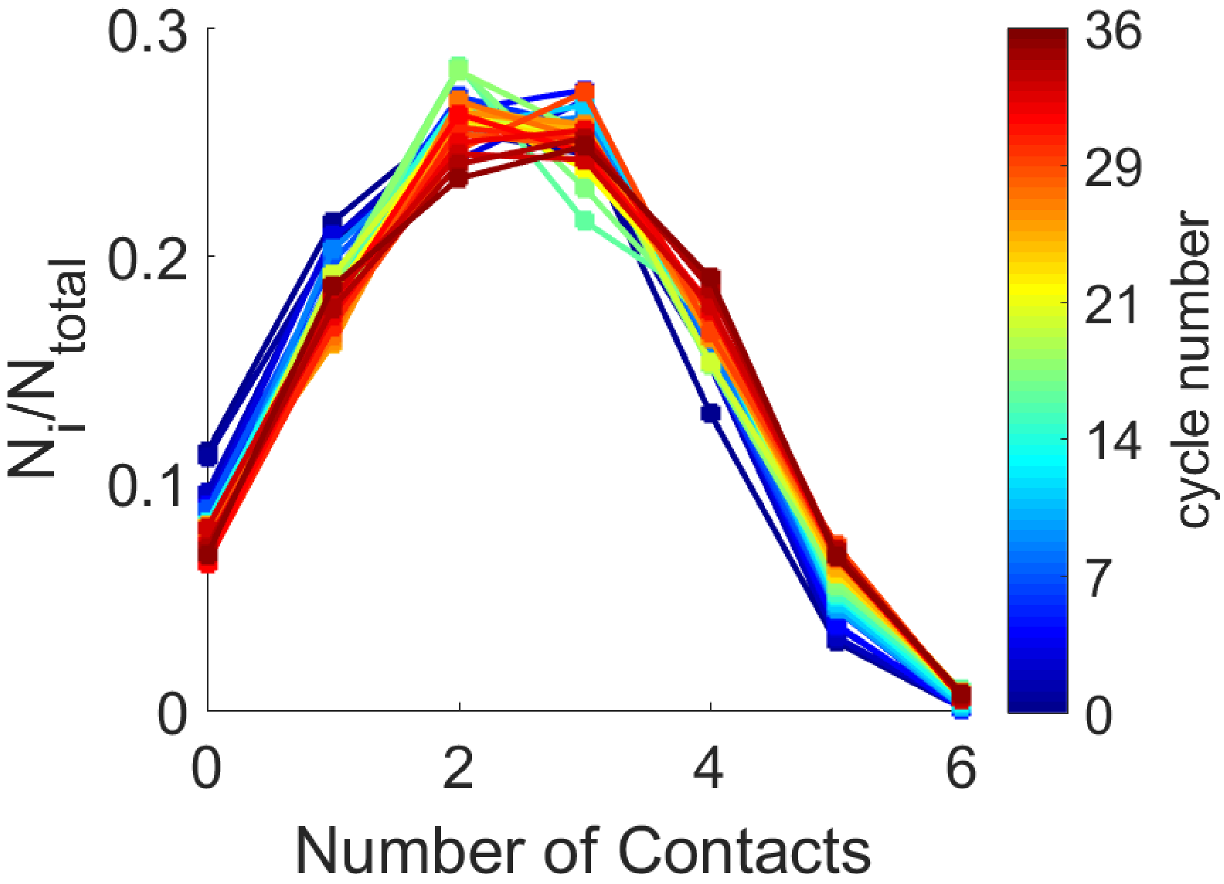


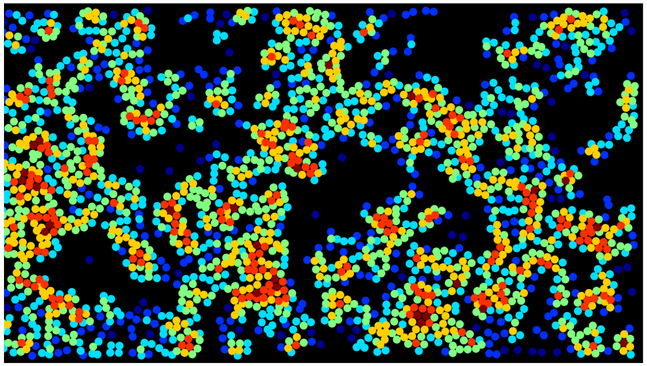
0 1 2 3 4 5 6

Particles

Aggregate connectivity Z_i

Particle contact defined by threshold distance of *1.2d*





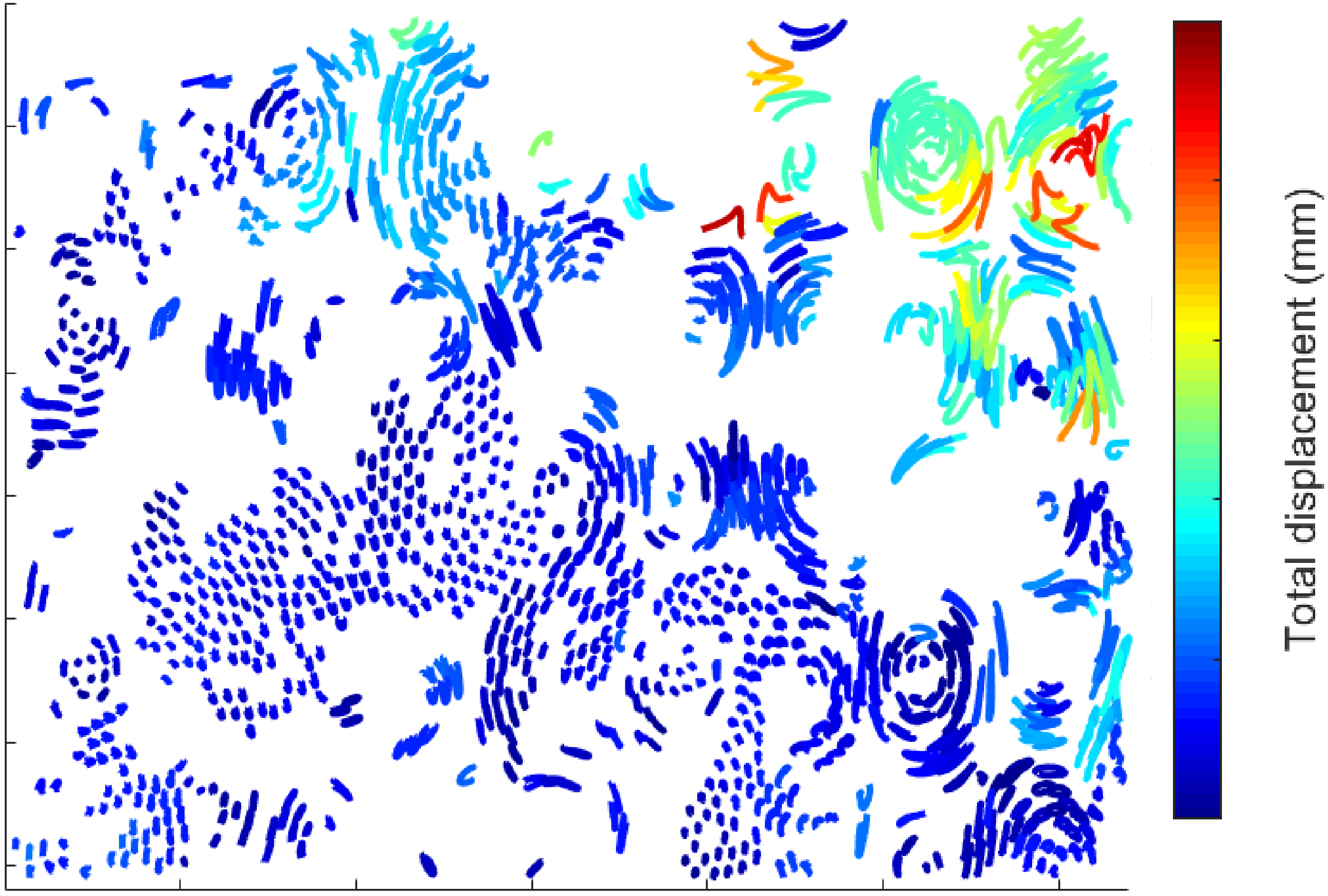
Particles shaded for Z_i

As flow continues, more particles gradually have higher Z_i

Berhanu and Kudrolli PRL (2010)

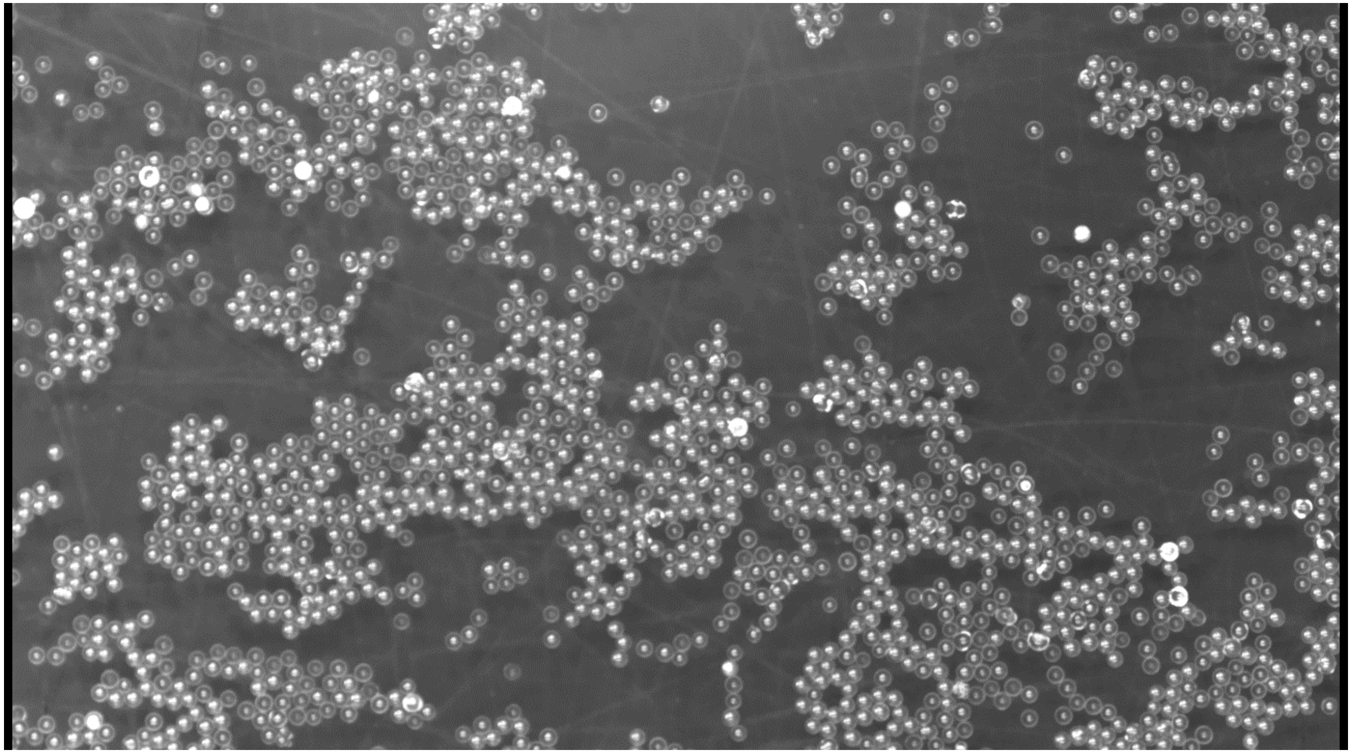
Particle mobility

- Particle motion to find evolution of collective dynamics
- Observe granular fluid regions



Particle trajectories during first cycle

Fluid and solid granular phases appear simultaneously



Mixture of fluid regions with high deformation and solid regions with static structure

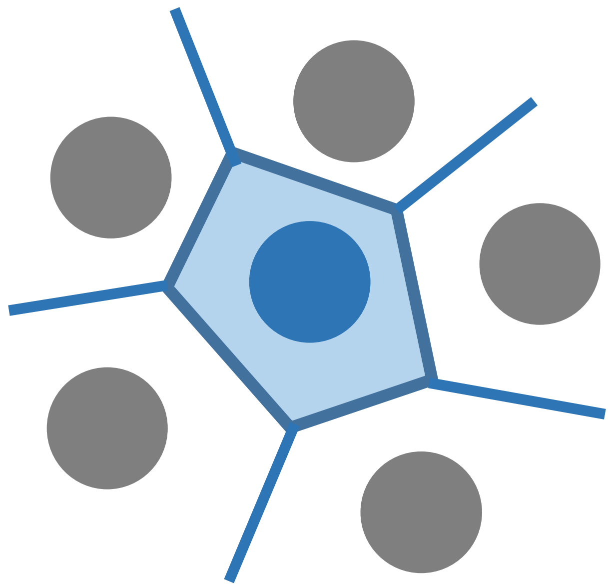
Particle exchanges among phases

K. Huang et al, Soft Matter (2012)

Voronoi cells –circularity

Voronoi tessellation to study packing configuration

Characterize voronoi cells using circularity ξ



$$\xi = \frac{P^2}{4\pi A}$$

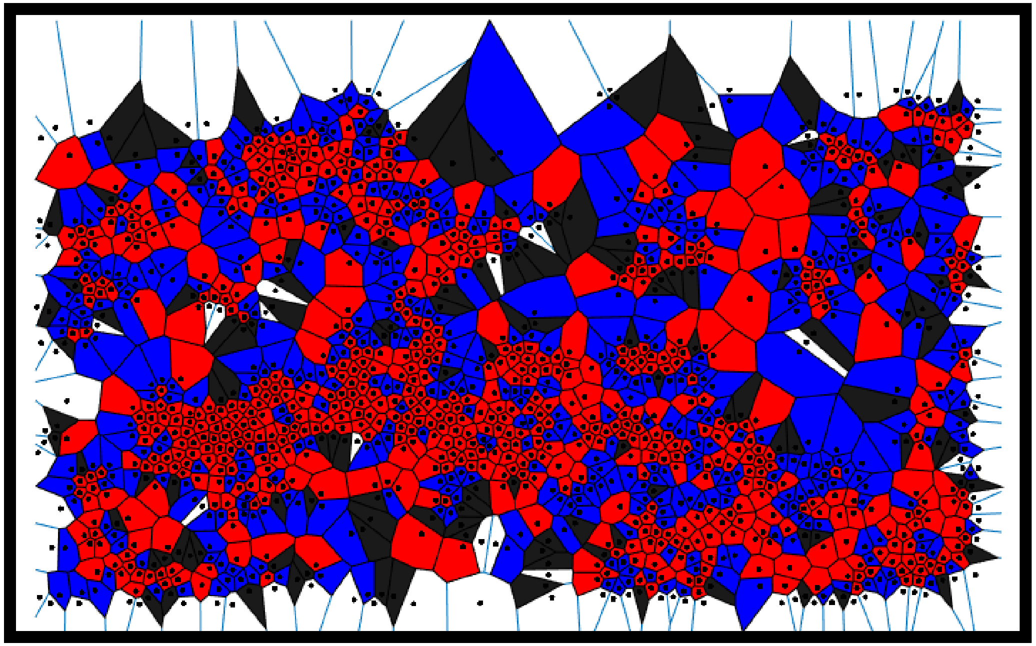
For a **circle** ξ = 1

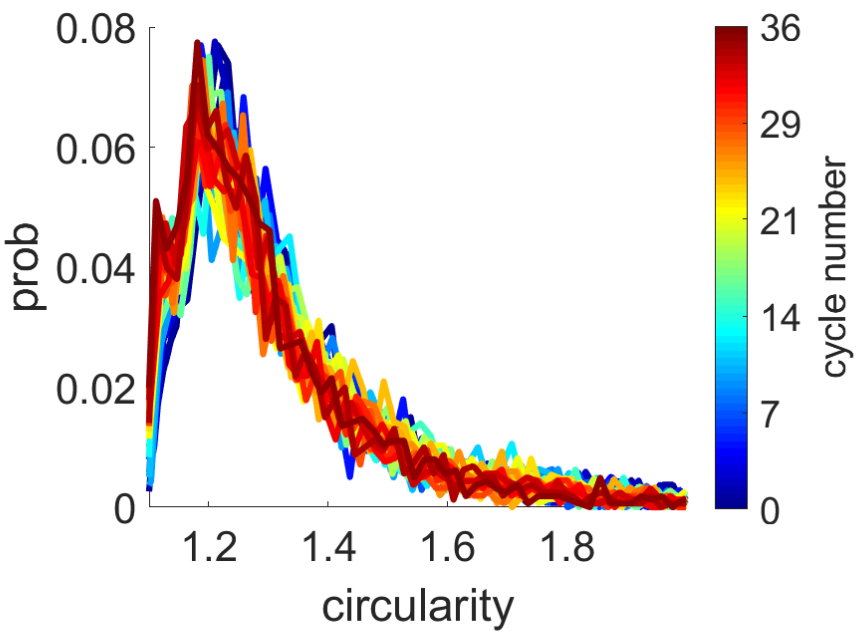
for a regular **hexagon** ξ = 1.1

ξ is higher for irregular shapes

Moucka et al PRL (2005)
Abate and Durian PRE (2006)
Berhanu and Kudrolli PRL (2010)

Voronoi diagram –circularity





$$\xi = \frac{P^2}{4\pi A}$$

Cells colored by *circularity* to visualize variation in particle arrangement

$\xi < 1.25$ **$1.25 > \xi < 1.5$** **$\xi > 1.5$**

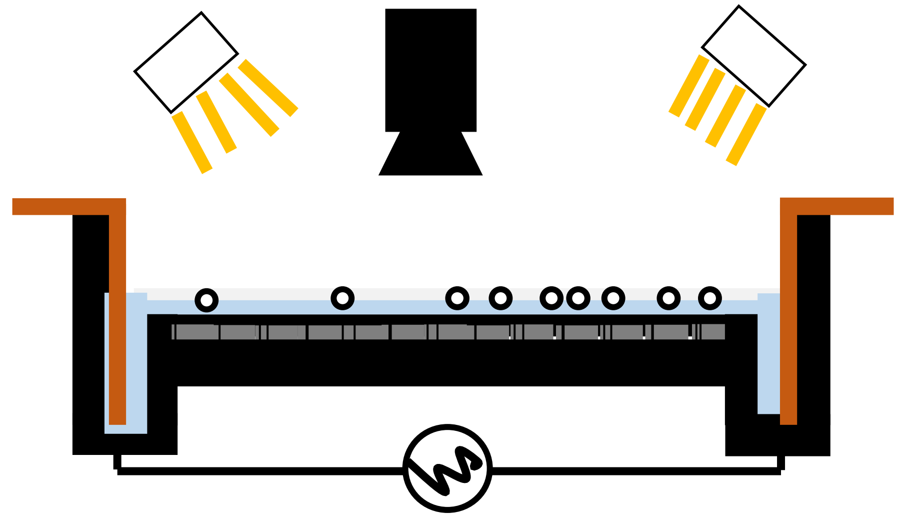
Phases

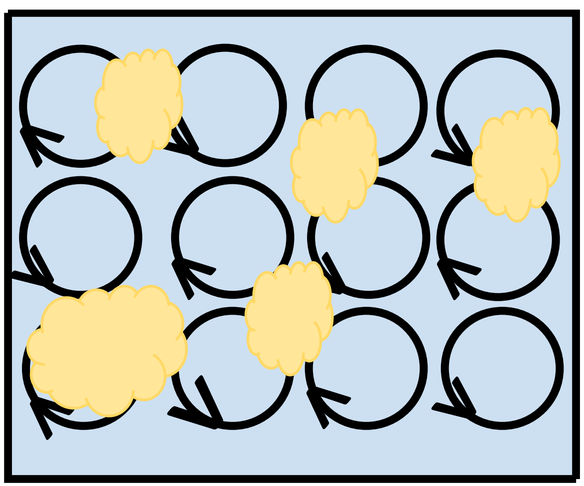
Moucka et al PRL (2005); Abate and Durian PRE (2006); Berhanu and Kudrolli PRL (2010)

Conclusion – aggregation in structured flows

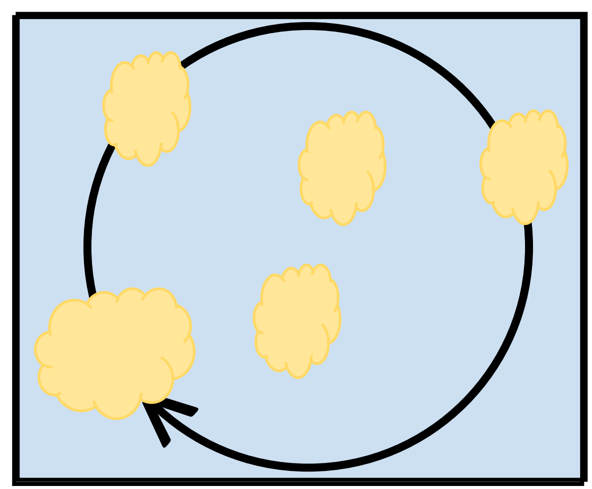
Novel experiment to explore aggregation in quasi-2D flows

- Flow structure and capillary attraction influence aggregate formation





or



Can create flows with same average shear but different spatial symmetry

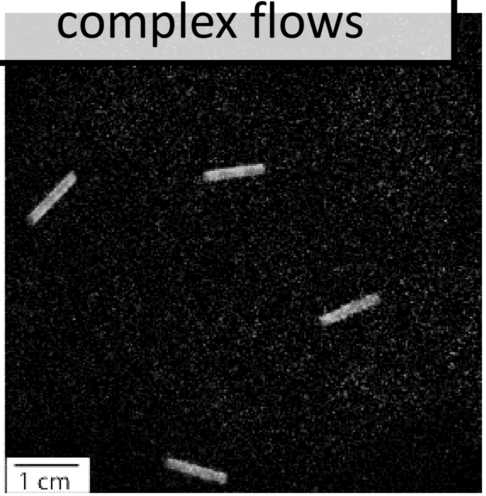
Discussion: Possible applications and connections

1. Connections of experimental approach to open questions in your research?
2. Simplifications (or added complexities) needed for connection to experiment?

Collisions of particles in structured flow

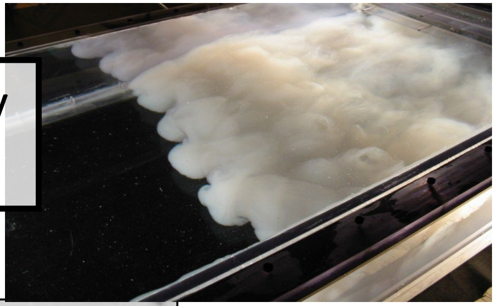
KITP: Multiphase flows of the environment

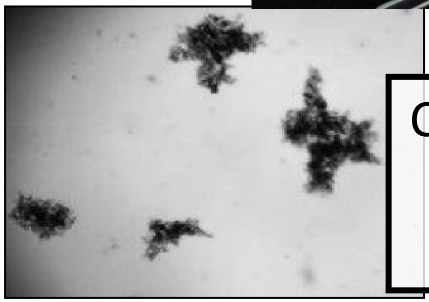
Inertial particles in complex flows



Turbulent clouds
R. Shaw, Ann. Rev. Fluid. Mech (2003)

Turbidity currents





Clay flocculation
K. Strom
B. Sutherland

Discussion: Possible applications and connections

1. Connections to open questions?
2. Simplifications (or added complexities) needed?

3. Relevant quantities to measure?
   Aggregate distribution, contacts….

4. Parameters to vary?
   Packing fraction, Stokes number, Reynolds number, vorticity, …

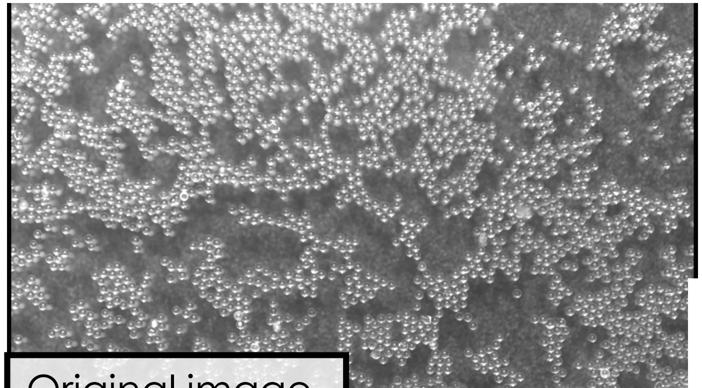
Collisions of particles in structured flow

KITP: Multiphase flows of the environment

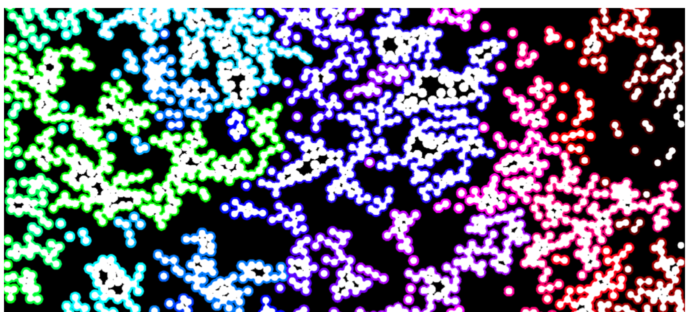
Discussion

BACKUP SLIDES

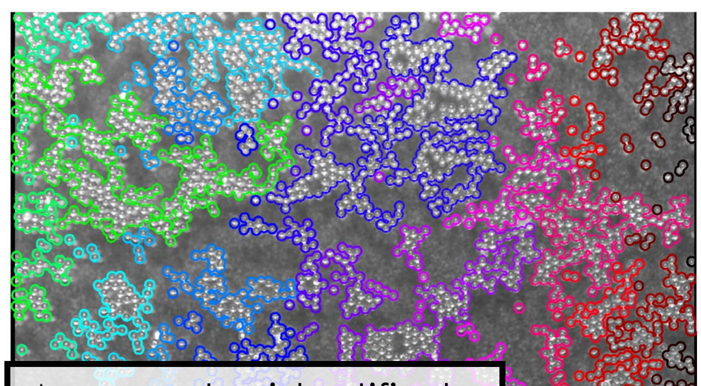
Stable aggregates when no flow



Original image

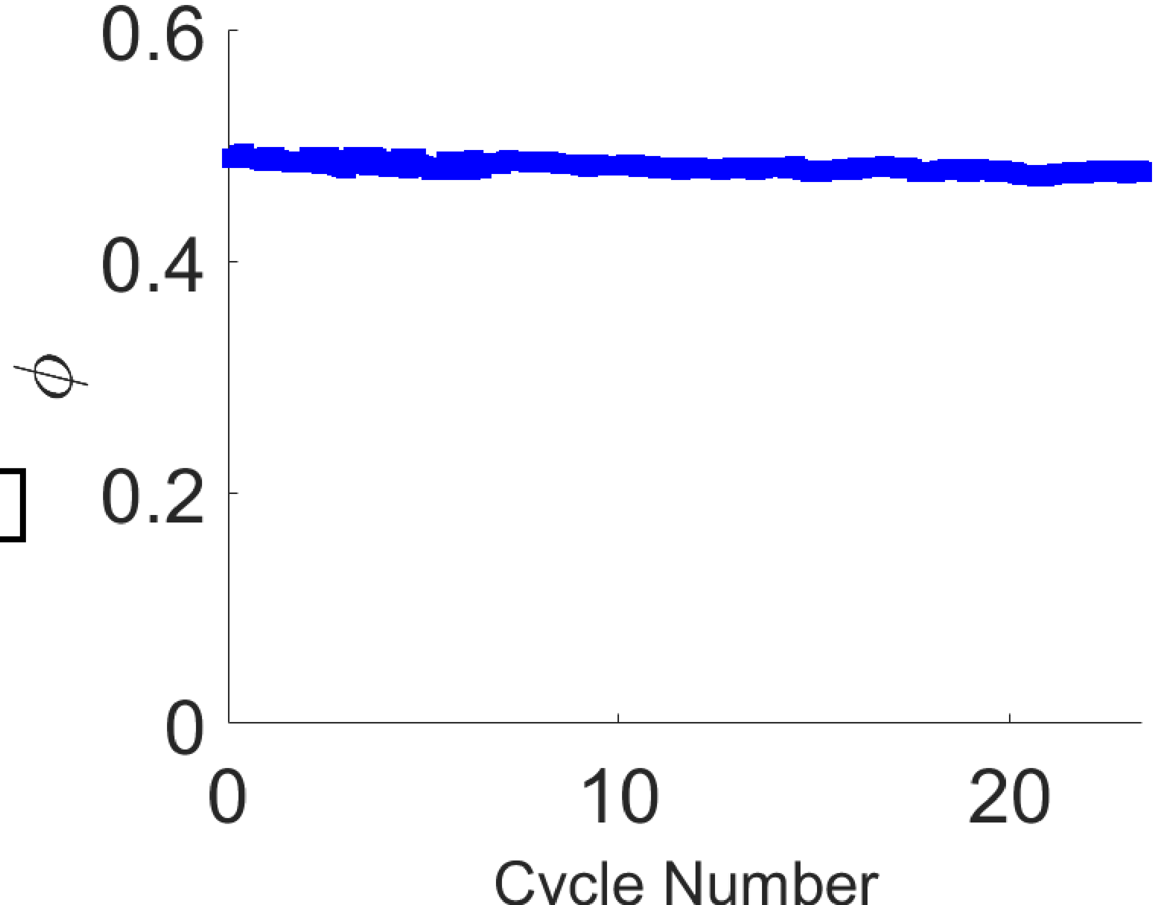


Binarized, connected components



Aggregates identified

Resolution: 1 pixel ~ 70 um



Aggregates