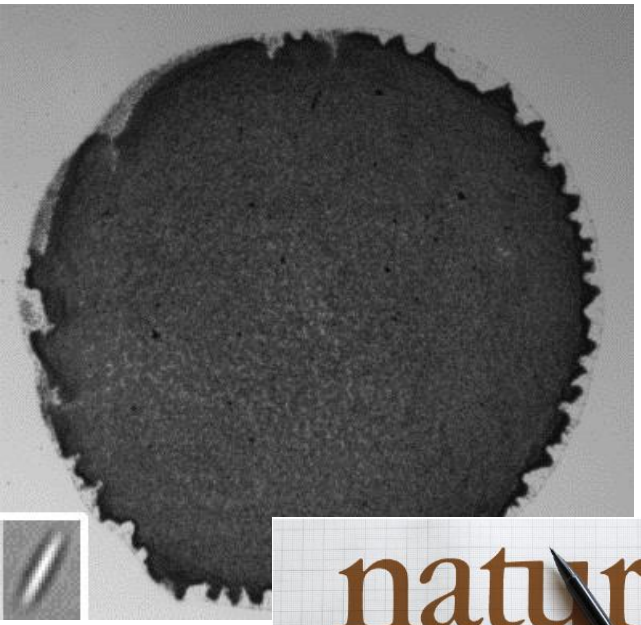
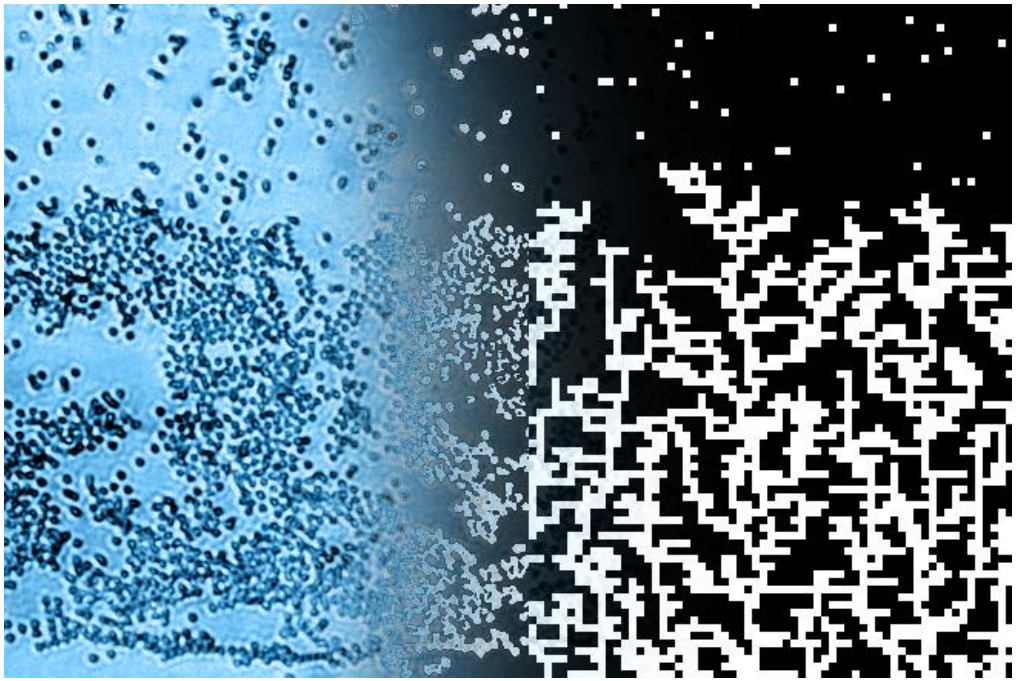
Growth Processes in Evaporating Drops





Peter Yunker (Harvard, UPenn, GT)
Tim Still, Matt Lohr,
Arjun Yodh, Doug Durian (UPenn)
Alexei Borodin (MIT)

P.J. Yunker, T. Still, M.A. Lohr, and A.G. Yodh, ***Nature*** 476, 308 (2011).
P.J. Yunker, *et al.*, PRL (2012).
P.J. Yunker, *et al.*, PRL (2013). P.J. Yunker, *et al.*, Physics Today (2013).

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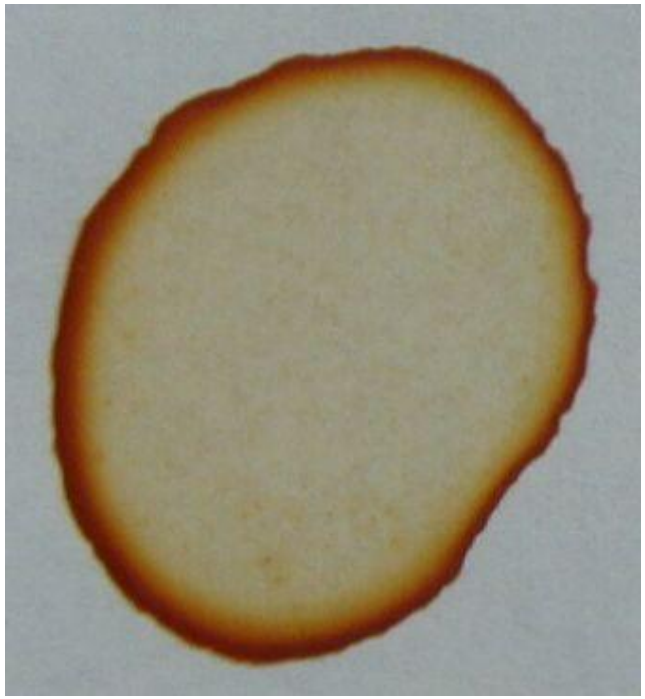
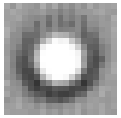
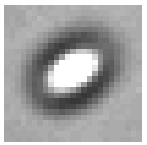
Growth process depends on particle shape



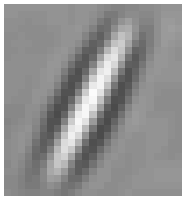
Coffee-ring effect



Poisson Process



KPZ Process

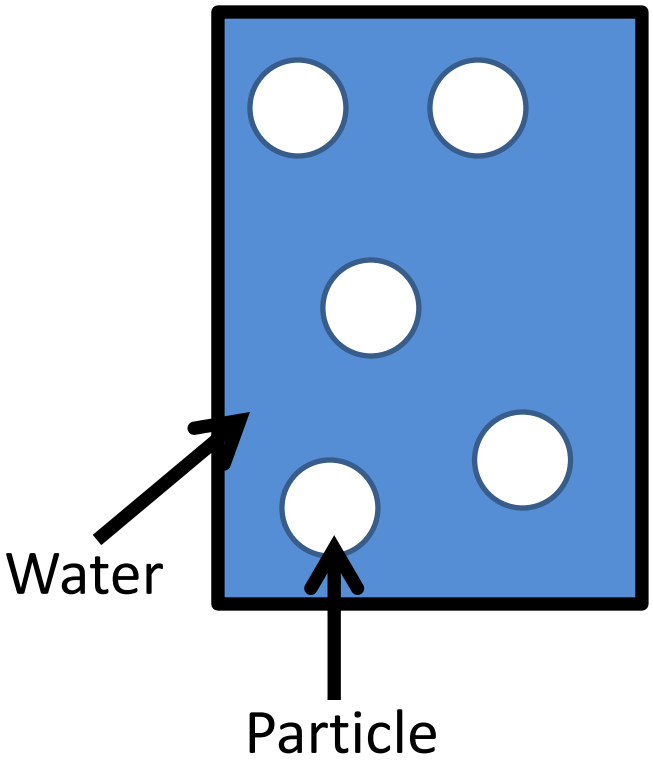


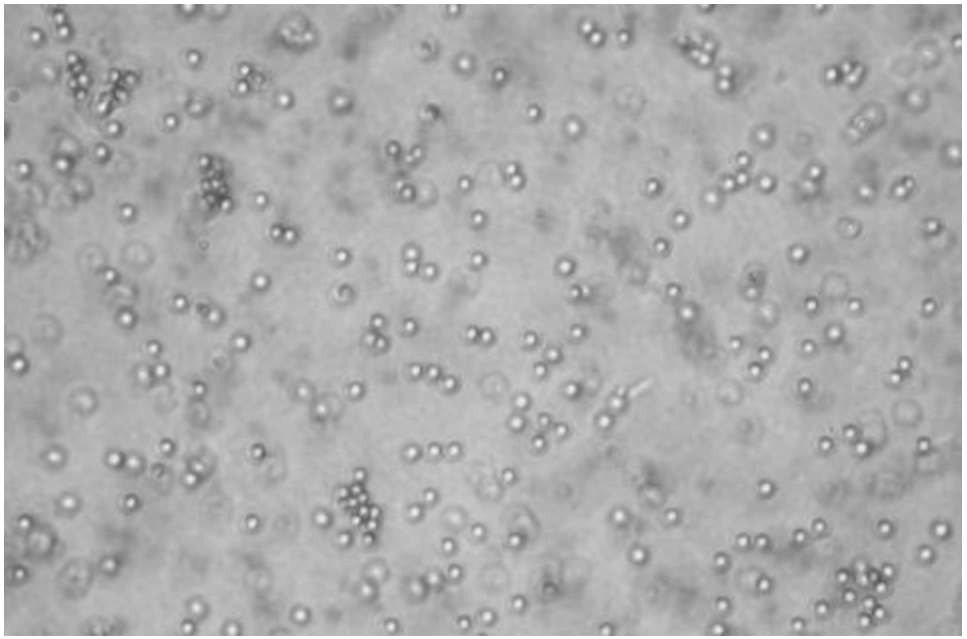
Colloidal Matthew Effect

Which growth processes?

Why particle shape?

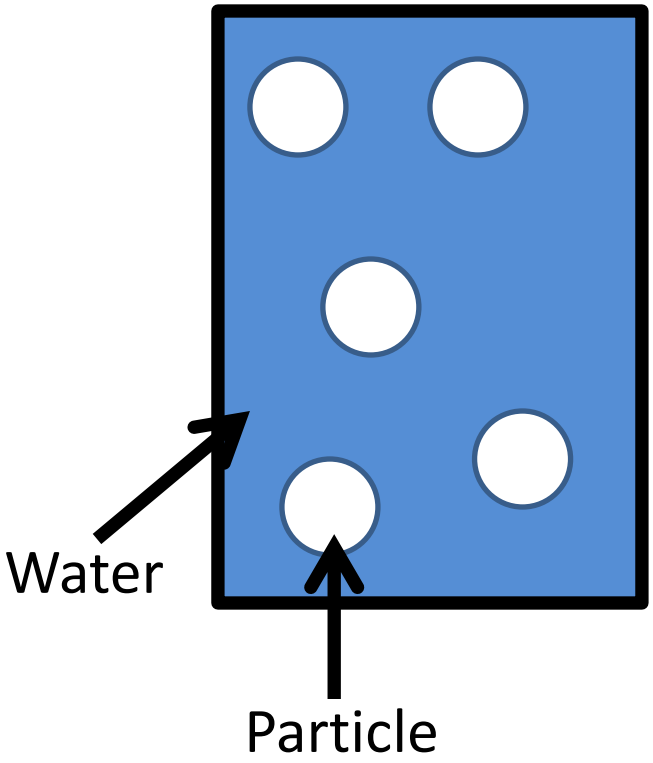
Colloidal particles: a convenient experimental tool

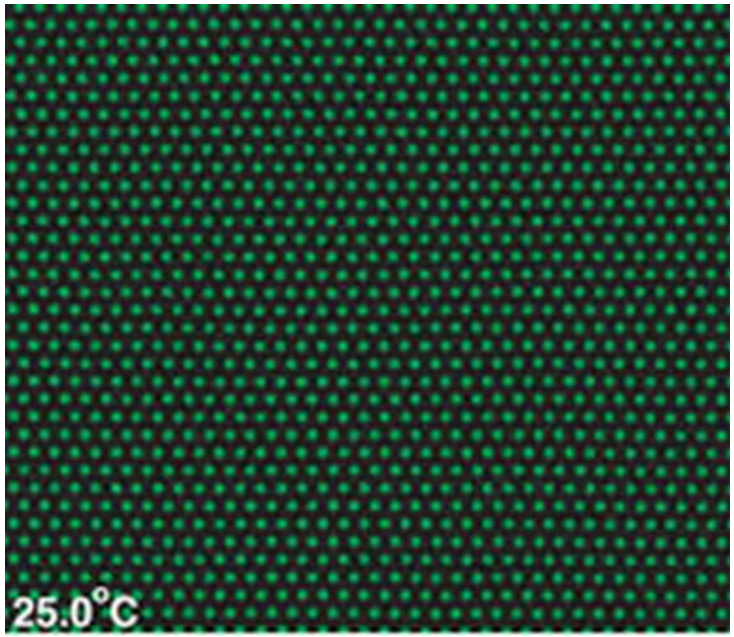




Colloidal Fluid

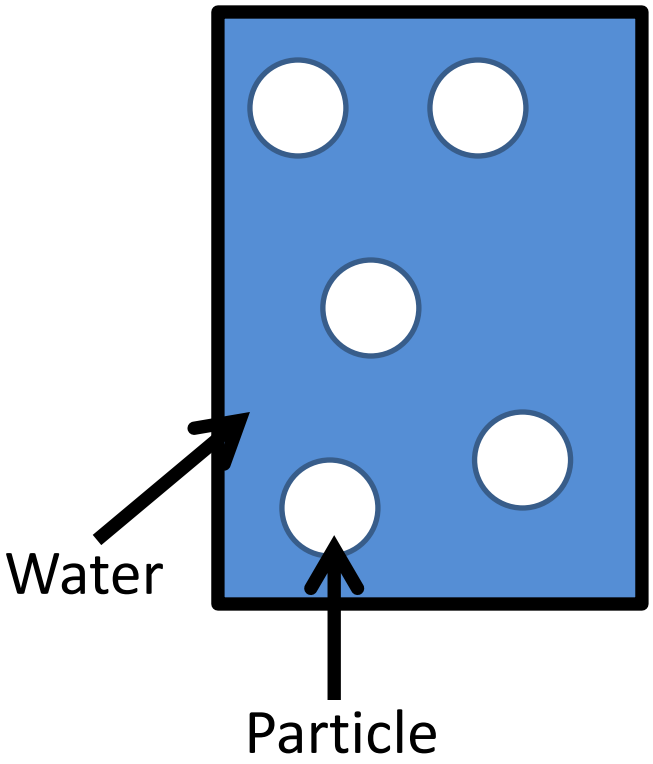
Colloidal particles: a convenient experimental tool

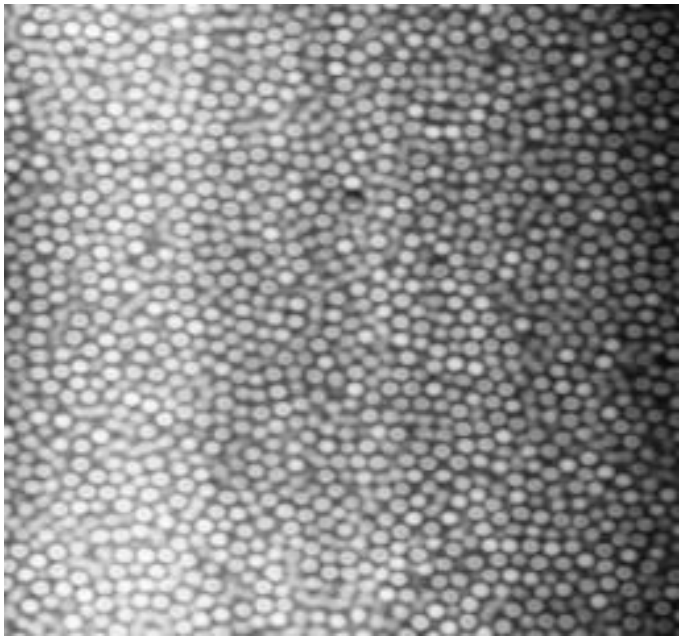




Colloidal Crystal

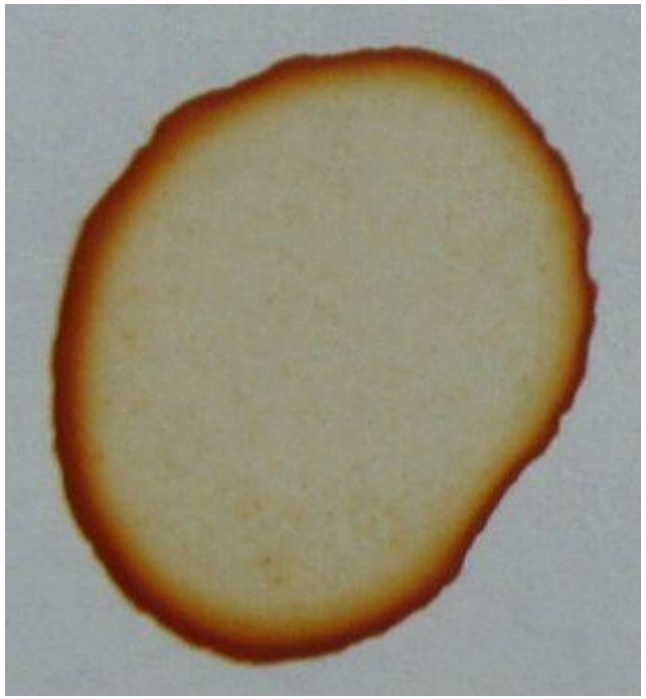
Colloidal particles: a convenient experimental tool



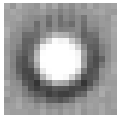


Colloidal Glass

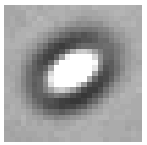
Growth process depends on particle shape



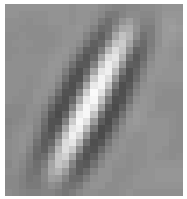
Coffee-ring effect



Poisson Process



KPZ Process



Colloidal Matthew Effect

Which growth processes?

Why particle shape?

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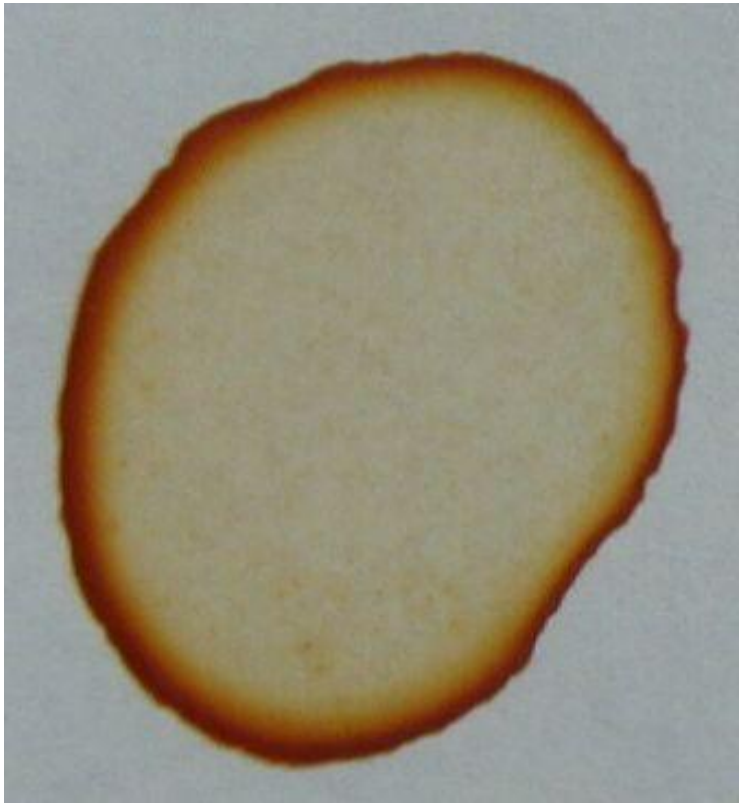
The Coffee Ring Effect

The Coffee Ring Effect



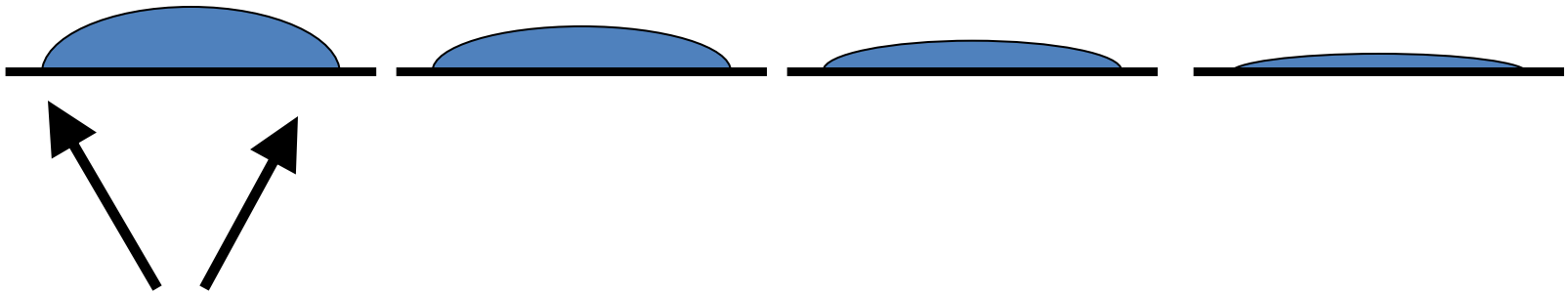
coffee

Robert D. Deegan, Olgica Bakajin, T.F. Dupont, G.Huber, Sidney R. Nagel , Thomas A. Witten, ***Nature*** (1997).

Drop Edges Pinned During Evaporation

Edges Unpinned – Diameter Decreases

Edges Pinned – Contact Angle Decreases



Drop edges pinned

Convective Fluid Flow from Middle of Drop to Edges

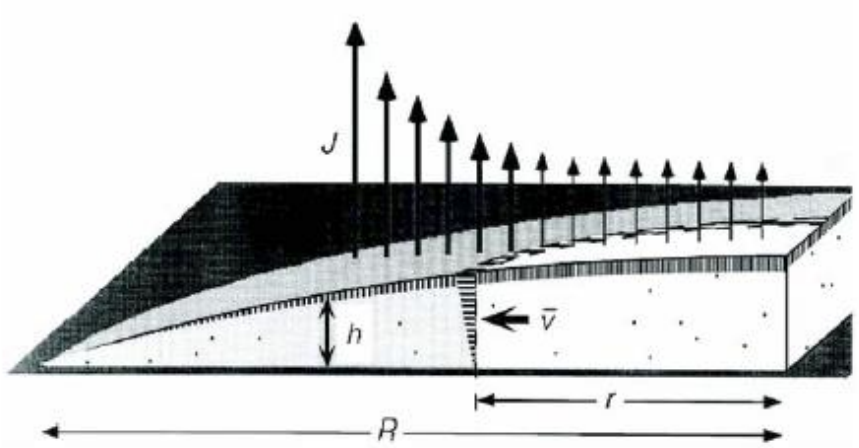
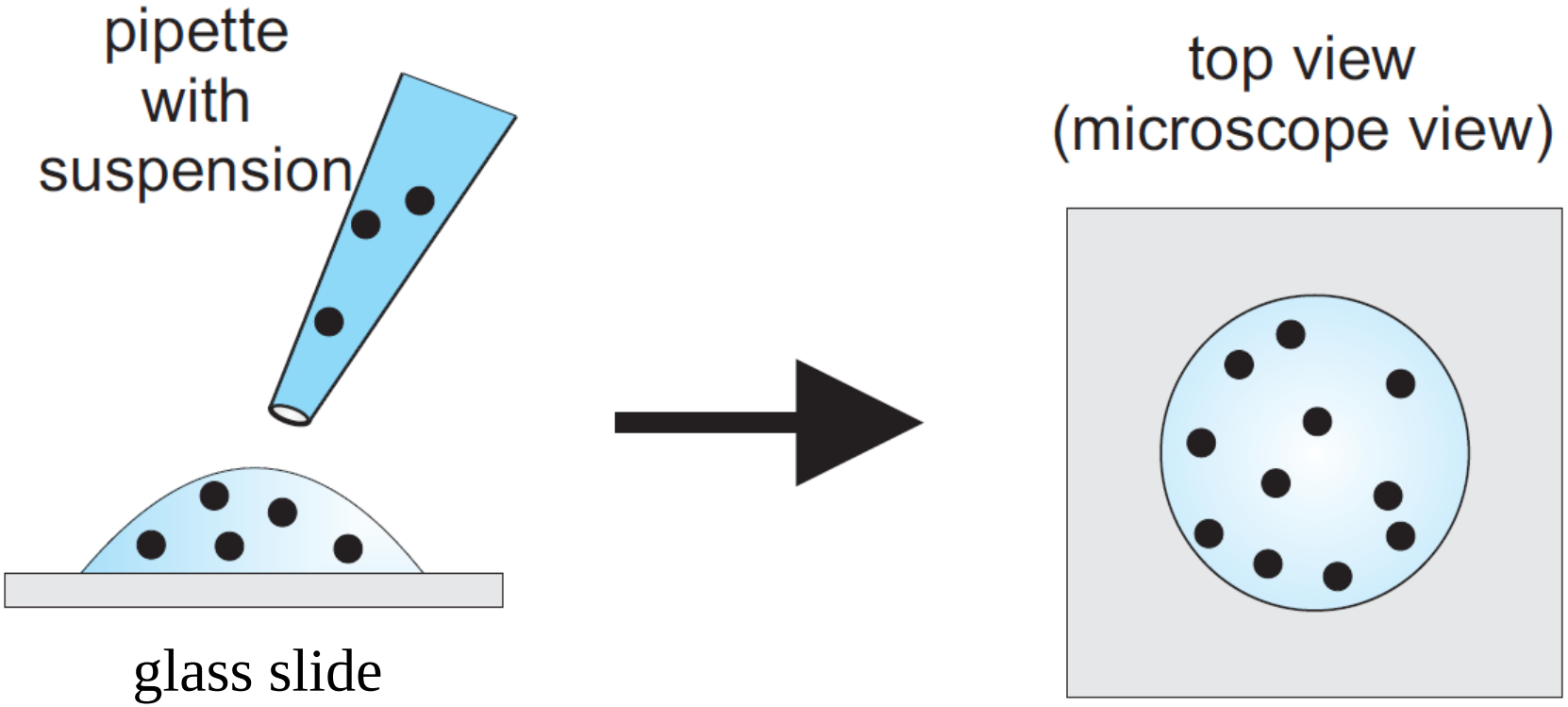


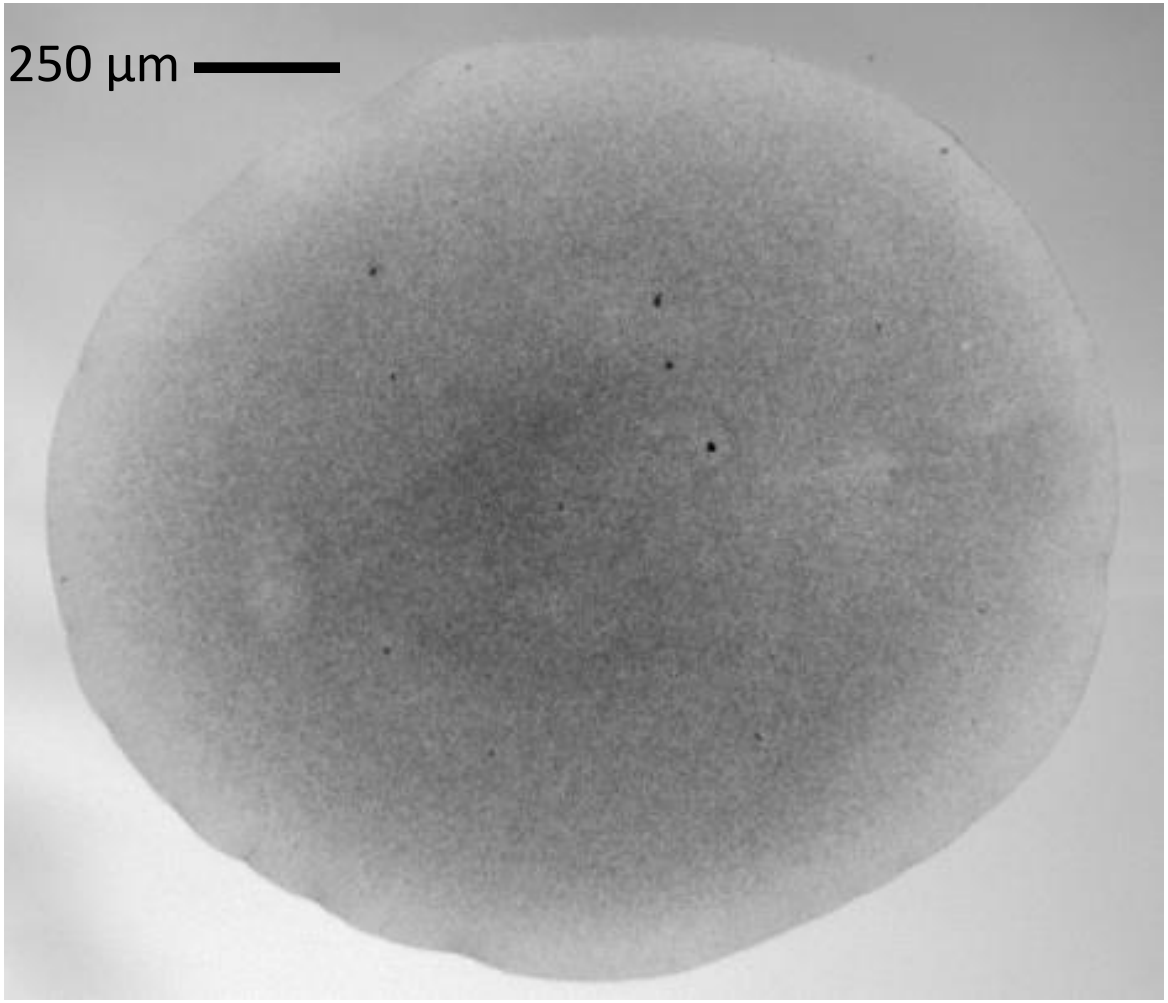
Figure from R. D. Deegan et al., Nature **389, 827 (1997).**

Basic Experiment



Drying Drops Containing Polystyrene Spheres

(20x faster)



Initial Volume Fraction $\phi = 0.005$

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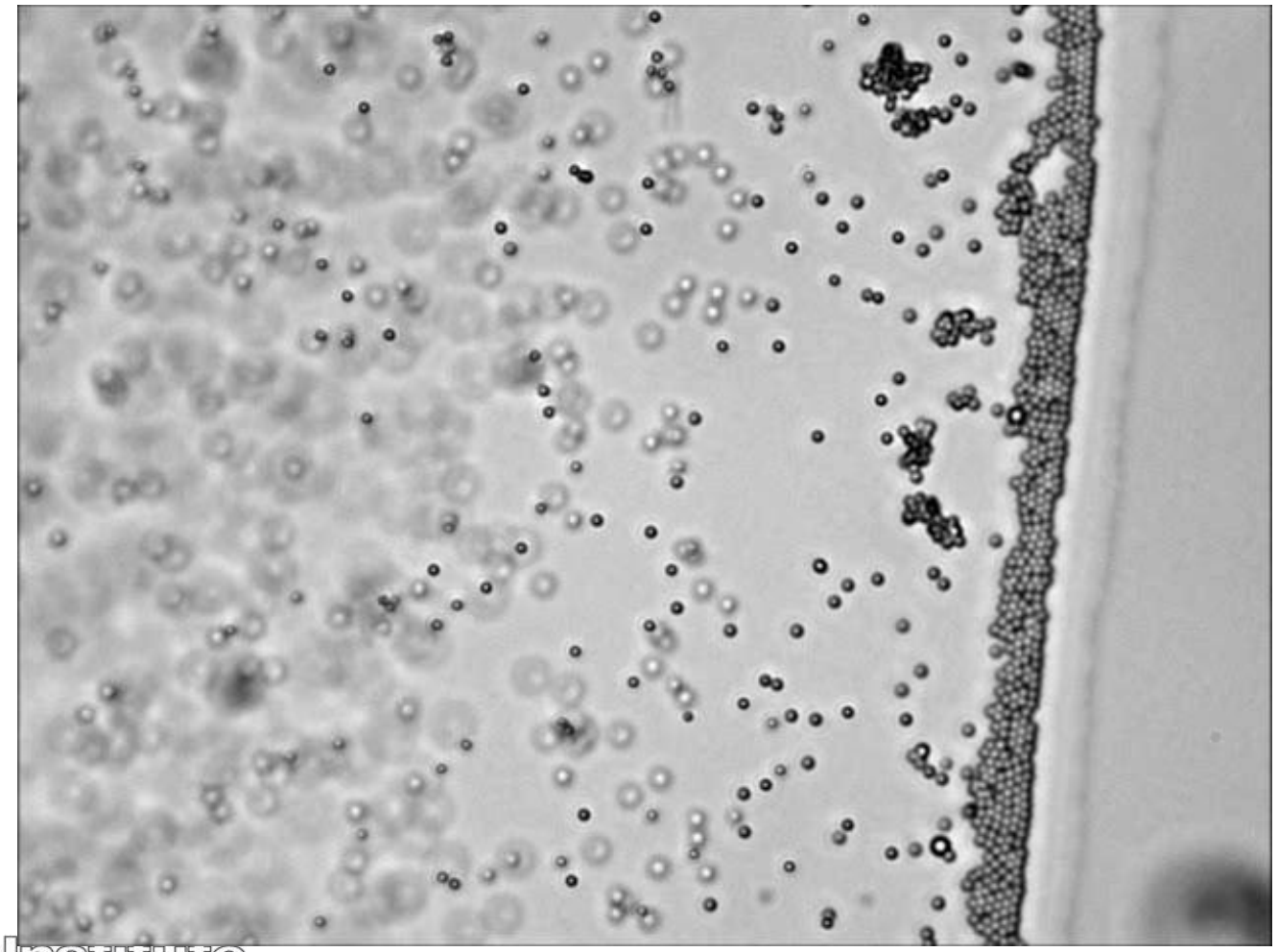
Drying Drops Containing Polystyrene Spheres

10 µm

(10x faster)



Drop Edge

Initial Volume Fraction $\phi = 0.005$

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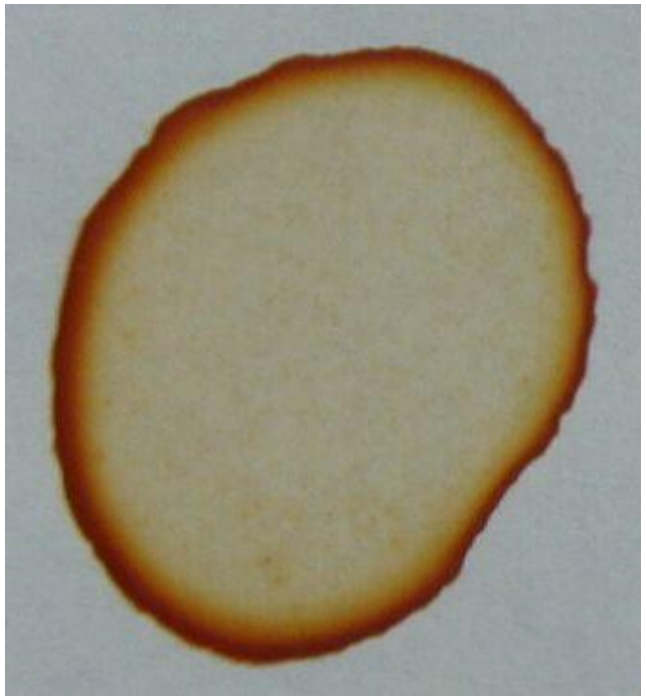
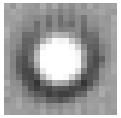
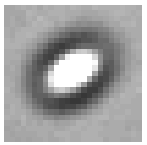
Growth process depends on particle shape



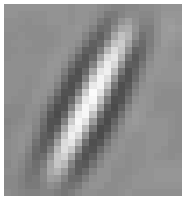
Coffee-ring effect



Poisson Process



KPZ Process



Colloidal Matthew Effect

Which growth processes?

Why particle shape?

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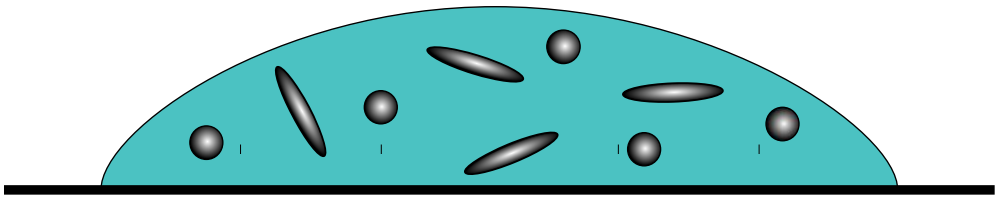
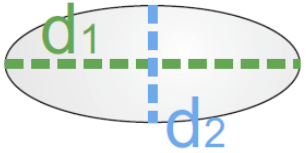
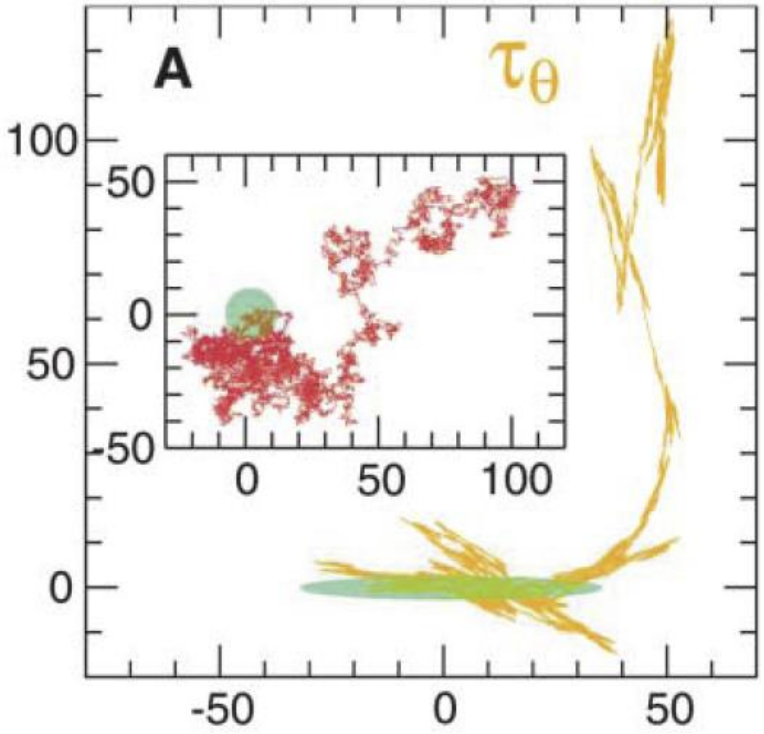
Why Does Particle Shape Matter?





$\varepsilon = d_1/d_2$



Han, Y., Alsayed, A.M., Nobili, M., Zhang, J., Lubensky, T.C., & Yodh, A.G., Brownian motion of an ellipsoid. ***Science*** (2006).

"Spheres" and "Ellipsoids" at low volume fraction will have fairly similar bulk behaviors.

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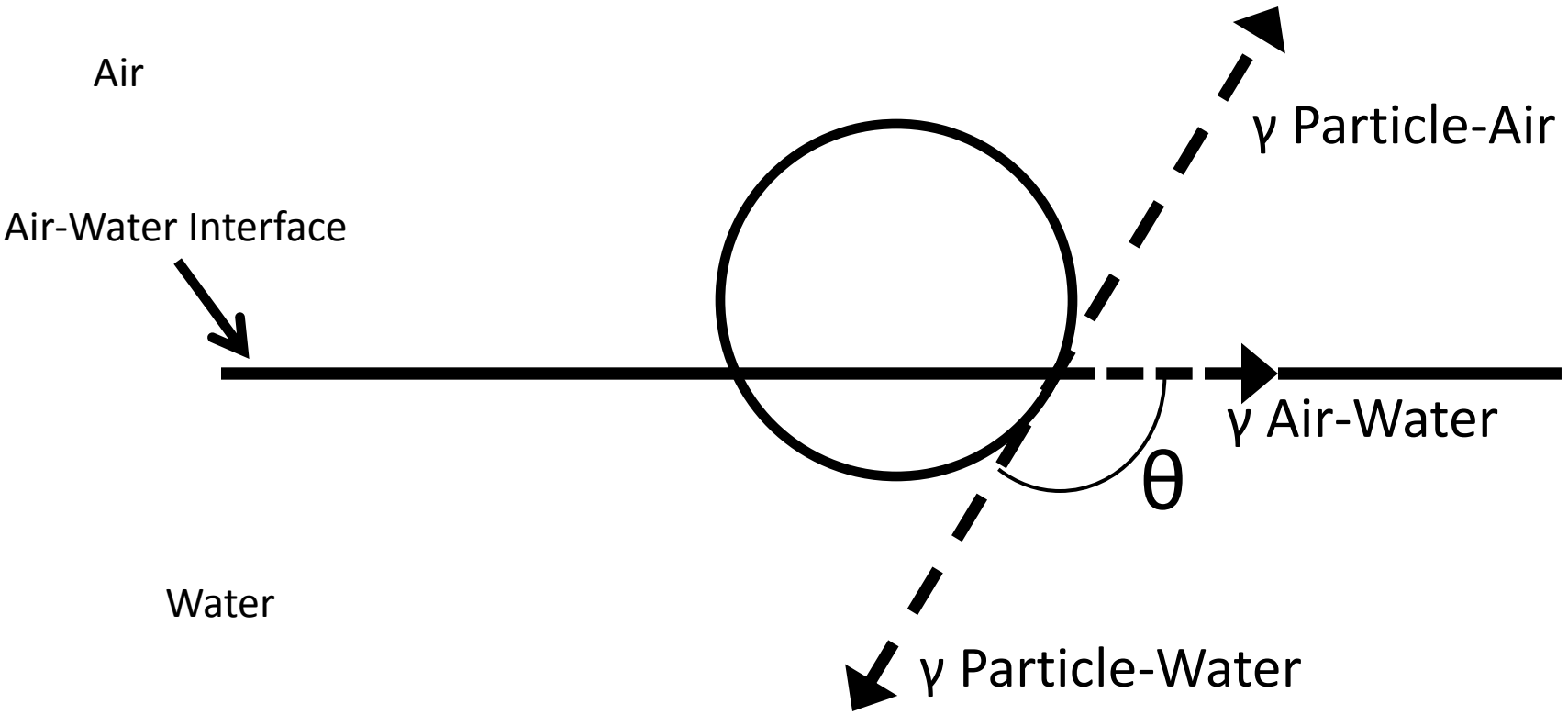
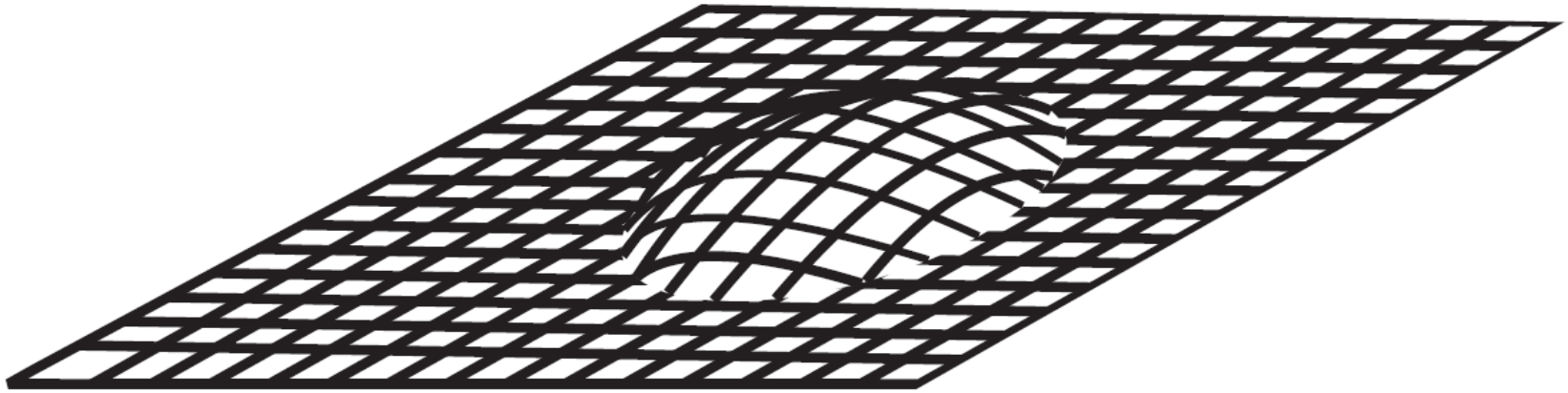
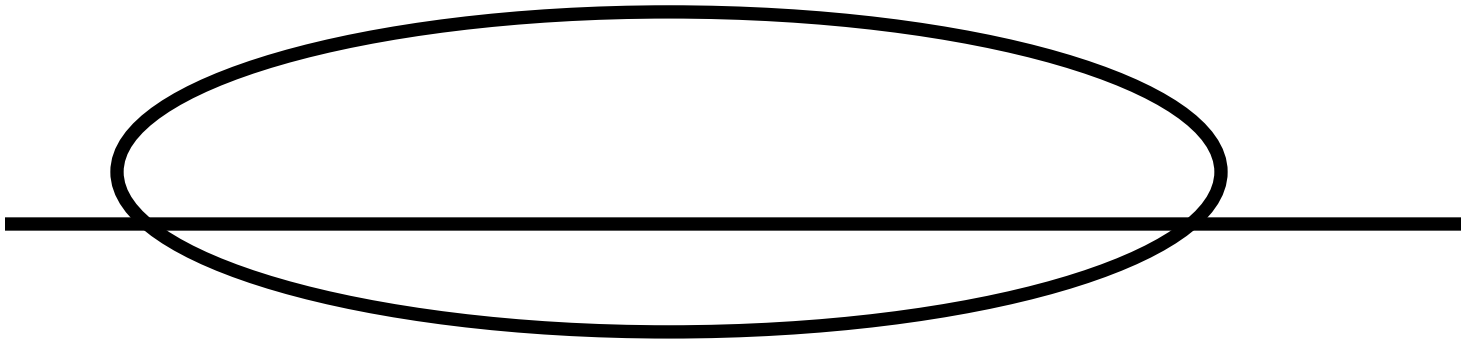
Interfacial tensions balance at equilibrium contact angle



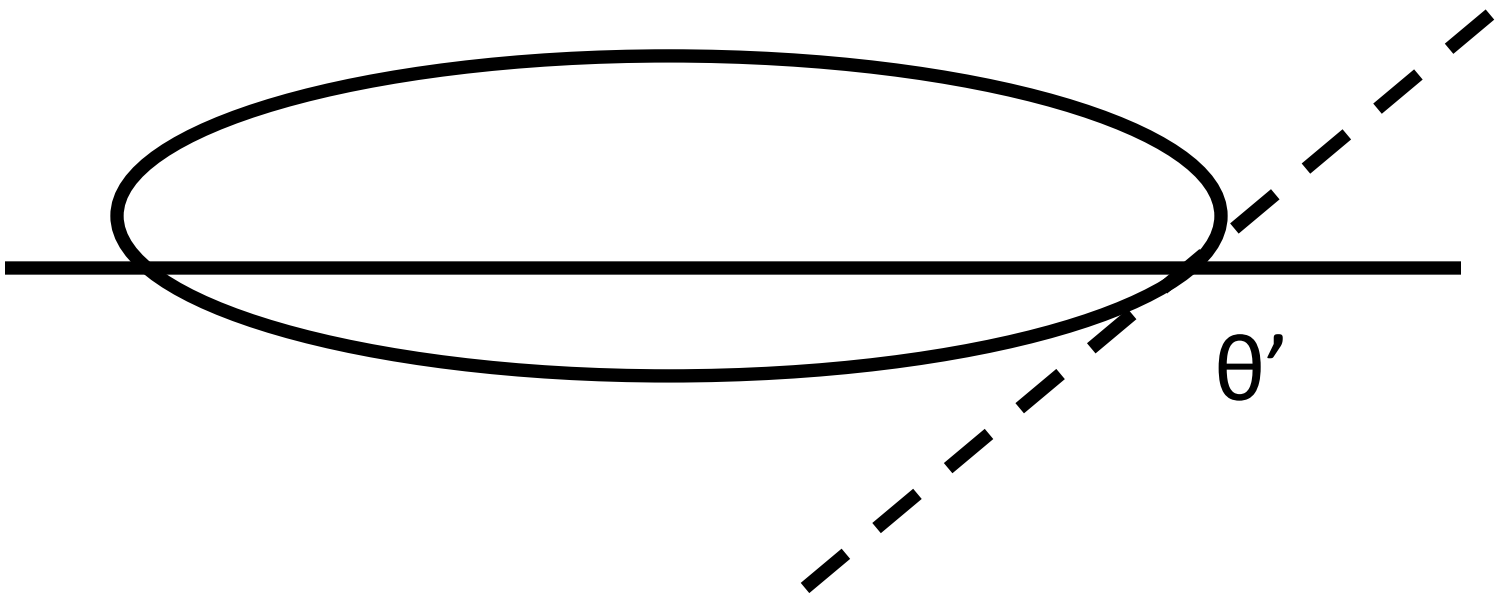
Interfacial tensions balance at equilibrium contact angle



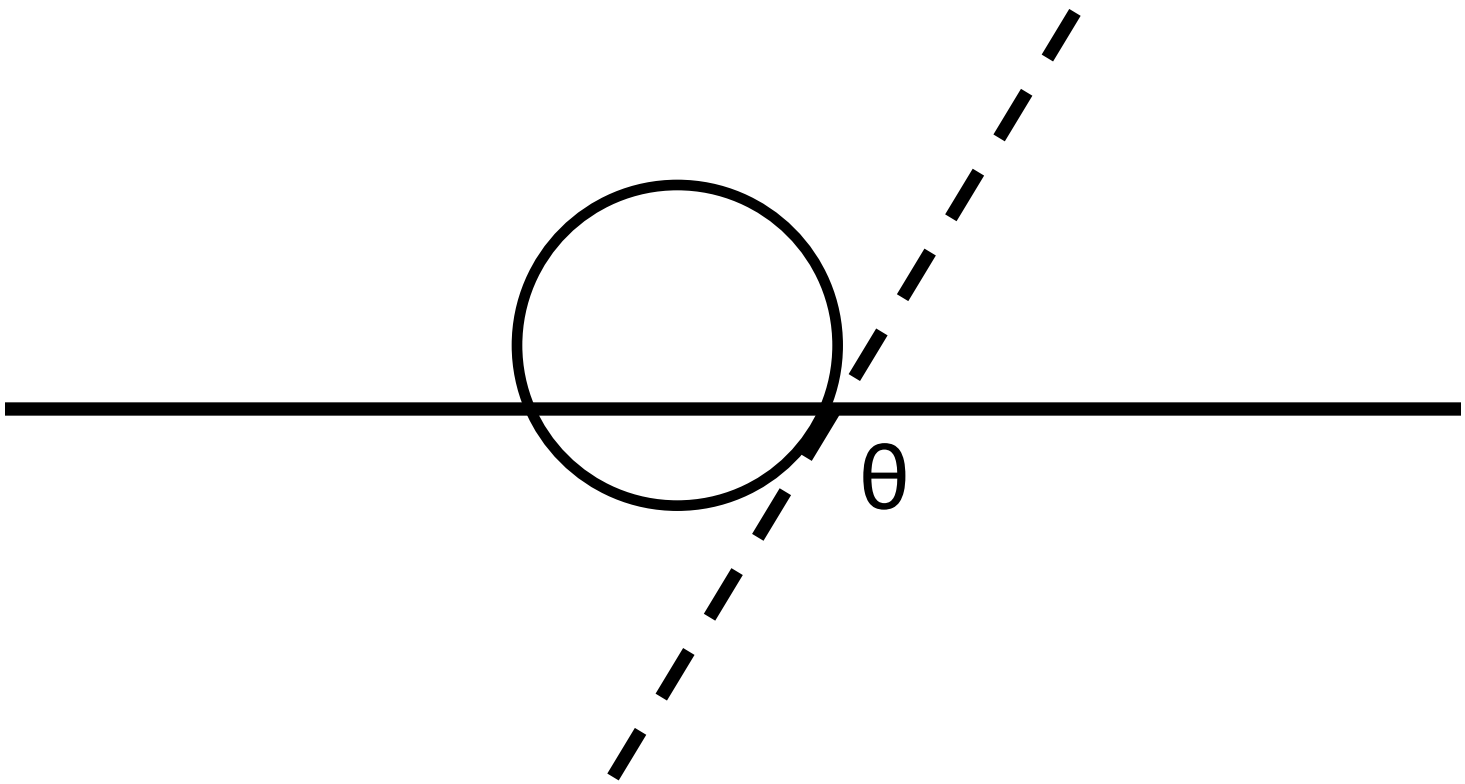
Interfacial tensions balance at equilibrium contact angle



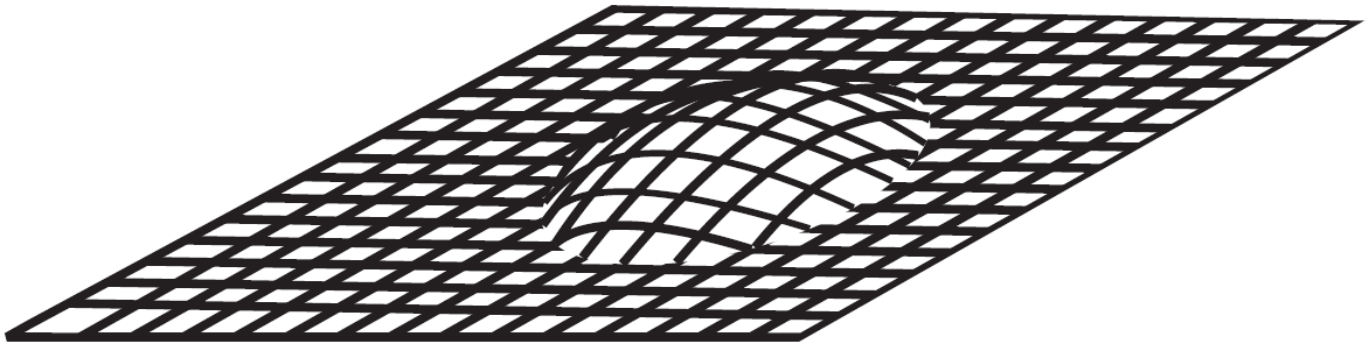
Interfacial tensions balance at equilibrium contact angle



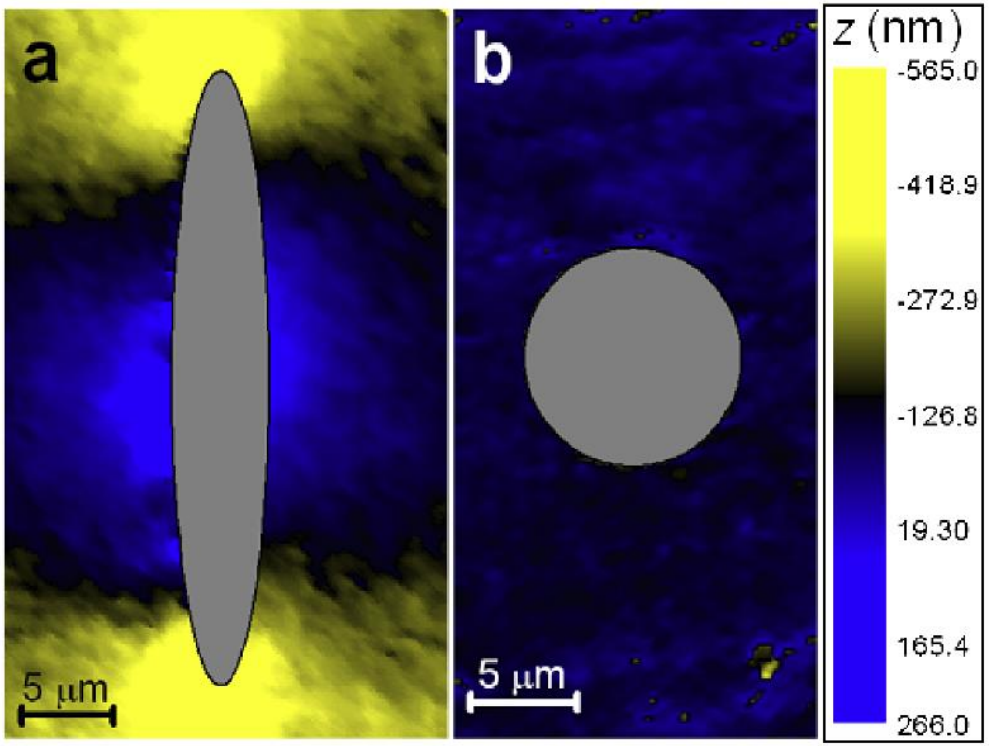
Interfacial tensions balance at equilibrium contact angle



Interfacial tensions balance at equilibrium contact angle



Shape Anisotropy Deforms Interface



Loudet, J.C., Alsayed, A.M., Zhang, J., and Yodh, A.G., ***Phys Rev Lett*** (2005); Loudet J.C., Yodh A.G., Pouligny B., ***Phys Rev Lett*** (2006); Kralchevsky, Paunov, Ivanov and Nagayama, J. Coll. Inter. Sci., (1992)

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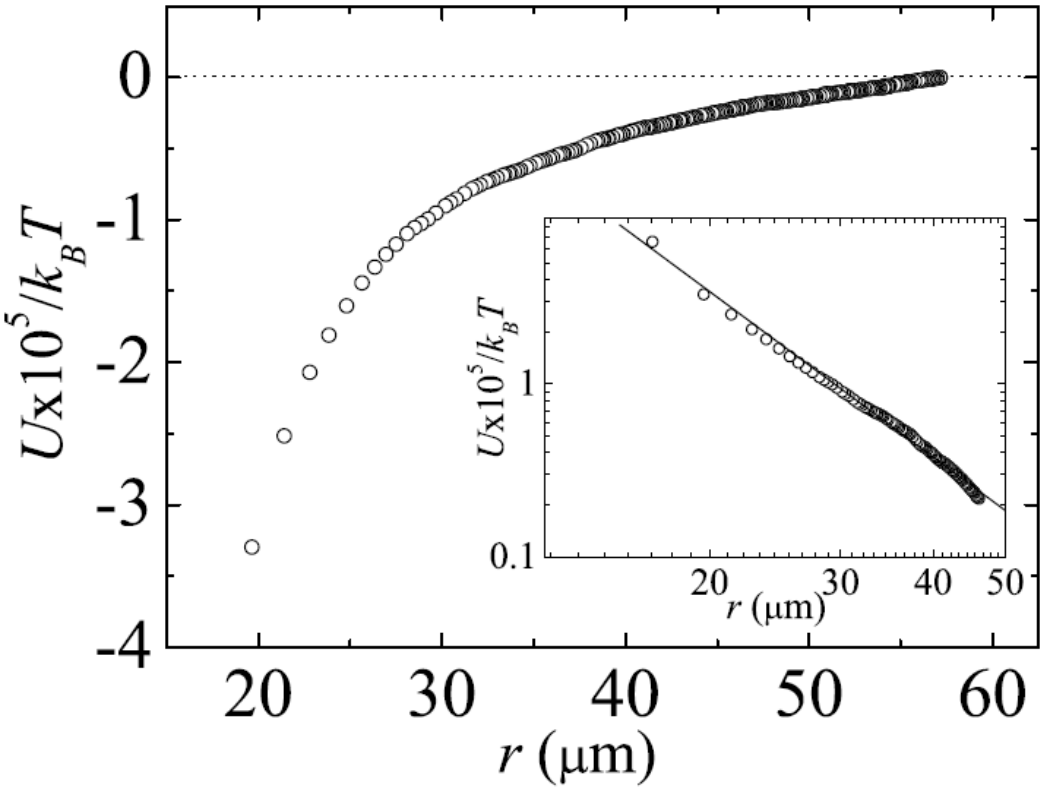
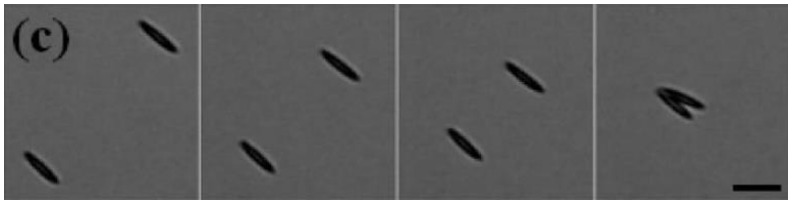
Interfacial Forces Depend on Particle Shape

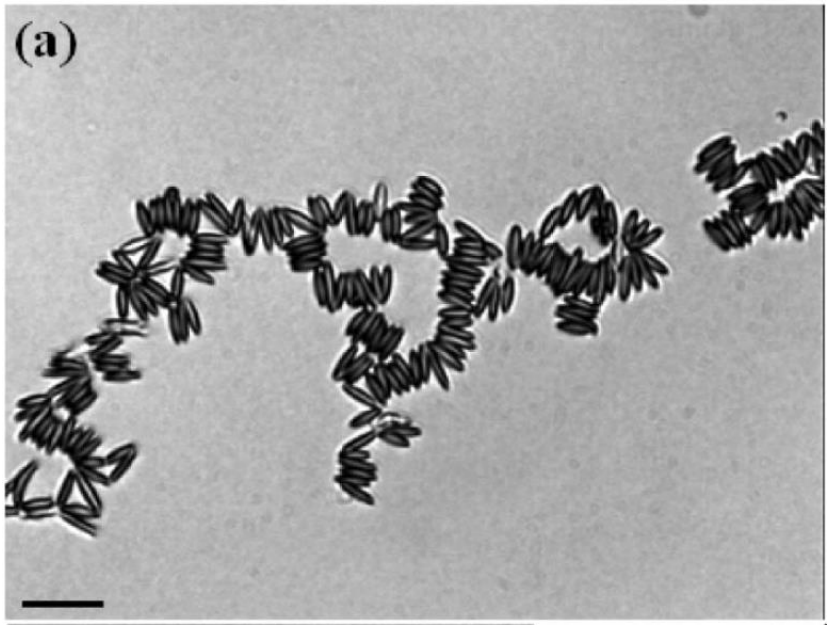


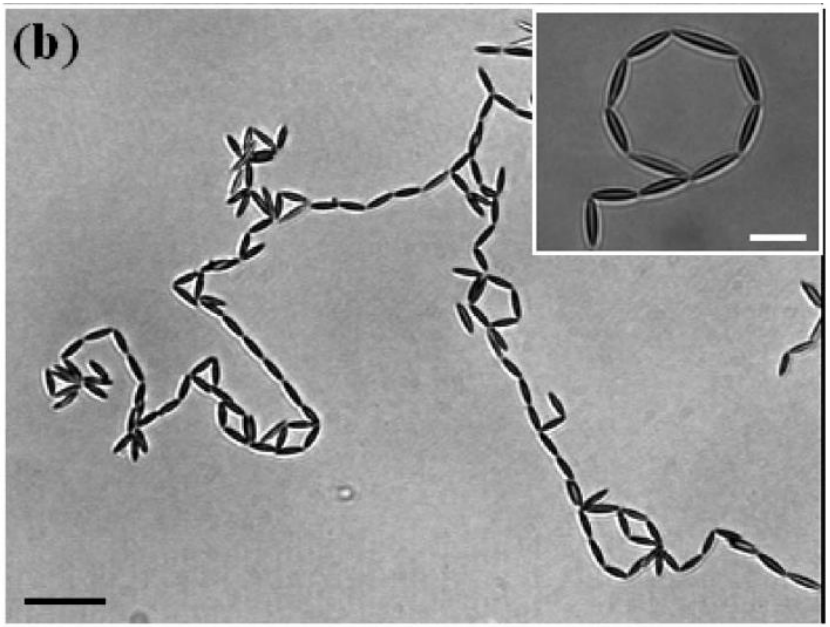


$$U \propto r^2(\varepsilon - 1)^2$$

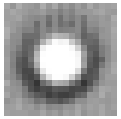
Loudet, J.C., Alsayed, A.M., Zhang, J., and Yodh, A.G., ***Phys Rev Lett*** (2005); Loudet J.C., Yodh A.G., Pouligny B., ***Phys Rev Lett*** (2006); Kralchevsky, Paunov, Ivanov and Nagayama, J. Coll. Inter. Sci., (1992)

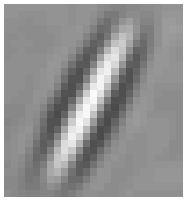
Highly anisotropic ellipsoids prefer tip-to-tip or side-to-side





Outward flows drive coffee ring-effect

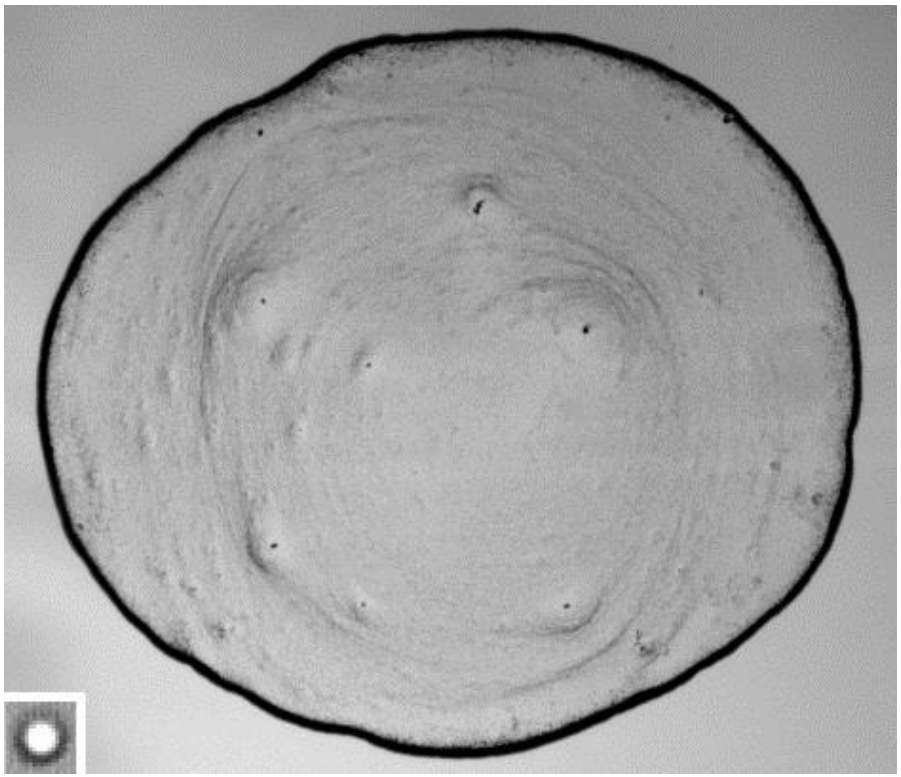


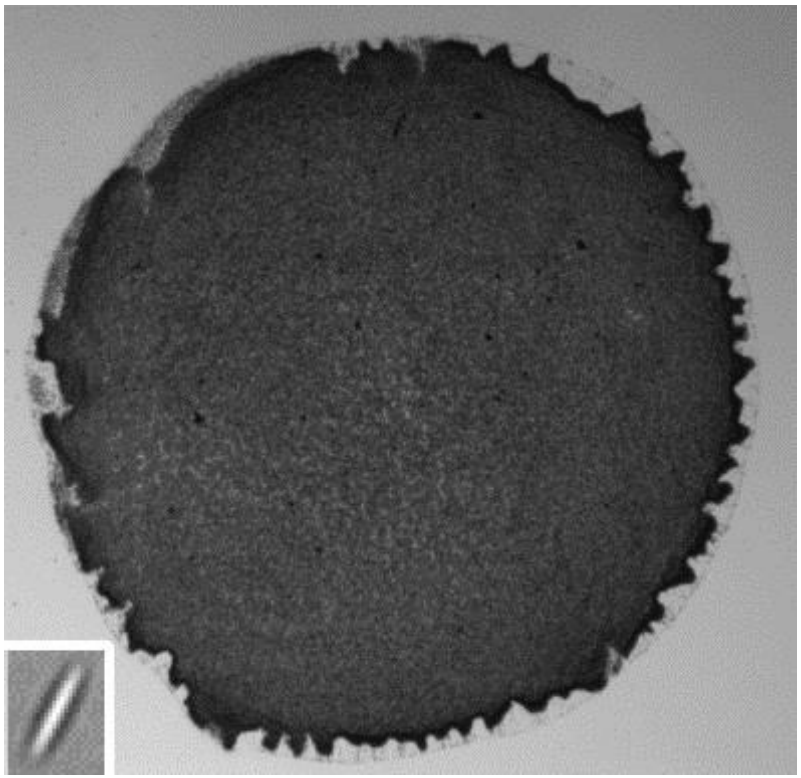


Spheres Ellipsoids

Robert D. Deegan, Olgica Bakajin, T.F. Dupont, G.Huber, Sidney R. Nagel , Thomas A. Witten, ***Nature*** (1997).

Coffee Rings for Spheres but not Ellipsoids!





250 µm

Initial Volume Fraction $\phi = 0.005$

Yunker, P.J., Still, T., Lohr, M.A., and Yodh, A.G., *Nature* (2011).

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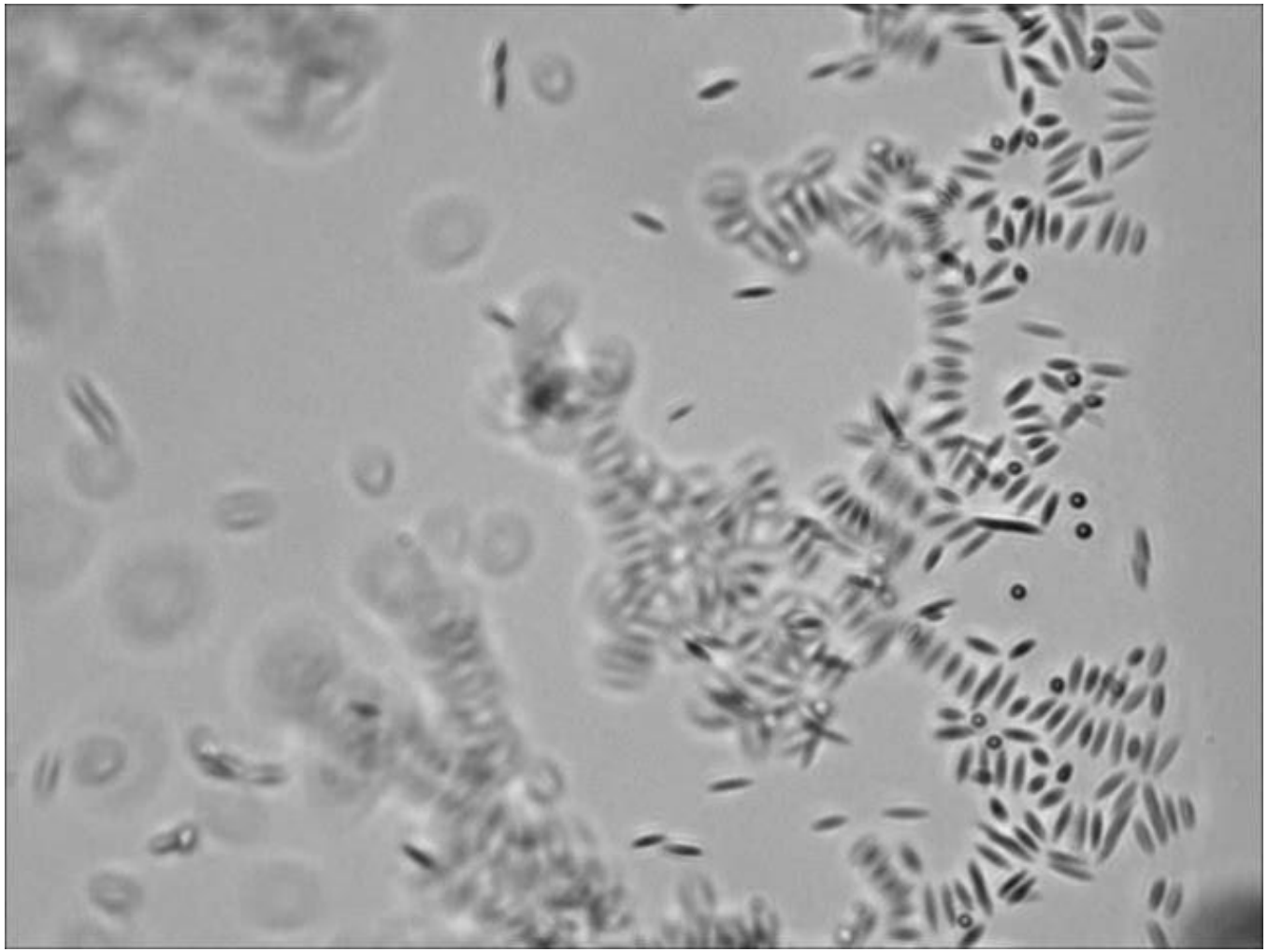
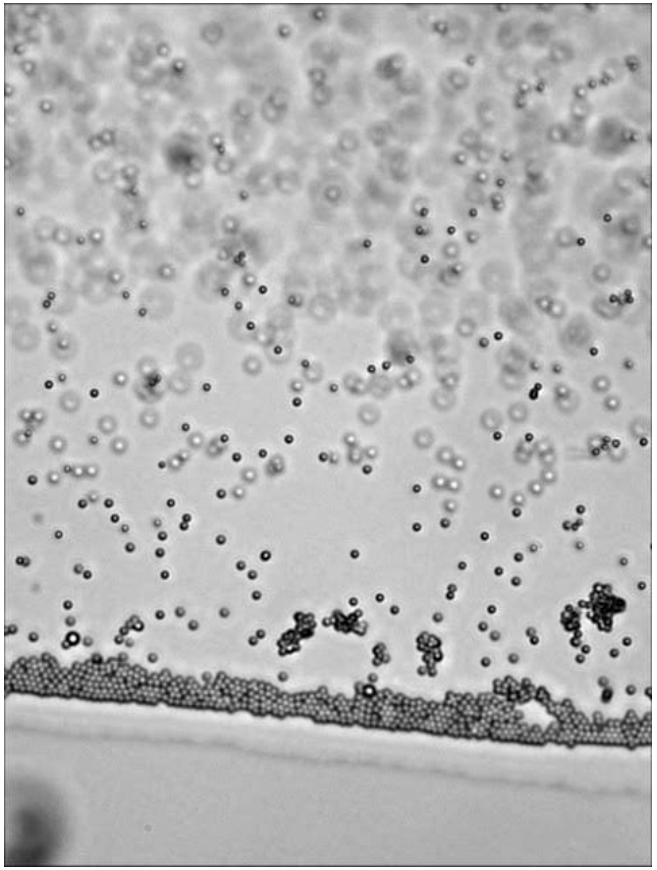
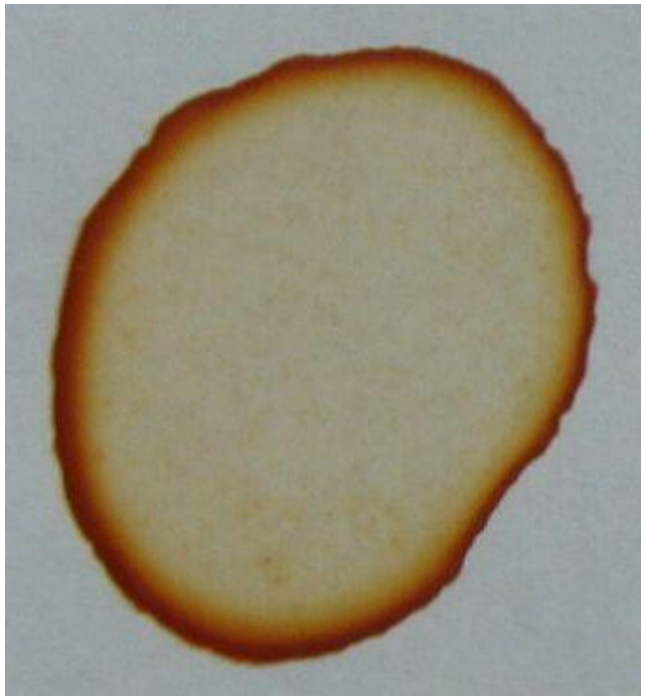
Ellipsoids form loosely-packed, open network



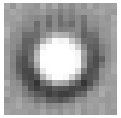
Reminiscent of growth process simulation



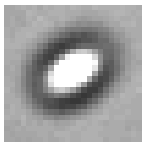
Growth process depends on particle shape



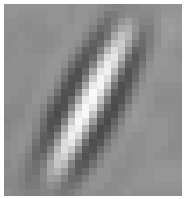
Coffee-ring effect



Poisson Process



KPZ Process



Colloidal Matthew Effect

Which growth processes?

Why particle shape?

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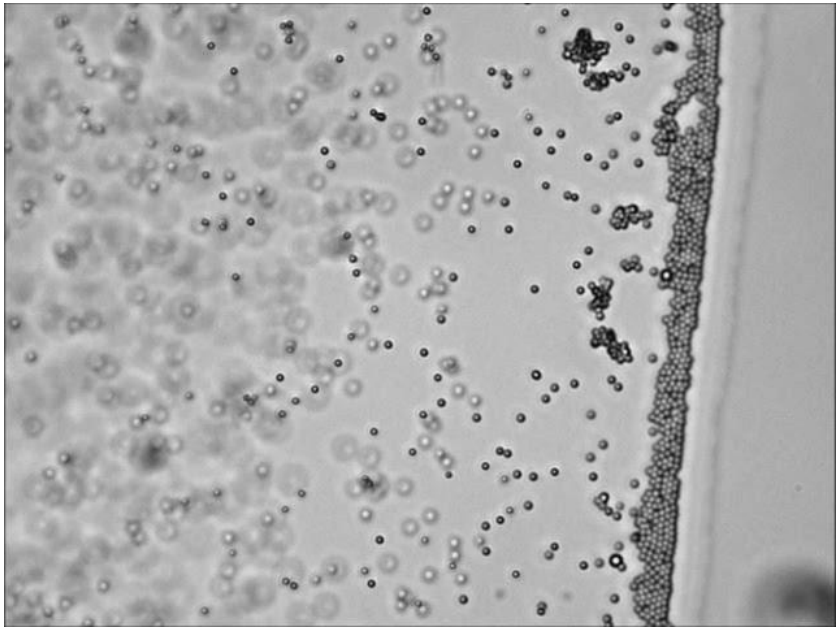
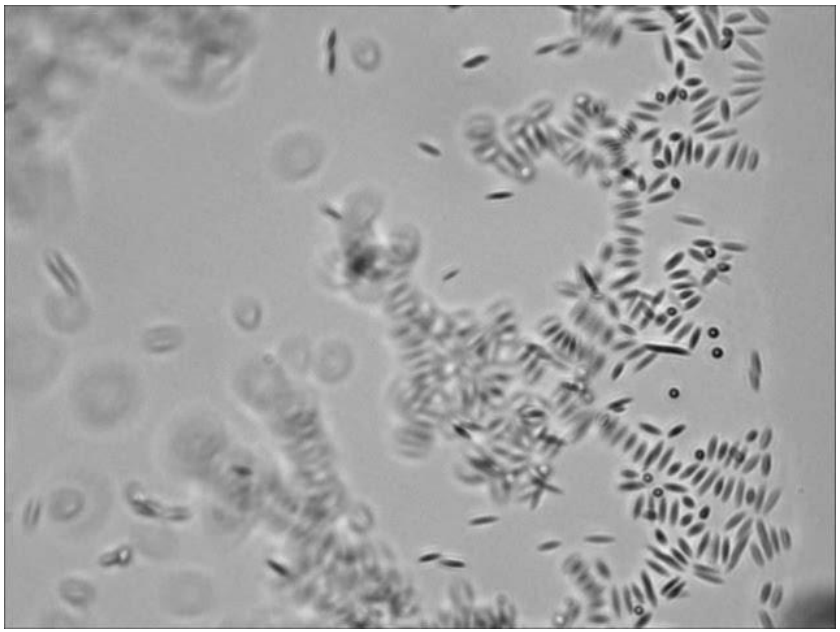
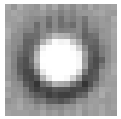
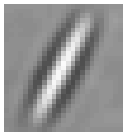
How do deposits grow during evaporation?







Spheres



Ellipsoids

What types of growth processes occur?

How does growth process depend on particle shape?

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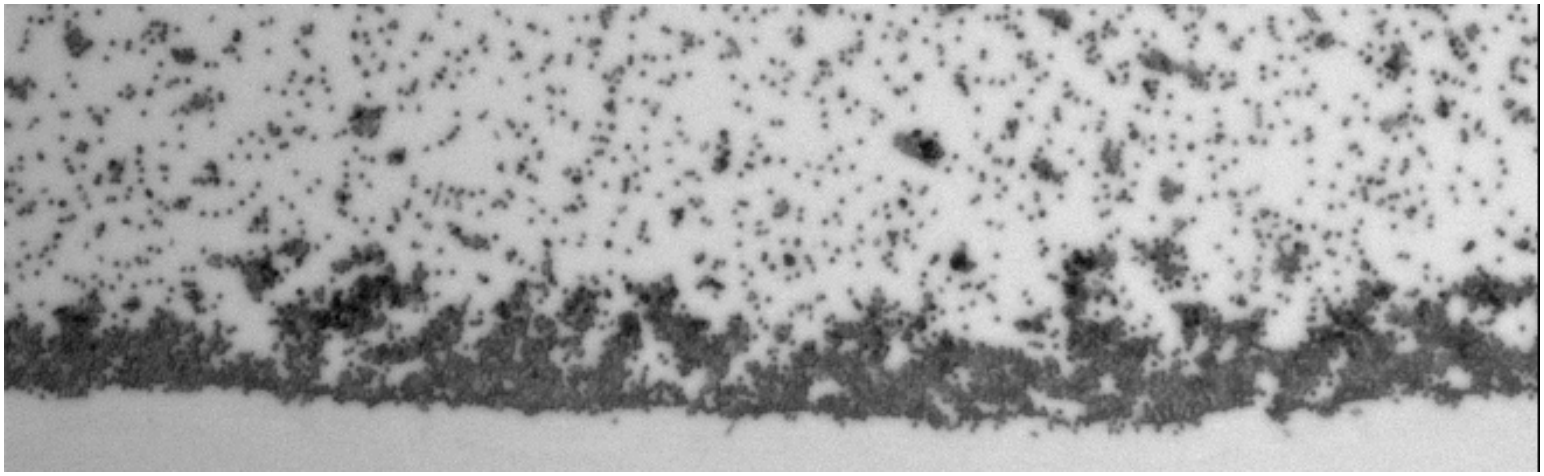
Deposit Characterization



25 µm

Georgia Institute of Technology

Slightly anisotropic particles
α = 1.2

Deposit Characterization

25 µm

Georgia Institute of Technology

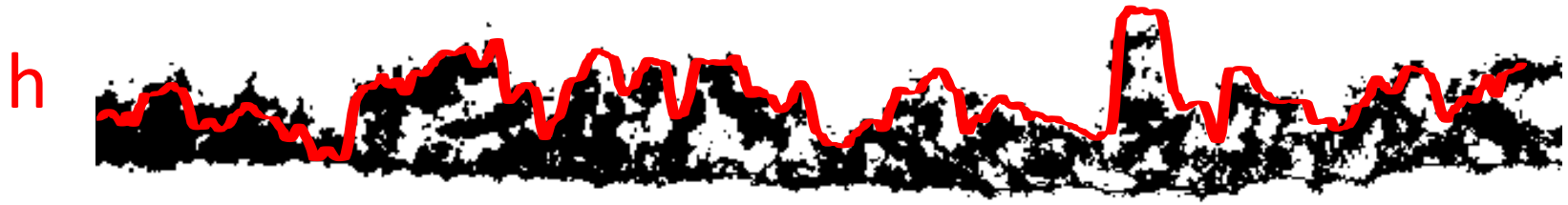
Slightly anisotropic particles
α = 1.2

Deposit Characterization

Georgia Institute of Technology

Slightly anisotropic particles
α = 1.2

Deposit Characterization

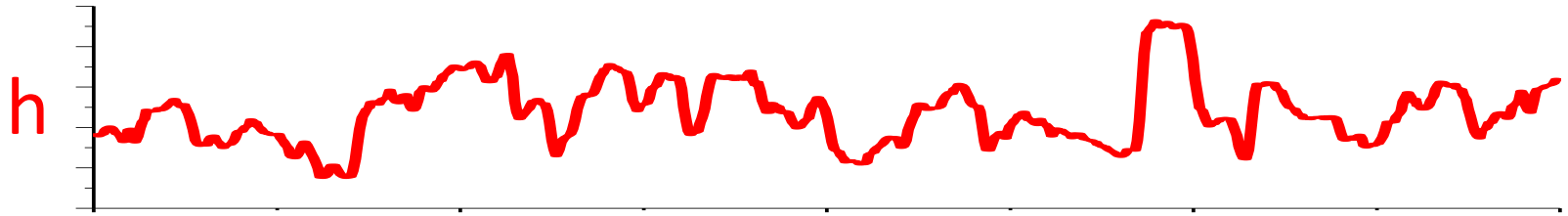


25 µm

Georgia Institute of Technology

Slightly anisotropic particles
α = 1.2

Deposit Characterization

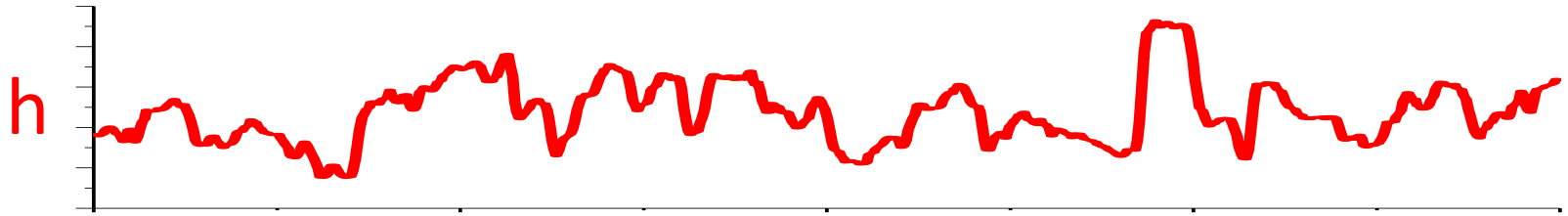


25 µm

Georgia Institute of Technology

Slightly anisotropic particles
α = 1.2

Deposit Characterization

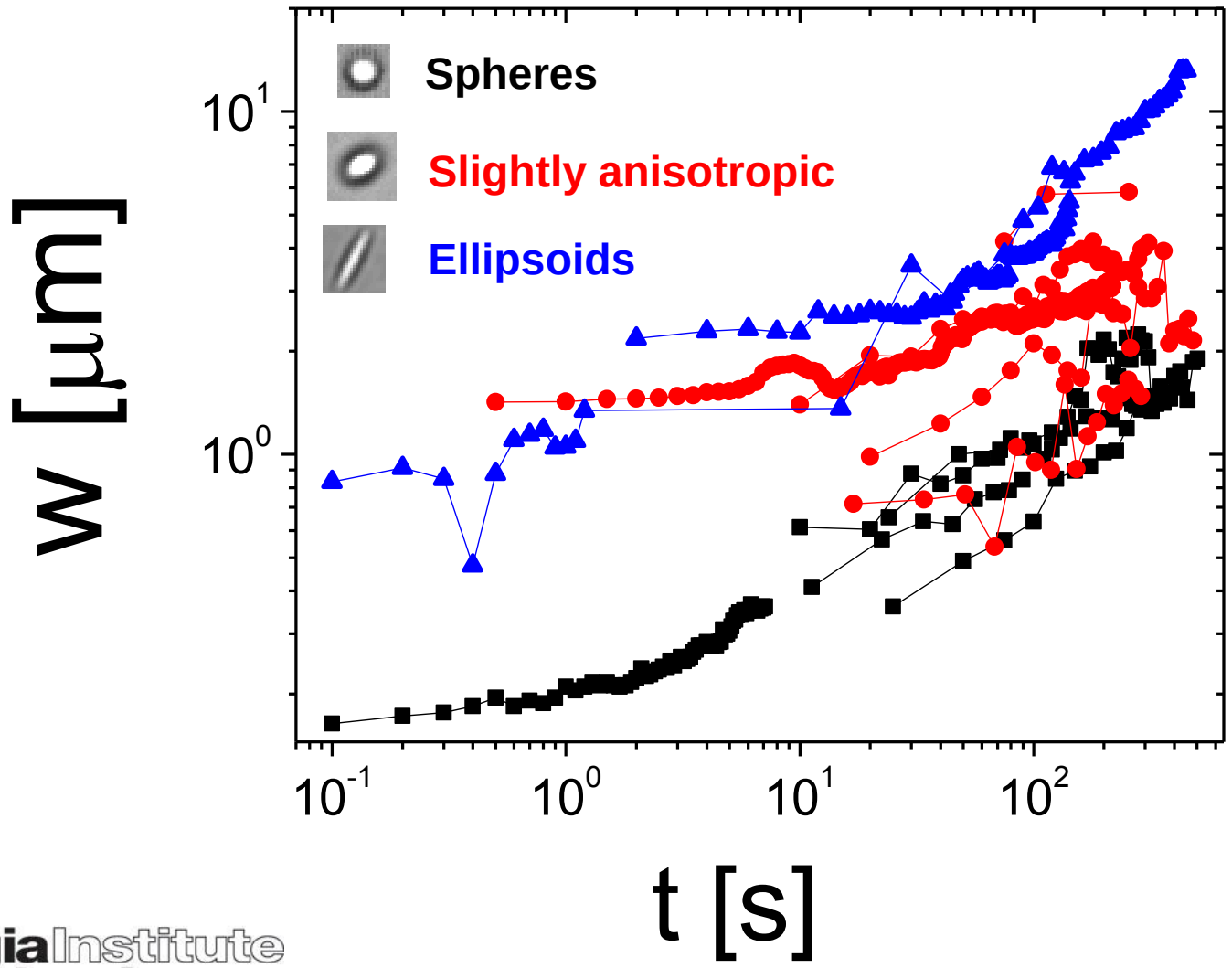


25 μm

$$\text{Width, } w = \left\langle \sqrt{\left\langle \left(h - \langle h \rangle\right)^2 \right\rangle} \right\rangle \sim t^{\beta}$$

Slightly anisotropic particles
α = 1.2

Deposit width increases over time



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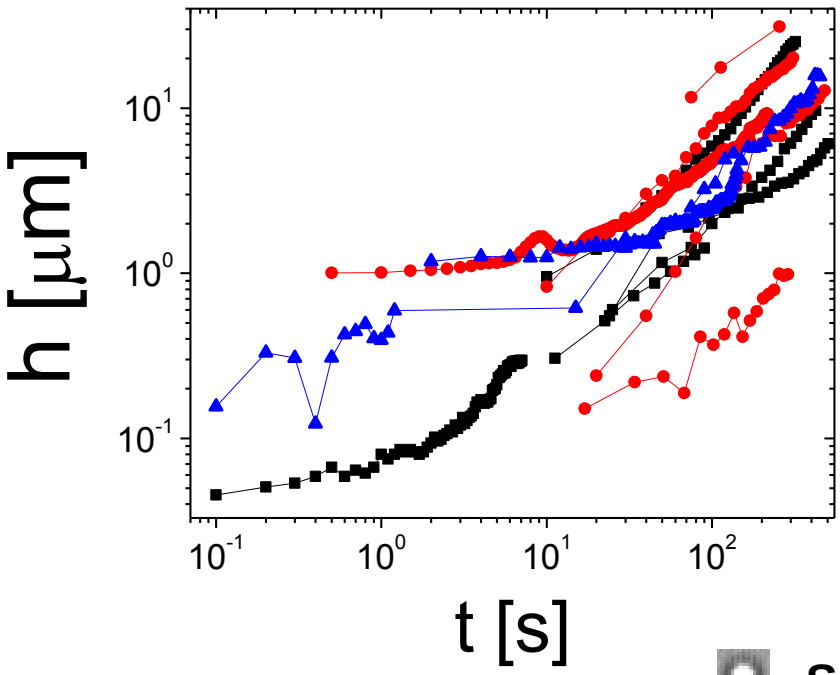
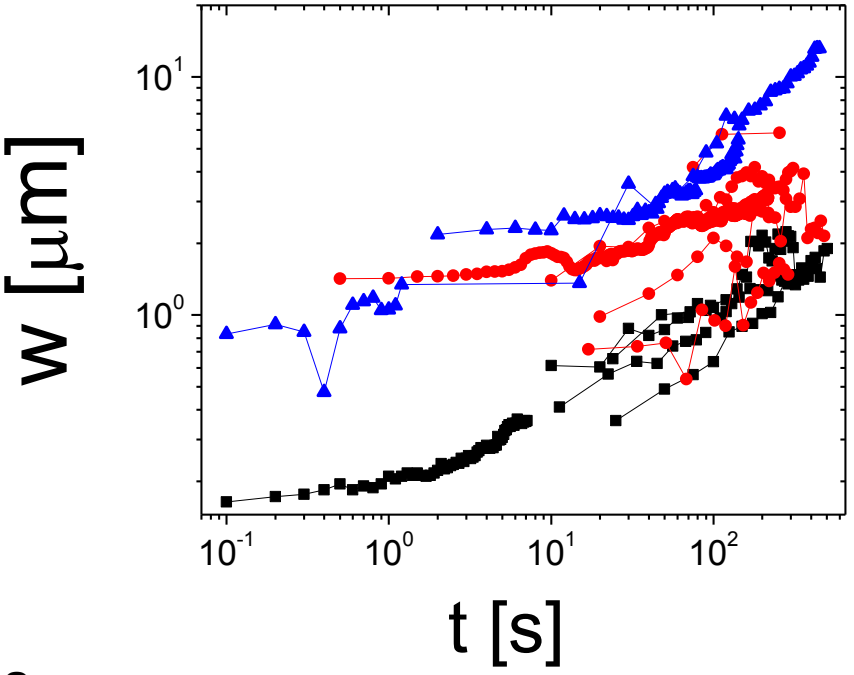
Use h instead of t






Spheres


Slightly anisotropic


Ellipsoids

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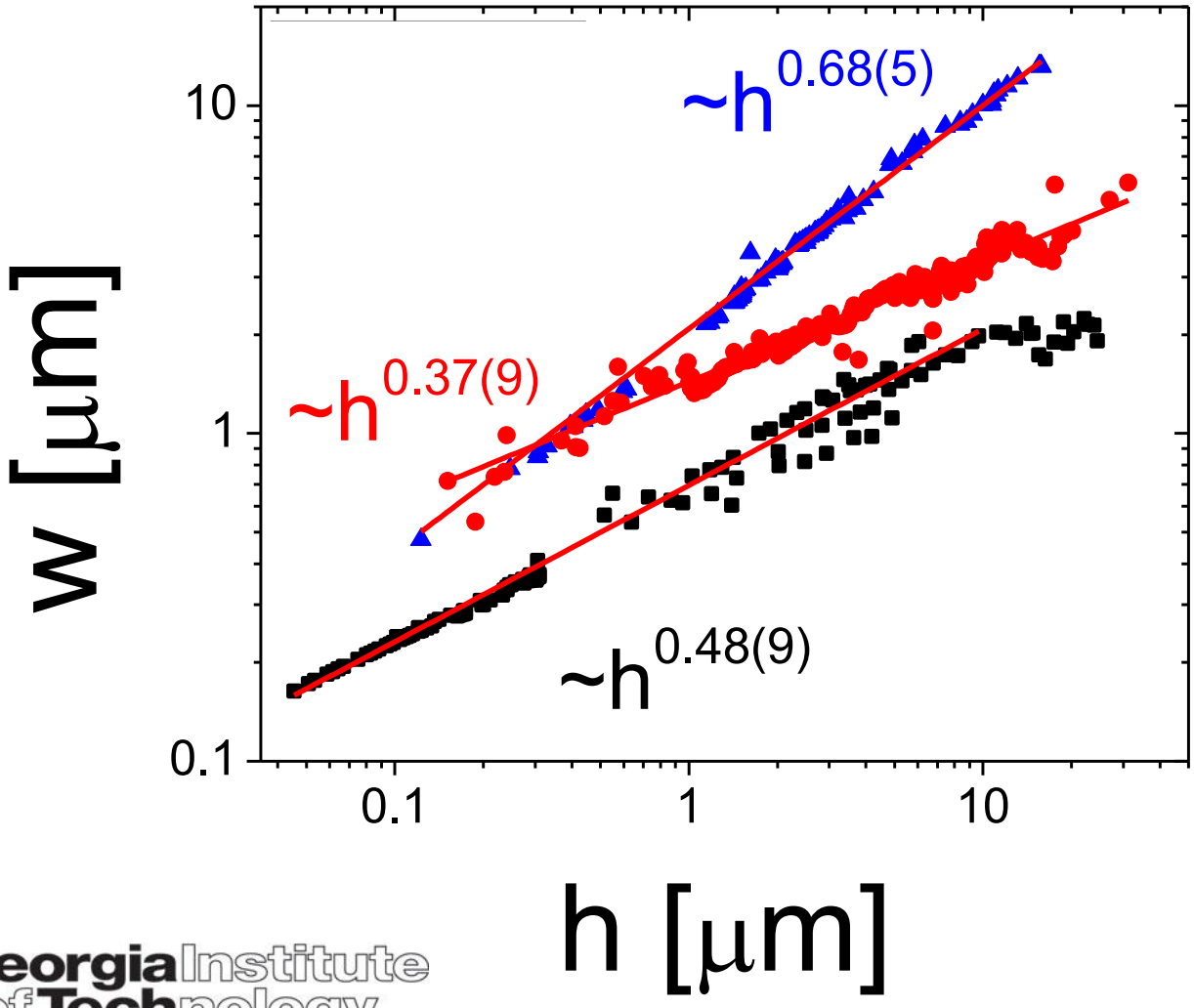
Data collapse into distinct trends based on particle shape




Ellipsoids


Slightly anisotropic


Spheres

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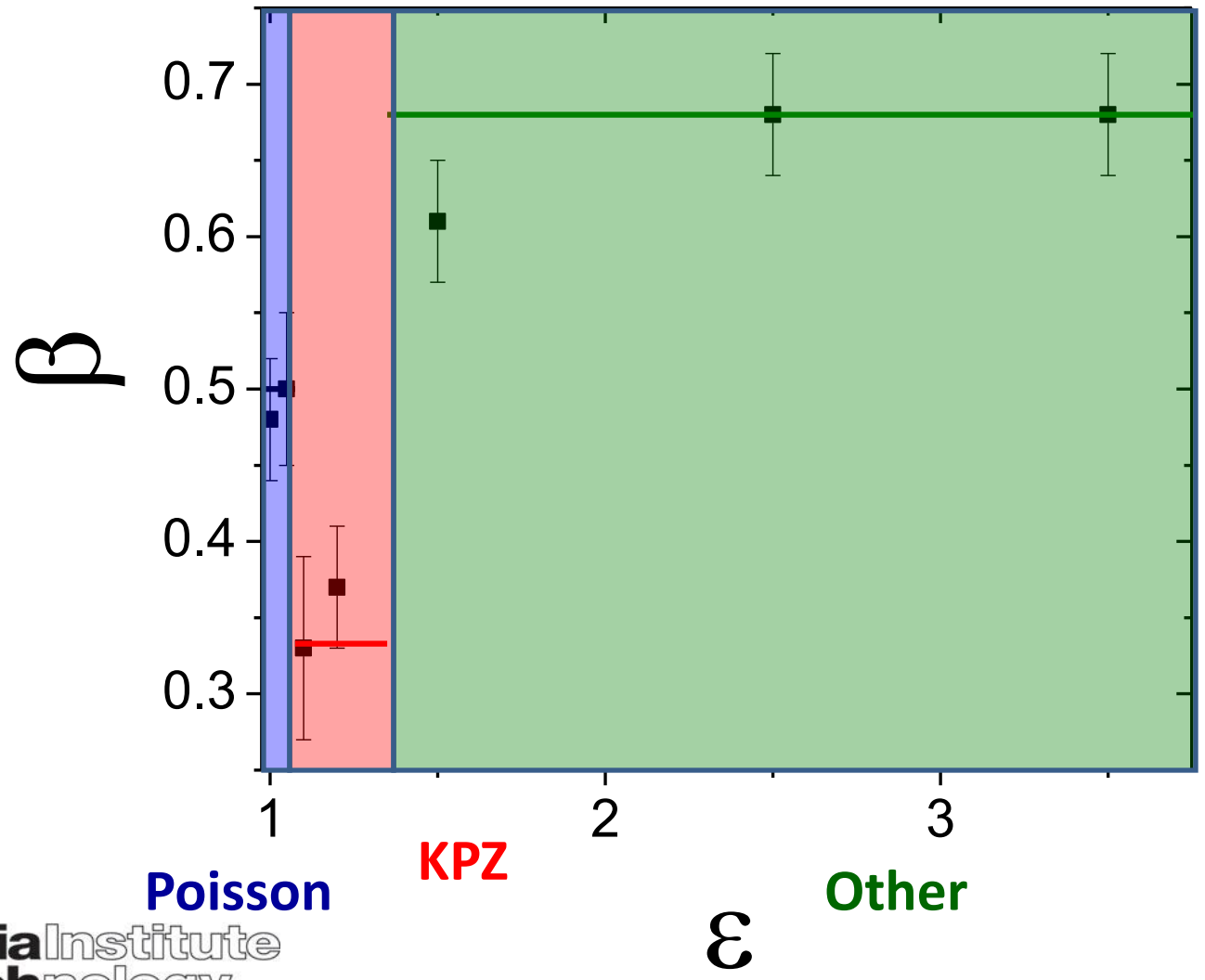
Three distinct regimes

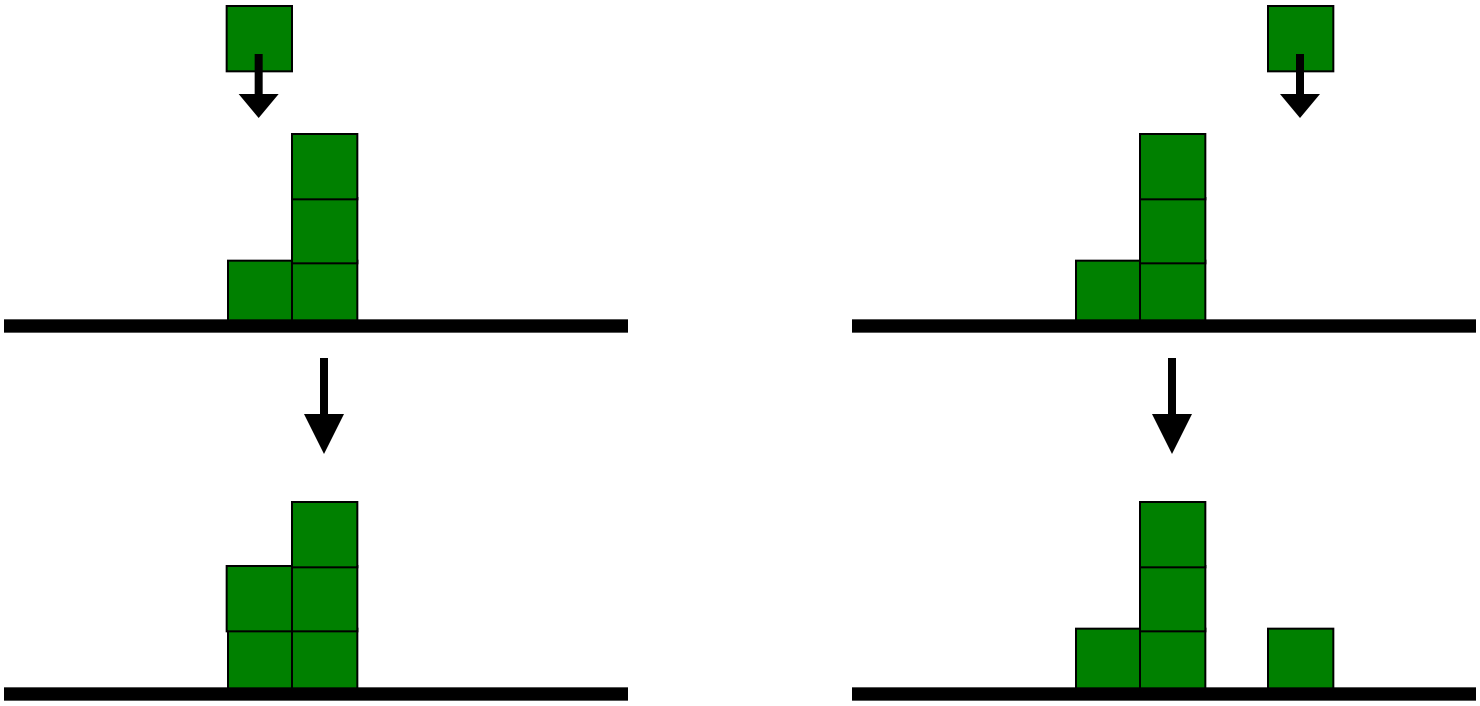


Spheres

$\varepsilon = 1.0, 1.05$

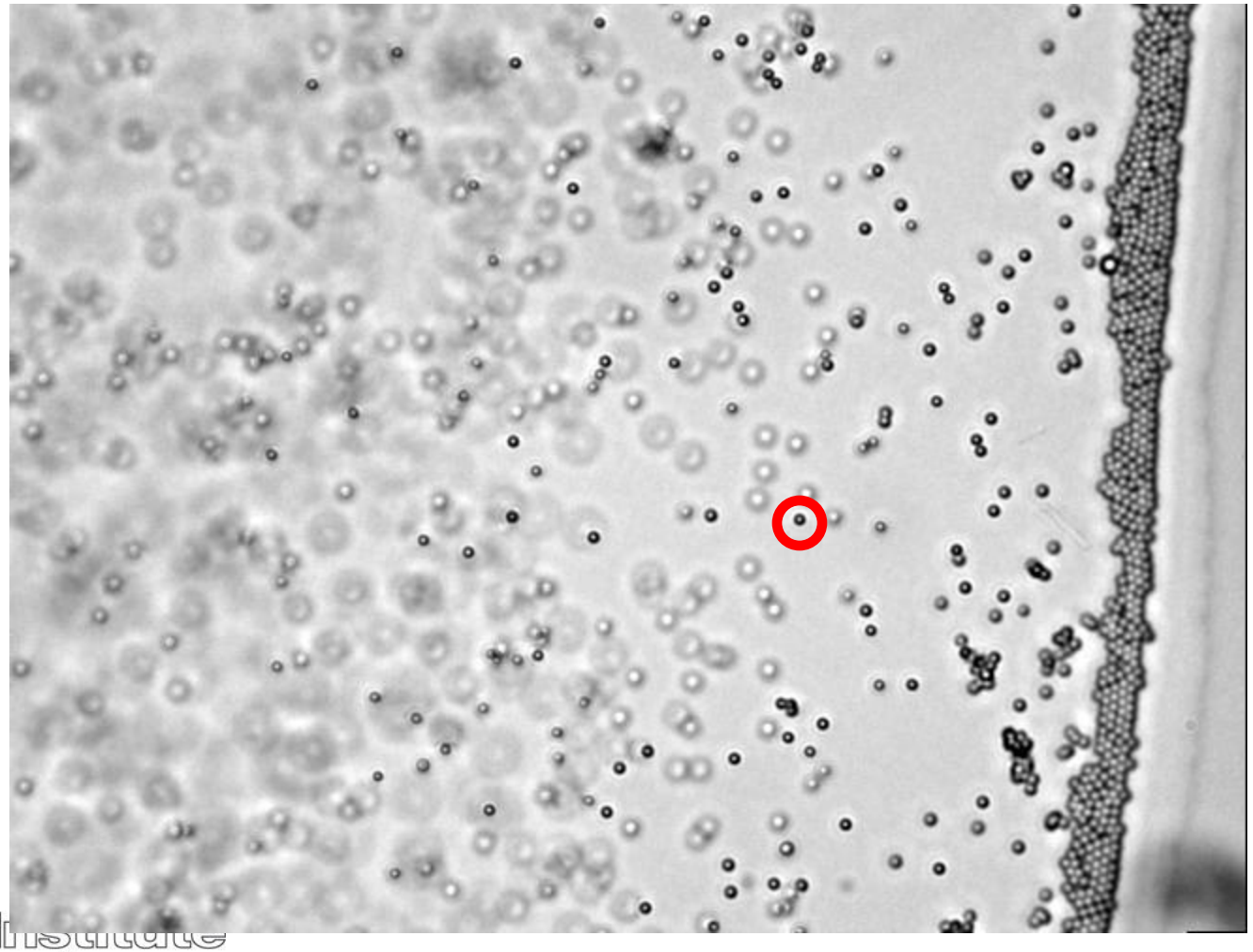
Poisson Process

Random deposition – Poisson process



Family, Physica A (1990)

Spheres densely pack at drop edge



Drop Edge

5 µm

t = 1 s

Initial Volume Fraction $\phi = 0.005$

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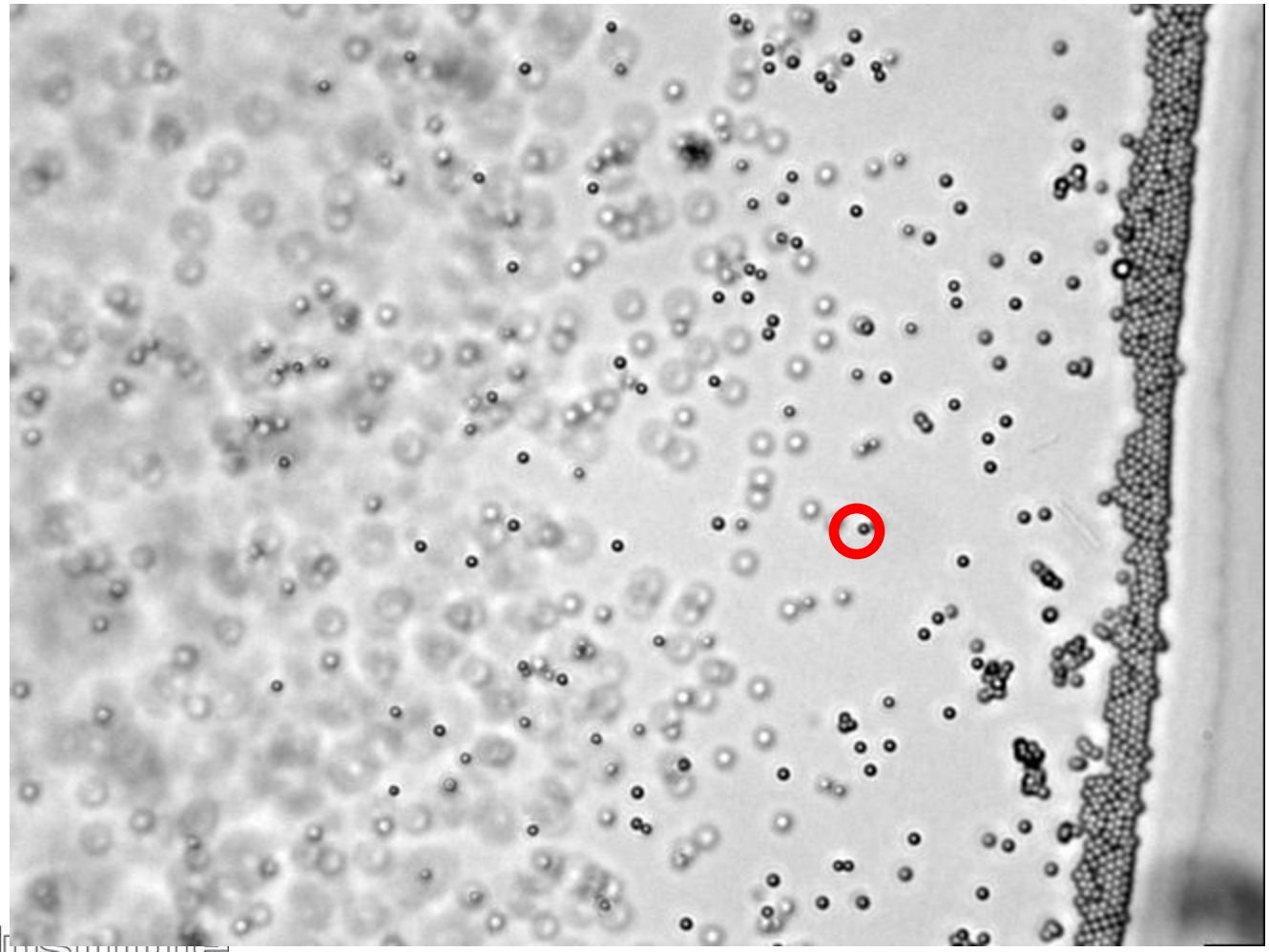
Spheres densely pack at drop edge



Drop Edge

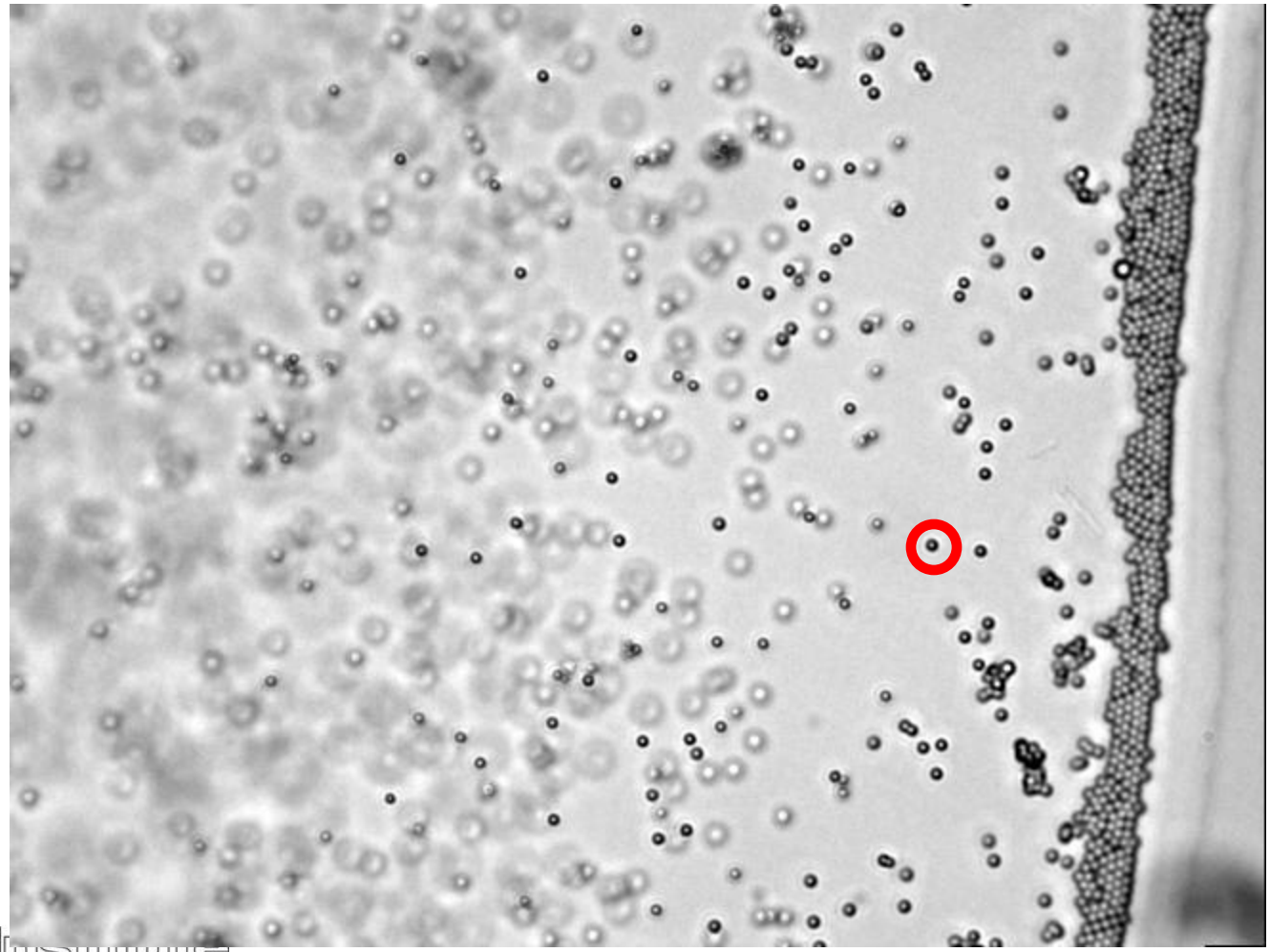
5 µm

t = 2 s

Initial Volume Fraction $\phi = 0.005$

Georgia Institute of Technology

Spheres densely pack at drop edge



Drop Edge

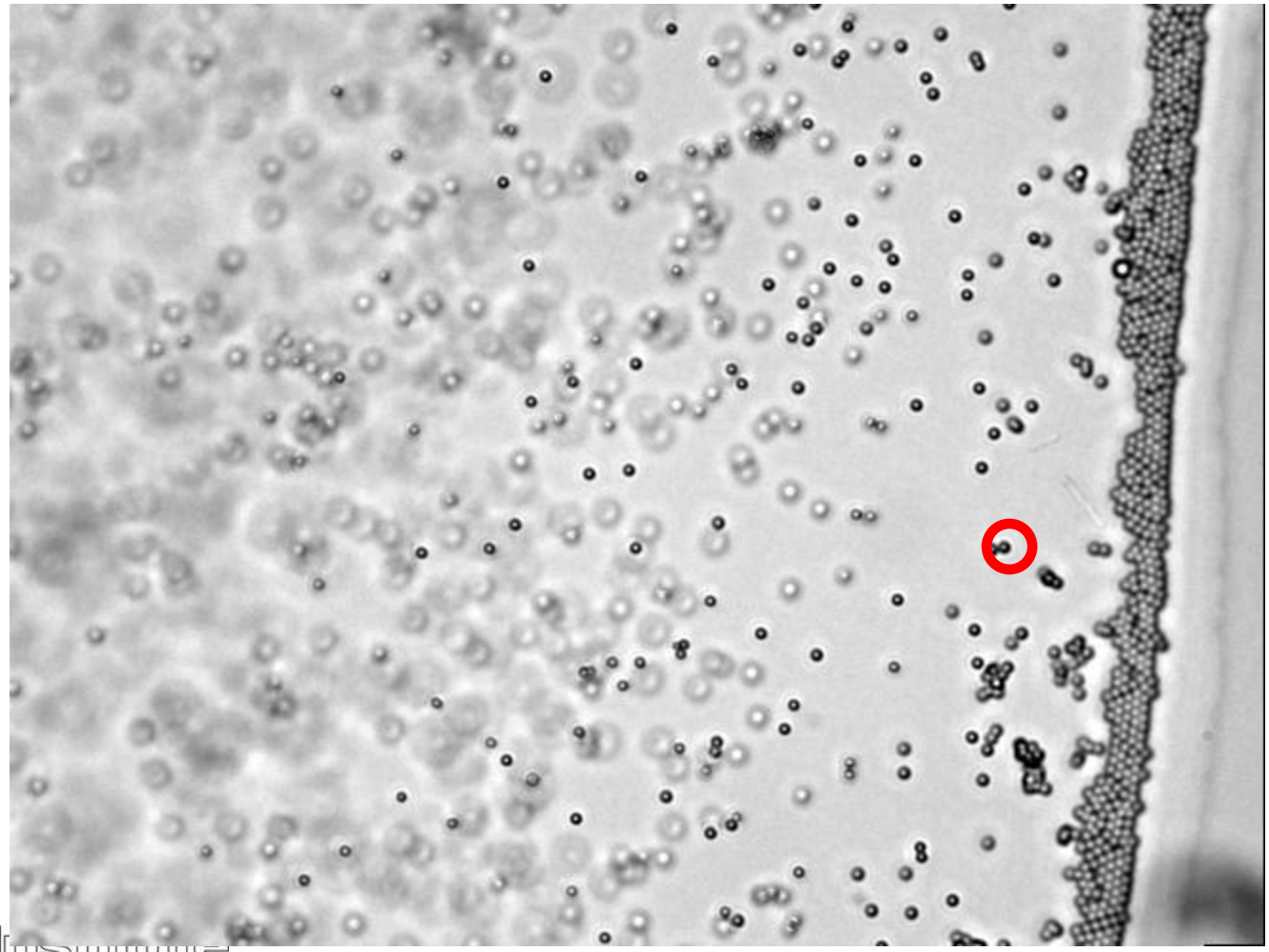
5 µm

t = 3 s

Initial Volume Fraction $\phi = 0.005$

Georgia Institute of Technology

Spheres densely pack at drop edge



Drop Edge

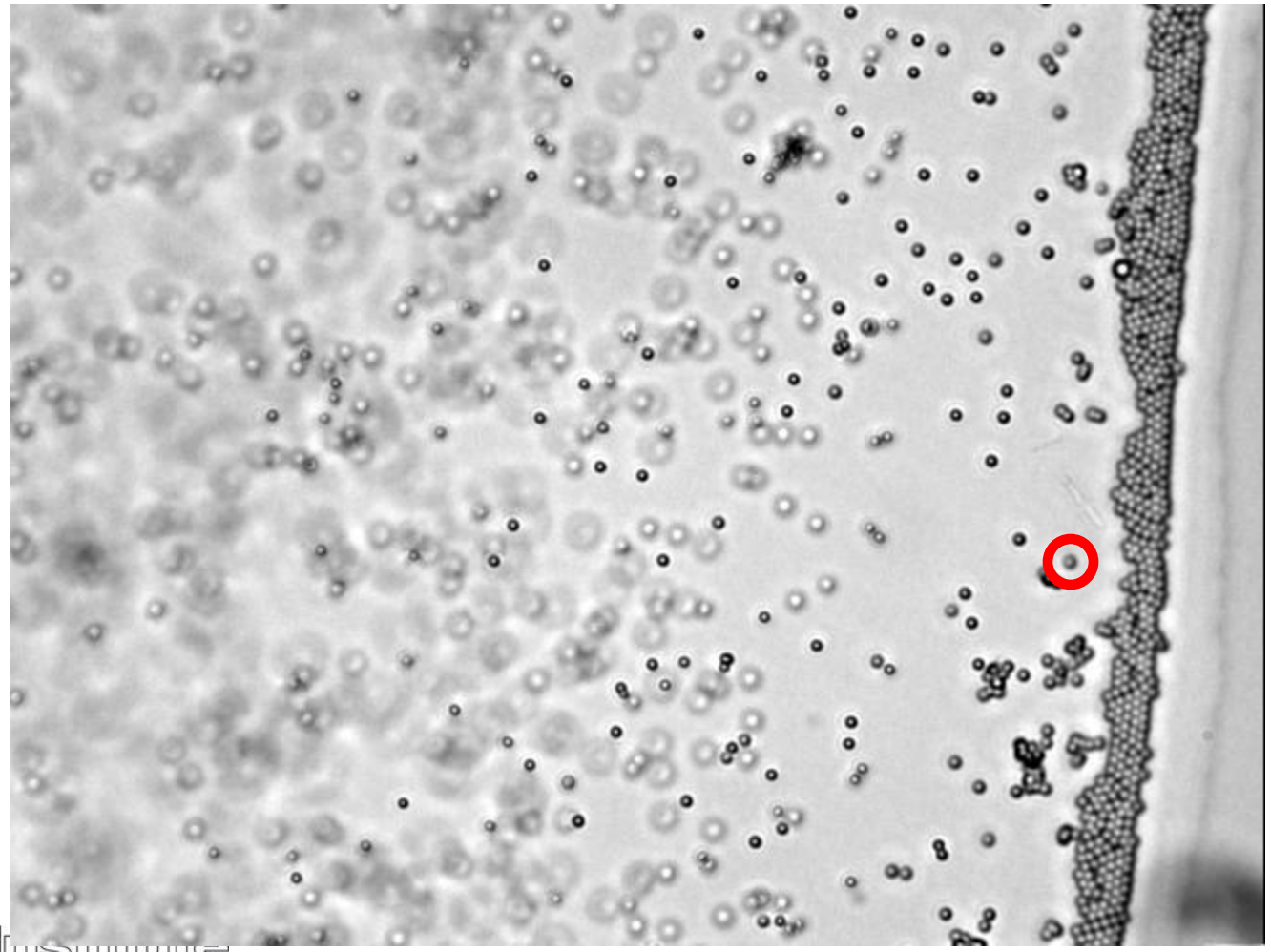
5 µm

t = 4 s

Initial Volume Fraction $\phi = 0.005$

Georgia Institute of Technology

Spheres densely pack at drop edge



Drop Edge

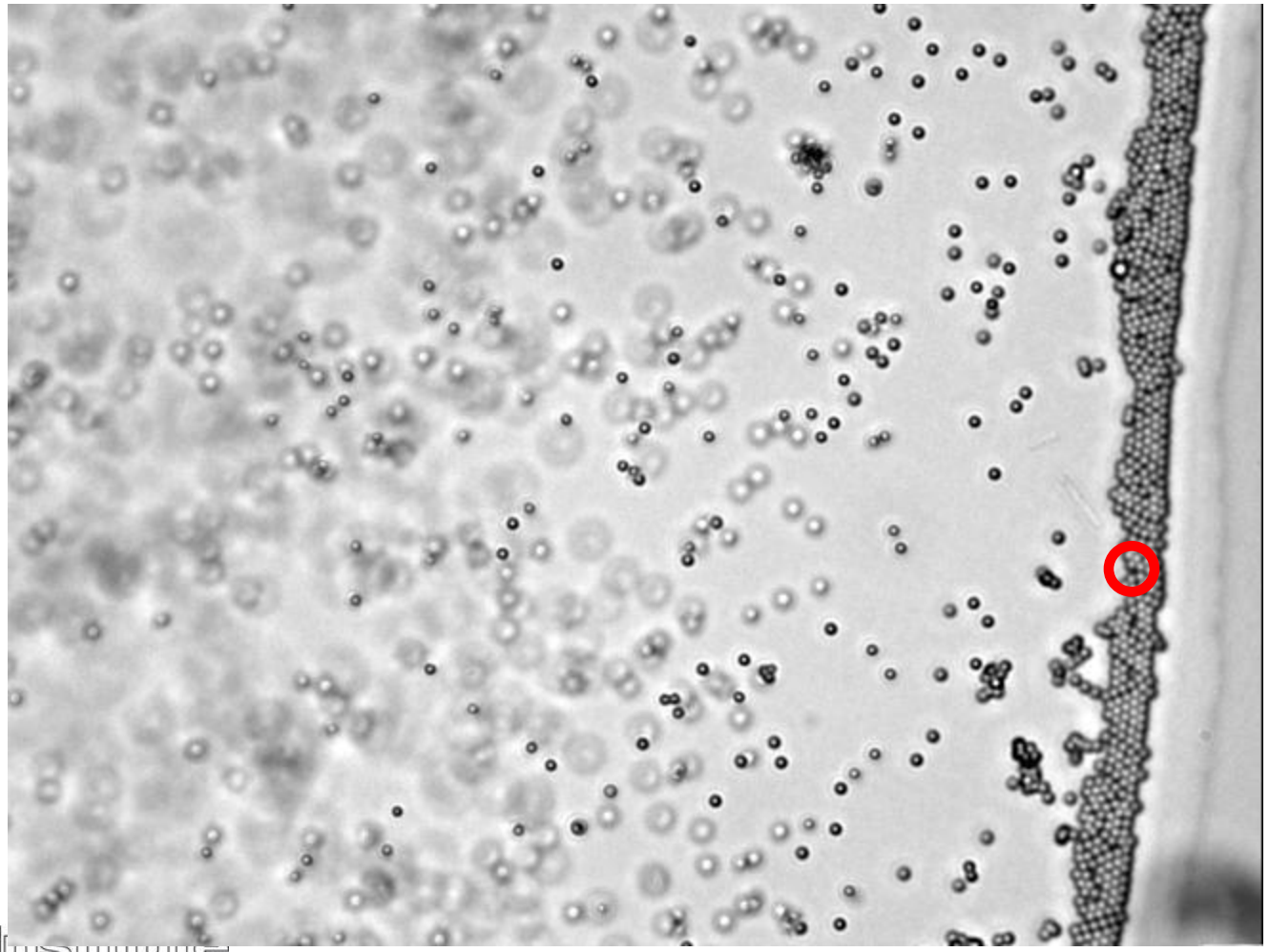
5 µm

t = 5 s

Initial Volume Fraction $\phi = 0.005$

Georgia Institute of Technology

Spheres densely pack at drop edge



Drop Edge

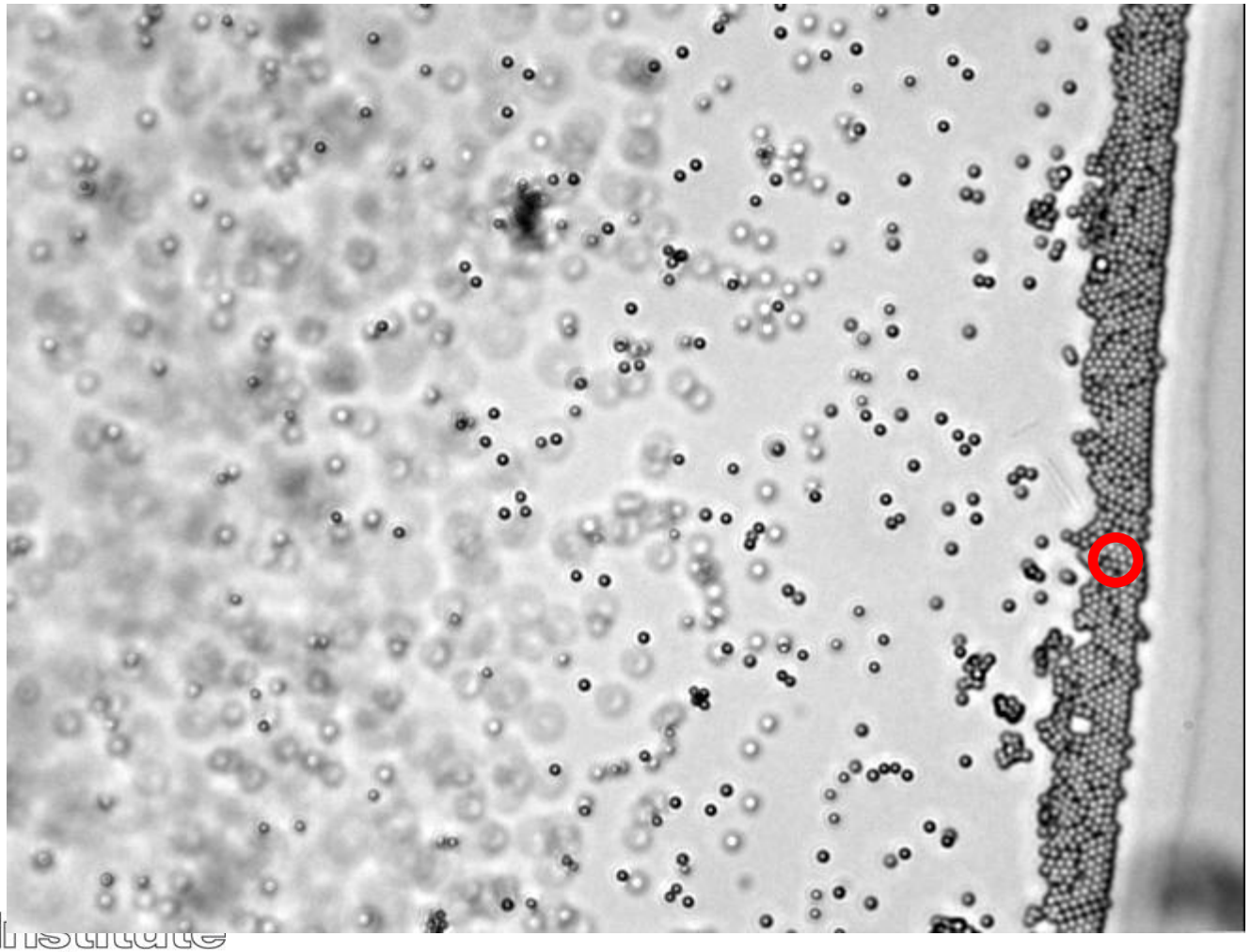
5 µm

t = 6 s

Initial Volume Fraction $\phi = 0.005$

Georgia Institute of Technology

Spheres densely pack at drop edge



Drop Edge

5 µm

t = 26 s

Initial Volume Fraction $\phi = 0.005$

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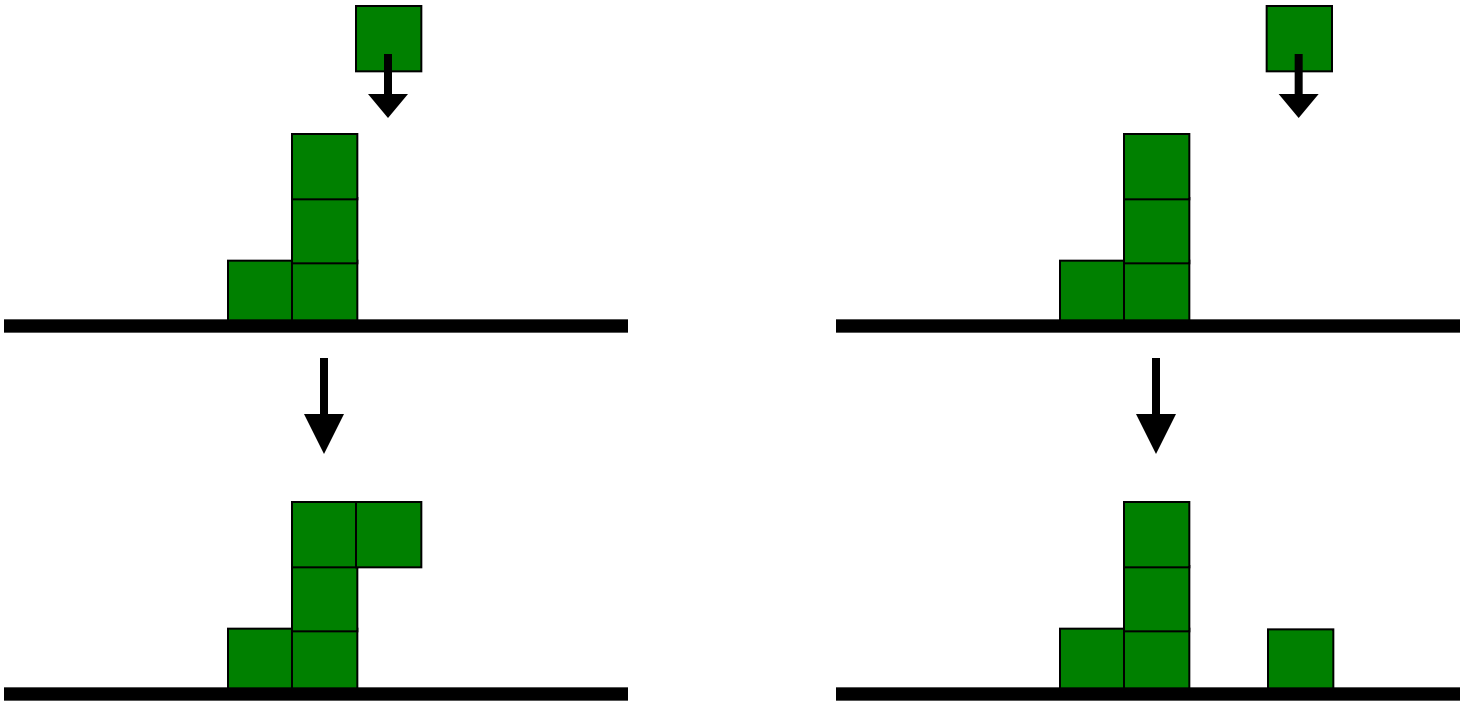
Slightly anisotropic particles

$\varepsilon = 1.1, 1.2$

KPZ Process

Slightly stretched particle deposition similar to ballistic deposition



Interparticle interaction is >> 1 $k_B T$ for nearest neighbors only

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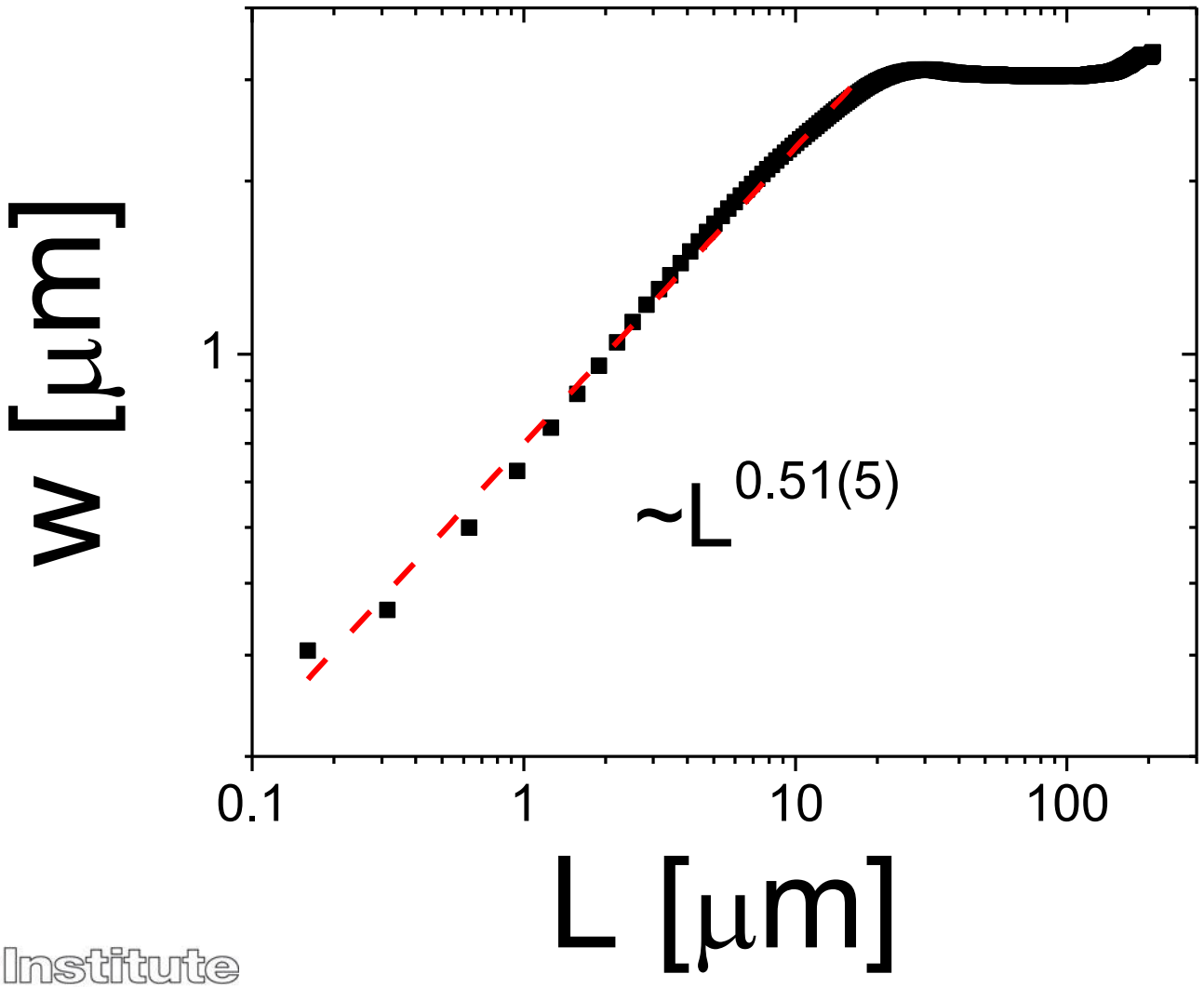
Stamou, Duschl, and Johannsmann PRE (2000); Family, Physica A (1990)

Roughness exponent α agrees with KPZ



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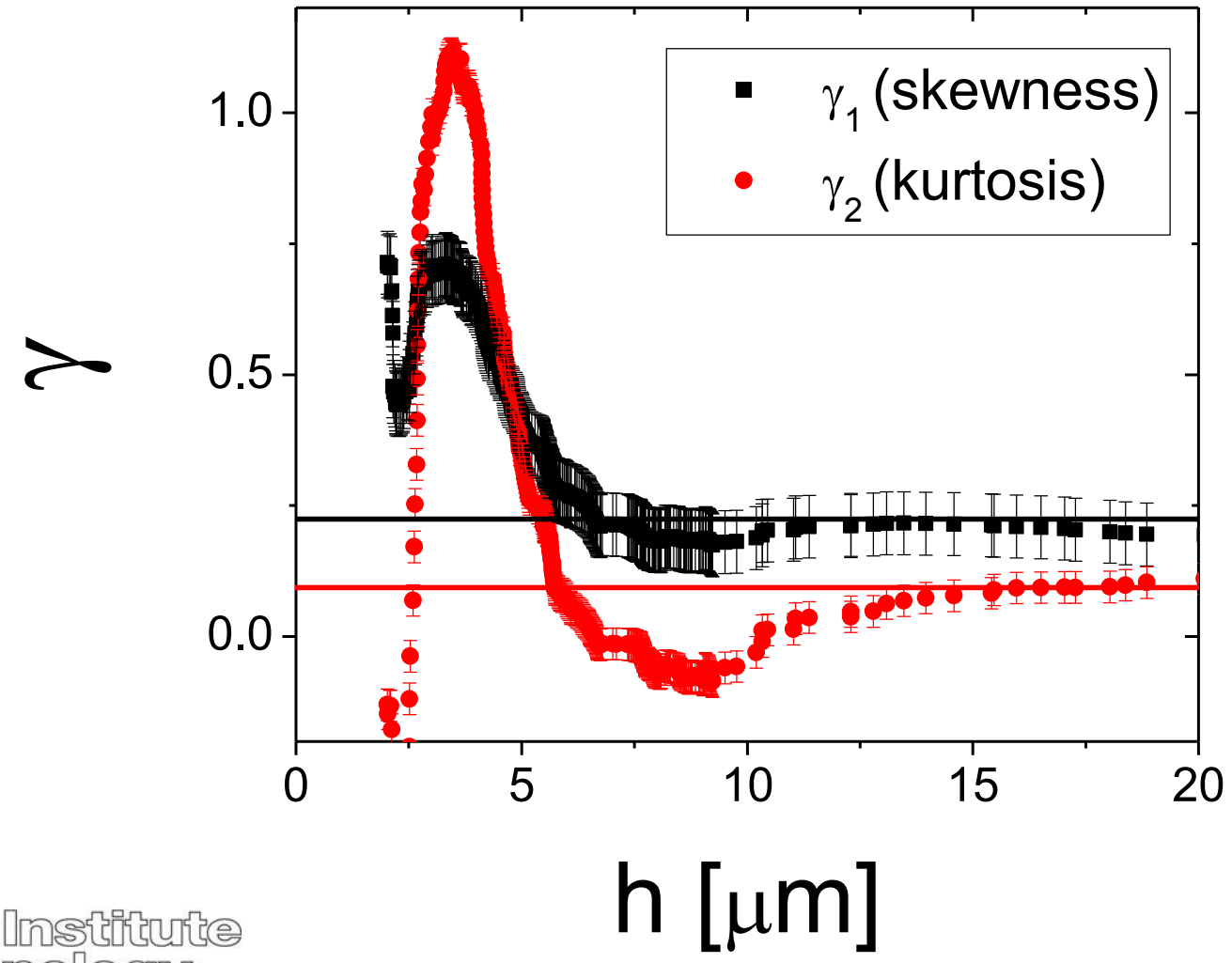
Skewness and Kurtosis approach KPZ values



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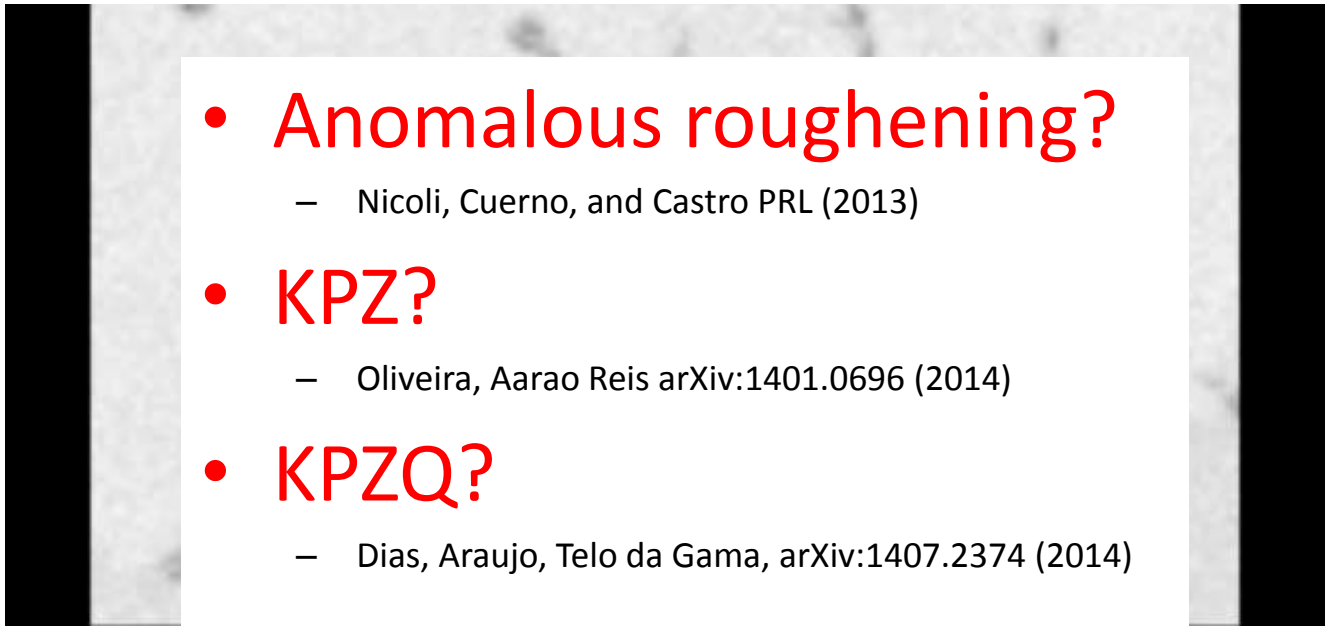
Very anisotropic ellipsoids

$\varepsilon > 1.2$

Colloidal Matthew Effect

Particle-rich regions get richer

What type of growth process is this?



- Anomalous roughening?
  - Nicoli, Cuerno, and Castro PRL (2013)
- KPZ?
  - Oliveira, Aarao Reis arXiv:1401.0696 (2014)
- KPZQ?
  - Dias, Araujo, Telo da Gama, arXiv:1407.2374 (2014)

Drop Edge

10 µm

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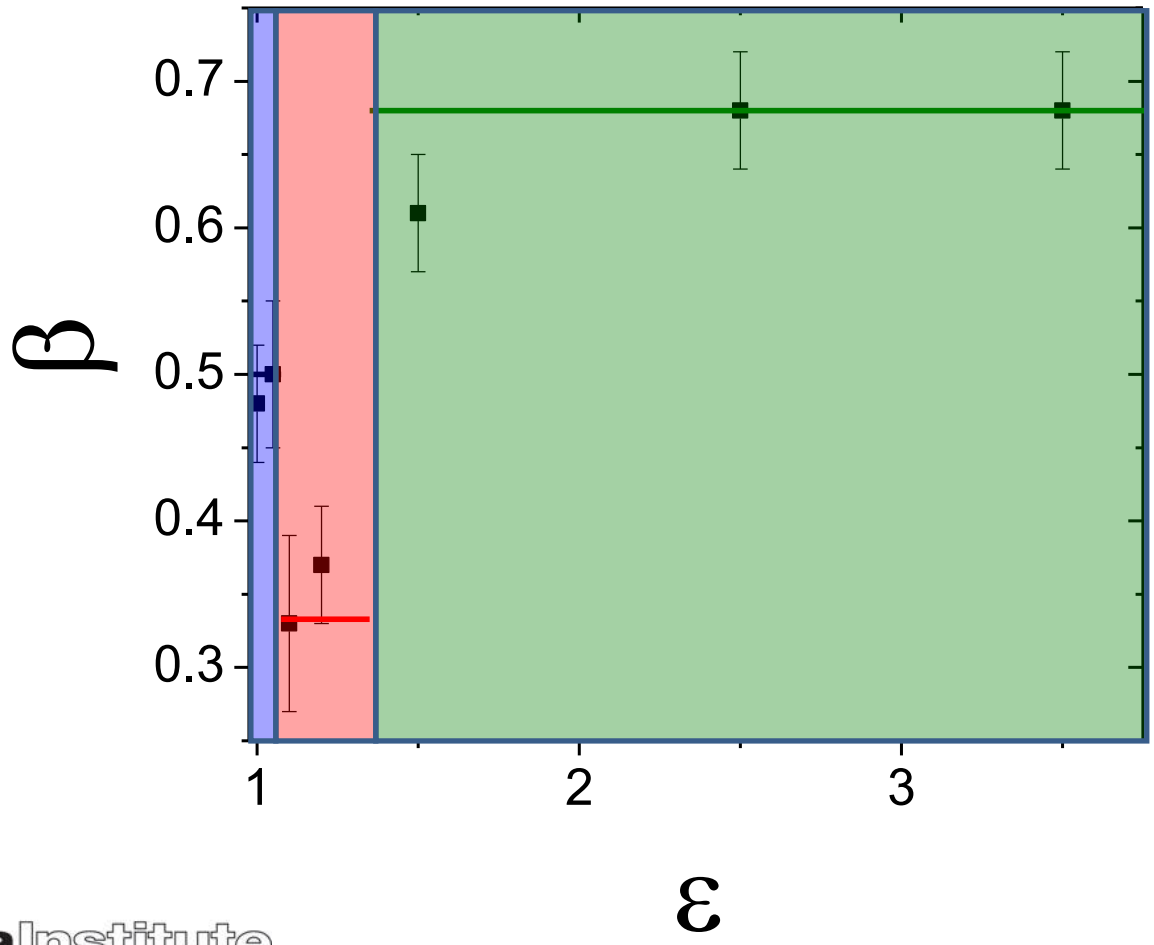
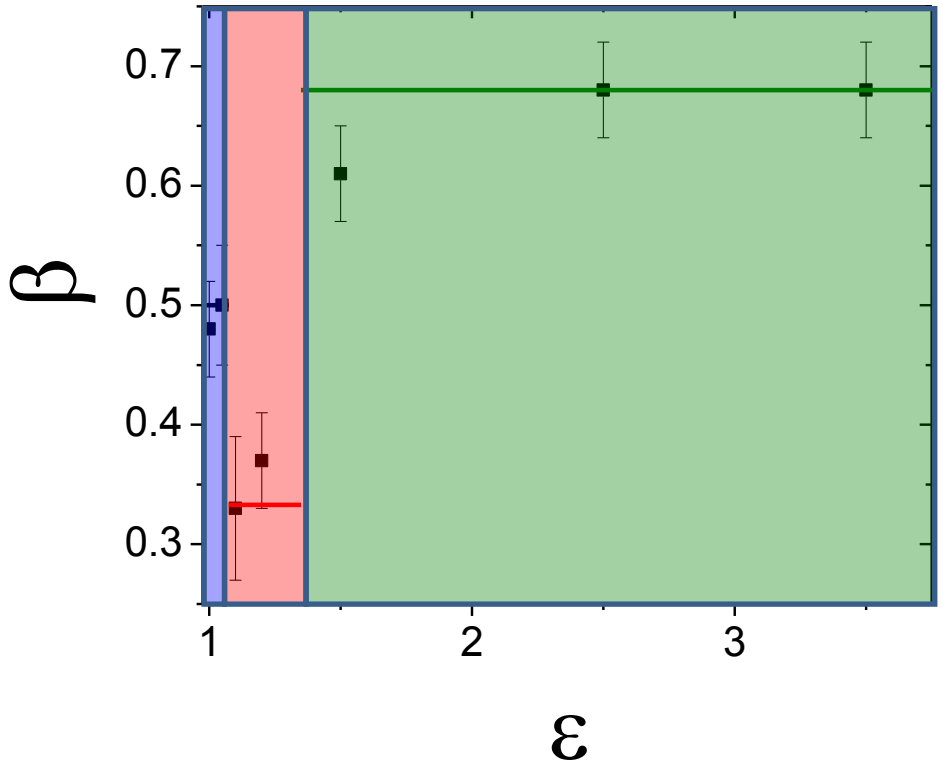
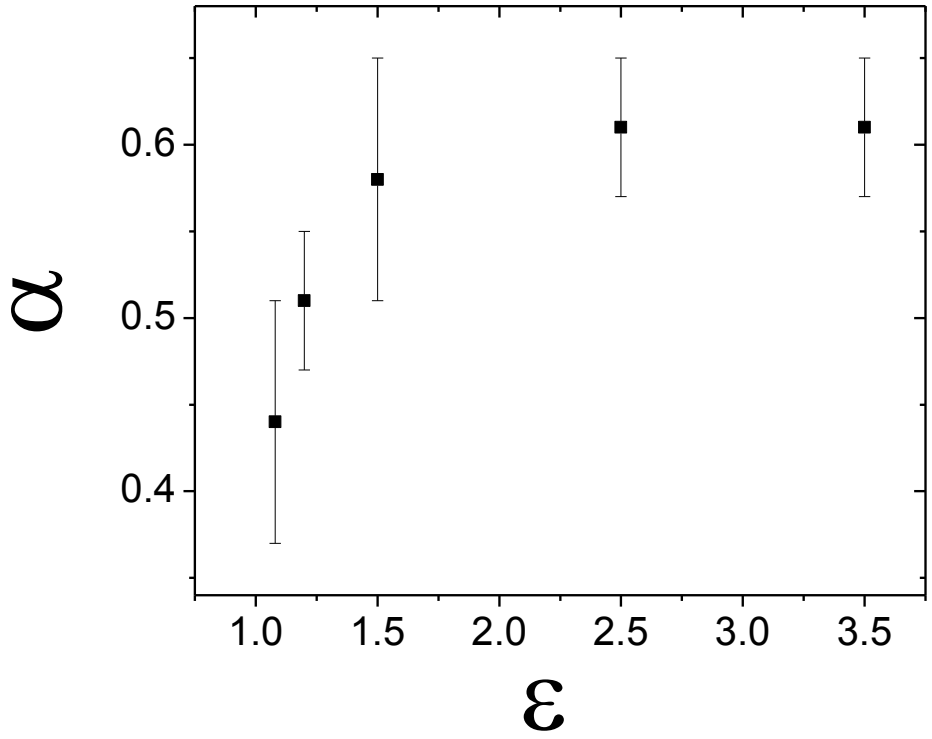
Must explain abrupt transition



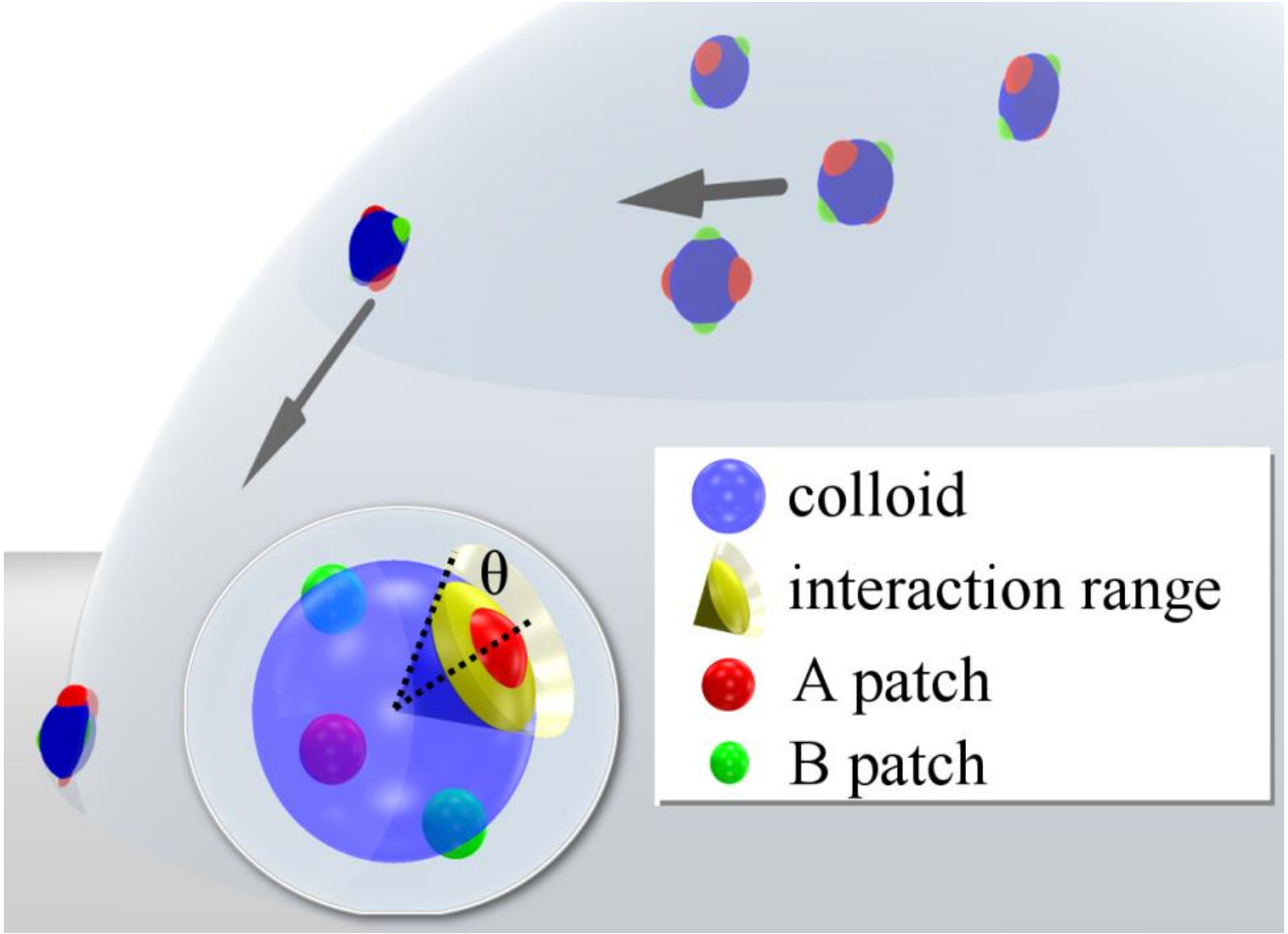
Must explain abrupt transition





Minimal simulation?

Simulation of patchy colloids



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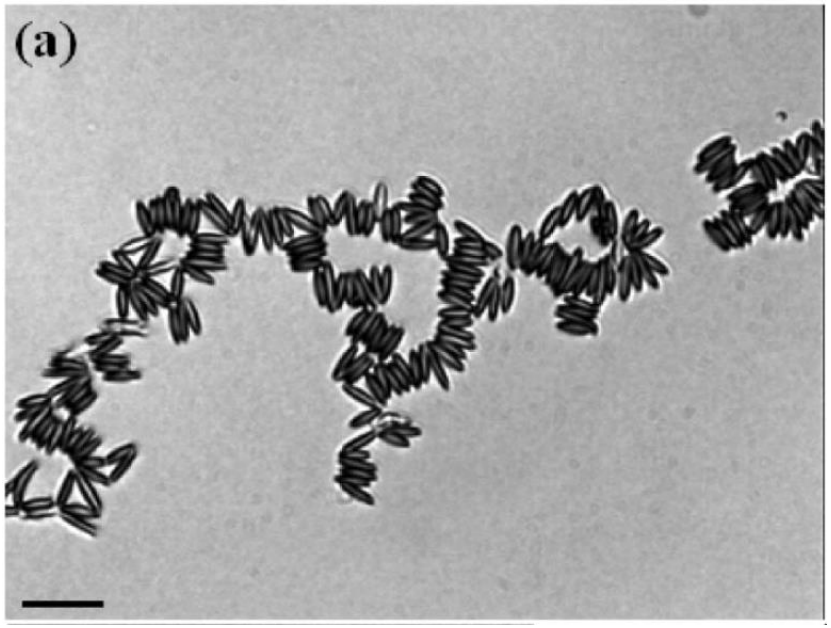
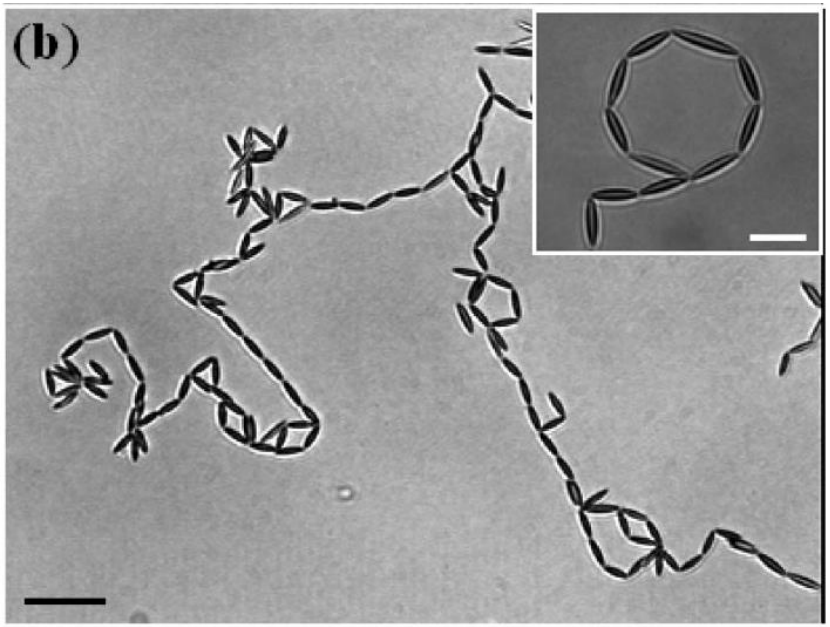
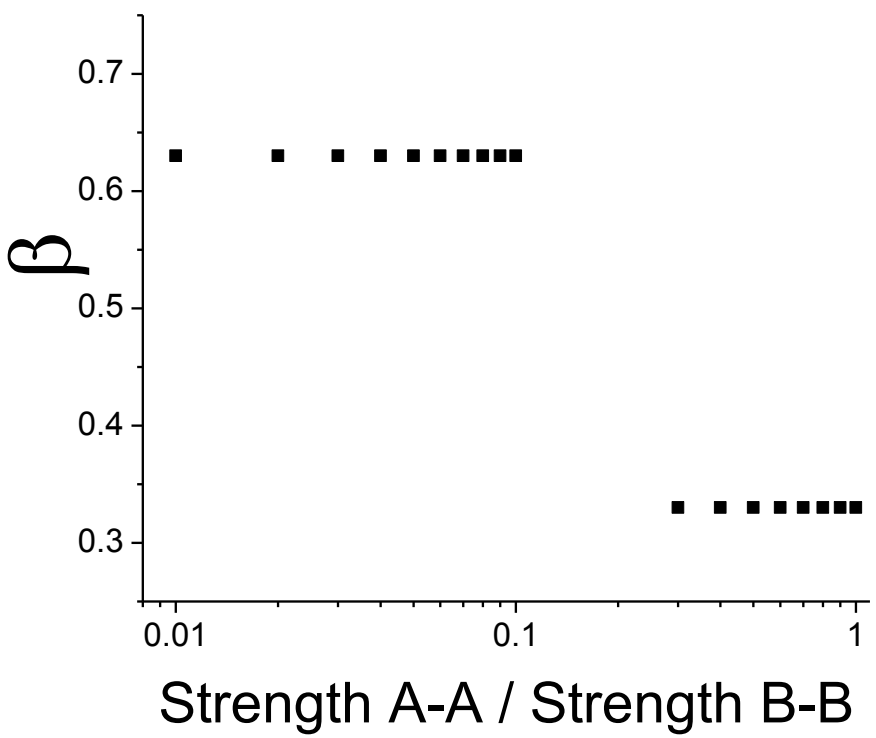
Dias, Araujo, Telo da Gama, arXiv:1407.2374

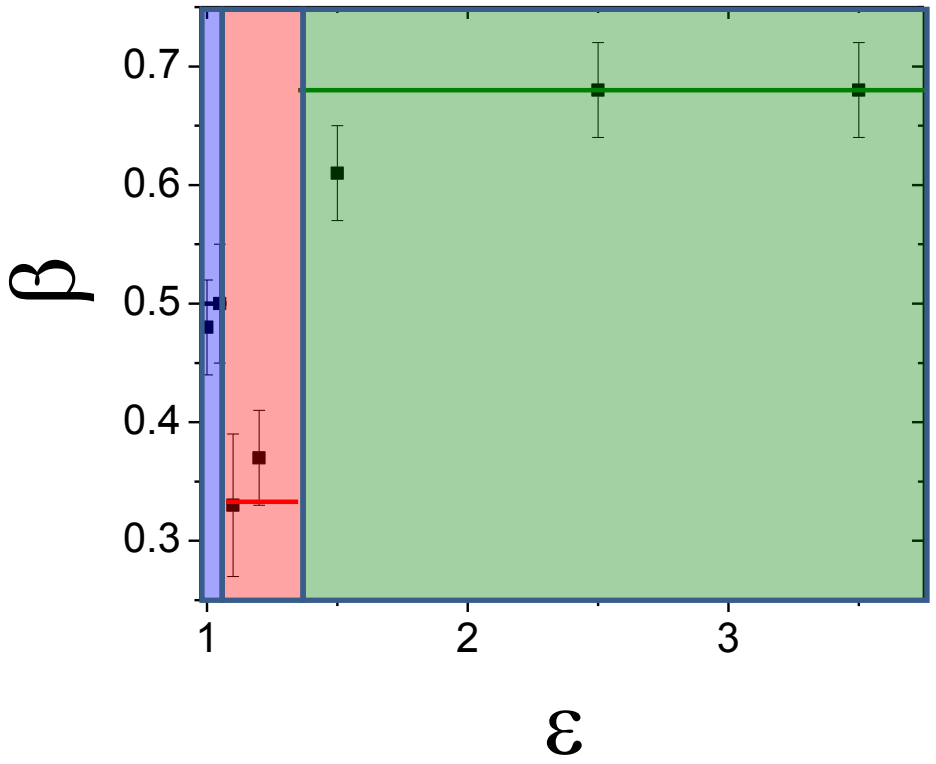
Highly anisotropic ellipsoids prefer tip-to-tip or side-to-side





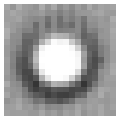
Abrupt transition occurs



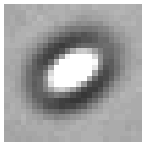


Summary

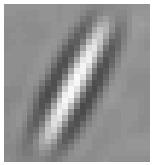
- Changing particle shape selects 3 distinct growth processes



Poisson Process



KPZ Process

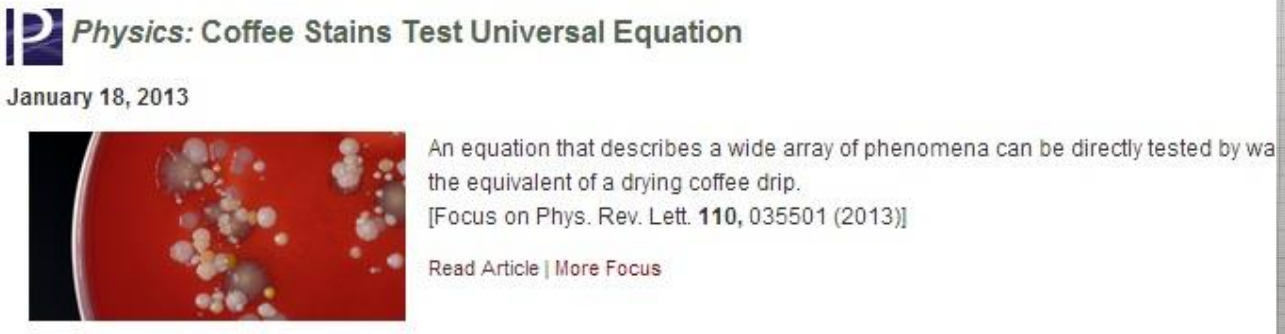


Colloidal Matthew Effect (other universal process?)

Kardar, Parisi, Zhang, PRL (1986); Family, Physica A (1990)

Acknowledgements

- Advisor: Arjun G. Yodh
- Collaborators: Alexei Borodin, Doug J. Durian, Tom Lubensky, Matthew A. Lohr, Tim Still



P. J. Yunker, T. Still, M.A. Lohr, A.G. Yodh, Nature (2011)
P. J. Yunker, M. Gratale, T. Still, M.A. Lohr, T.C. Lubensky, A.G. Yodh, PRL (2012)
P. J. Yunker, T. Still, M.A. Lohr, D.J. Durian, Alexei Borodin, A.G. Yodh, PRL (2013)
P. J. Yunker, D.J. Durian, A.G. Yodh, Physics Today (2013)

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