INSTITUTE FOR RESEARCH IN ELECTRONICS & APPLIED PHYSICS

3D Imaging of Segregation in Granular Shear Flows

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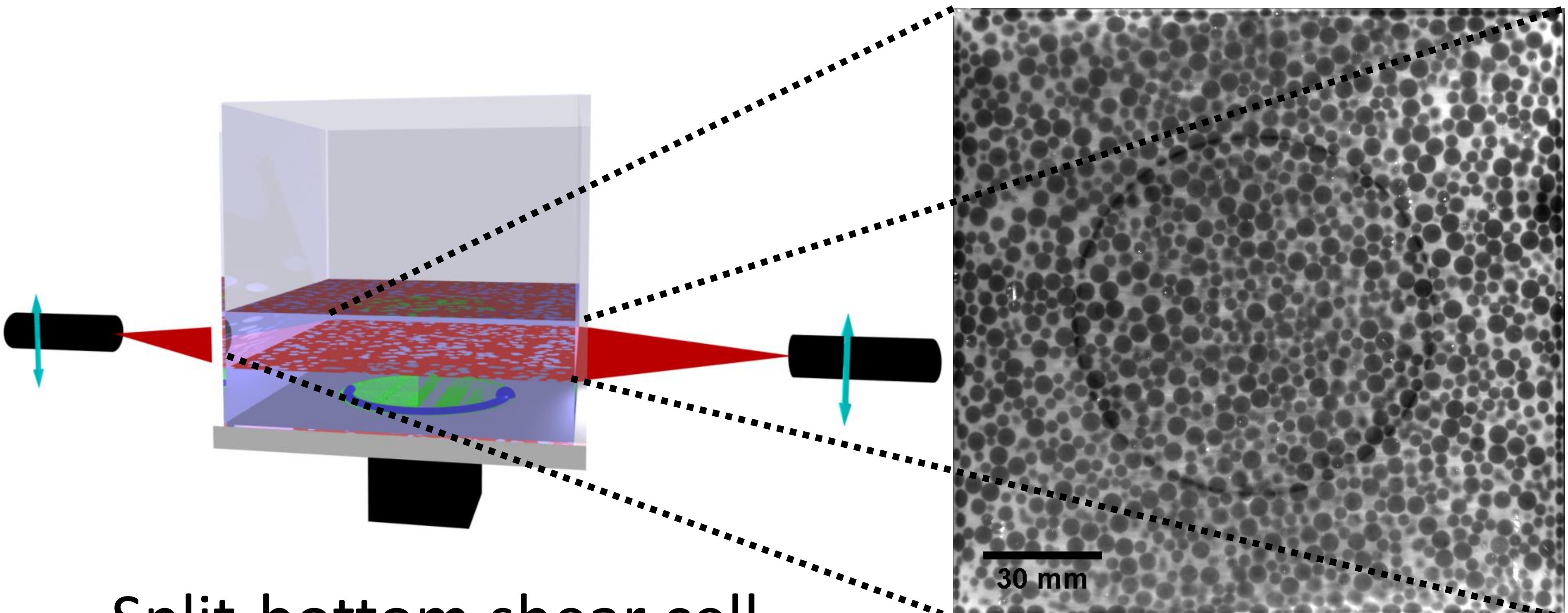
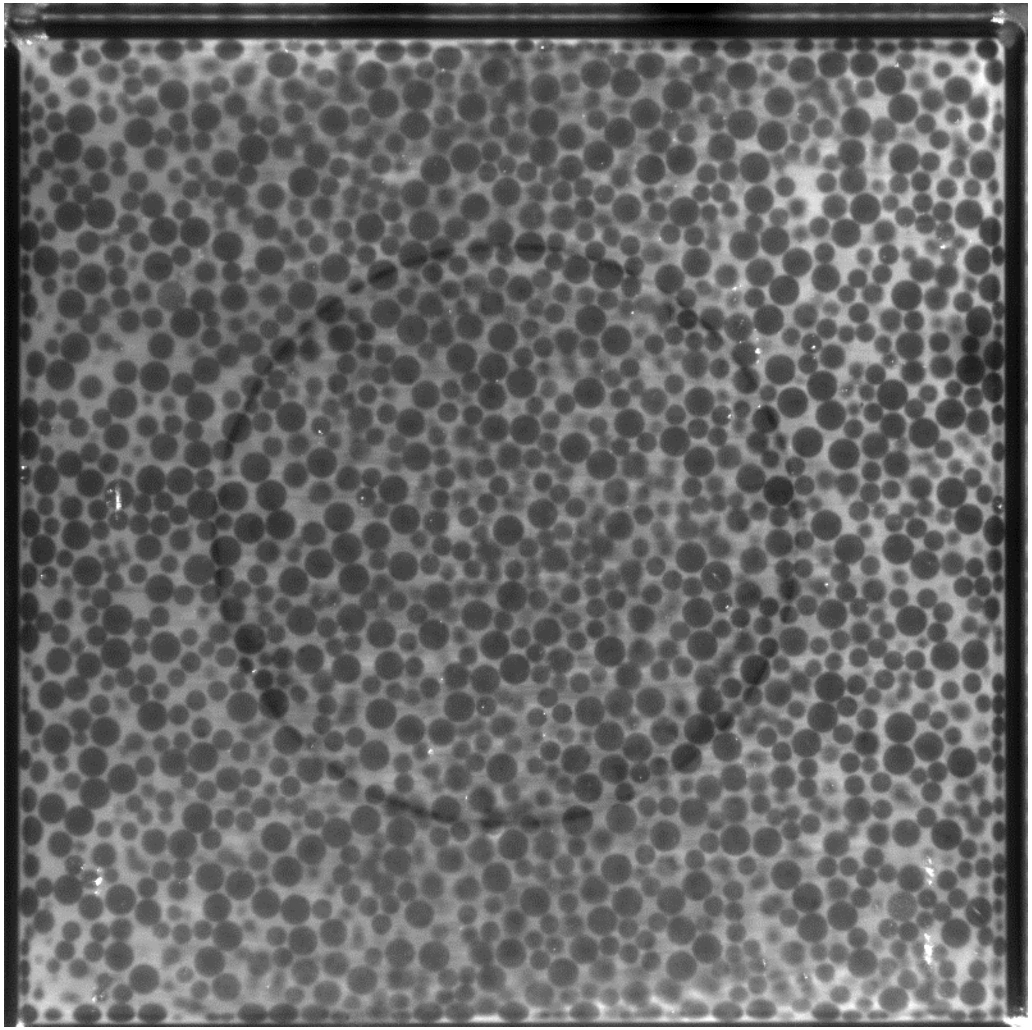
Refractive Index Matched Scanning (RIMS)

Invited Review: Dijksman, et al, *Rev. Sci. Instr.* 2012



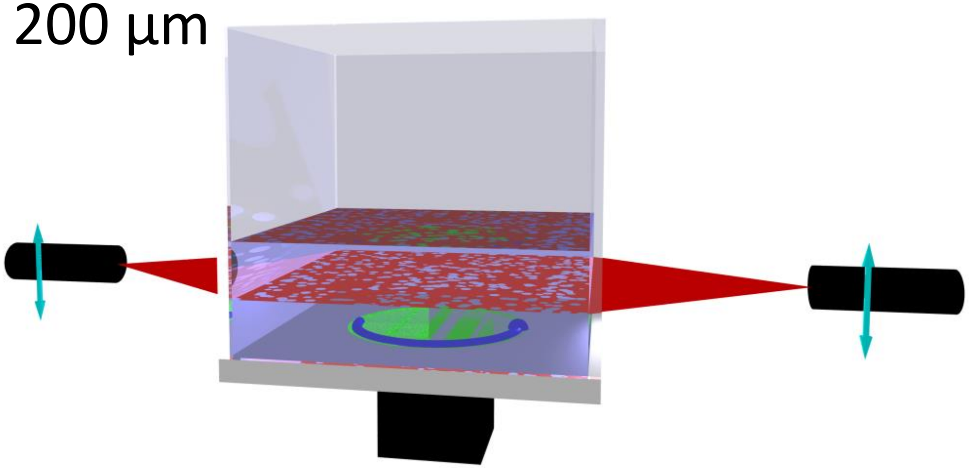
Split-bottom shear cell

Flythrough



Parameters:

- Quasi-static shear rate Ω = 0.001 rad/s (Dijksman, et al, *PRE* 2010)
- Shear is performed in 2° (0.035 radian) steps
- R_s = 45 mm, L = 150 mm
- 1 voxel ≈ 200 μm x 200 μm x 200 μm

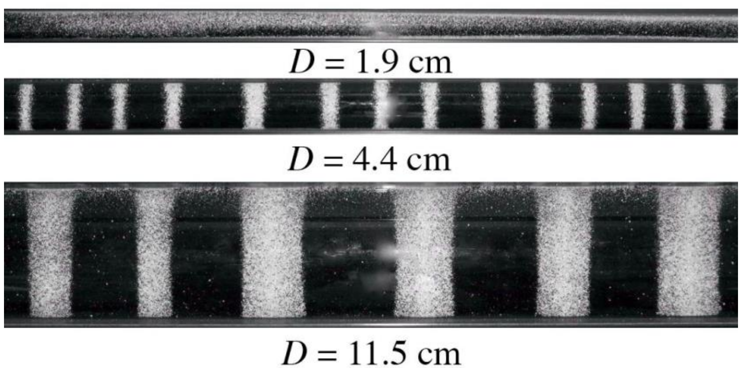


Procedure:

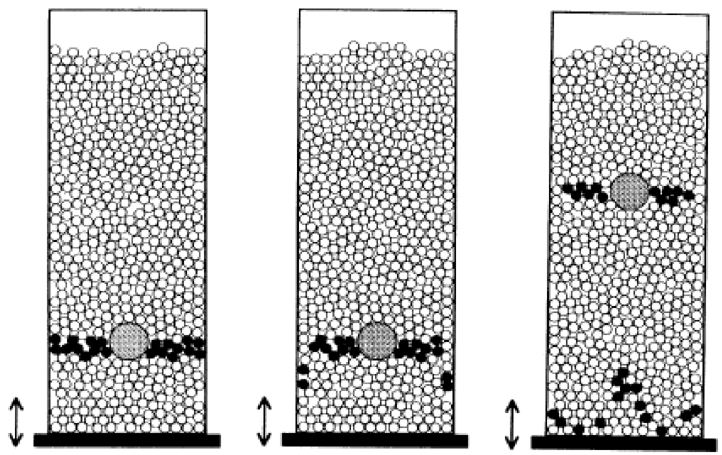
- Capture images after each shear increment
- Convolution kernel gives 3D particle center locations (Tsai and Gollub, *PRE* 2004)
- Particle center resolution of ~100 μm
- Lagrangian Particle Tracking (Ouellette, et al, *Exp. Fluids* 2006)

Segregation: definition and examples

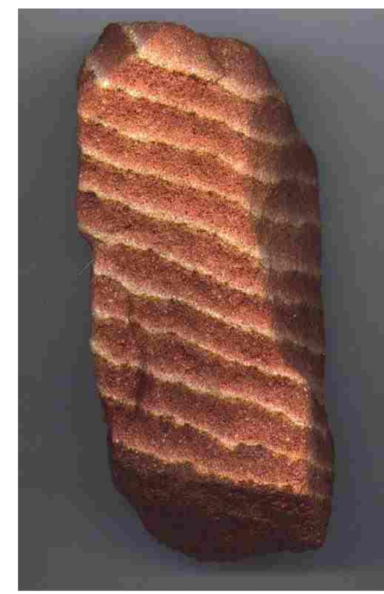
Segregation is the separation of granular mixtures by physical property (e.g., size, density) under a driving force



Charles, et al, *Gran. Matt.* 2006



Knight, et al, *PRL* 1993



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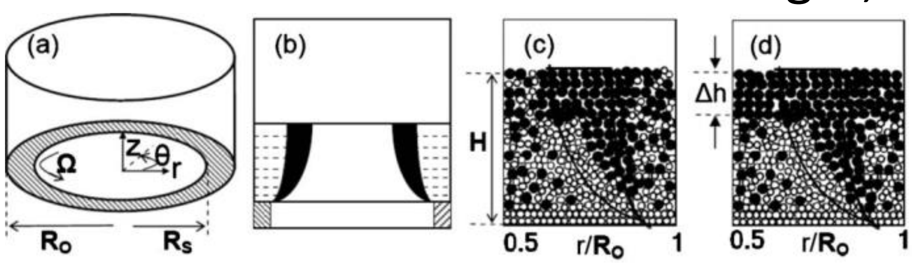


Fan & Hill, *PRE* 2010

What we don't (and would like to) know

Consistent, robust predictive model for shear-driven segregation of a dense 3D granular material

What do we need?

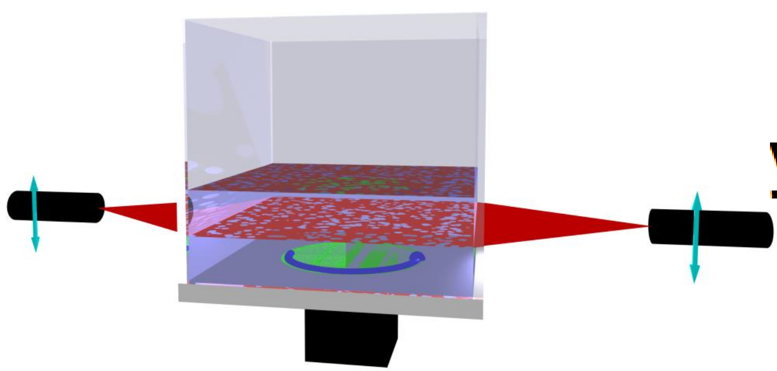
- Account for seemingly inconsistent experimental results
- Absolute particle size effects – segregation length scale?
- Particle-scale dynamics?
- Internal dynamics/flows?

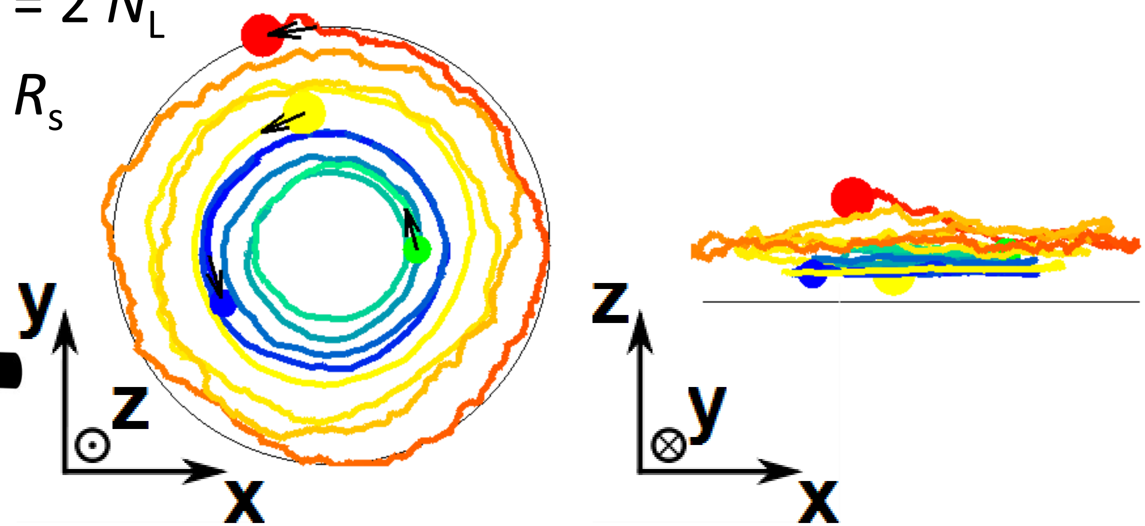
Bidisperse setup

- PMMA (acrylic) spheres: Refractive index $n = 1.49$

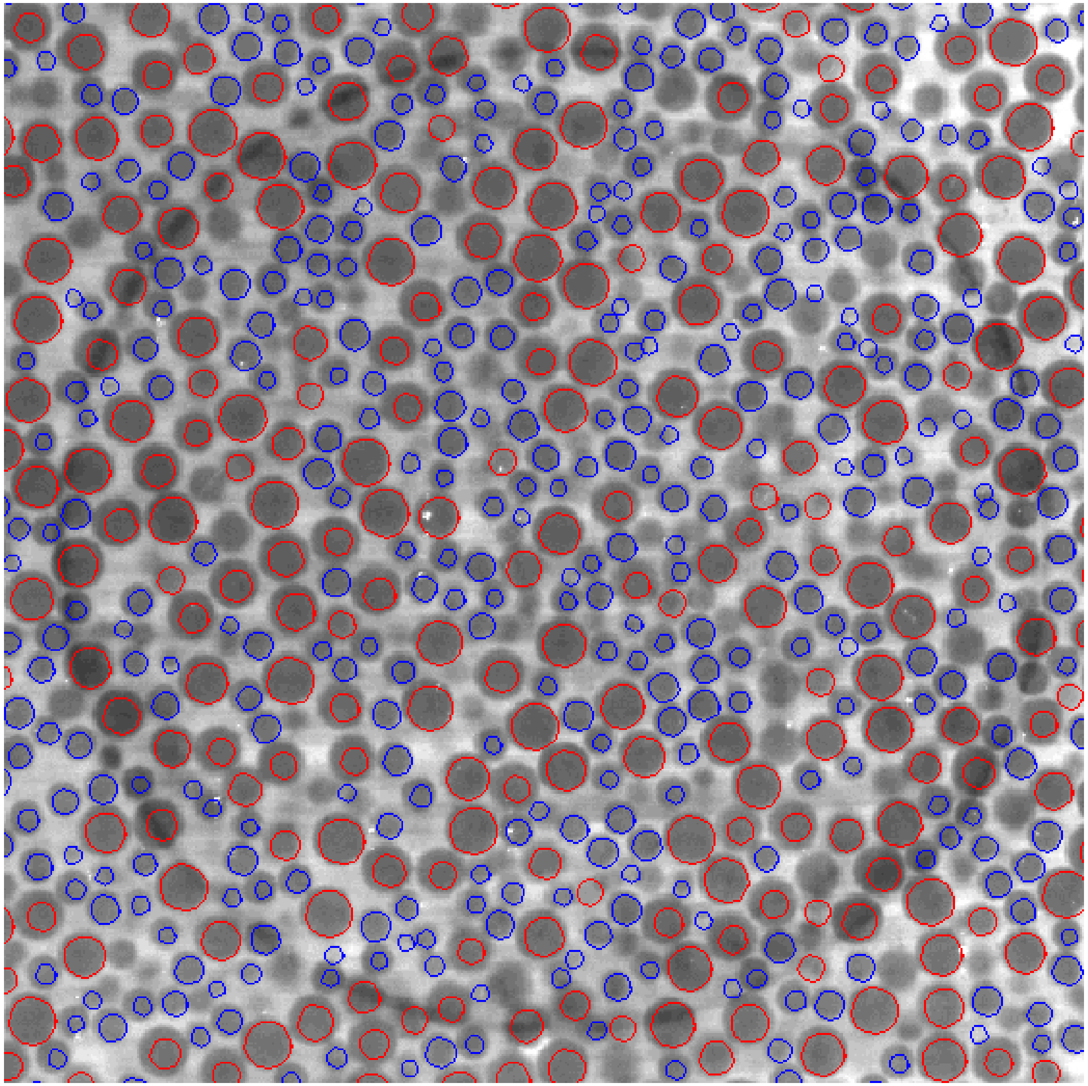
  D_S = 1/8 inch (3.2 mm) and D_L = 3/16 inch (4.8 mm)

  → $3\,D_S = 2\,D_L$
- Index-matched fluid: Triton X-100 with Nile Blue 690 Perchlorate
- Twin laser sheets with λ = 635 nm
- $27\,M_S = 16\,M_L \leftrightarrow N_S = 2\,N_L$
- H = 46 mm ≈ 10 D_L ≈ R_s



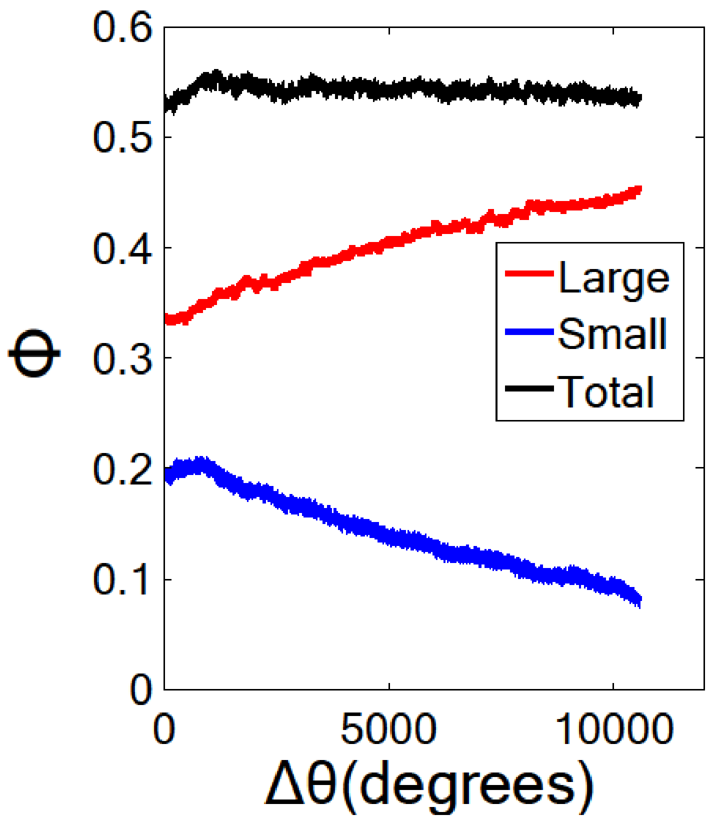


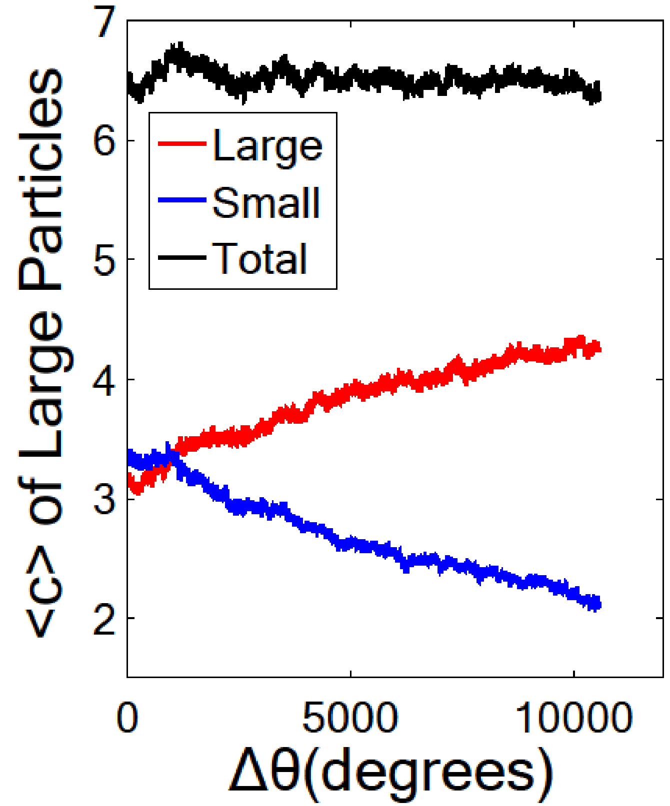
Steady shear at z = 3.8 cm (8 D_L)



Segregation under steady shear

Global and local phenomenon





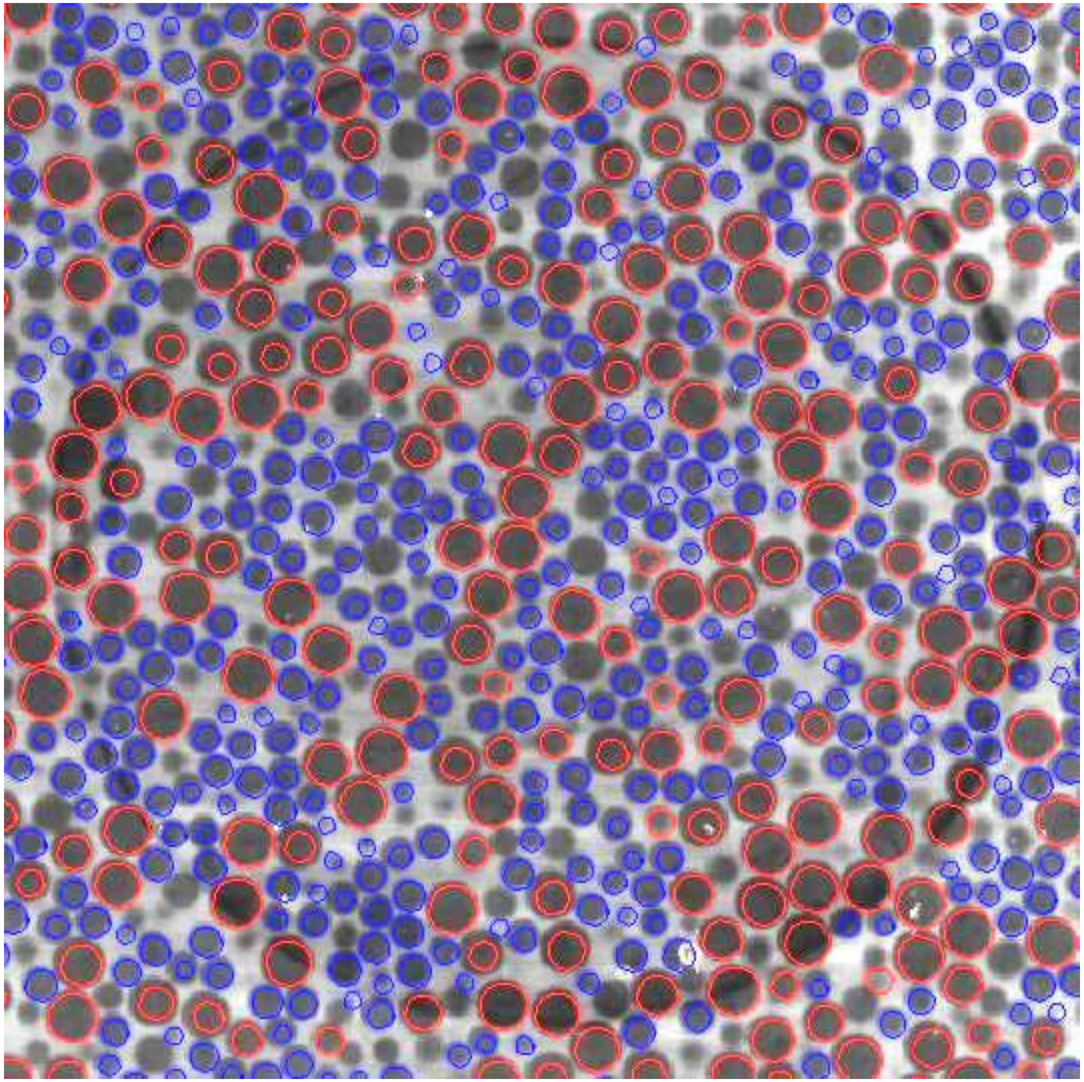
Volume fraction -- **GLOBAL**

Average coordination number – **LOCAL**

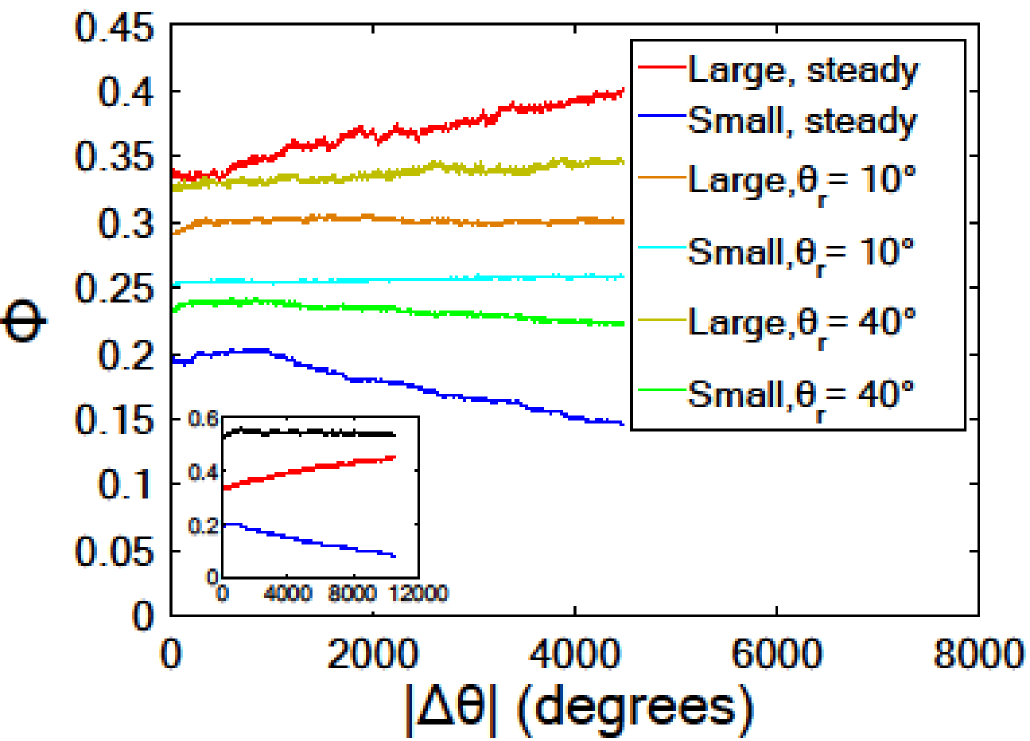
$$\phi = \frac{V_{parts}}{V_{space}}$$

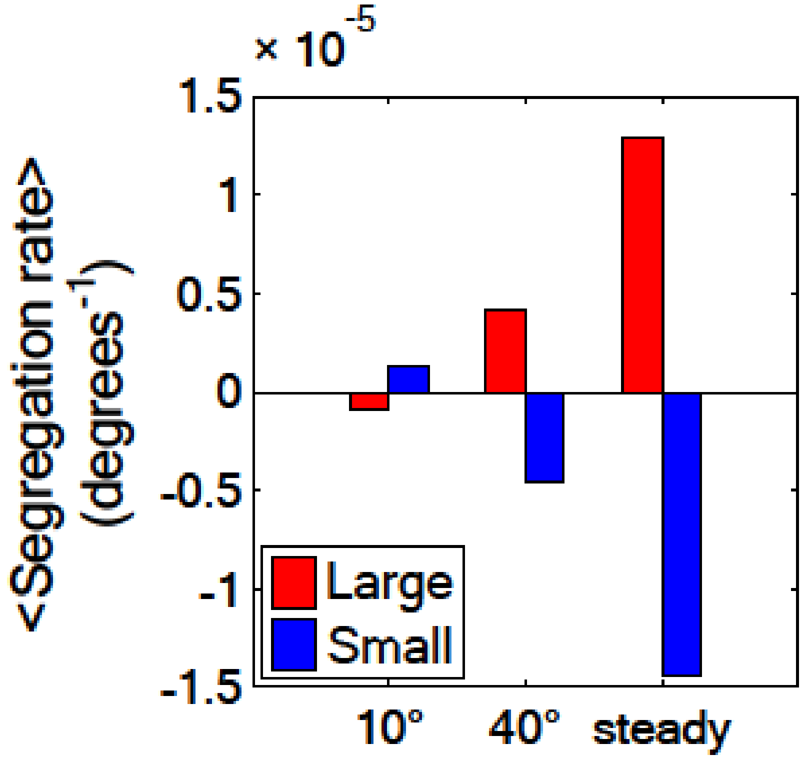
$\langle c \rangle =$ Average number of large/small contacts

10° cyclic shear at z = 3.8 cm (8 D_L)



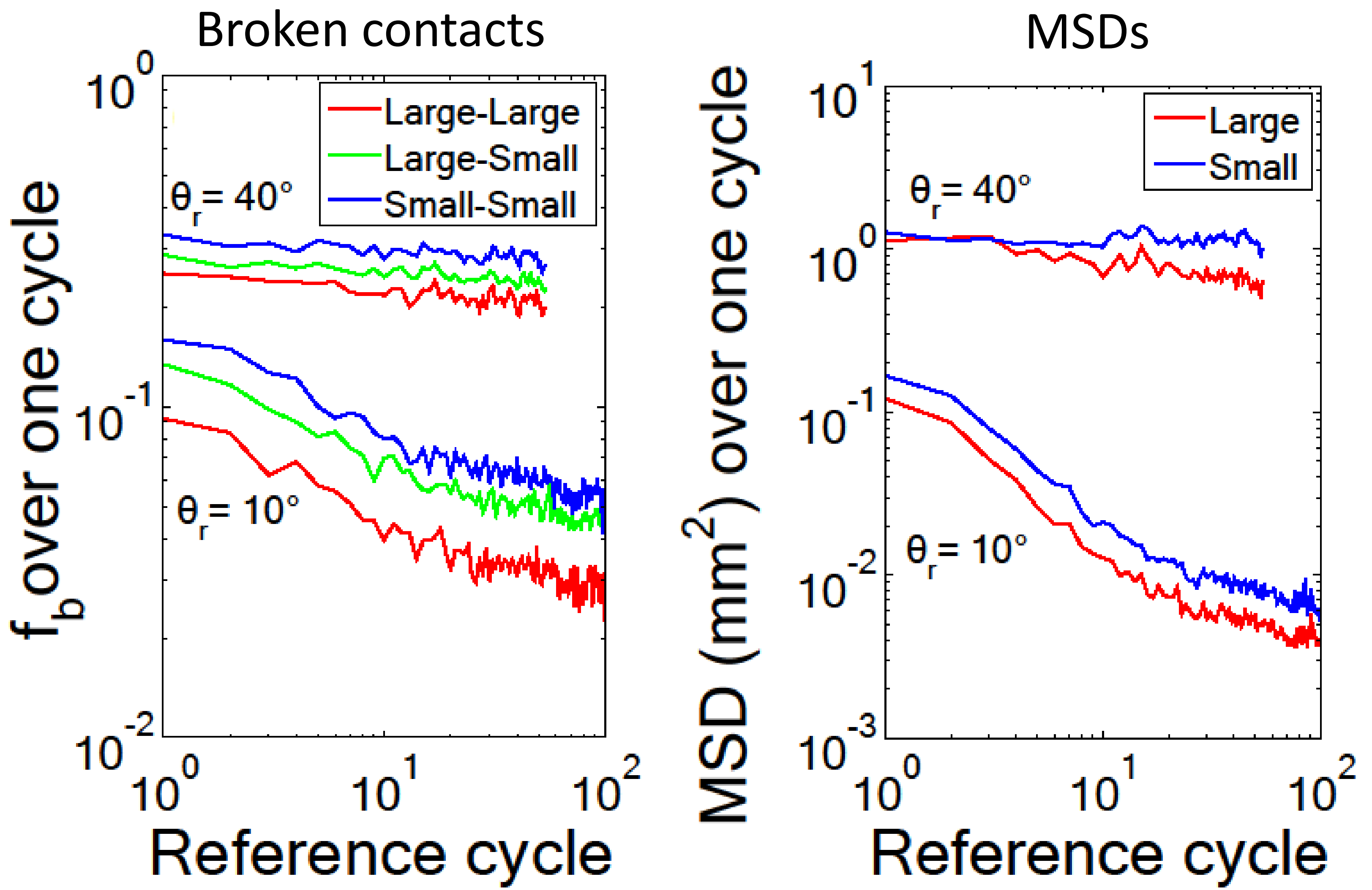
Segregation under cyclic shear?





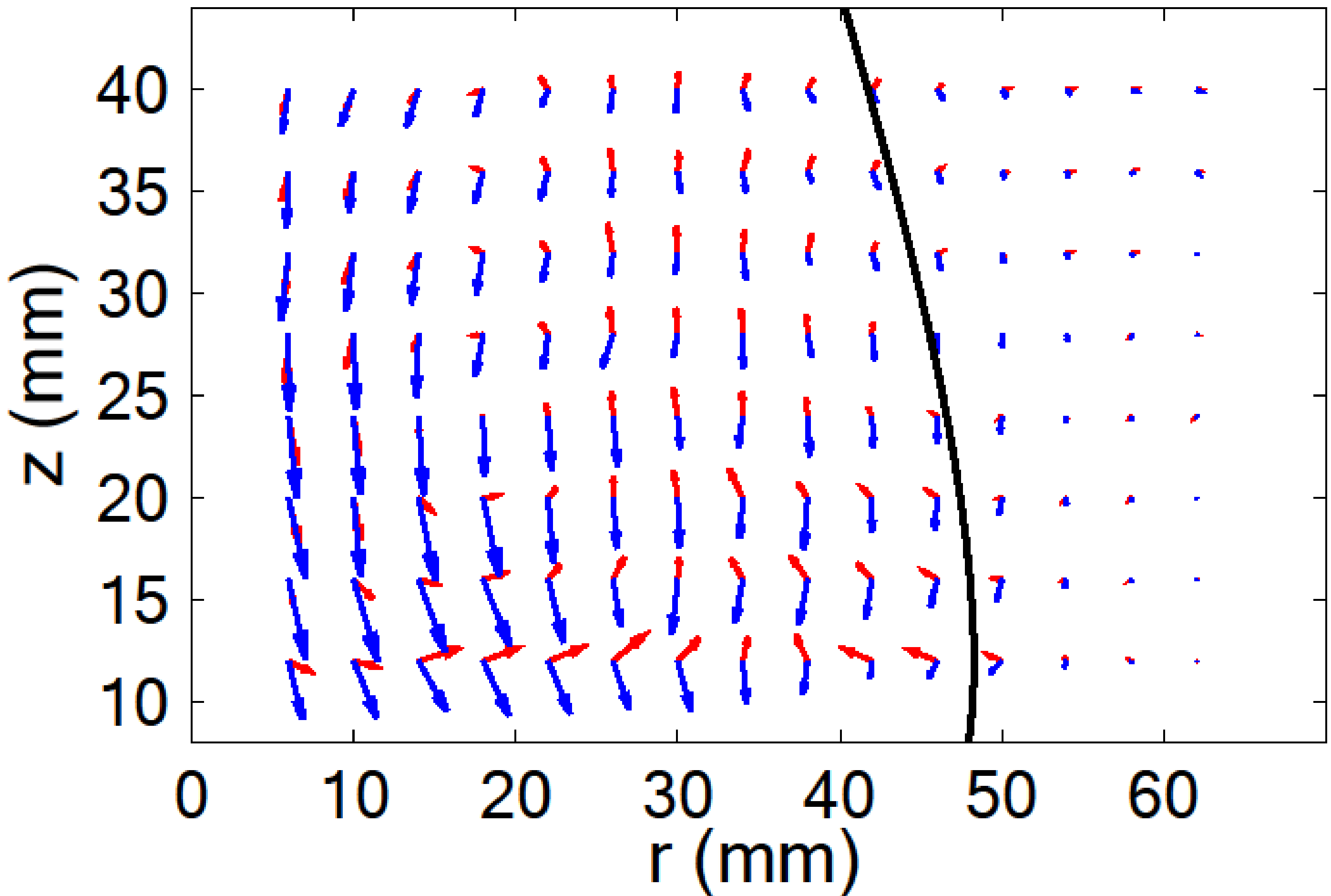
There appears to be a segregation transition between 10° and 40° cyclic shear

Microscale Reversibility



Similar trends for D_L monodisperse system (Slotterback, et al, *PRE* 2012)

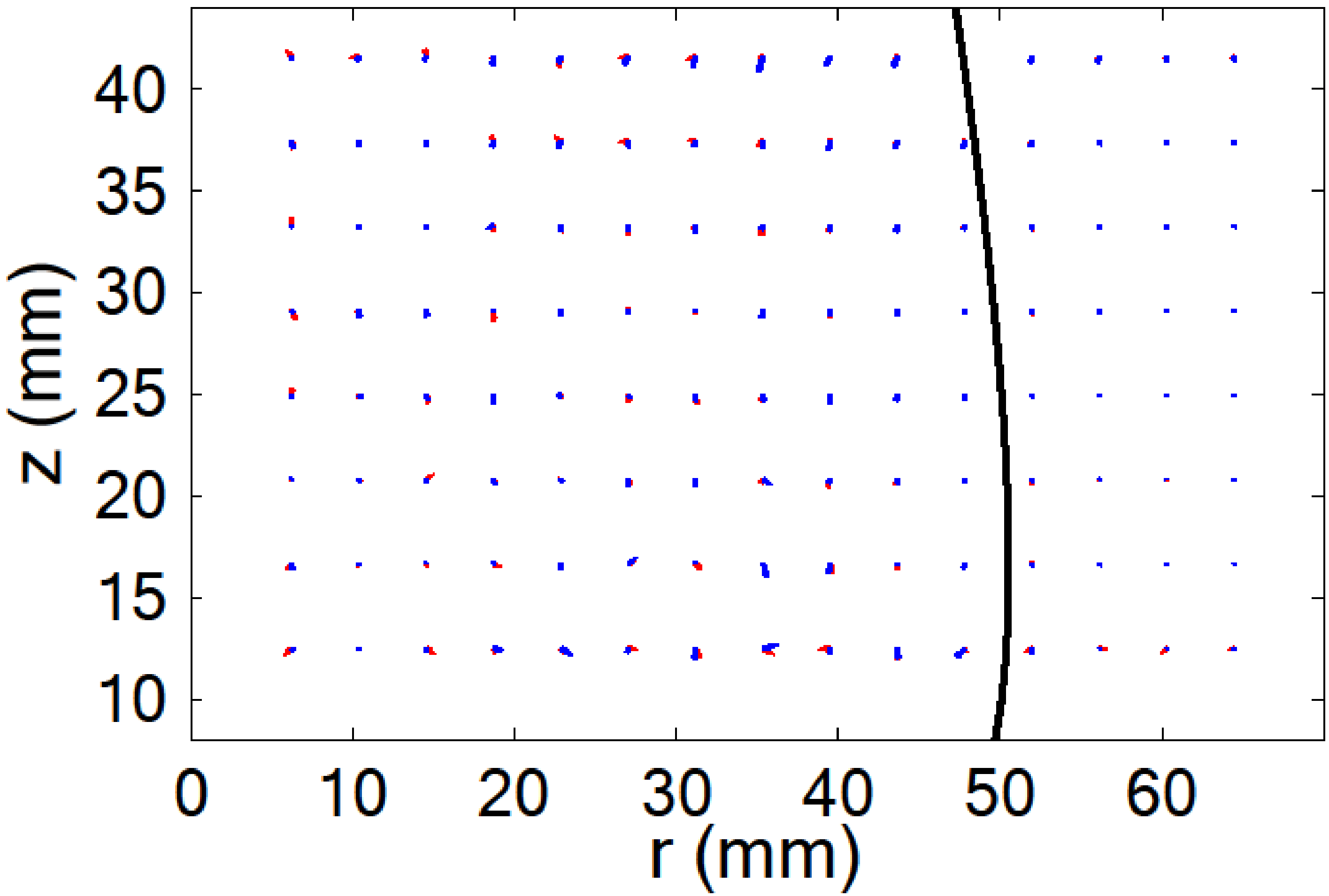
Secondary flows – steady shear



Convection of large grains

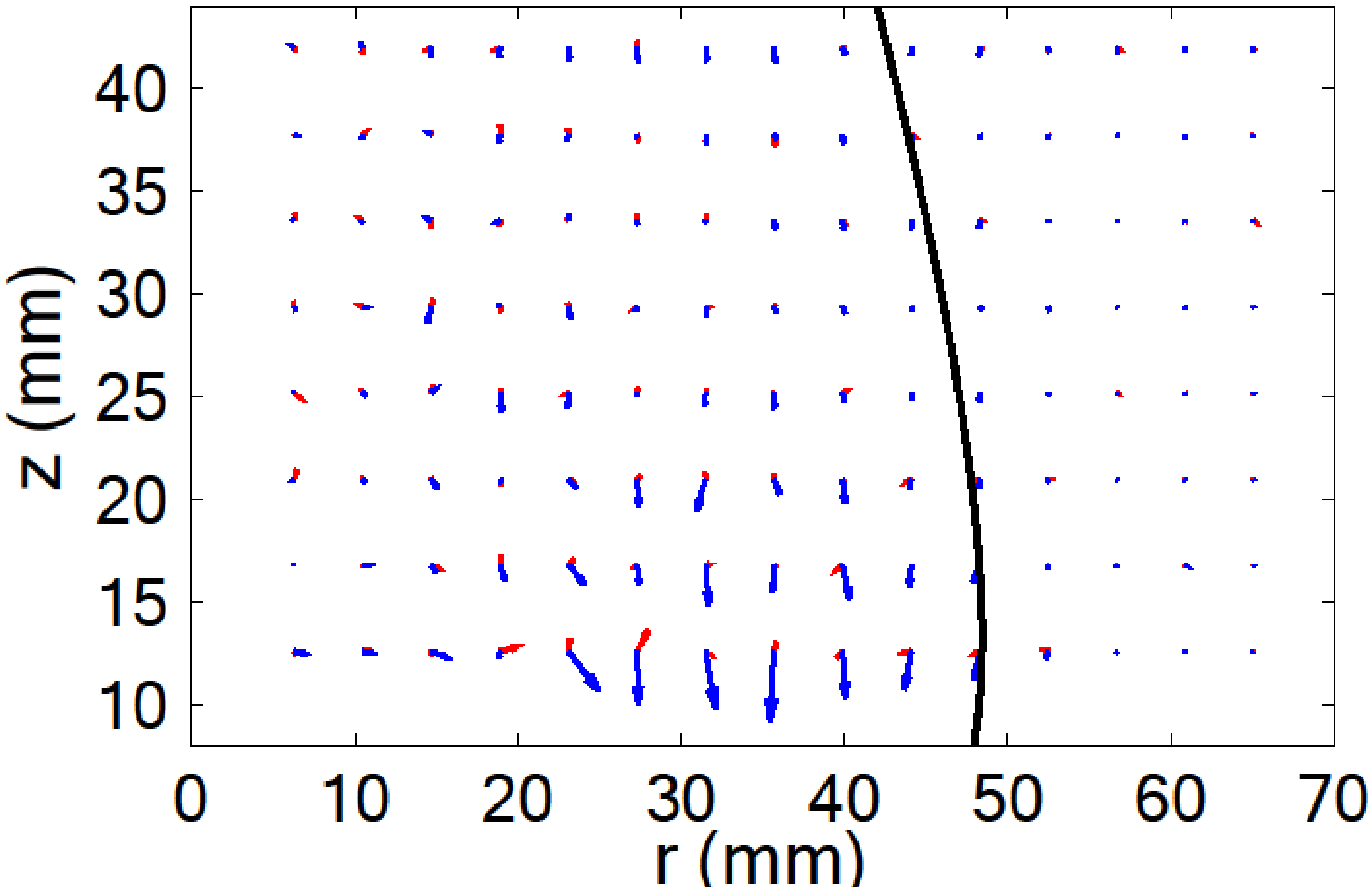
Net downward flux of small grains

Secondary flows – θ_r = 10°



Very diminished magnitude of flows

Secondary flows – $\theta_r = 40°$



Convection starts to develop

Downward drift of small grains near disk

Summary

- Critical strain amplitude for segregation under cyclic shear
  - Continuum gradient-based models are not enough!
- Bulk segregation concurrent with microscale irreversibility
- Amplitude-dependent secondary flows:
  - Convection of large grains
  - Downward drift of small grains

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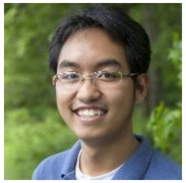
Steve Slotterback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