EXPERIMENTS OF PARTICLE COLLISIONS AND RHEOLOGY

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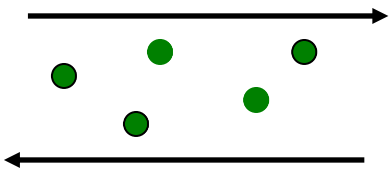
Rheology: suspension to a granular flow



SHEAR RATE, γ

Shear and Normal Stresses,
T and *P*

Granular Flows

Collisional interactions

$$T\ ,\ P \propto \rho_p\, d^2\, \gamma^2$$

ρ_p particle density

d particle diameter

Dilute Suspension

Viscous interactions

$$T = \mu' \gamma\ ;\ P \propto \gamma$$

μ' - corrected viscosity,

$\mu' = \mu f(\phi)$ with ϕ as the solid fraction

We are interested in this "idealized" transition.

Need to understand collisions.

Single particle collisions in a liquid

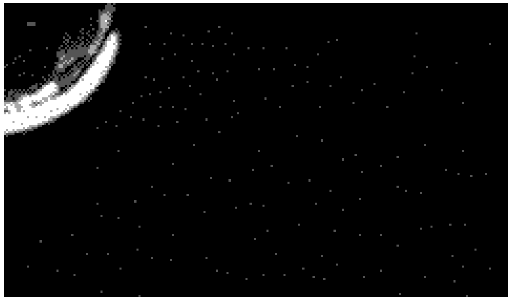
- Coefficient of restitution from rebound (U_r) to impact velocities (U_i)

  $e=-U_r/U_i$

- Controlled collision with an immersed pendulum into a hard surface
- Effect of Stokes number

  $St = \rho_p U_i d_p / 9\mu$

Joseph, Zenit, Hunt & Rosenwinkle 2001; see also, Davis, et al 1986, 2002; Gondret, et al 1999, 2002

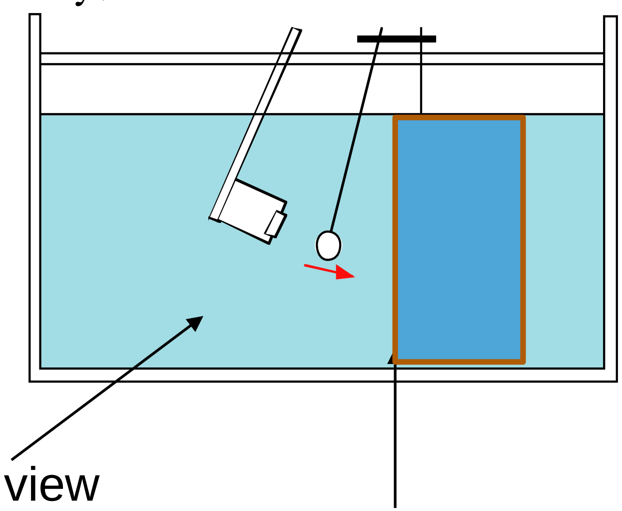


12 mm Delrin particle impacting a zeodur (hard) wall in water at St≈400;

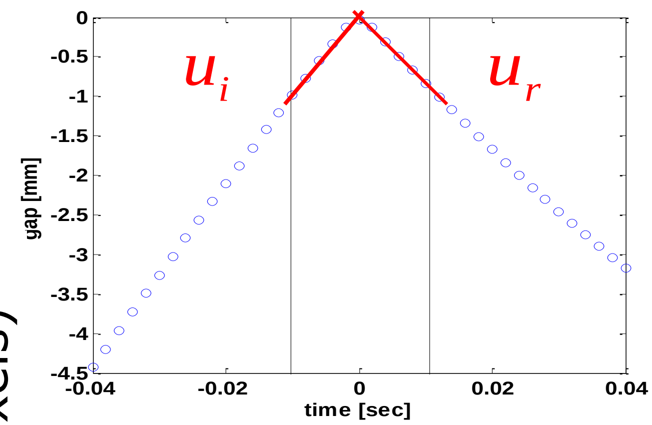
$e=-U_r/U_i=0.80$

Particle-wall and particle-particle

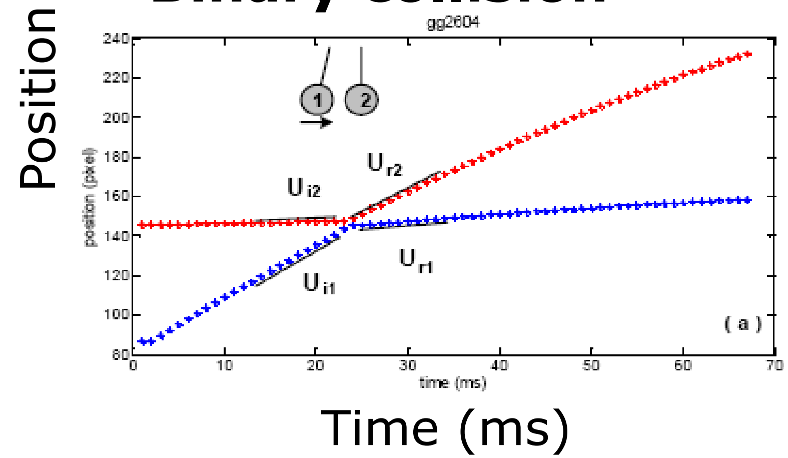
- Particle-wall: zeodur (hard); glass, steel, delrin, nylon particles
- Particle-particle collisions; mobility of target particle
- Particles of same and different density; same size



Particle-wall



Binary collision



Particle-wall coefficient of restitution (*e*)

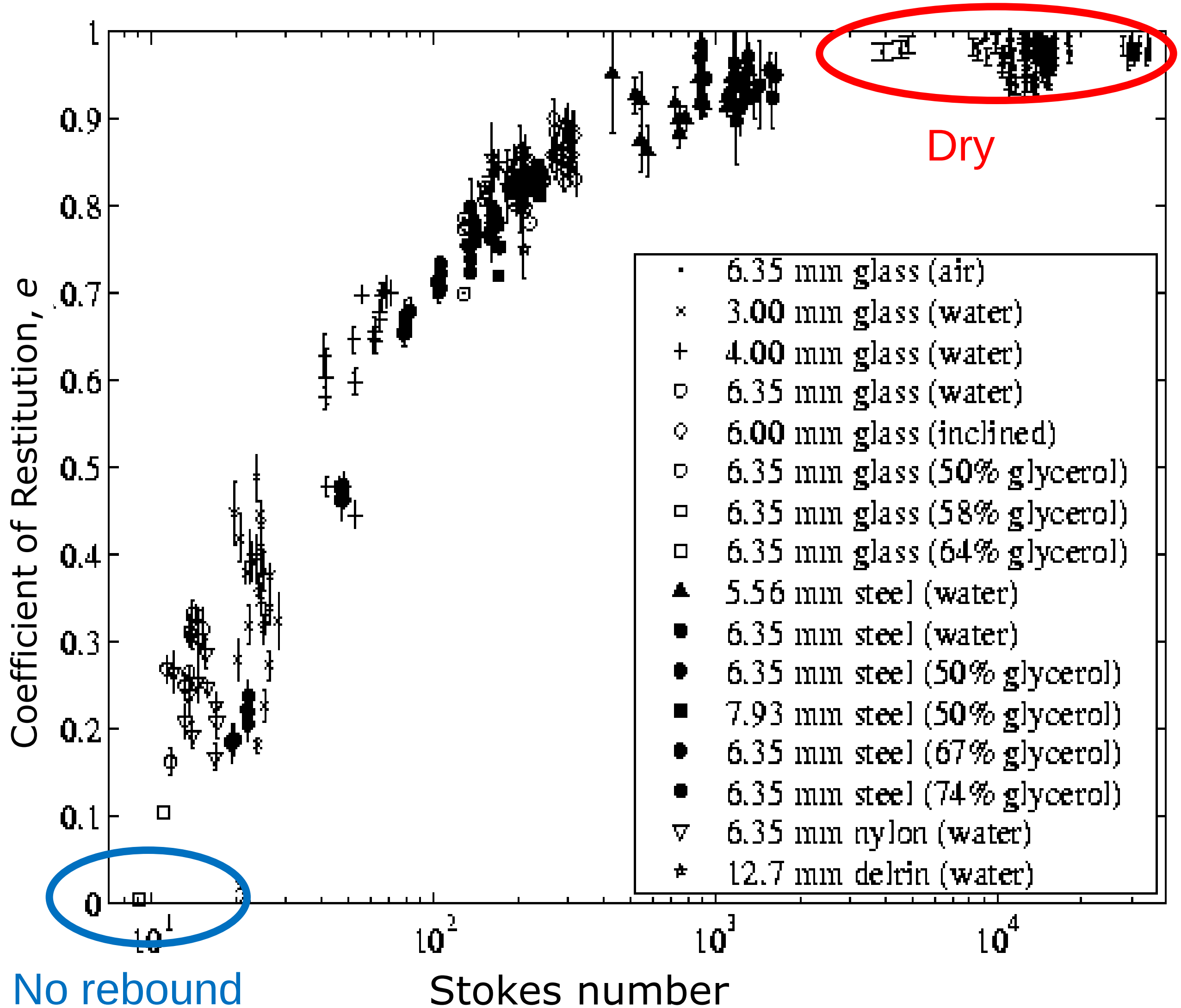
Hard target surface.

Stokes number,

$St = \rho_p d U_i / 9\mu$

No rebound for $St \leq 10$

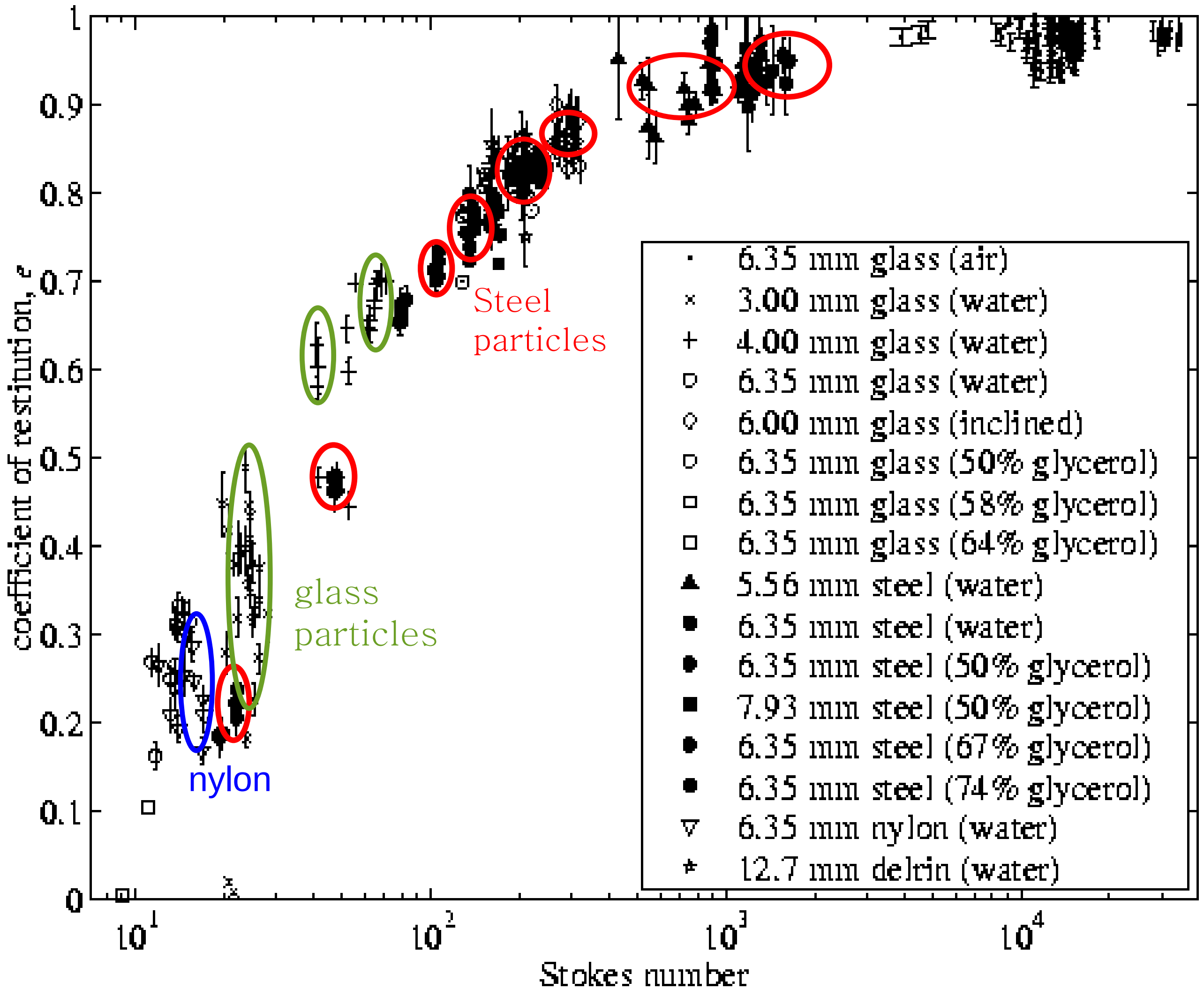
Dry-like behavior for $St \geq 2000$



Joseph, et al, ***JFM***, 2001

Coefficient of restitution – surface roughness

In some cases, variation in e that was as large as a factor of 2.

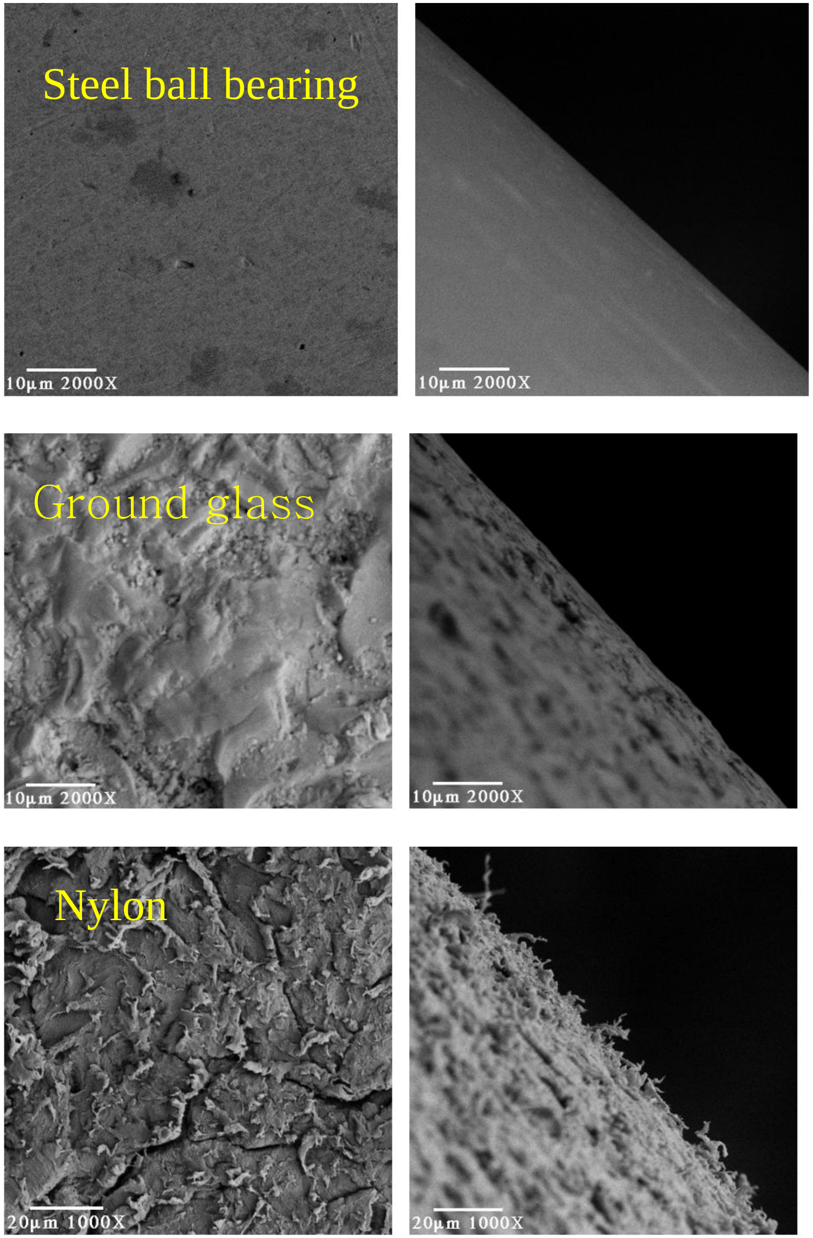


Surface conditions

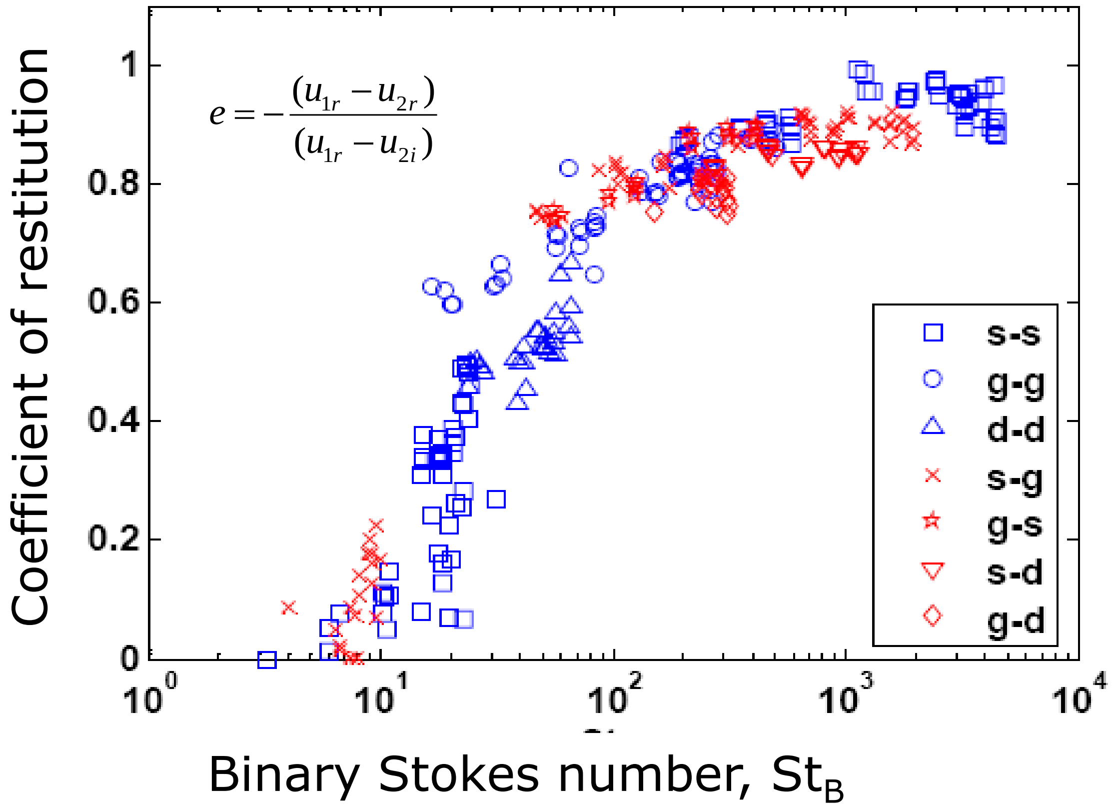
Measured surface roughness (σ_s) and correlation distance between asperities (λ_s) ; minimum distance (h_m) and Hertzian contact area (A_h) for St ≤ 80. Minimum distance based on elastohydrodynamic theory of Davis, Serayssol & Hinch 1986.

$$h_m \sim (\mu U_{io} a^{3/2}/E^*)^{2/5}$$

	σ_s / h_m	A_h / λ_s^2
Nylon	73	2
Glass	5.4	7.3
Steel	0.5	3



Particle-particle restitution



Despite particle mobility, particle-particle collisions follow trends for particle-wall collisions

s=steel

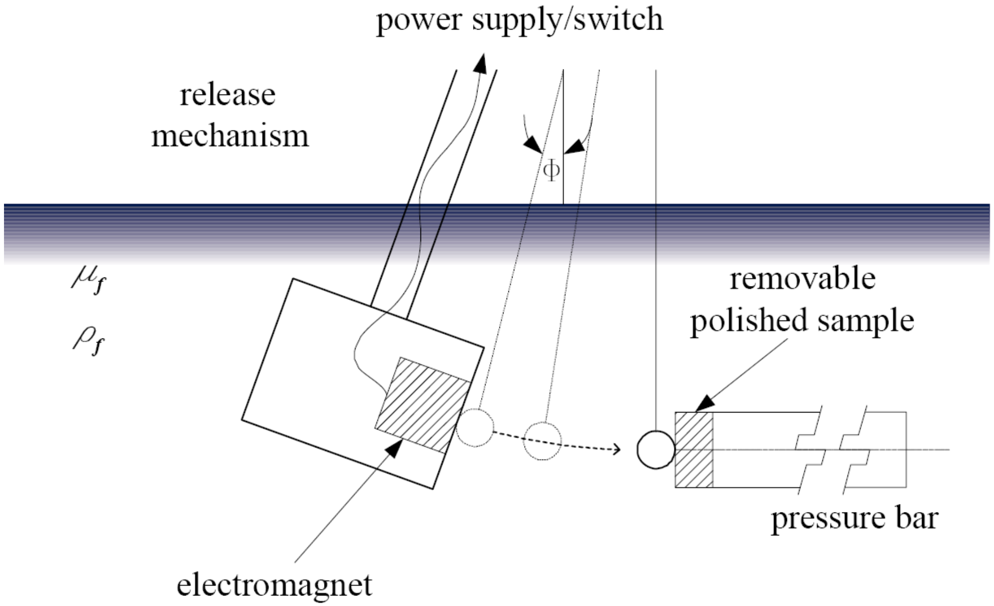
g=glass

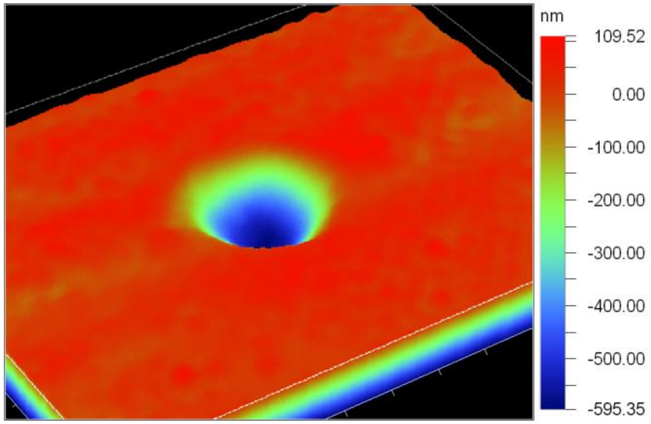
d=delrin

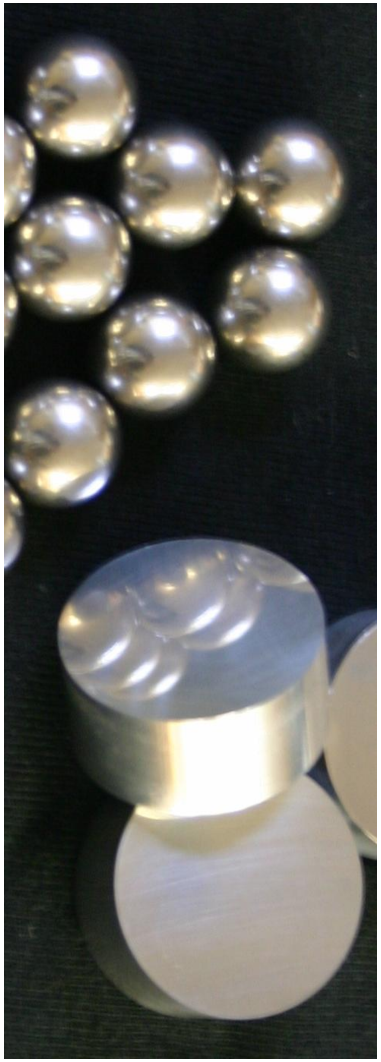
Yang & Hunt, 2006

Surface deformation due to impact

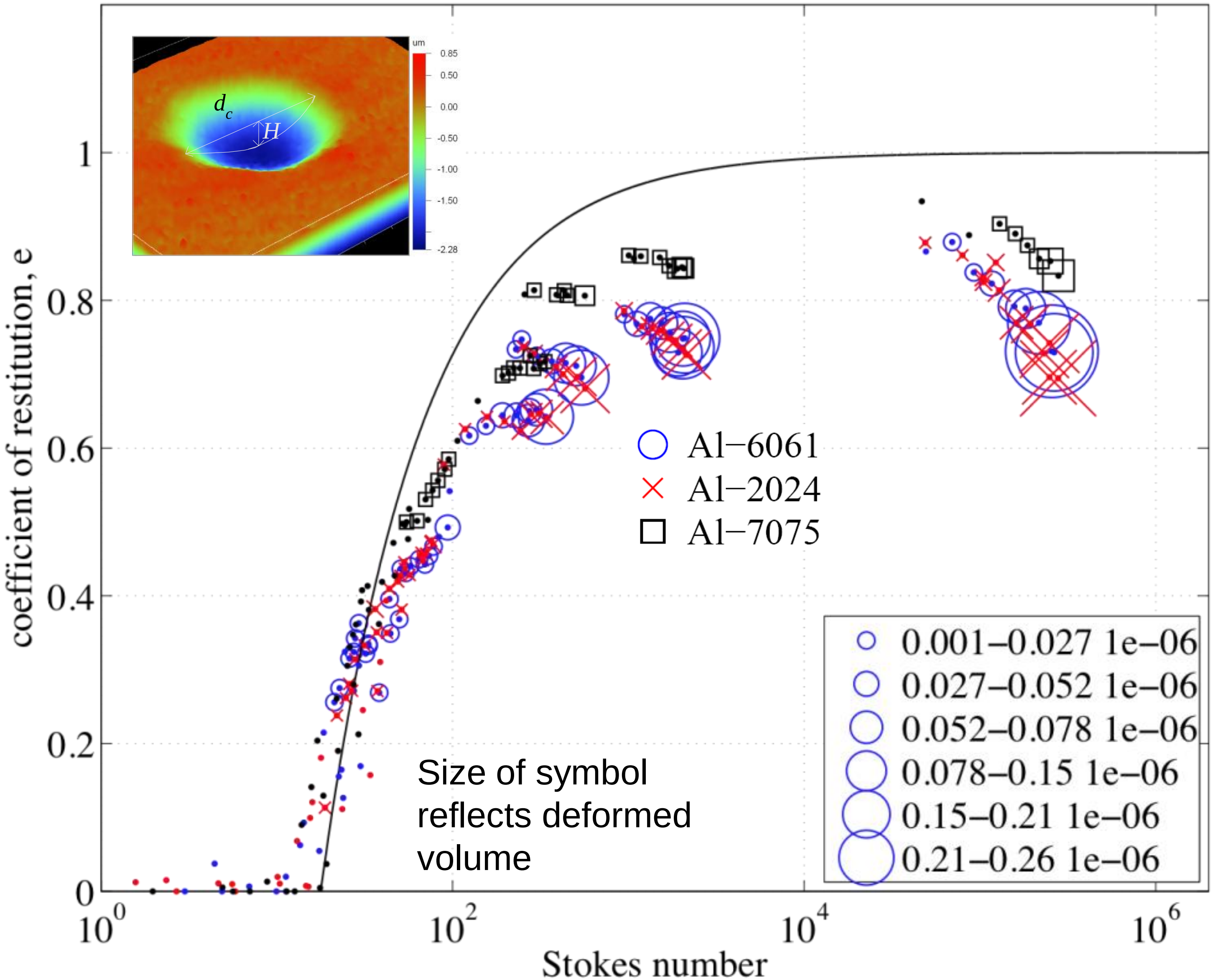
- Ductile aluminum surfaces
- Measure coefficient of restitution and crater size with optical profilometer







Surface deformation due to impact



Ruiz & Hunt, 2014

Prior Work: Rheology

- Bagnold (1954)

Neutrally buoyant wax spheres; 1 mm dia. Outer rotating cylinder. Solid fraction from 0.1 to 0.64.

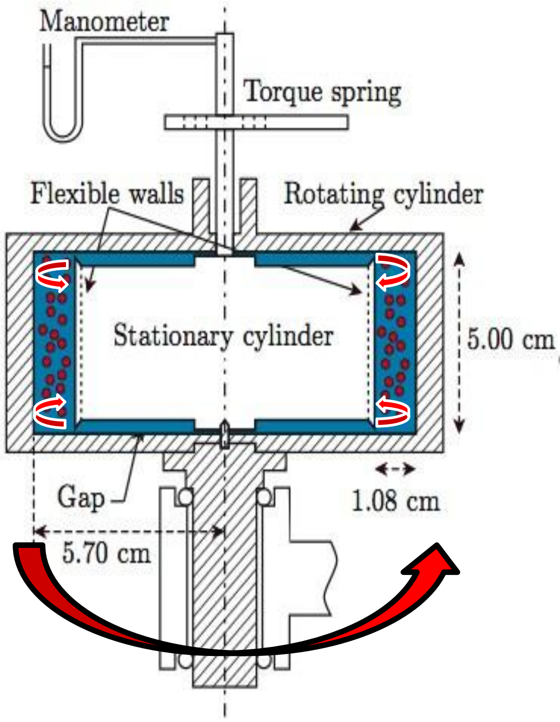
Secondary flows within annulus (Hunt, et al 2002).

Gap Reynolds number $Re_b = \rho r_o \omega b/\mu$;

Re_b from 8,800 to 33,000.

For $b/r_o = 0.19$, critical Reynolds number of 18,000.

Only "macroviscous" torque measurements were not affected by second flows.



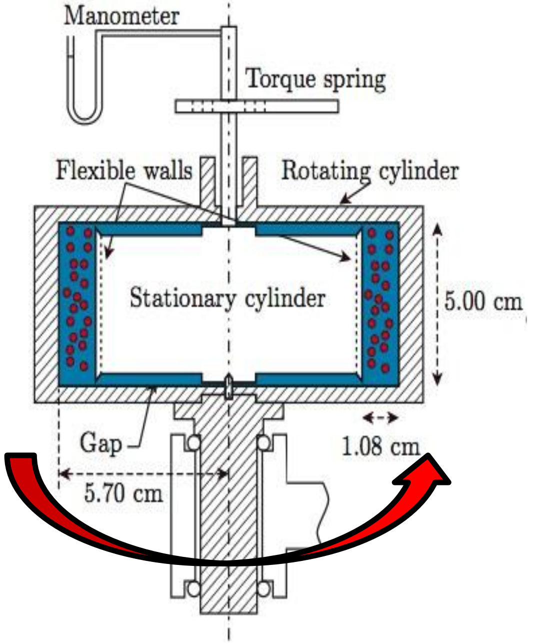
Gap:
$b = r_o - r_i = 1.08$ cm

Height:
$h = 5.0$ cm

Prior work

- Bagnold (1954)

  Neutrally buoyant wax spheres; 1 mm dia. Outer rotating cylinder. Solid fraction from 0.1 to 0.64. Secondary flows at higher shear rates.

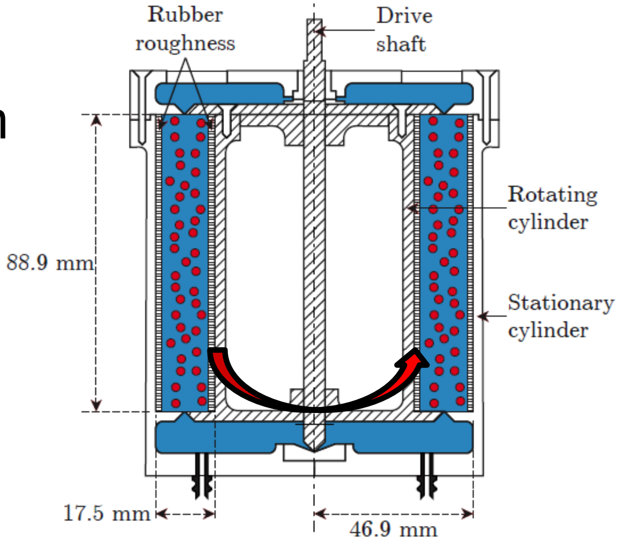


- Savage & McKeon (1983)

  Neutrally buoyant polystyrene spheres ~1 mm diameter. Inner rotating cylinder. Taylor Couette vortices.

  Critical Reynolds number, $Re_b \approx 100$

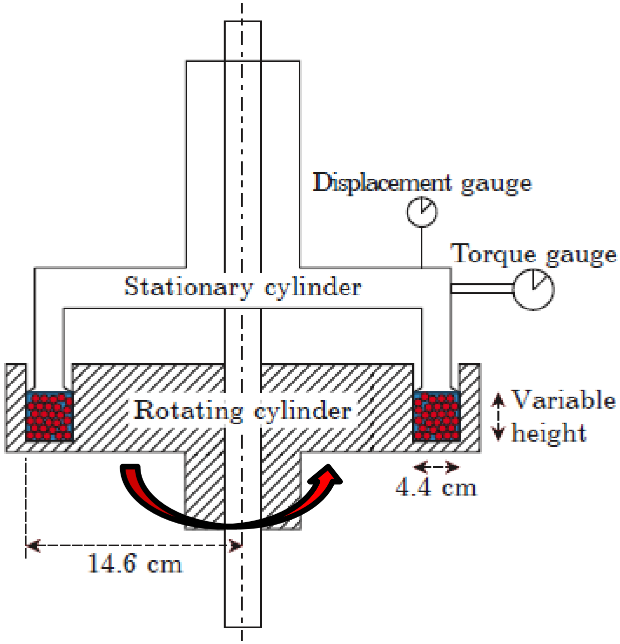
  For pure fluid Re_b ranged from 500 to 5000



Prior Work (Continued)

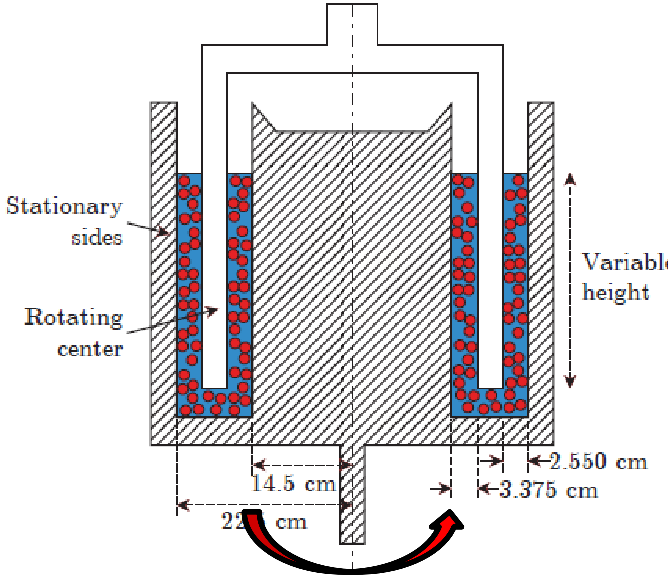
- Hanes & Inman (1985)

  Glass beads 1-1.8 mm dia in water; non-neutrally buoyant. Heavy particles caused partial shearing of flow.



- Acrivos, et al (1994)

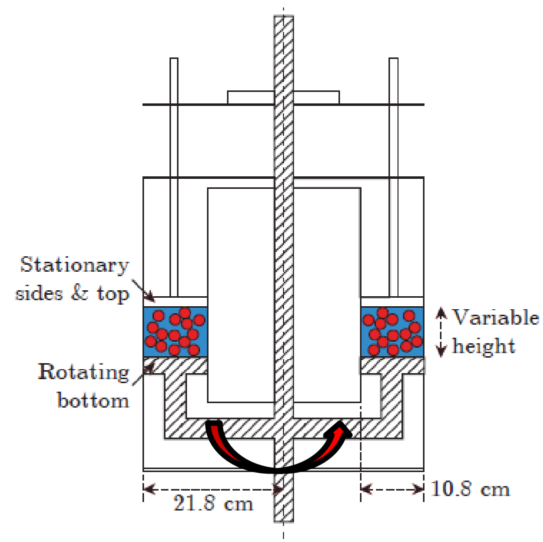
  Neutrally buoyant; PMMA 0.14 mm; acrylic 0.09 mm. Designed for neutrally buoyant but there was settling.



Prior Work (Continued)

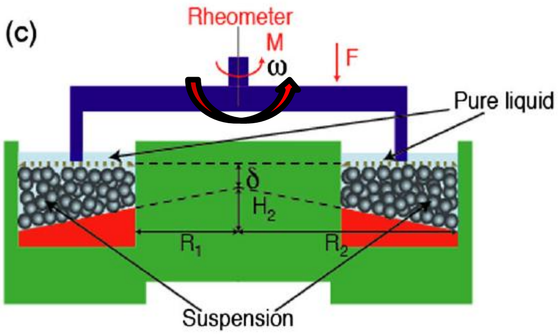
- Prasad & Kytomaa (1995)

  Neutrally and non-neutrally buoyant; 3.2 mm dia acrylic spheres



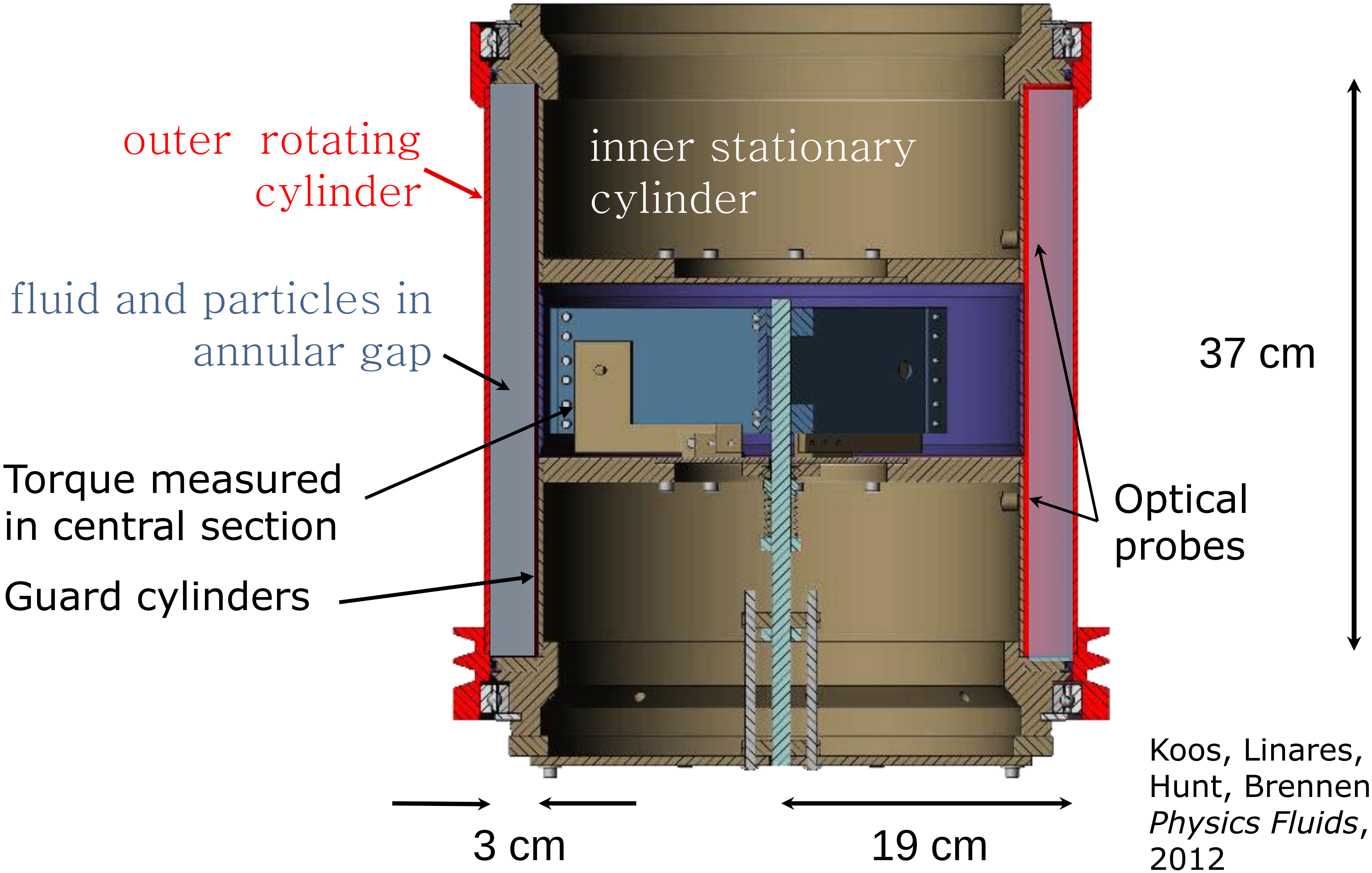
- Boyer, Guazzelli & Pouliquen (2011)

  Neutrally buoyant; 1.1 mm PMMA spheres; 0.58 mm polystyrene

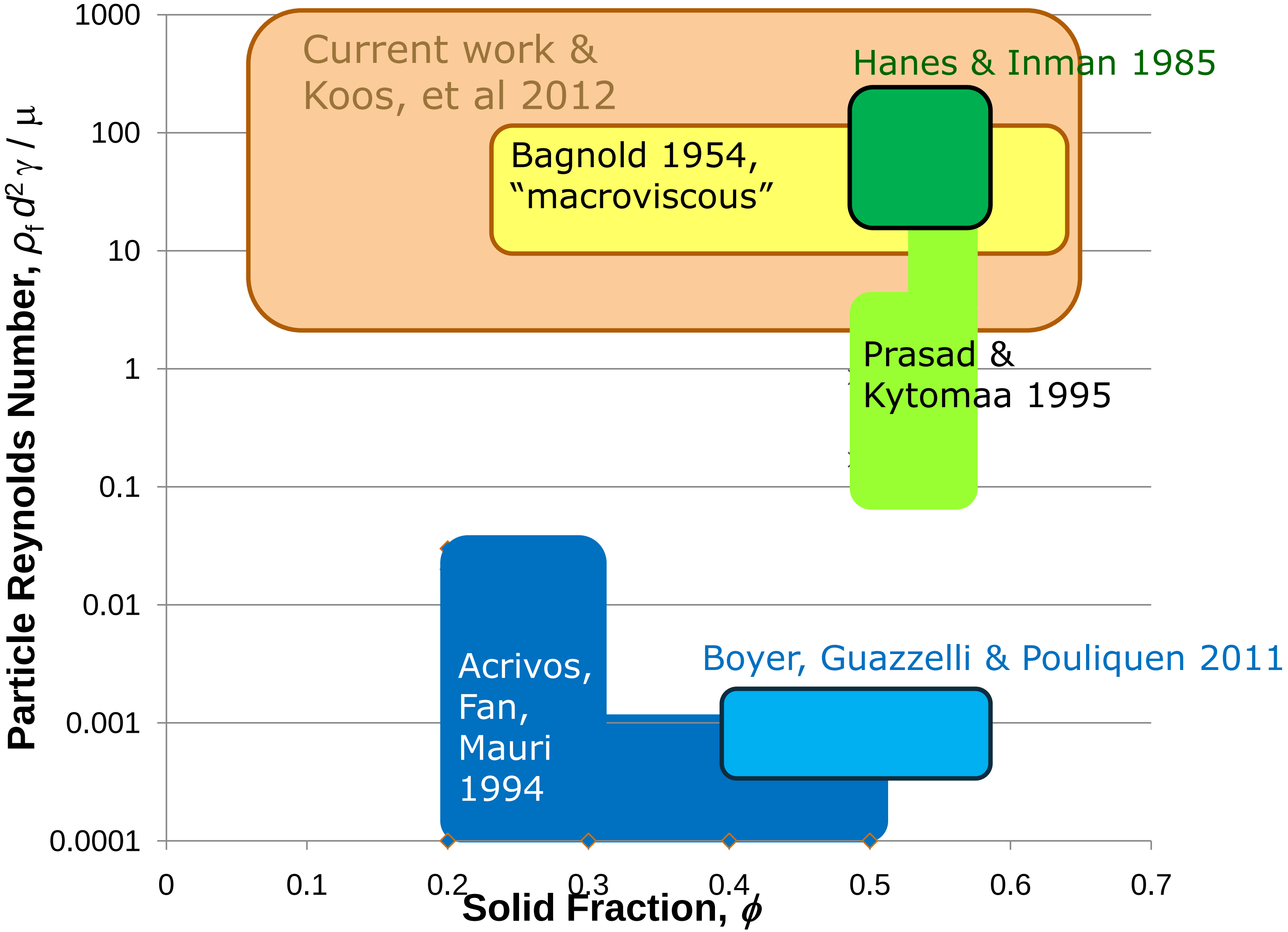


R_2-R_1=46 mm;
H_2=18 mm

Our rheometer



Koos, Linares, Hunt, Brennen, *Physics Fluids*, 2012



$Re=\rho_f d^2\gamma/\mu$

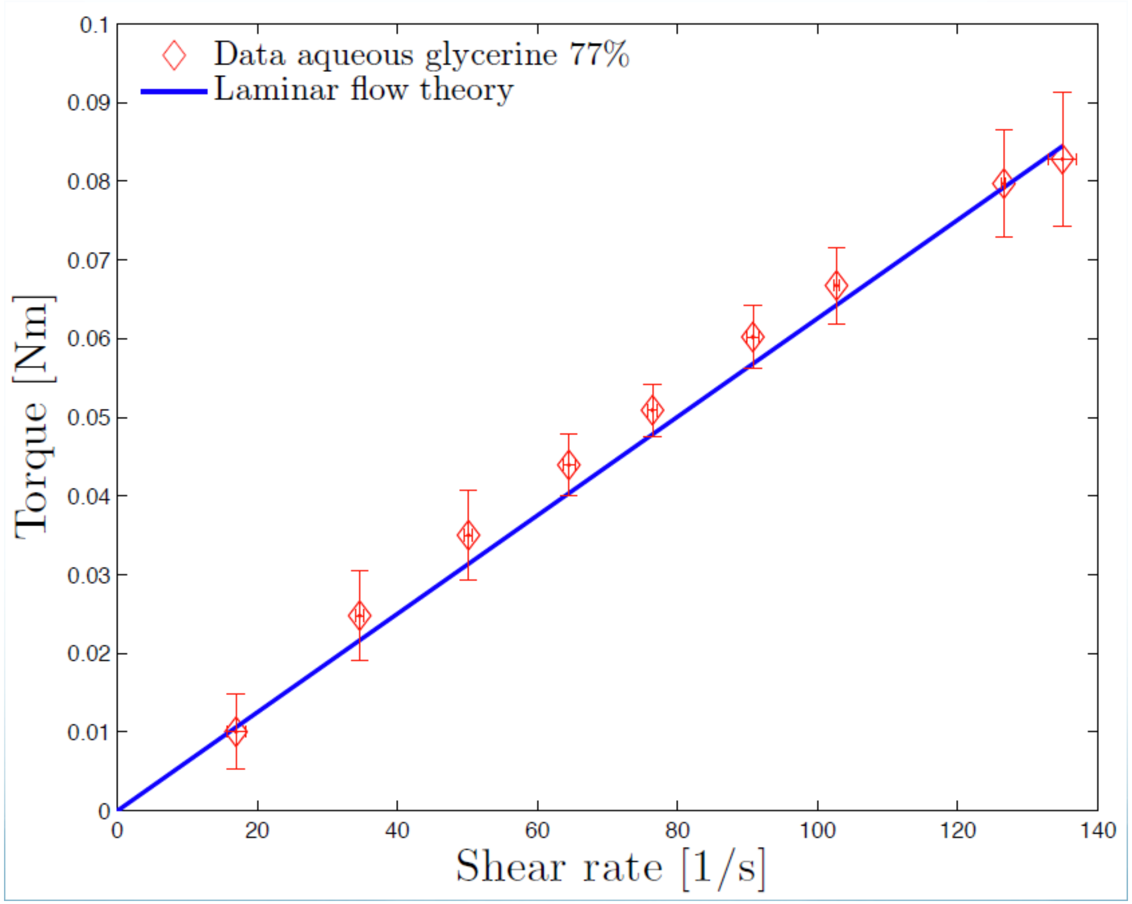
Our pure fluid tests

- Laminar flow; smooth walls
- Case shown is for Re_b= 520 to 3700
- For our geometry, Re_{cr}≈15,000

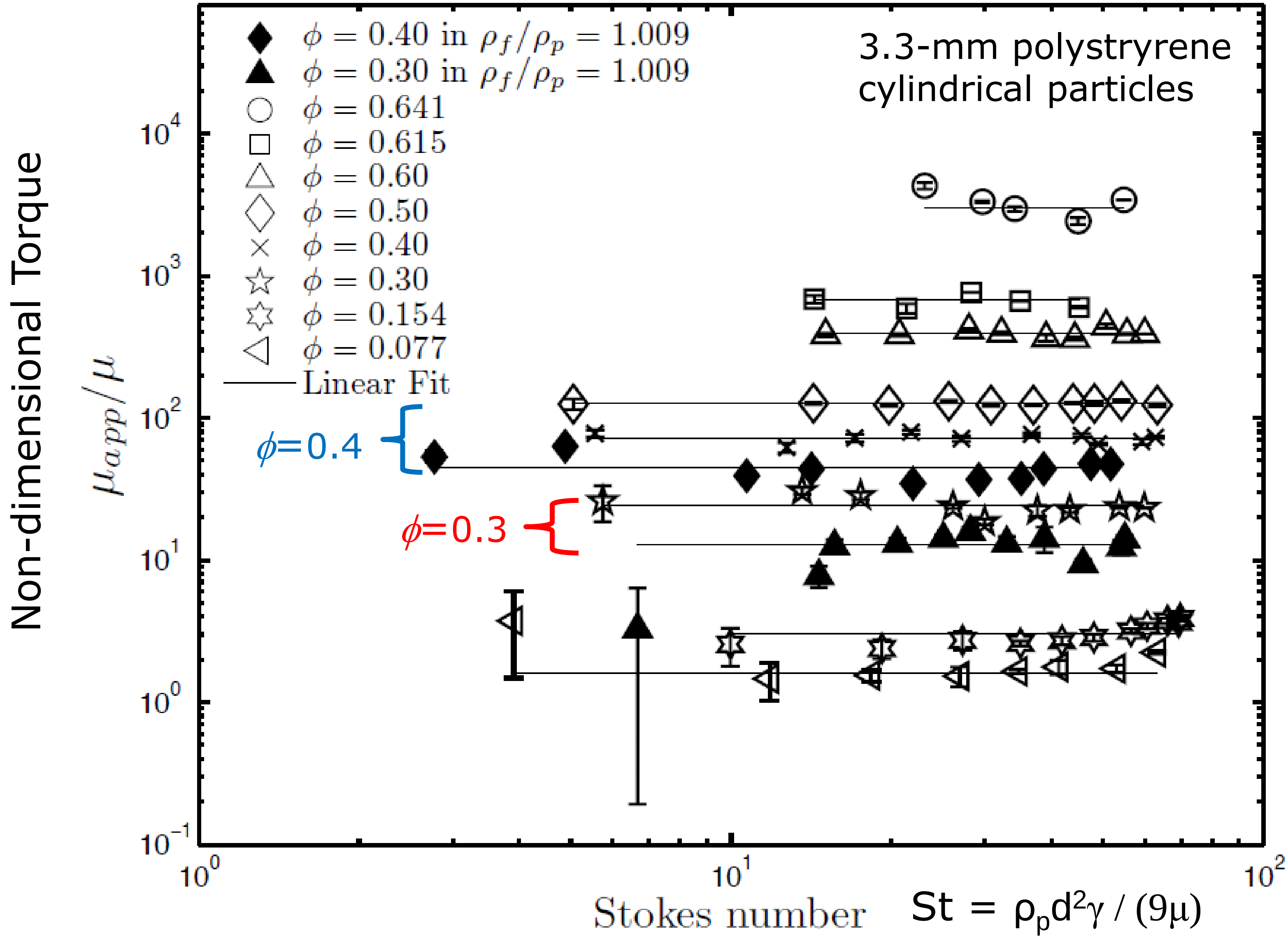
Pure fluid laminar:

$M=4\pi\mu H\omega r_i^2 r_o^2/(r_o^2-r_i^2)$

$=2\pi r_i^2 H\mu\gamma$



Results for flows with $\rho_p \approx \rho_f$ and smooth walls



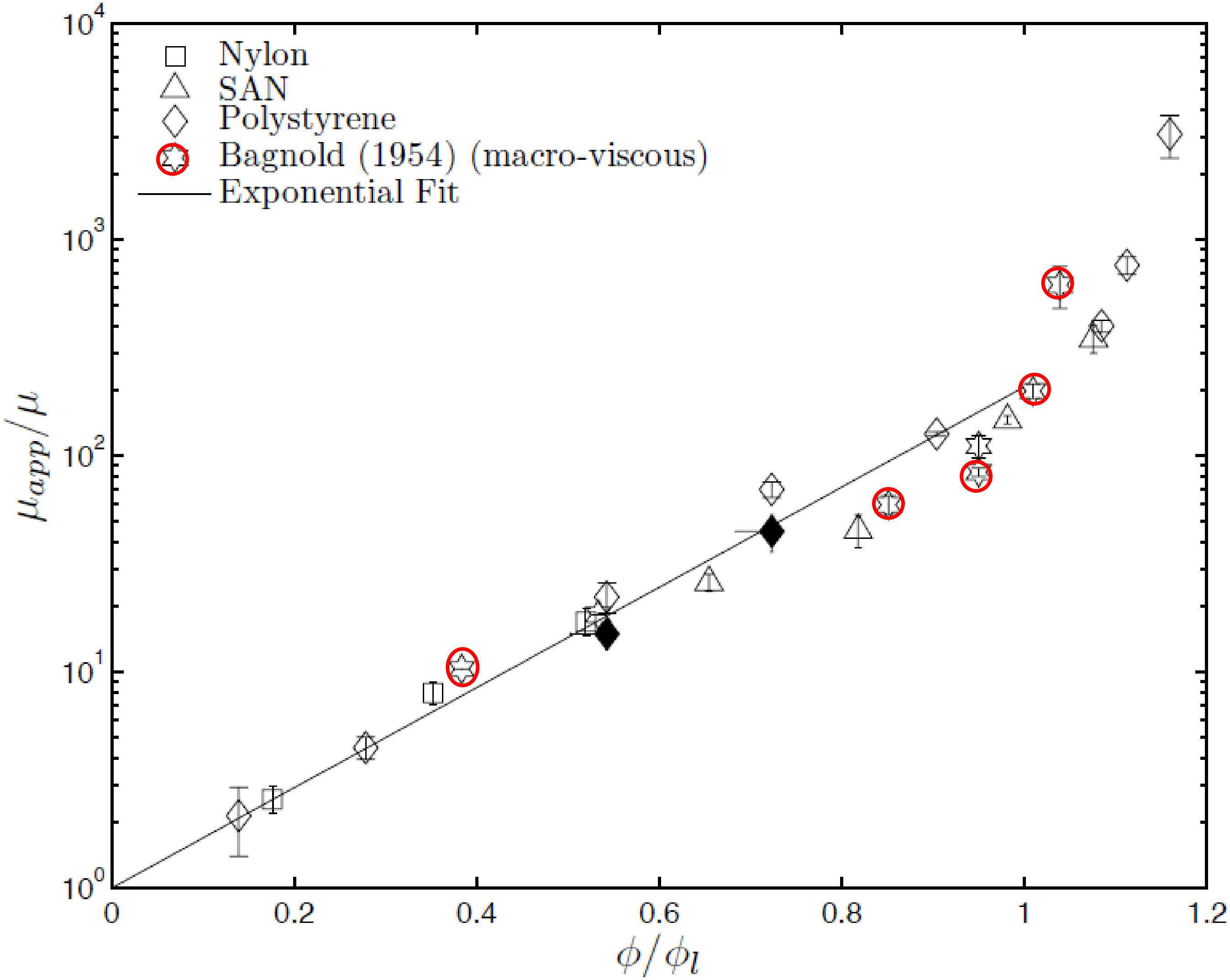
Results: different particles with $\rho_p \approx \rho_f$ and smooth walls; Bagnold macro-viscous data

ϕ_l is random loose pack solid fraction

Nylon spheres 6.4 mm diameter: ϕ_l =0.57

SAN spheres 3.2 mm diameter ϕ_l =0.61

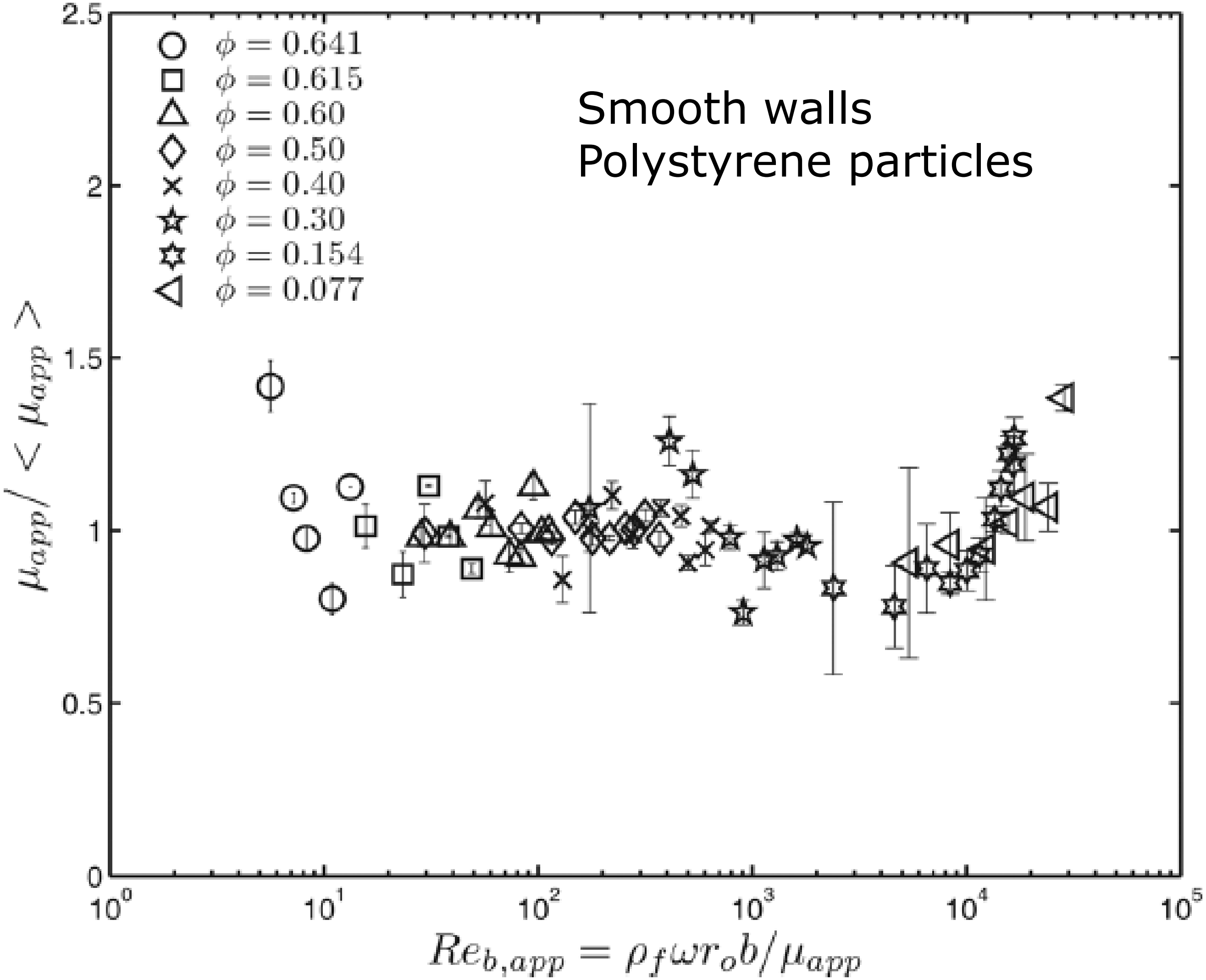
Polystyrene cylinders 3.3 mm: ϕ_l =0.55



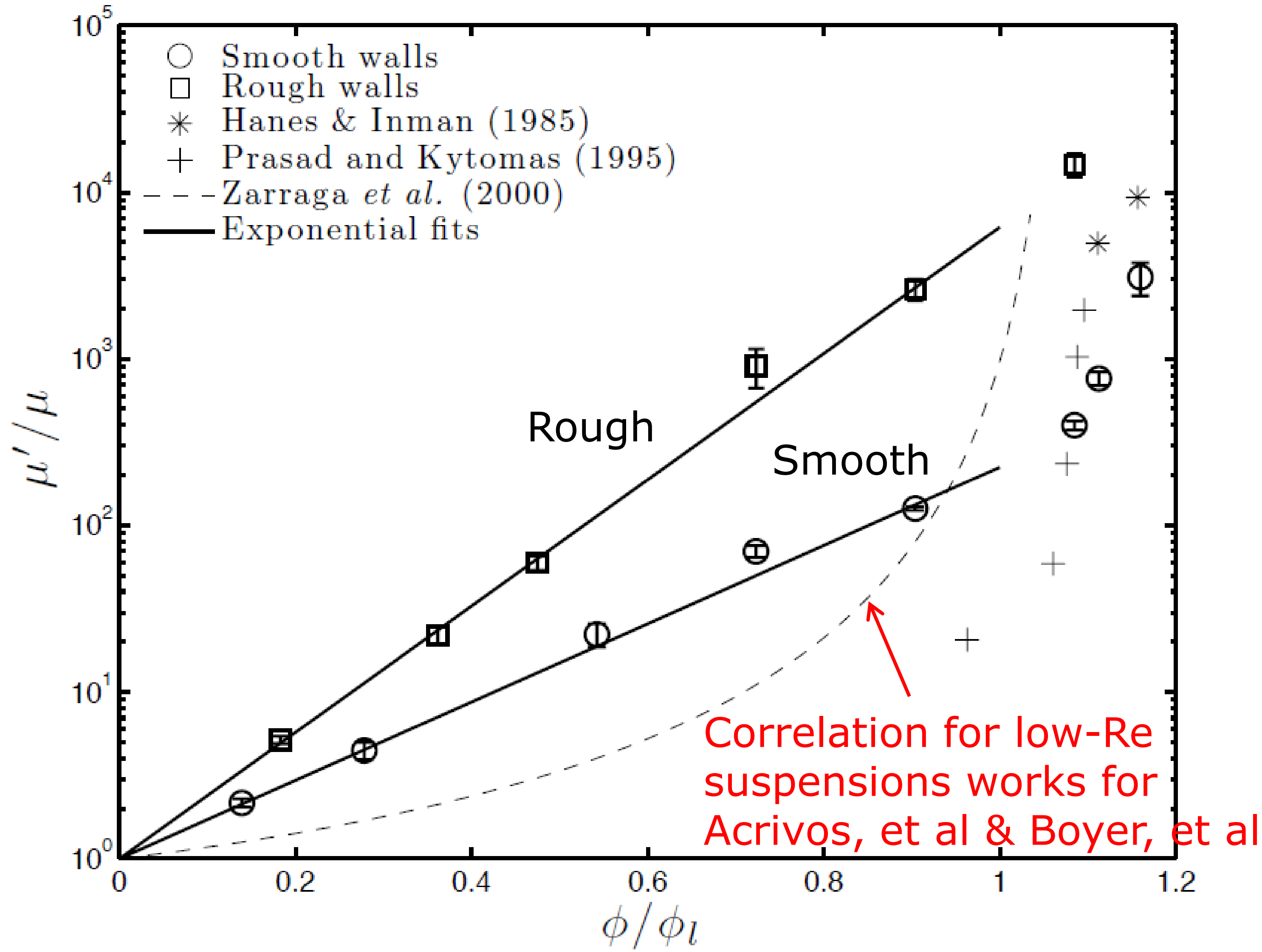
Critical Reynolds Number

Assumes that we can use effective viscosity and the transition criteria for pure fluid.

For our geometry, critical $Re_b \approx 15{,}000$



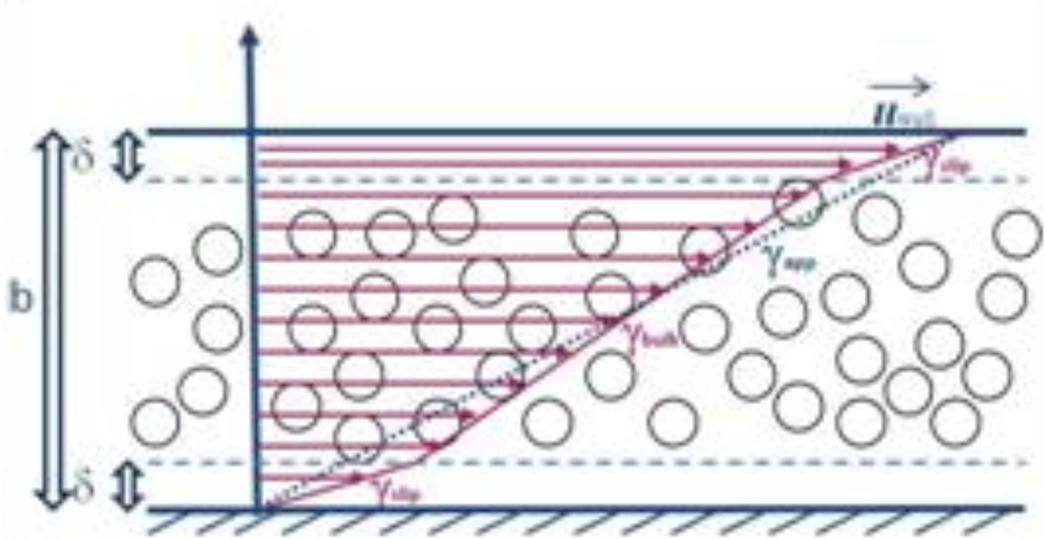
Results for smooth & rough walls



Overall results for flows with $\rho_p \approx \rho_f$

With smooth walls, measured torque is lower relative to rough-wall results because of slip along walls.

Modeled slip using depletion layer. Calculate using measured wall velocities and particle counts.



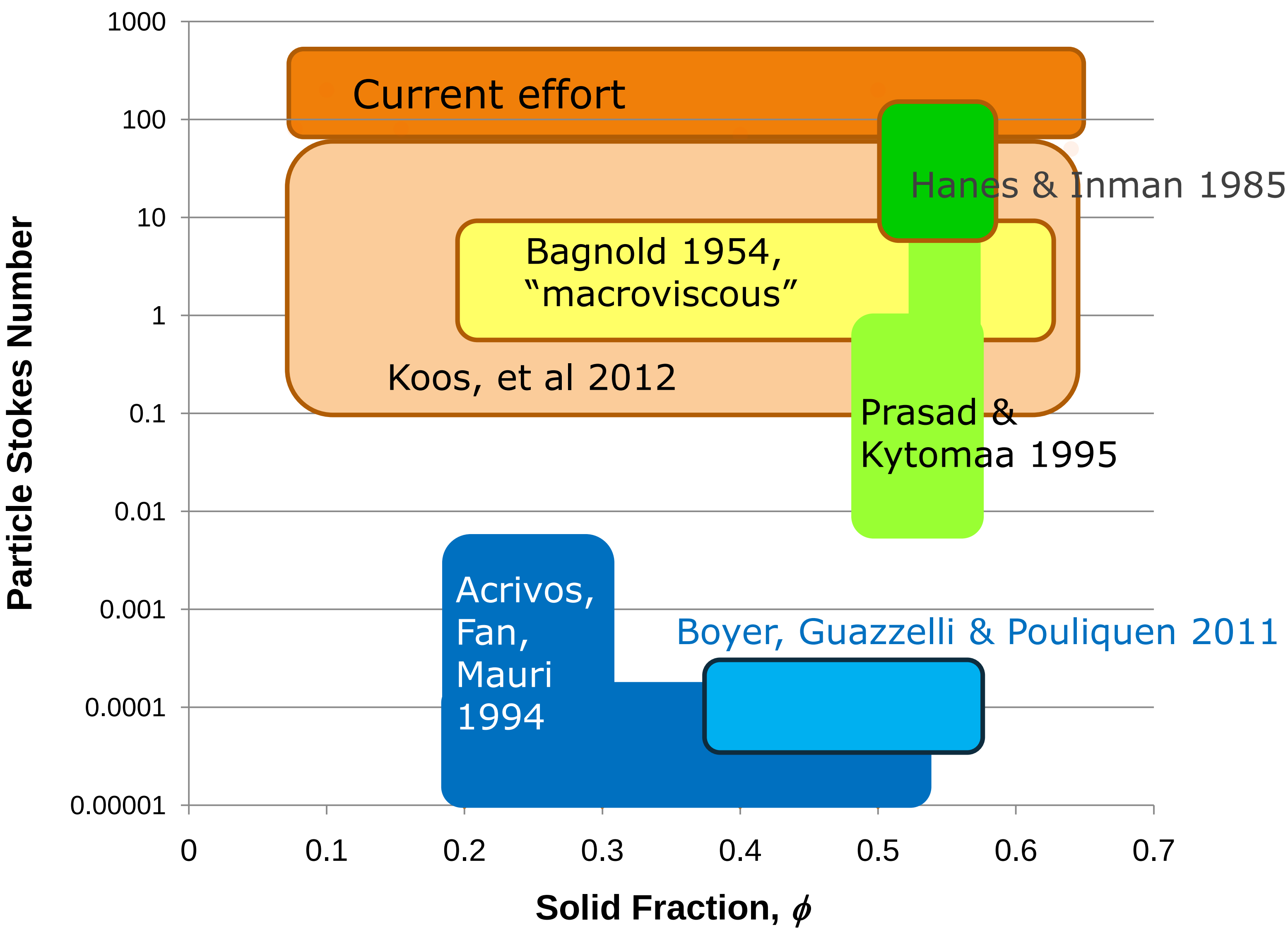
Koos, et al 2012

Effective viscosity larger than found for low-Reynolds number suspension flows.

Why didn't we transition to granular-flow rheology dominated by particle collisions?

Over range of experiments, torques depended linearly on shear rate.

Possible answer – local Stokes number may not be high enough. Doing additional rough-walled experiments with higher density particles and lower viscosity fluids.



$St = \rho_p d^2 \gamma / 9\mu$

Relative viscosity (Acrivos, Fan & Mauri 1994)

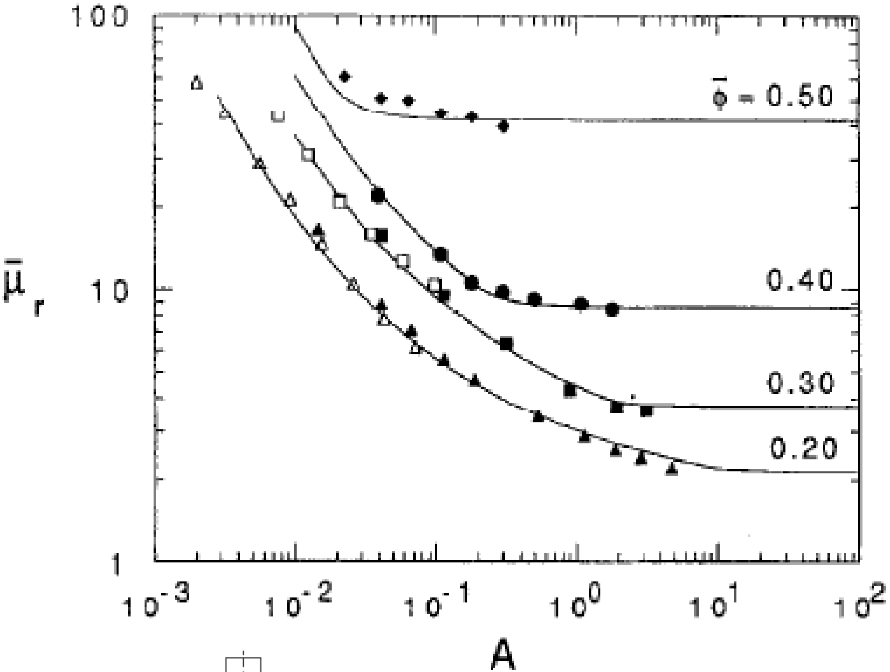
- Height-averaged relative viscosity, $\bar{\mu}_r$ as a function of averaged solid fraction $\bar{\varphi}$ and

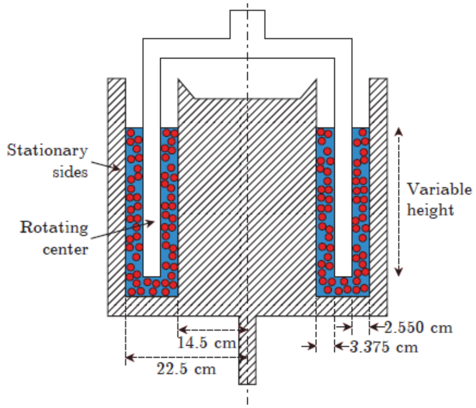
$$A = \frac{9}{2}\frac{\mu\gamma}{h_o g \Delta\rho}$$

with γ = shear rate and h_o is height of sheared region.

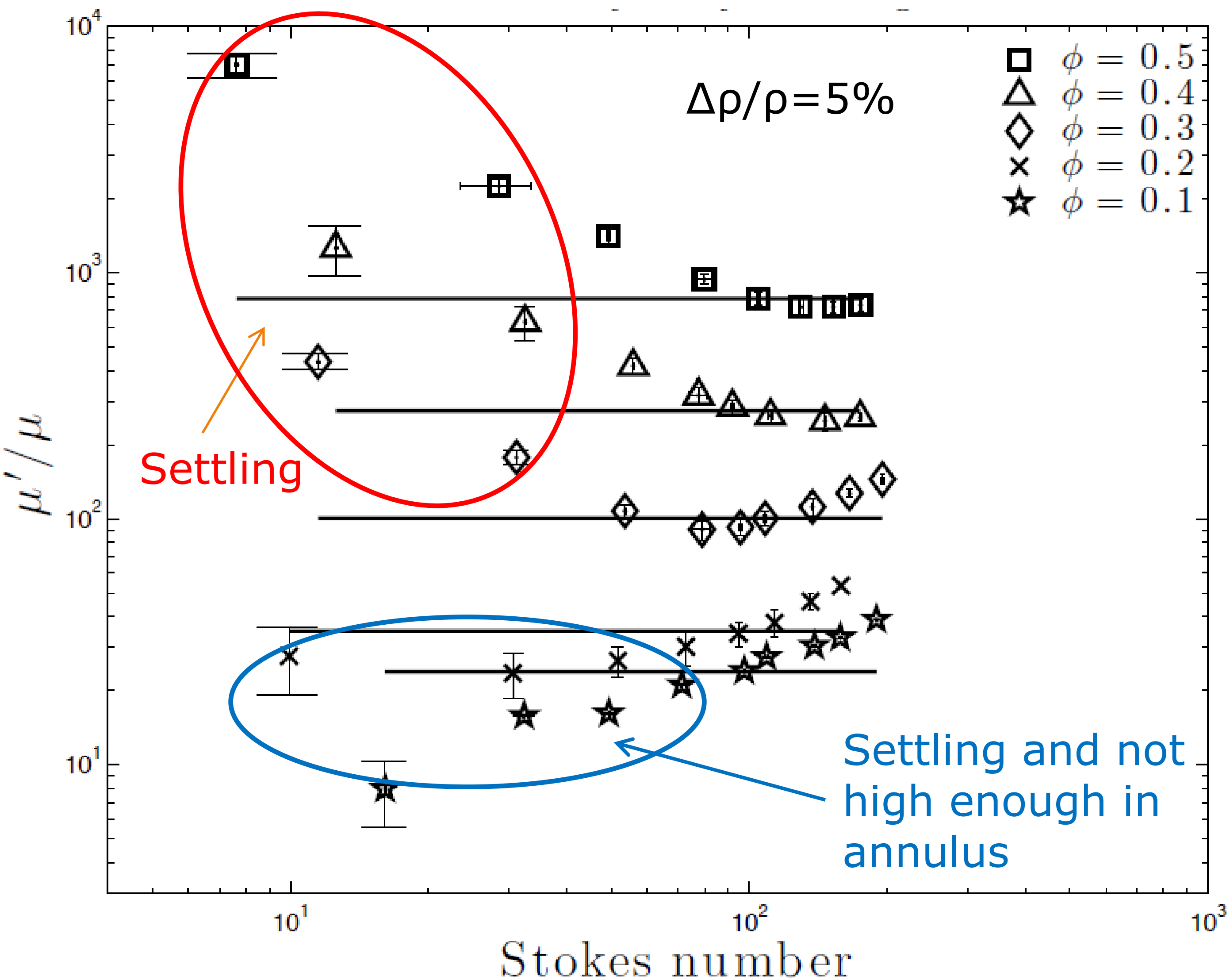
Balance of low-Reynolds number settling and shear induced migration.

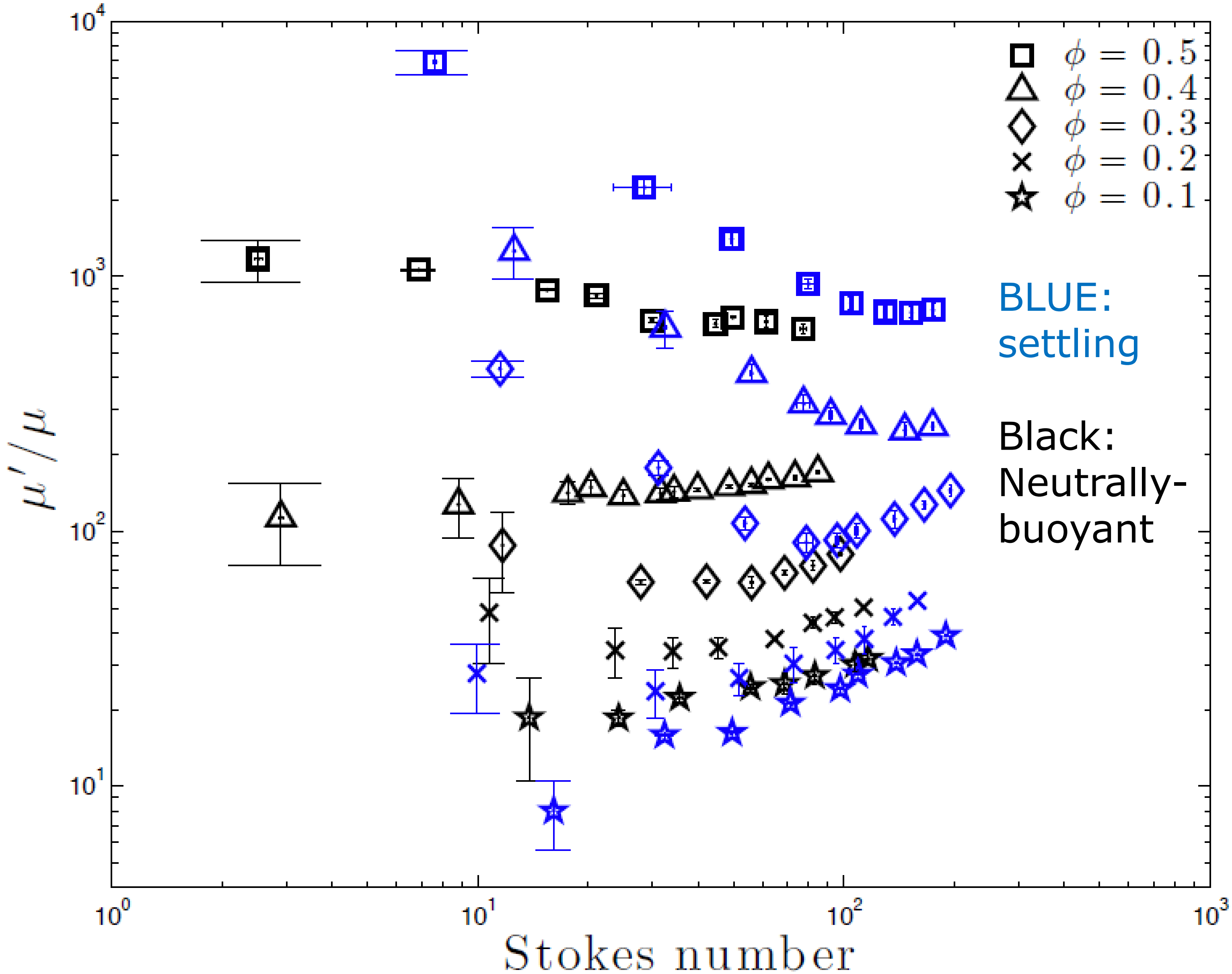
$\Delta\rho/\rho$ = 2-3%



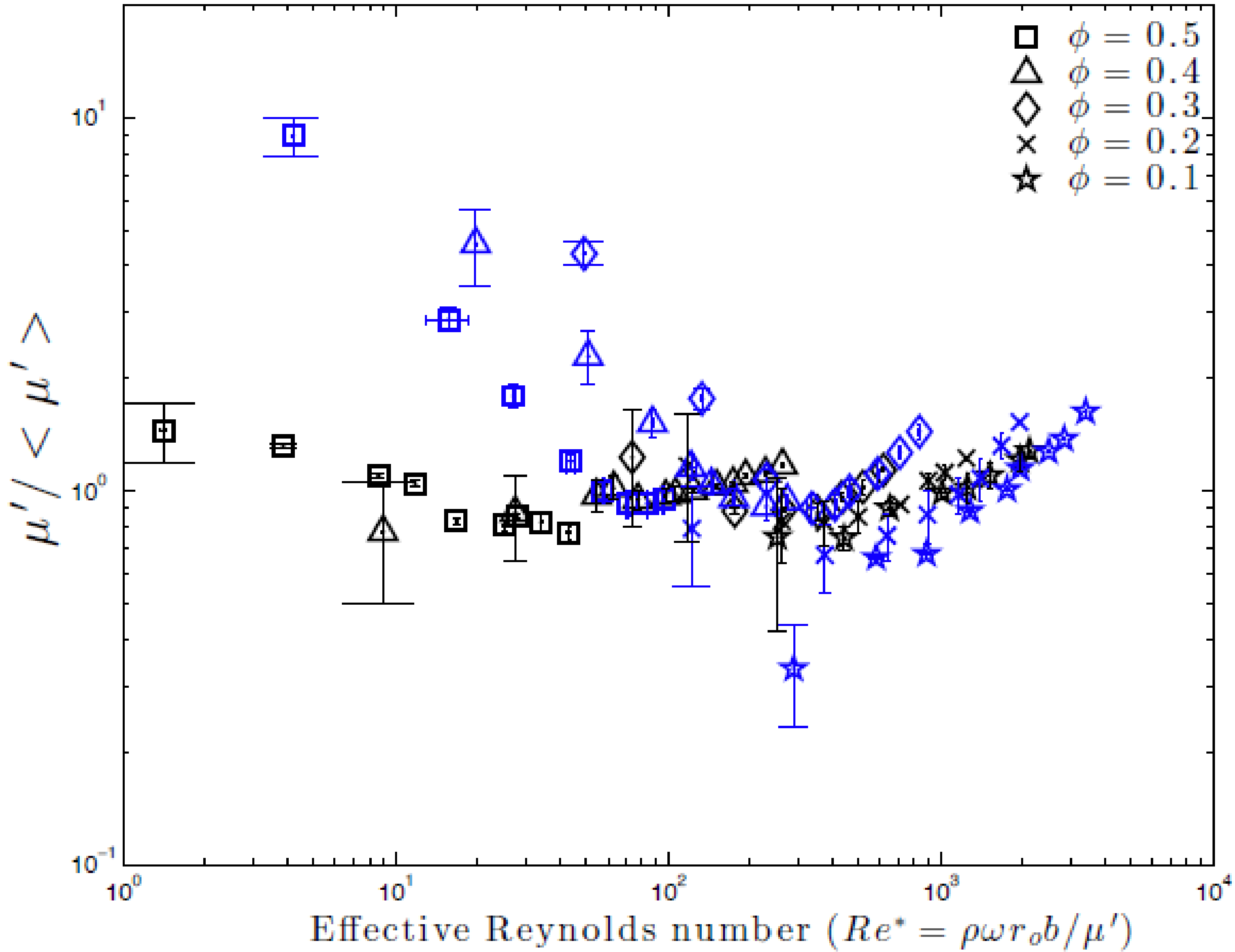


Rough Walls & Non-Neutrally Buoyant



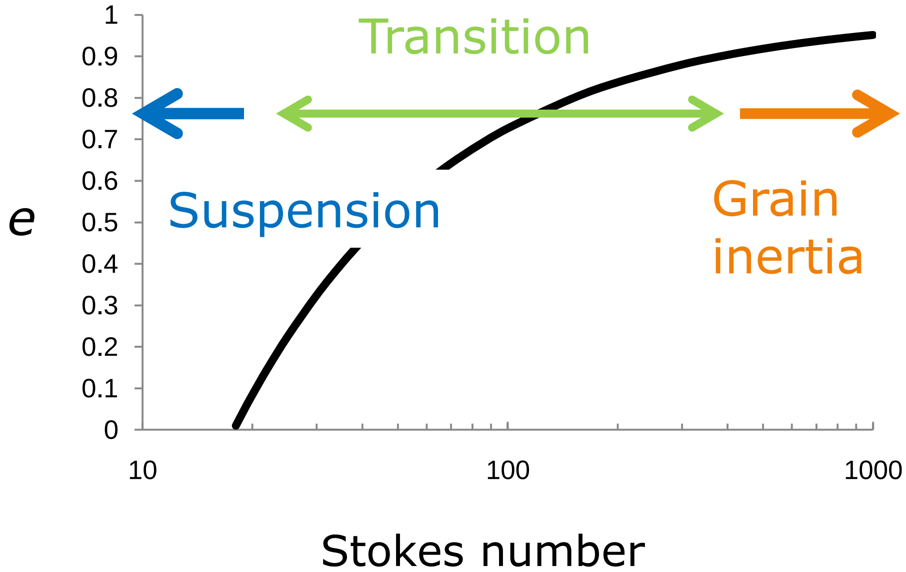


10^4
10^3
10^2
10^1
10^0
10^1
10^2
10^3
μ'/μ
Stokes number
$\phi = 0.5$
$\phi = 0.4$
$\phi = 0.3$
$\phi = 0.2$
$\phi = 0.1$
BLUE: settling
Black: Neutrally-buoyant



$\phi = 0.5$
$\phi = 0.4$
$\phi = 0.3$
$\phi = 0.2$
$\phi = 0.1$
10^{1}
10^{0}
10^{-1}
$\mu' / < \mu' >$
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Effective Reynolds number ($Re^{*} = \rho \omega r_o b / \mu'$)

Summary



In our prior experiments,

Max Stokes numbers ≈ 80

Pushing higher St to

See if there is transition to collisional interactions.

More experiments at higher Stokes number

- Denser particles & less viscous fluids
- More accurate measurements of solid fraction

Questions?