Instabilities in Particle Flows: Assessing Hydrodynamics and Understanding Dominant Mechanisms

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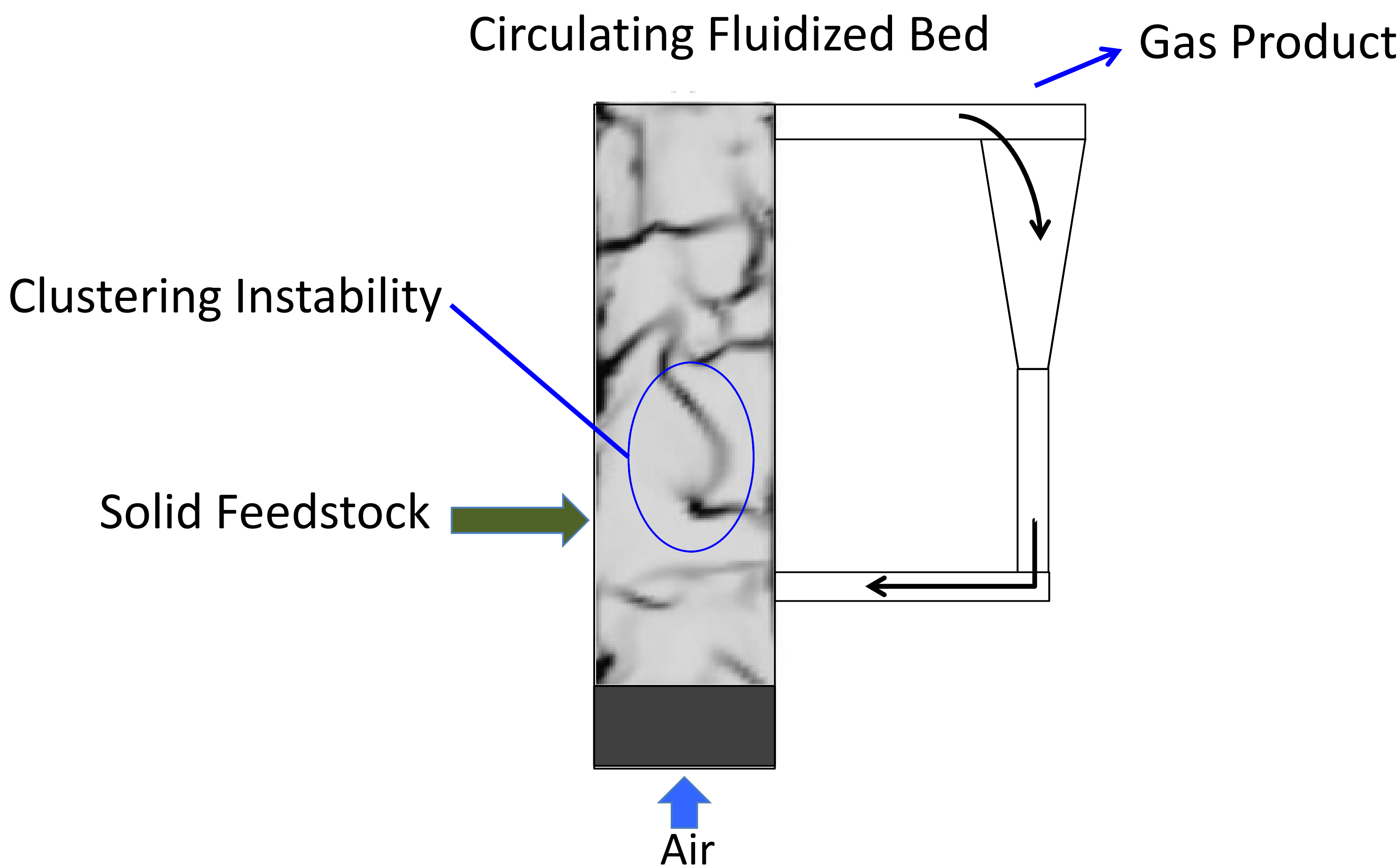
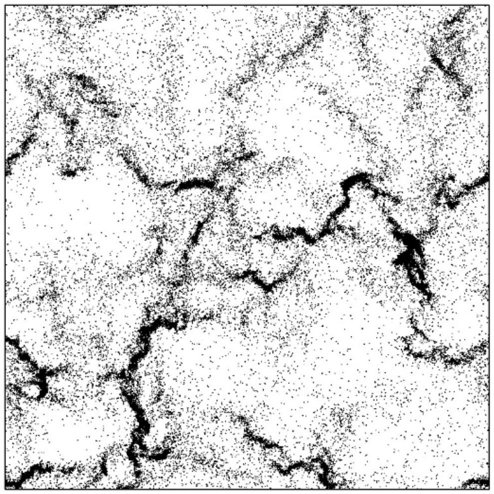
Motivation: Instabilities in Particulate Flows



CFD simulation from Agrawal, Loezos, Syamlal, Sundareson, J. Fluid Mech. (2001)

Particle Clustering Instability: Known Mechanisms

Homogeneous Cooling System



Granular Work

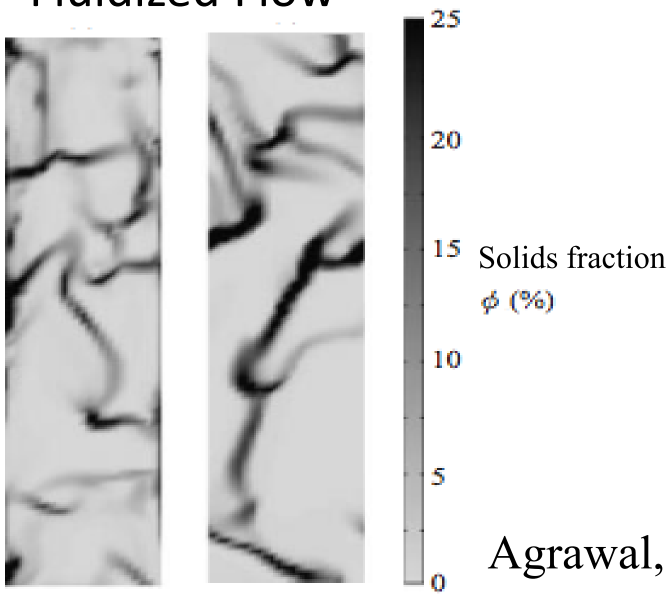
Solid Effects
(Dissipative Collisions)

Inelasticity
- Hopkins & Louge 1991
- Goldhirsch et al. 1993

Friction
- Mitrano et al.

Goldhirsch, et al., *J. Sci. Comput.* (1993)

Fluidized Flow



Fluidization Work

Fluid Effects

Mean Drag
- Glasser et al. 1998
- Agrawal et al. 2001

Viscous Damping
- Wylie & Koch 2000

Agrawal, et al., *J. Fluid Mech.* (2001)

Objectives

- Relative importance of mechanisms in gas-solid flow instabilities
  - DNS, MD simulations, hydrodynamics
- Hydrodynamic description for developed gradients and correlated particle velocities
  - MD simulations, hydrodynamics
- Hydrodynamic description of binary mixture of particles
  - MD simulations, linear hydrodynamics

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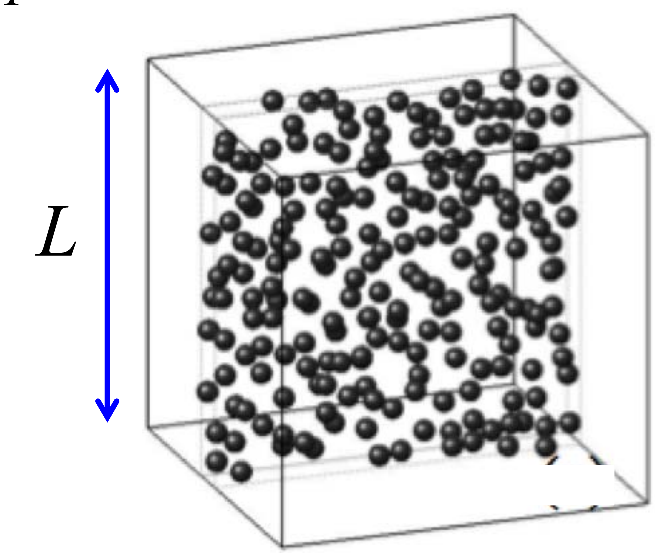
Input: Typical CFB Conditions

- Restitution coefficient: $0.8 \le e \le 1.0$
- Solids fraction: $0.1 \le \phi \le 0.4$
- Density ratio: $800 \le \dfrac{\rho_{solid}}{\rho_{fluid}} \le 1500$
- System length scale $L/d = 30 \times 30 \times 4$
- Reynolds Number: $3 \le \mathrm{Re}_T \le 30$

$$\mathrm{Re}_T \propto \rho_{fluid}\sqrt{T_0}$$

$$\propto \frac{\text{Particle inertial forces}}{\text{Fluid viscous forces}}$$

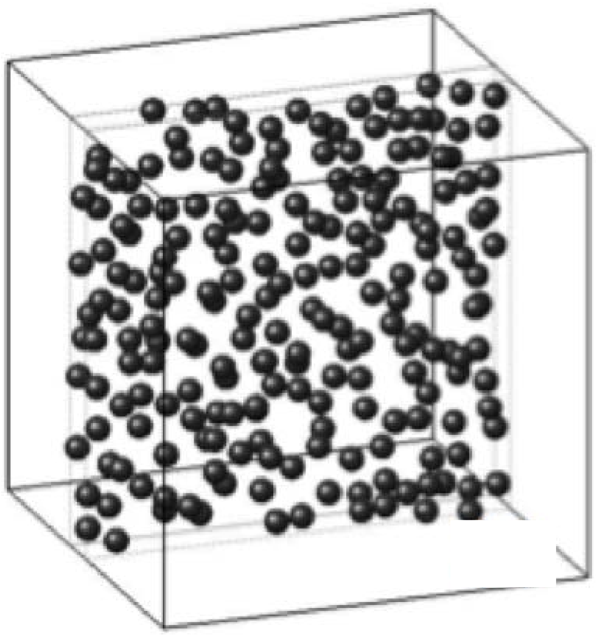


System

Homogeneous Cooling System (HCS)

- No external forces
- Periodic boundaries
- 3-D domain
- Random initial configuration
- No net momentum

} Kinetic energy decays over time

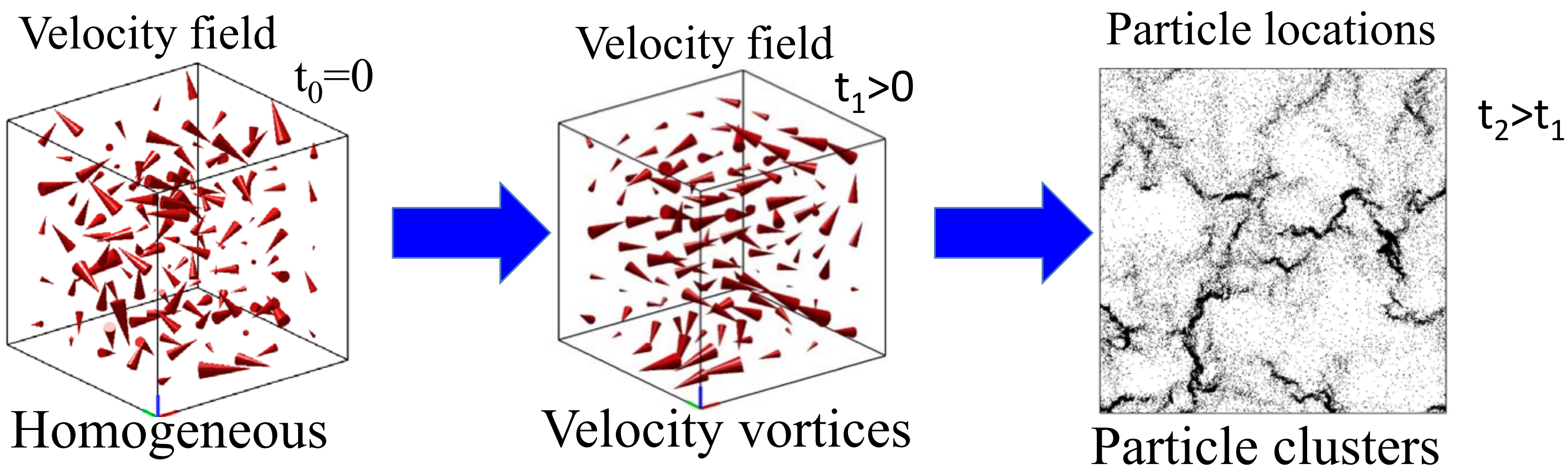


Particle properties

- Coefficient of normal restitution (e)
- Monodisperse, frictionless spheres

Previous HCS work

Granular flow: *inelastic* solids; no gas (Goldhirsch 1993)



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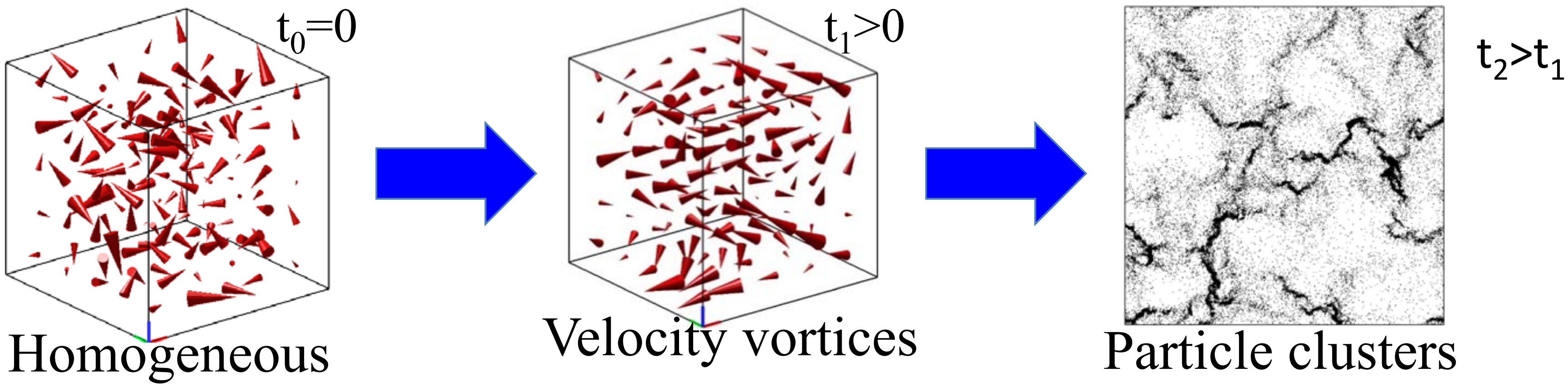
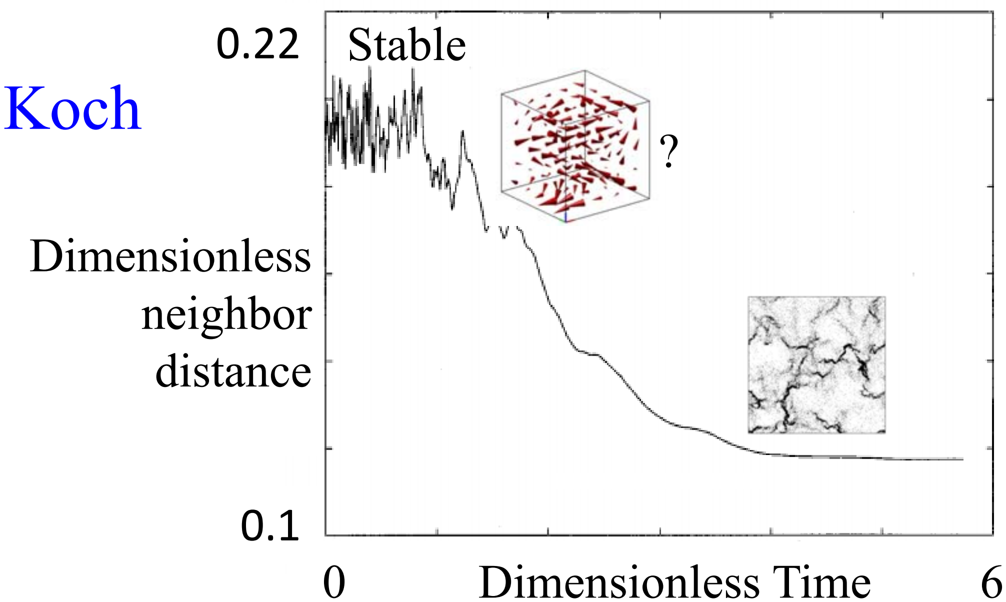


Gas-solid flow (Wylie & Koch 2000)

- *elastic* particles in viscous fluid flow

Focus: viscous effects



Kinetic Theory

$$\frac{dT}{dt} = -\zeta T - \frac{2T}{m}\gamma$$

ζ cooling rate due to collisions
γ cooling rate due to viscous forces
T granular temperature

Energy balance for stable, homogeneous cooling

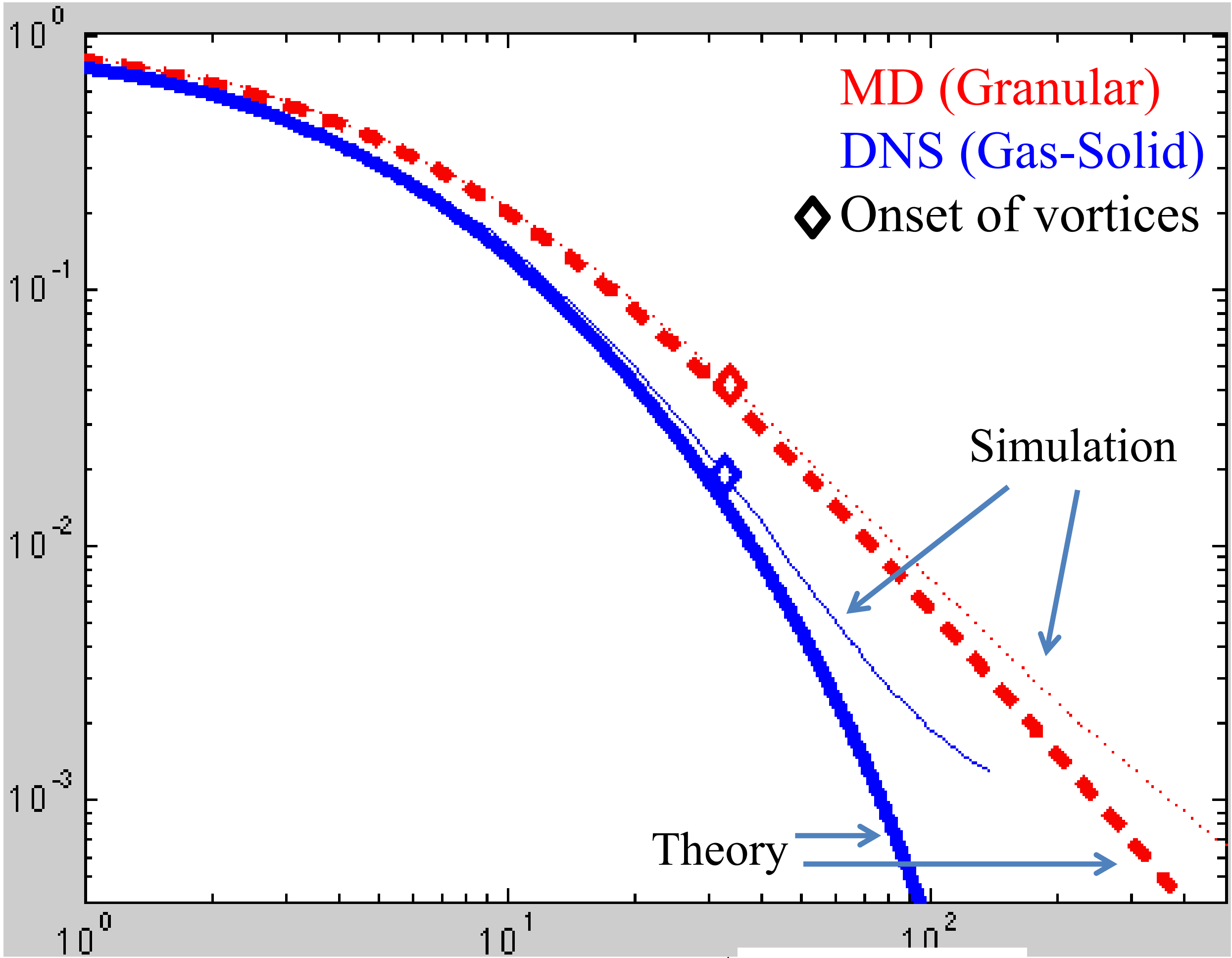
1. Verification of instability-detection method
2. Preliminary validation for new theory*

$$(\bar{\mathbf{U}}_s - \bar{\mathbf{U}}_f) \rightarrow (\mathbf{U}_s - \mathbf{U}_f)$$

New theory: rigorous incorporation of *instantaneous* viscous force in starting kinetic (Enskog) equation

*Garzó, Tenneti, Subramaniam, Hrenya, *J. Fluid Mech.* (2012)

Simulation vs. Kinetic Theory



$$\frac{KE}{KE_0}$$

$$\frac{t}{\sqrt{md^2 KE_0}}$$

$e = 0.9$

$\varphi = 0.2$

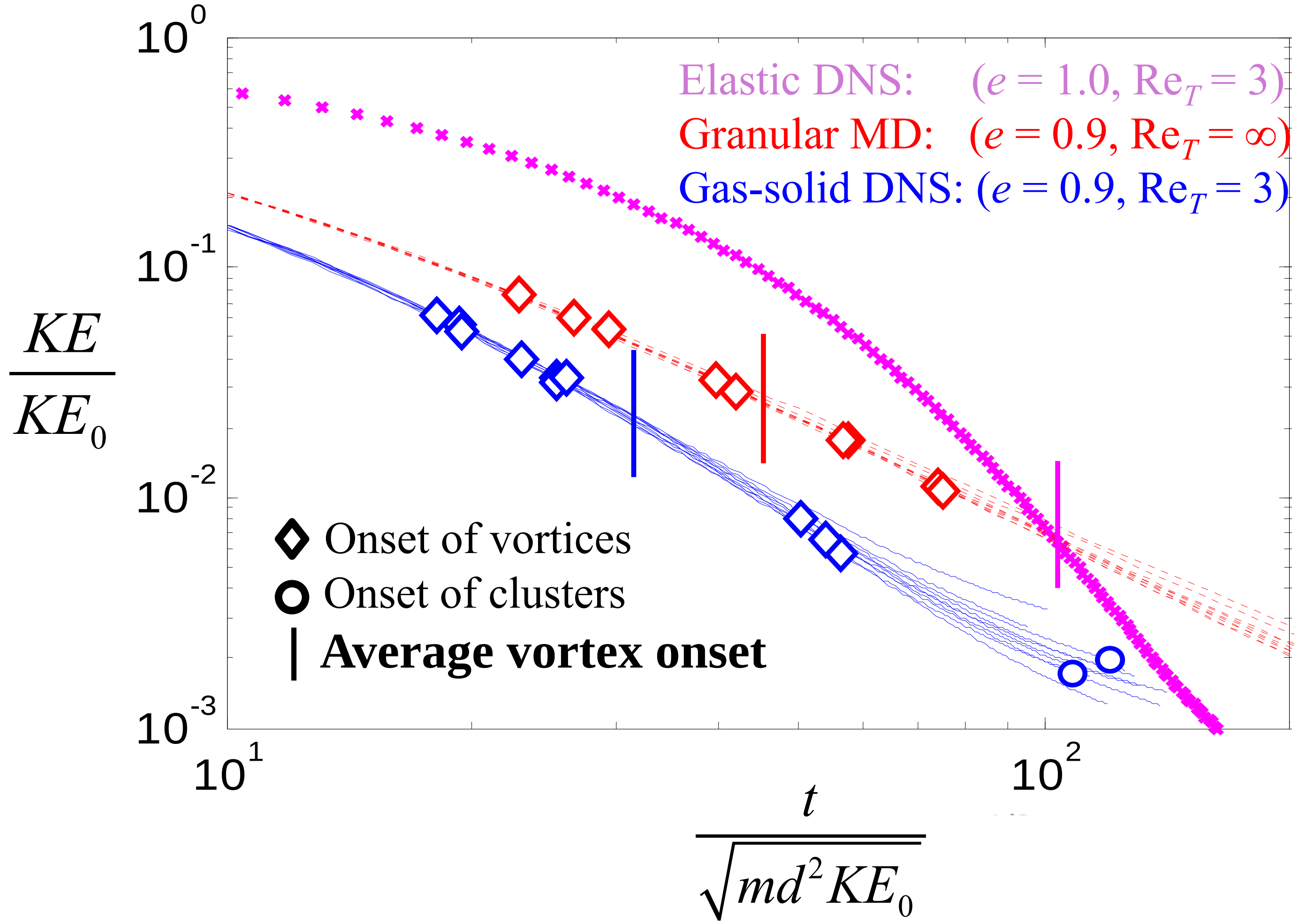
DNS:

$\mathrm{Re}_T = 3$

$$\frac{\rho_{solid}}{\rho_{fluid}} = 1000$$

Theory agrees with simulation *before onset of instability* (as expected)

Influence of Dissipative Mechanisms

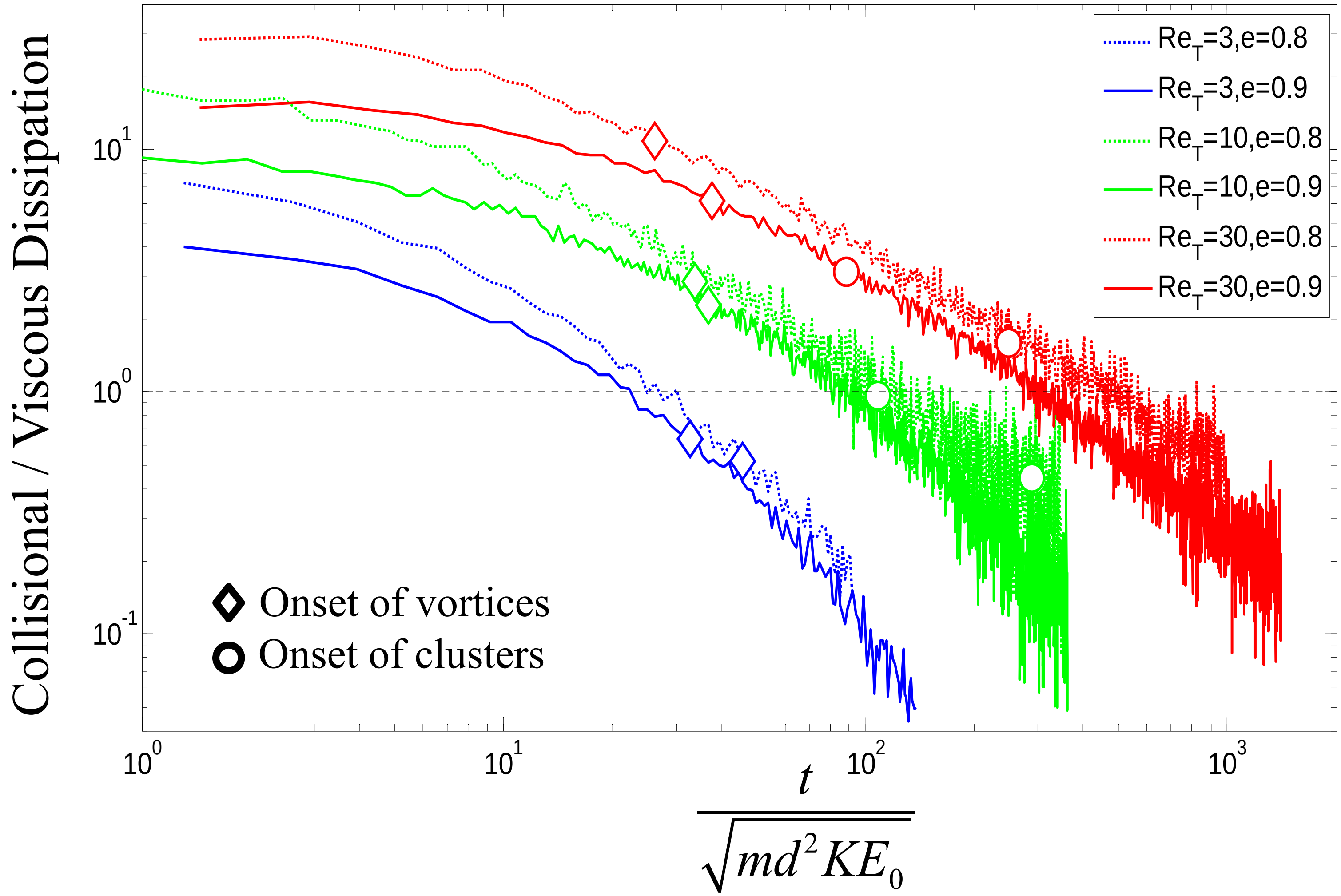


$$\frac{\rho_{solid}}{\rho_{fluid}} = 1000$$

$$\phi = 0.2$$

Increased dissipation promotes instability, regardless of mechanism

Relative Importance of Dissipative Mechanisms

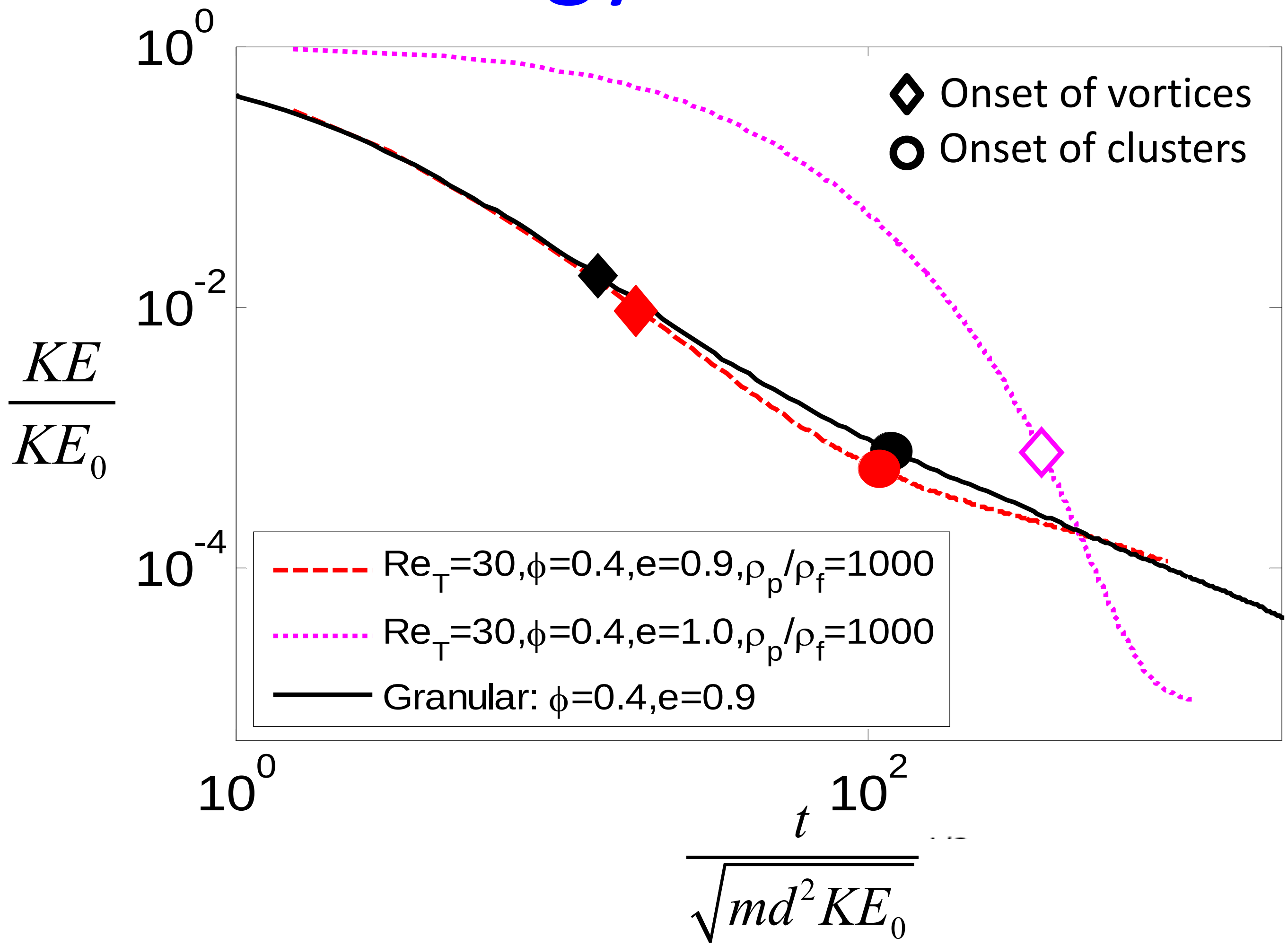


$$\frac{\rho_{solid}}{\rho_{fluid}} = 1000$$

$$\phi = 0.2$$

Collisional dissipation dominates for high Re_T

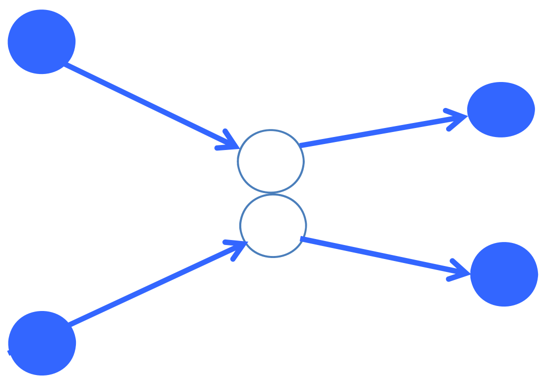
Energy Crossover



More dissipative systems may actually possess higher energy levels due to velocity vortices

Energy Crossover: Physical Mechanism

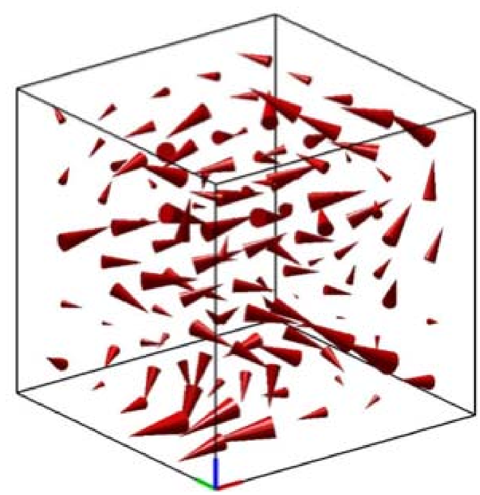
- Dissipation promotes velocity vortex instability
- Collisions reduce normal relative velocity to greater extent than tangential relative velocity



- Both collisional and viscous losses align particle motion

- Dissipation decreases with normal relative velocity

1. Velocity vortices
2. Glancing collisions
3. Smaller relative normal velocity
4. Reduced dissipation



Outline

- Relative importance of mechanisms in gas-solid flow instabilities
  - DNS, MD simulations, hydrodynamics
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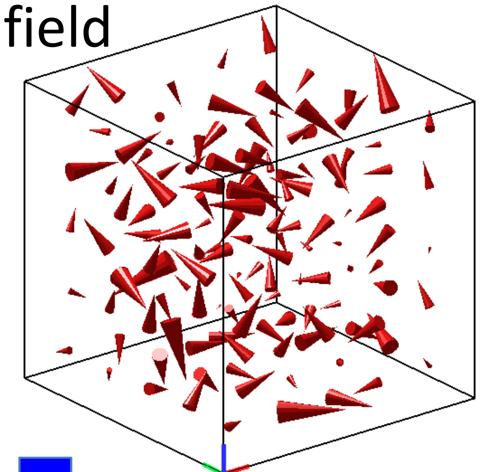
Critical Length Scales for Instability

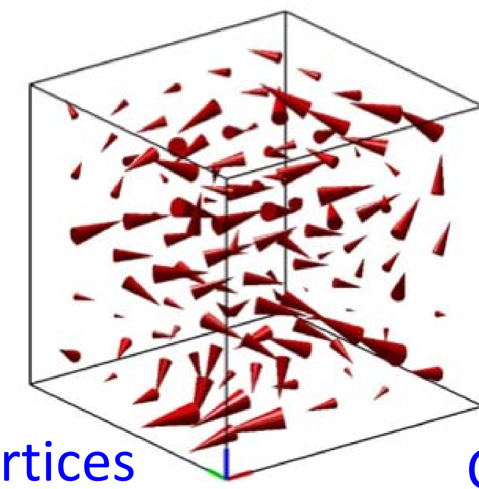
Velocity field



Molecular dynamics (MD) simulations of the HCS

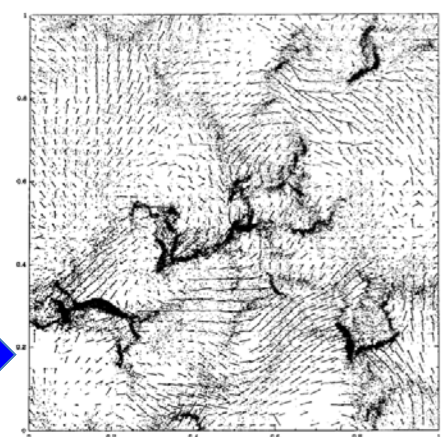
- Dissipative collisions
- Sufficiently large system domain

Velocity field



Vortices

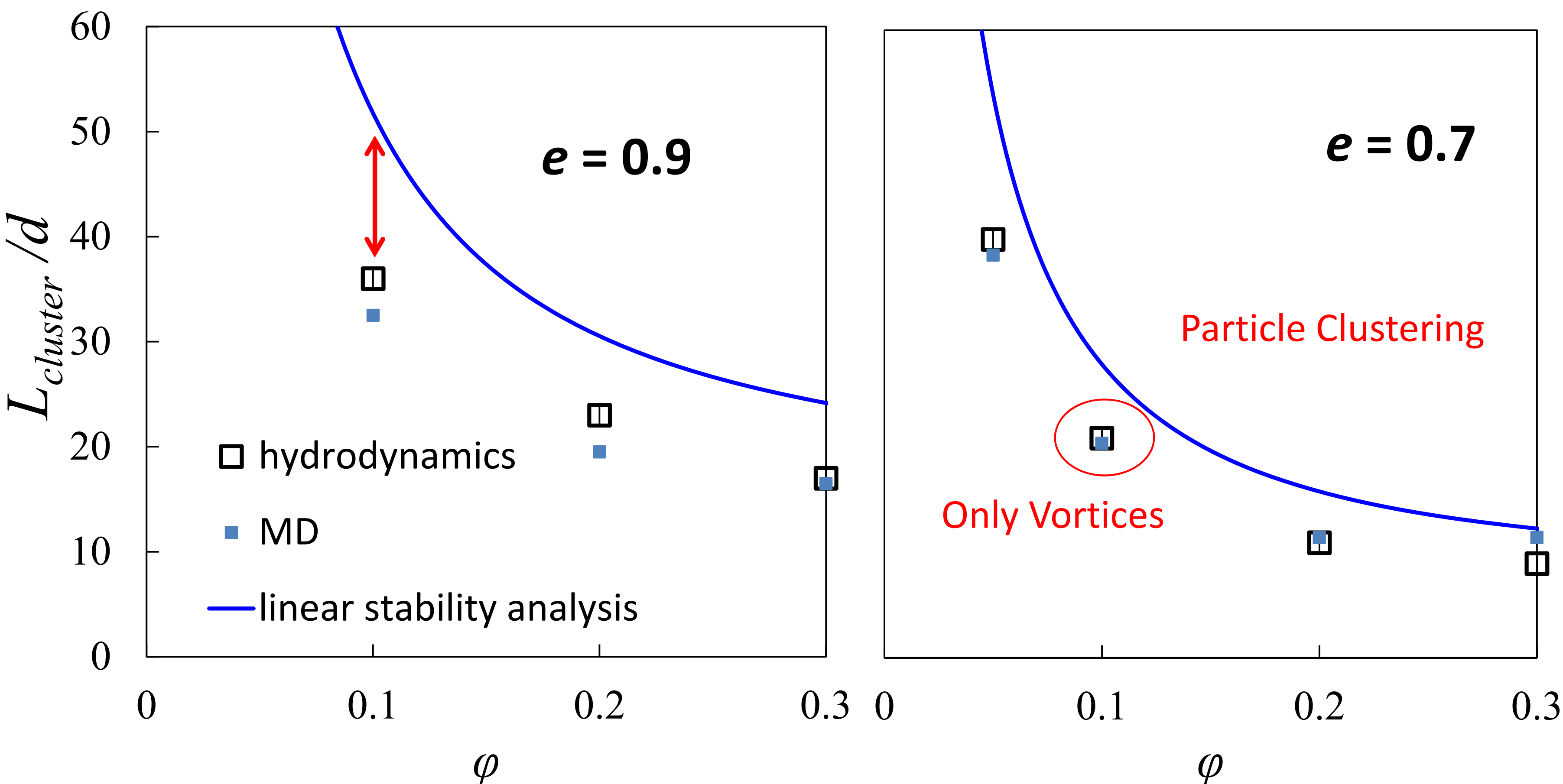
Particle locations



Clusters

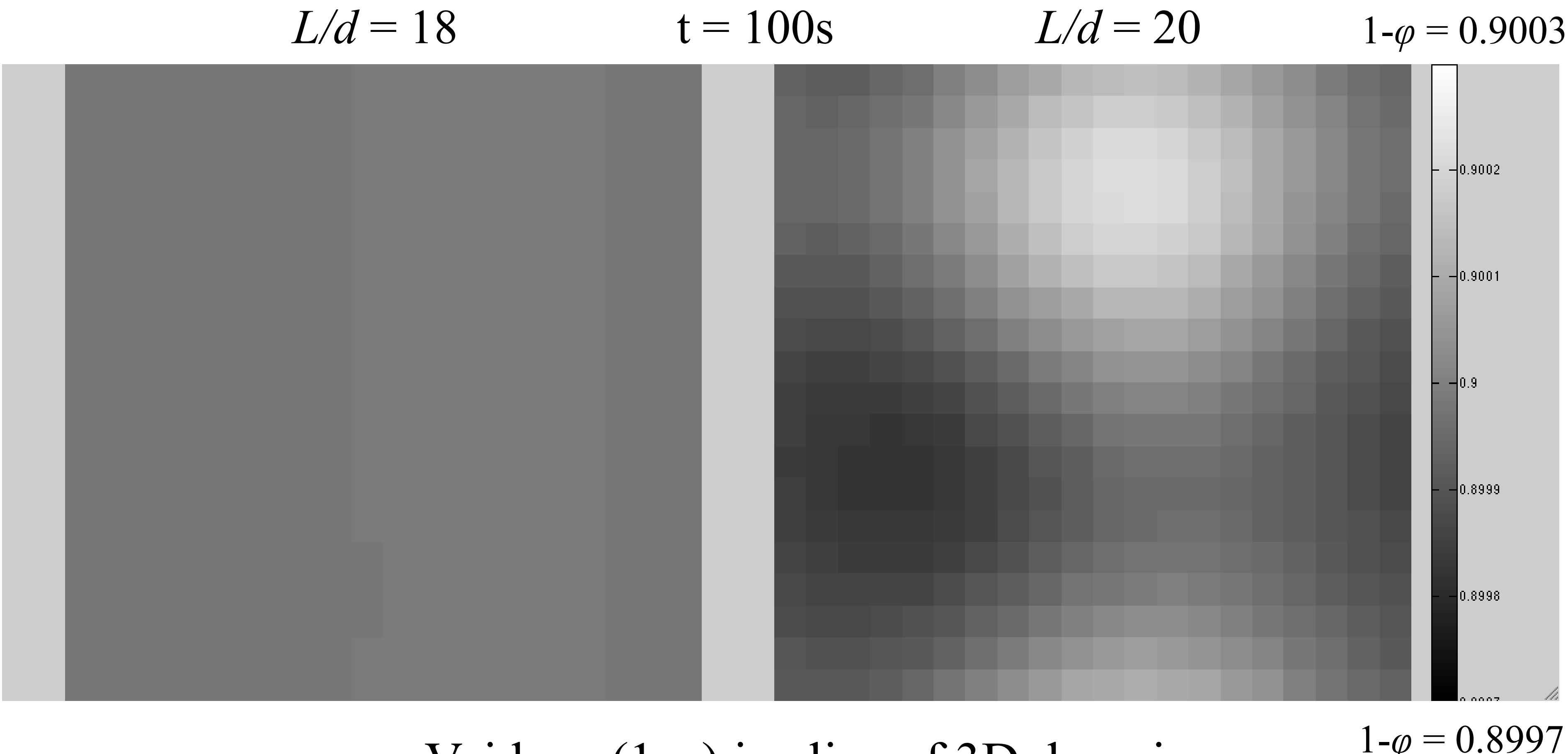
Goldhirsch, Tan, Zanetti, J. Sci. Comput. (1993)

Hydrodynamics vs. MD



Non-linear mechanisms (e.g. viscous heating) are important to cluster formation

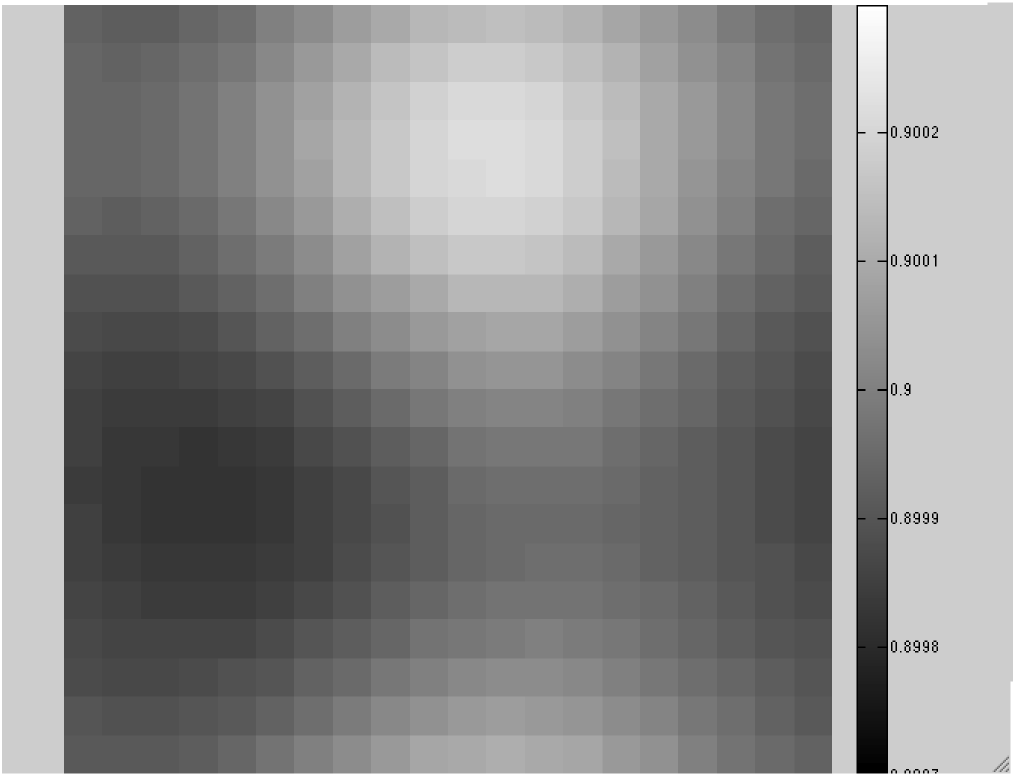
Hydrodynamics: Onset of Instability

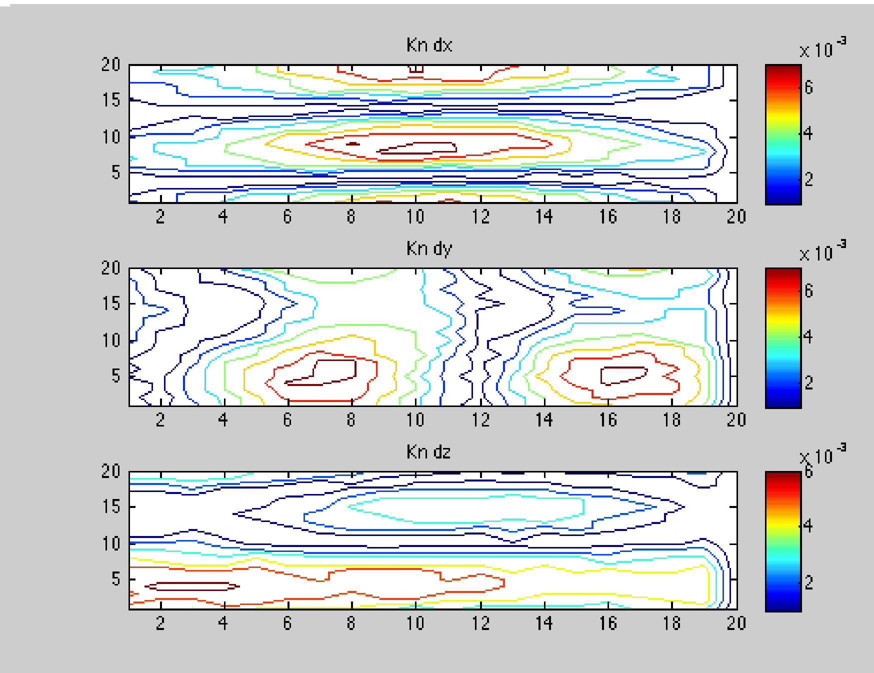


Voidage (1-φ) in slice of 3D domain

Hydrodynamics: Onset of Instability

Voidage $(1-\varphi)$ $\quad 1-\varphi = 0.9003$ $\quad$ Concentration Kn map





Concentration Kn ~10^{-3}

$1-\varphi = 0.8997$

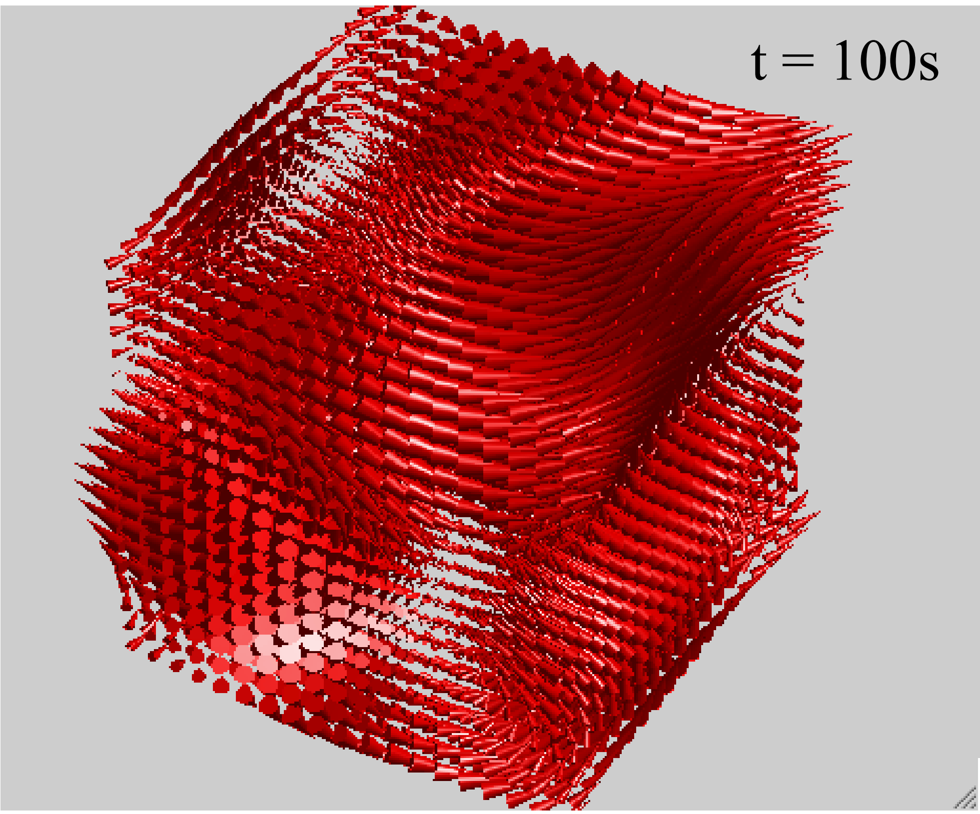
$L/d = 20$, t=100s

Hydrodynamics: Onset of Instability

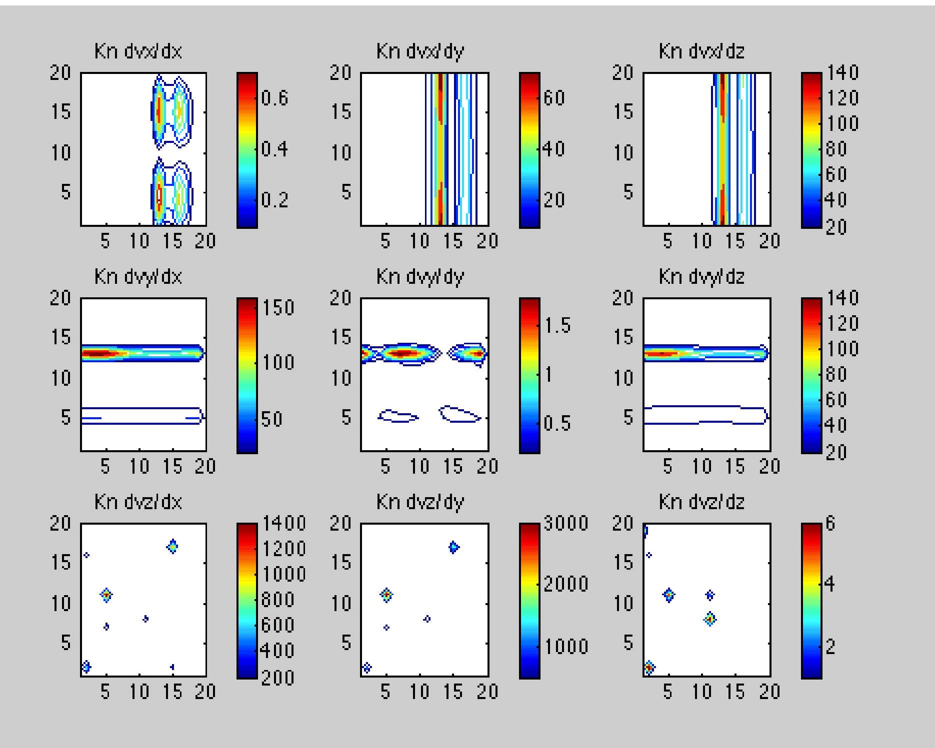
Velocity field

$L/d = 20$

Velocity Kn maps (2D slice)



t = 100s



Velocity Kn < $O(10^3)$

Small-Kn and molecular chaos assumptions not so restrictive to hydrodynamics

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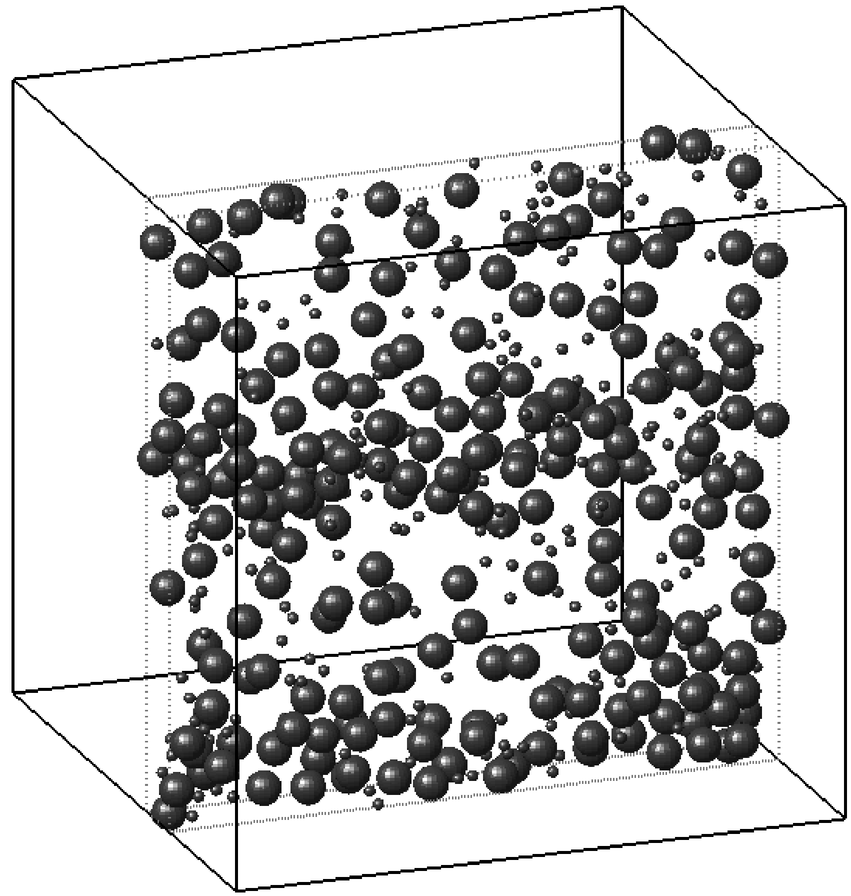
Binary Systems: Extra Input

- Diameter ratio
  - d_1/d_2
- Mass ratio
  - $\int = m_1/m_2$
- Number fraction
  - $x_1 = n_1/N$
  - n_1 = number of type 1 particles
  - N = total number of particles



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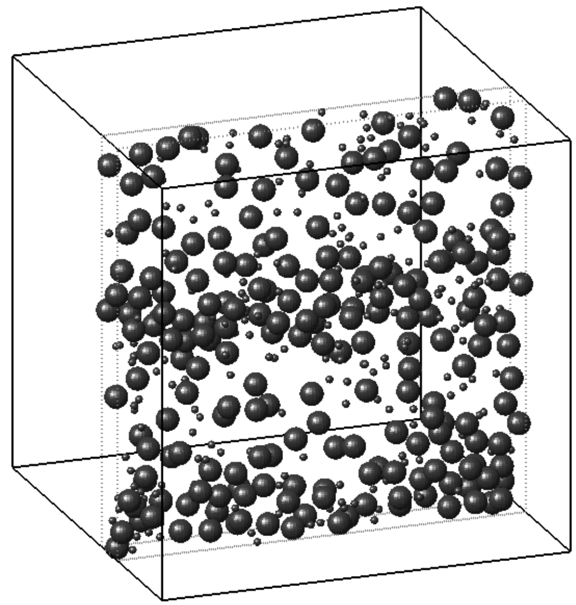

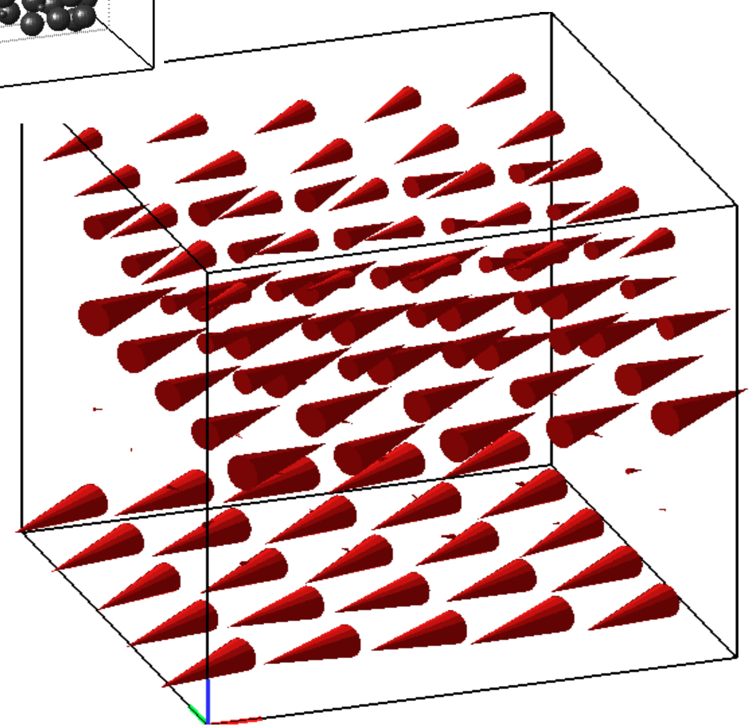

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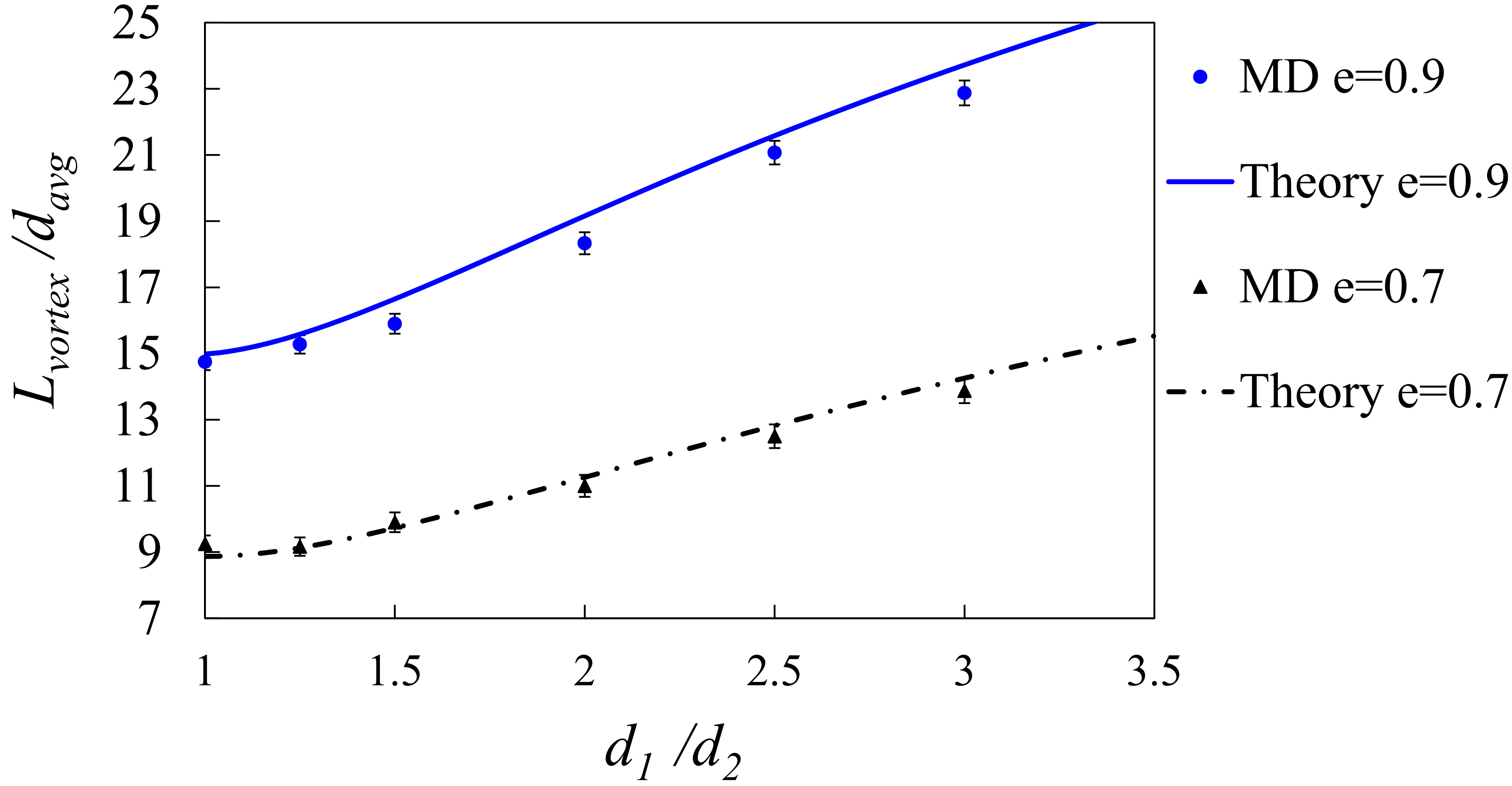
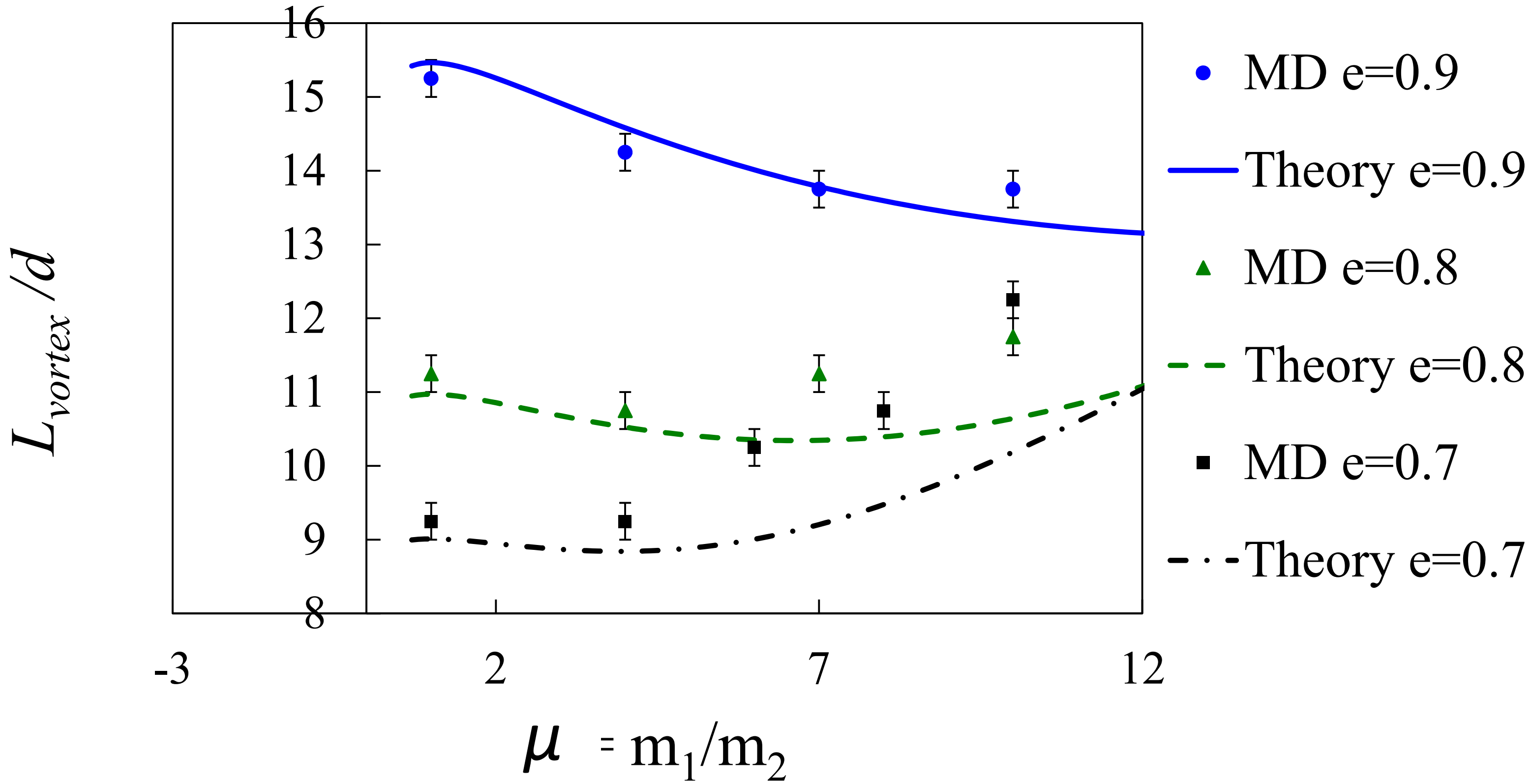
Diameter Ratio

$x_1 = n_1/N = 0.5$, $\mu = m1/m2 = 2$, $\phi = 0.2$



Mass Ratio

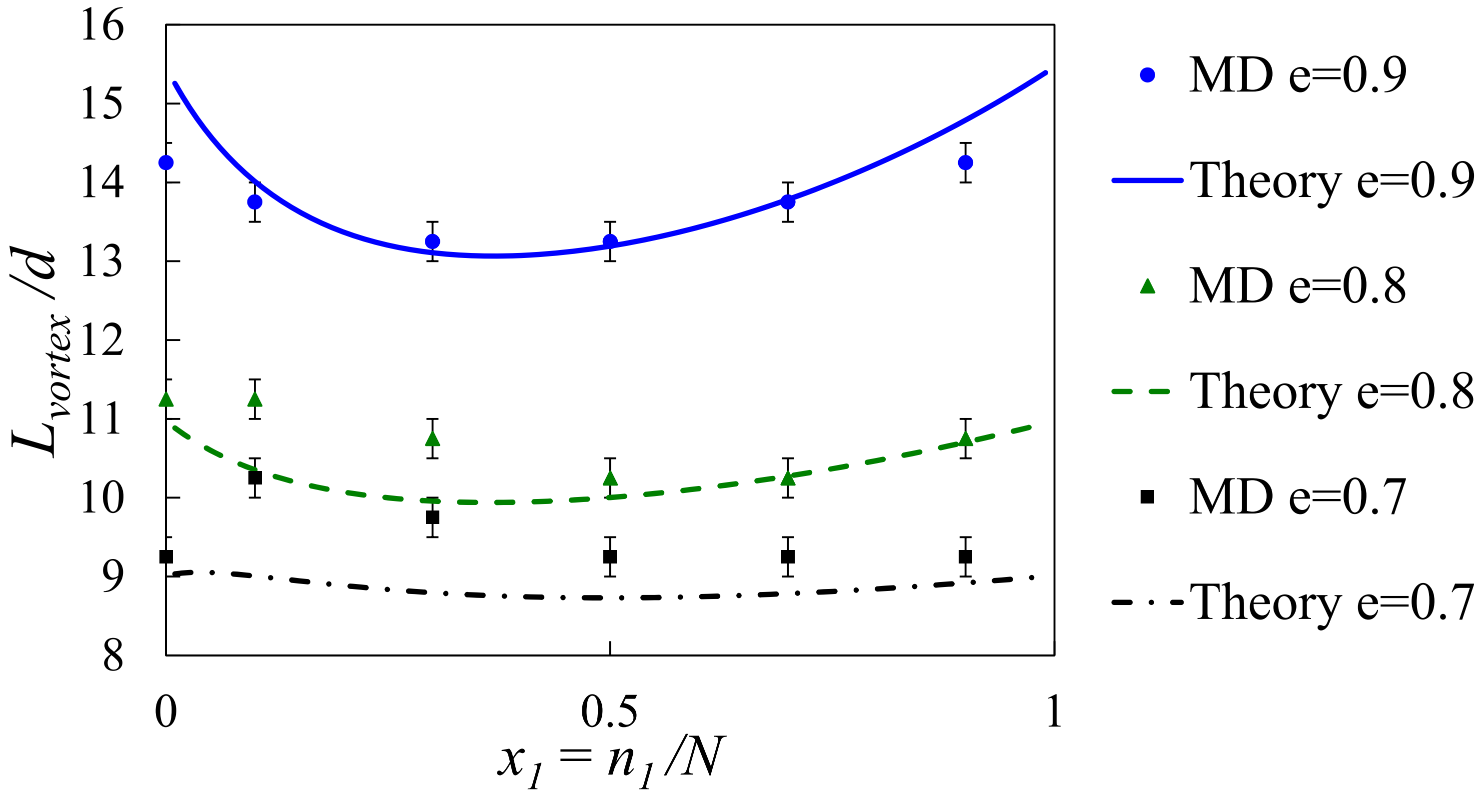
$d_1/d_2 = 1$, $x_1 = n_1/N = 0.1$, $\phi = 0.2$



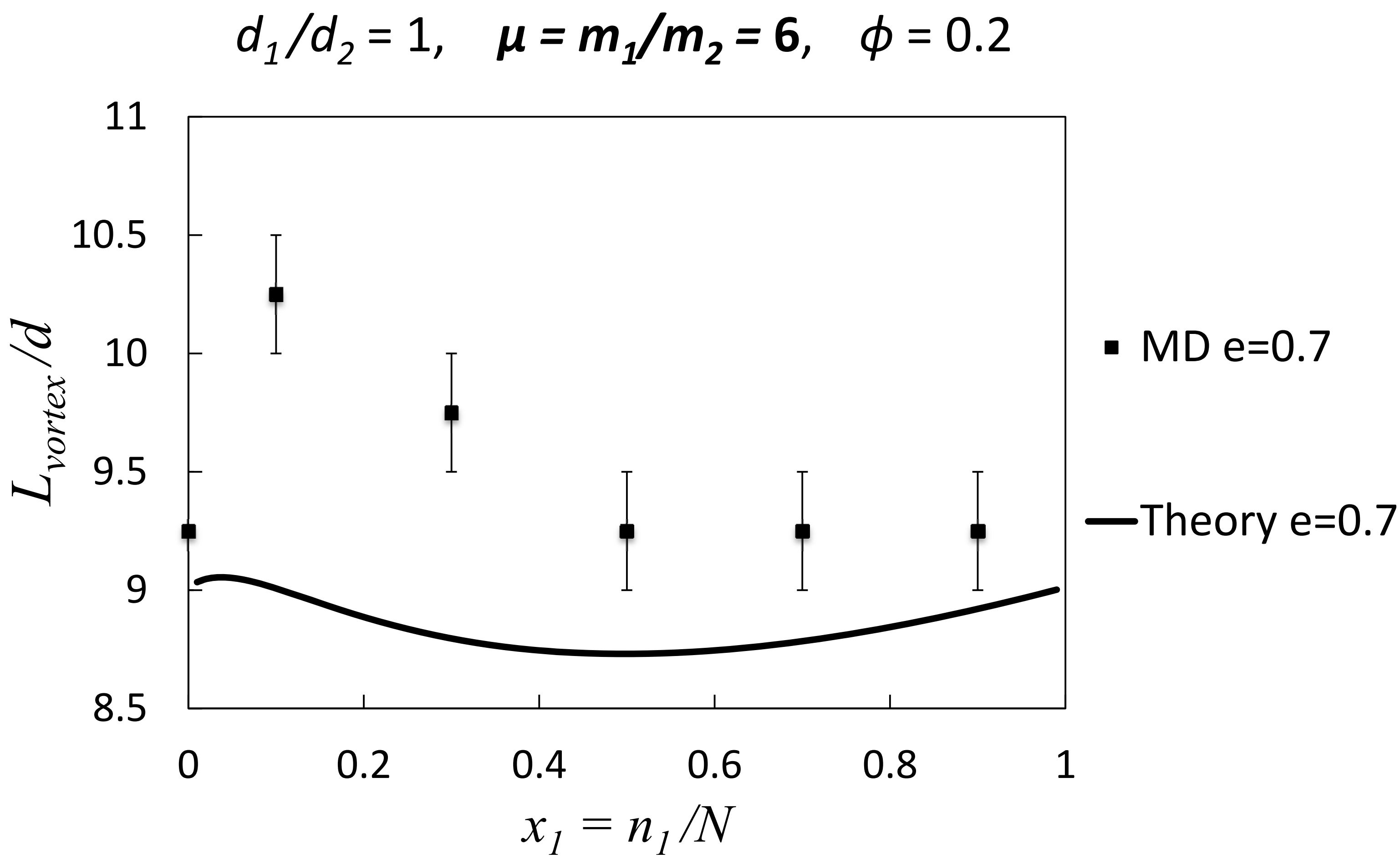
Theory does quite well until moderate dissipation is combined with disparate particle species

Number Fraction

$d_1/d_2 = 1$, $\boldsymbol{\mu = m_1/m_2 = 6}$, $\phi = 0.2$



Number Fraction: Zoomed In



Concluding Remarks

- Both dissipative collisions and viscous losses are important for conditions studied

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- More dissipative systems may actually possess highly levels energy due to vortices
- Molecular chaos and small Knudsen number assumptions not so restrictive
- Binary mixture hydrodynamics do well until moderate dissipation is combined with disparate species parameters

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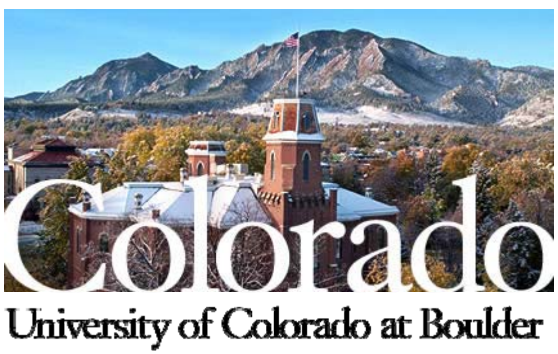

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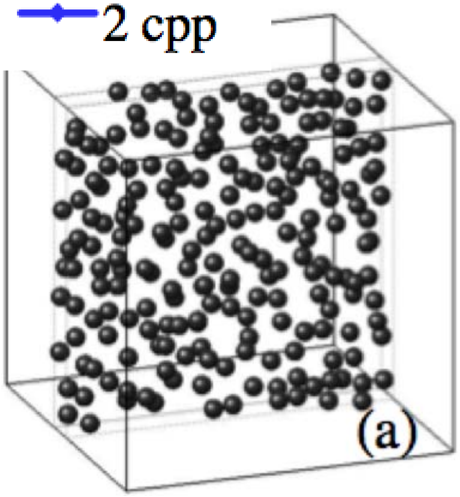
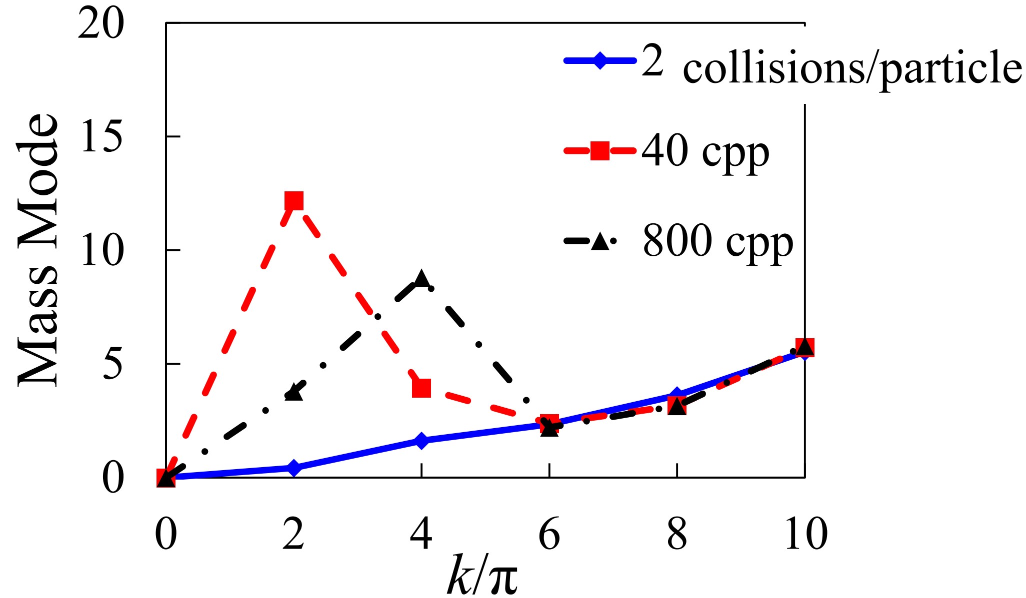
Lattice Boltzmann Information

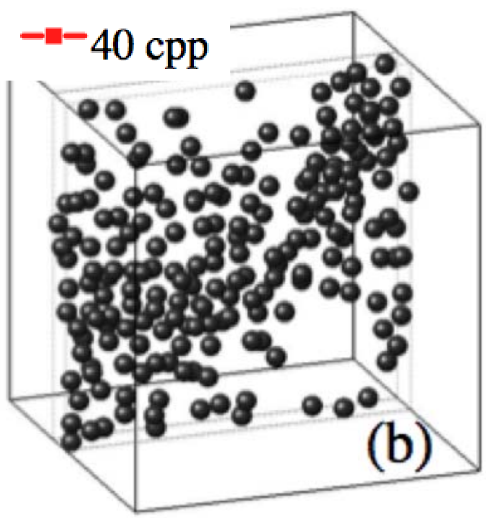
- Susp3D – A 3D particulate flow solver[1, 2]
  - Fluid flow is solved by a D3Q19 lattice Boltzmann model
  - Fluid-particle interaction is fully resolved
  - Particle motion is based on Newton's equation
- Particle-particle short-range interaction models
  - Lubrication interaction is implemented analytically[3]
  - Particle-particle collisions are treated as normal dissipative collisions between hard spheres (i.e. normal restitution, no friction)
- Simulation parameters
  - Domain size: 300(dx) × 300 (dx) x 40 (dx) where dx is the lattice spacing
  - Particle size: ~10(dx)
  - Fluid kinematic viscosity: 1/6 (dx^2/dt) at low Re and 1/100 (dx^2/dt) at high Re
- System parameters
  - Re: 1-30
  - Solid fraction: 0.1-0.4
  - Normal restitution coefficient: 0.8, 0.9, 1.0
  - Particle-fluid density ratio: 800, **1000**, 1500

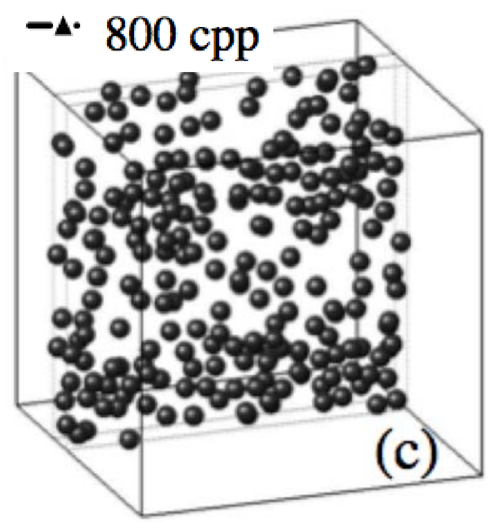
[1]*Ladd 1994a, 1994b, J. Fluid Mech.*
[2]*Ladd and Verberg 2001, J. Stat. Phys.*
[3]*Nguyen and Ladd 2002, Phys. Rev. E*

MD: Fourier Analysis





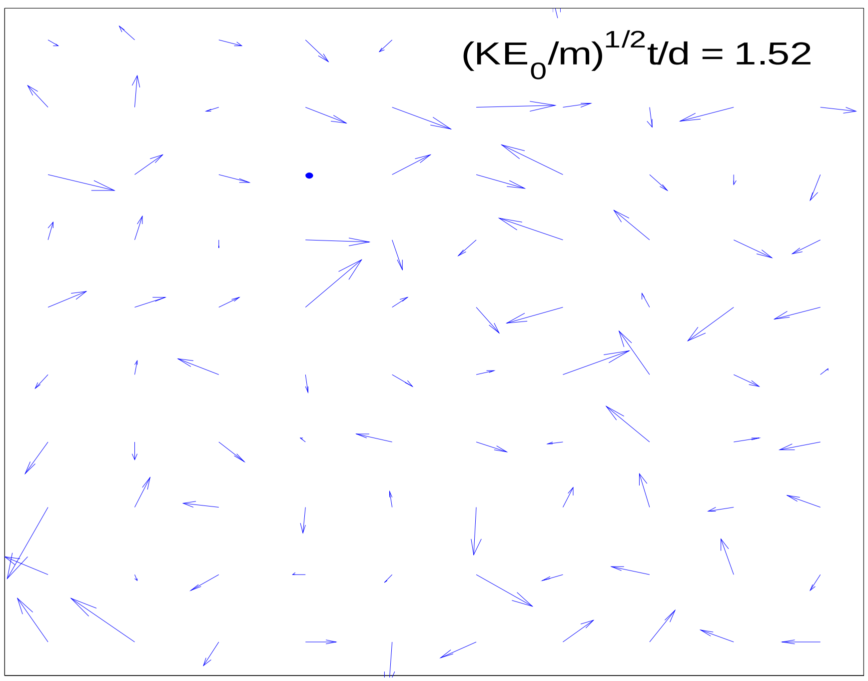


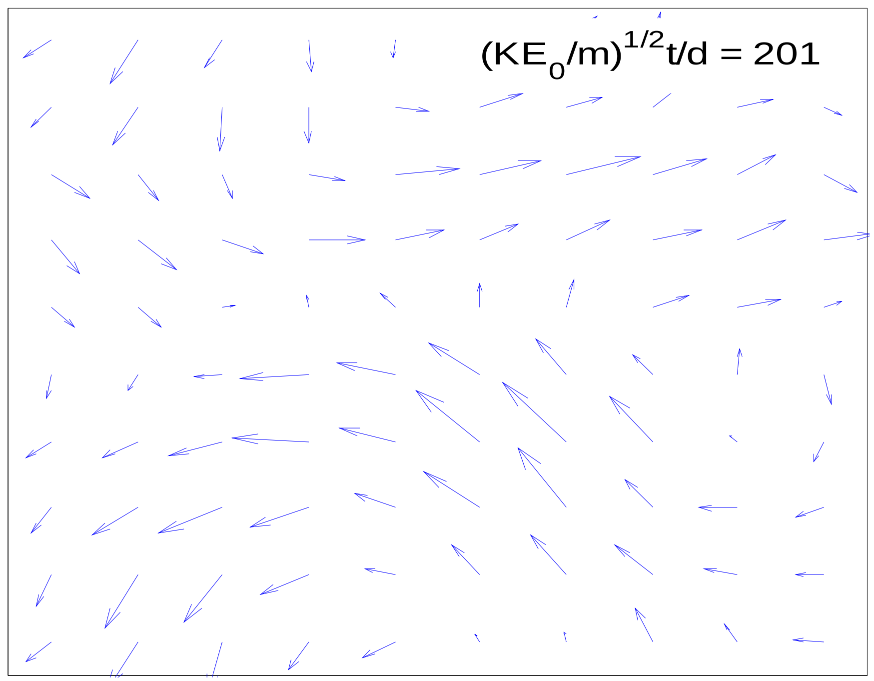


e=0.6, ϕ=0.2
N=2000

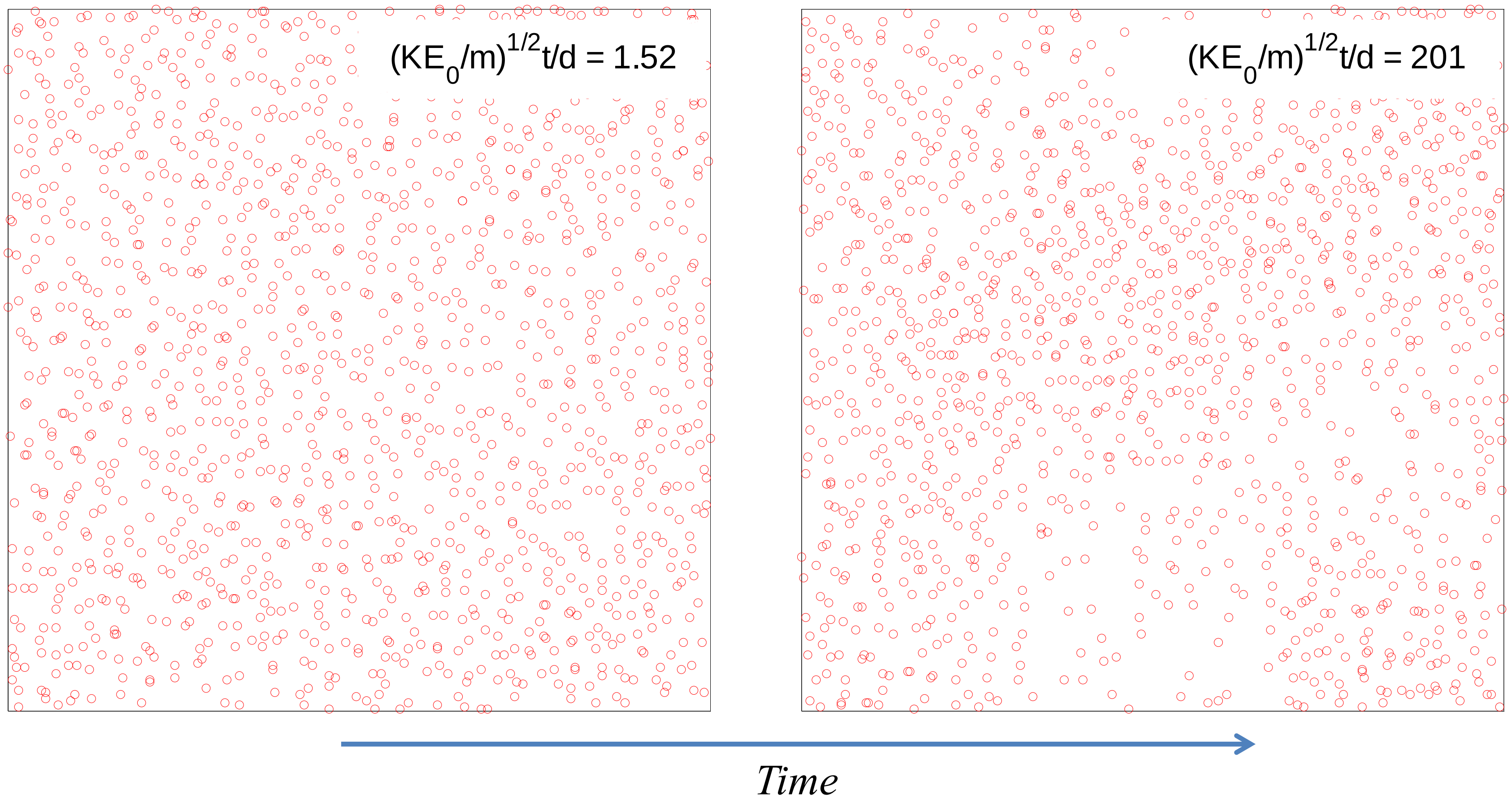
Mitrano et al.,
PRE (2012)

Velocity Vortices

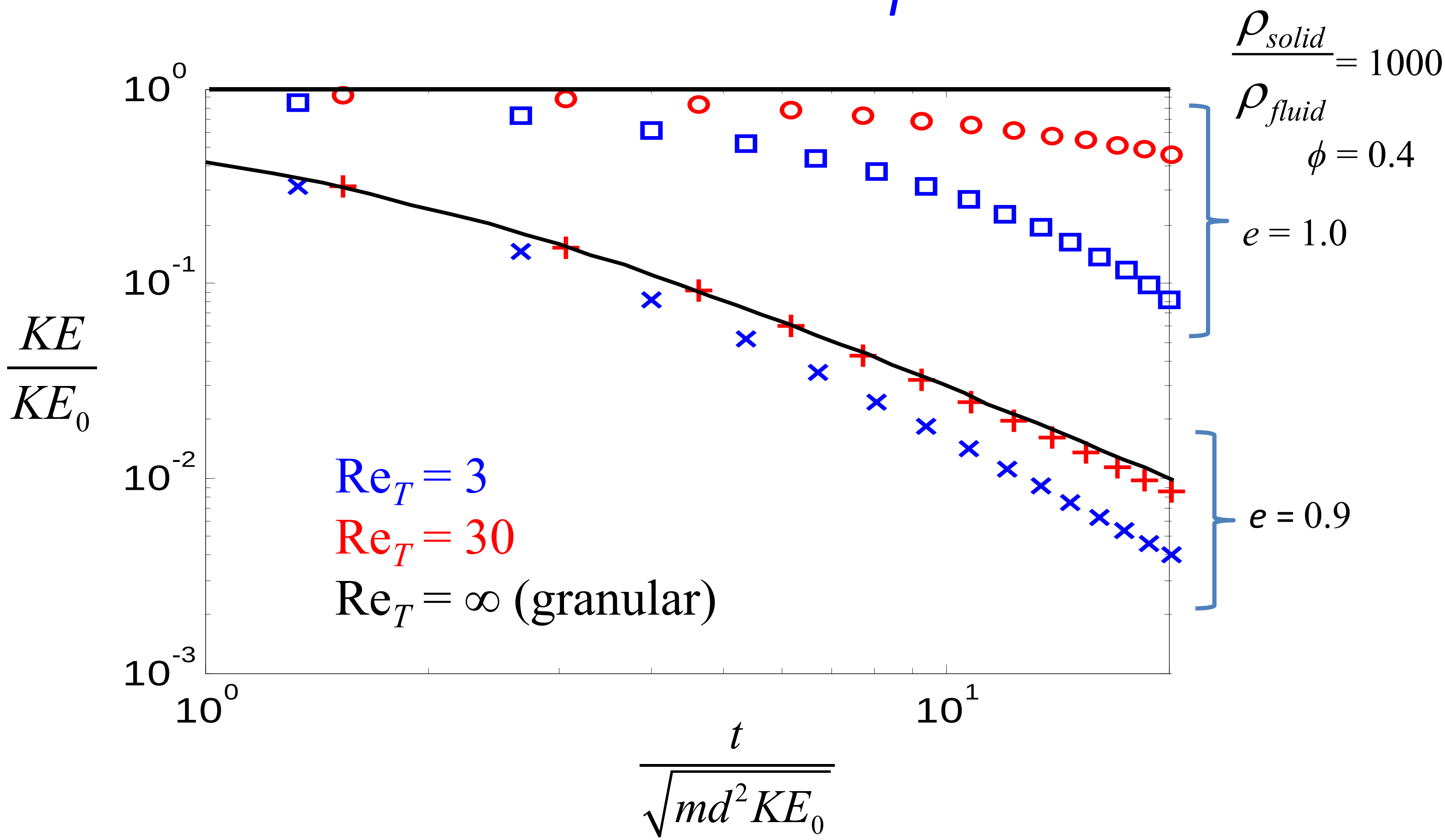




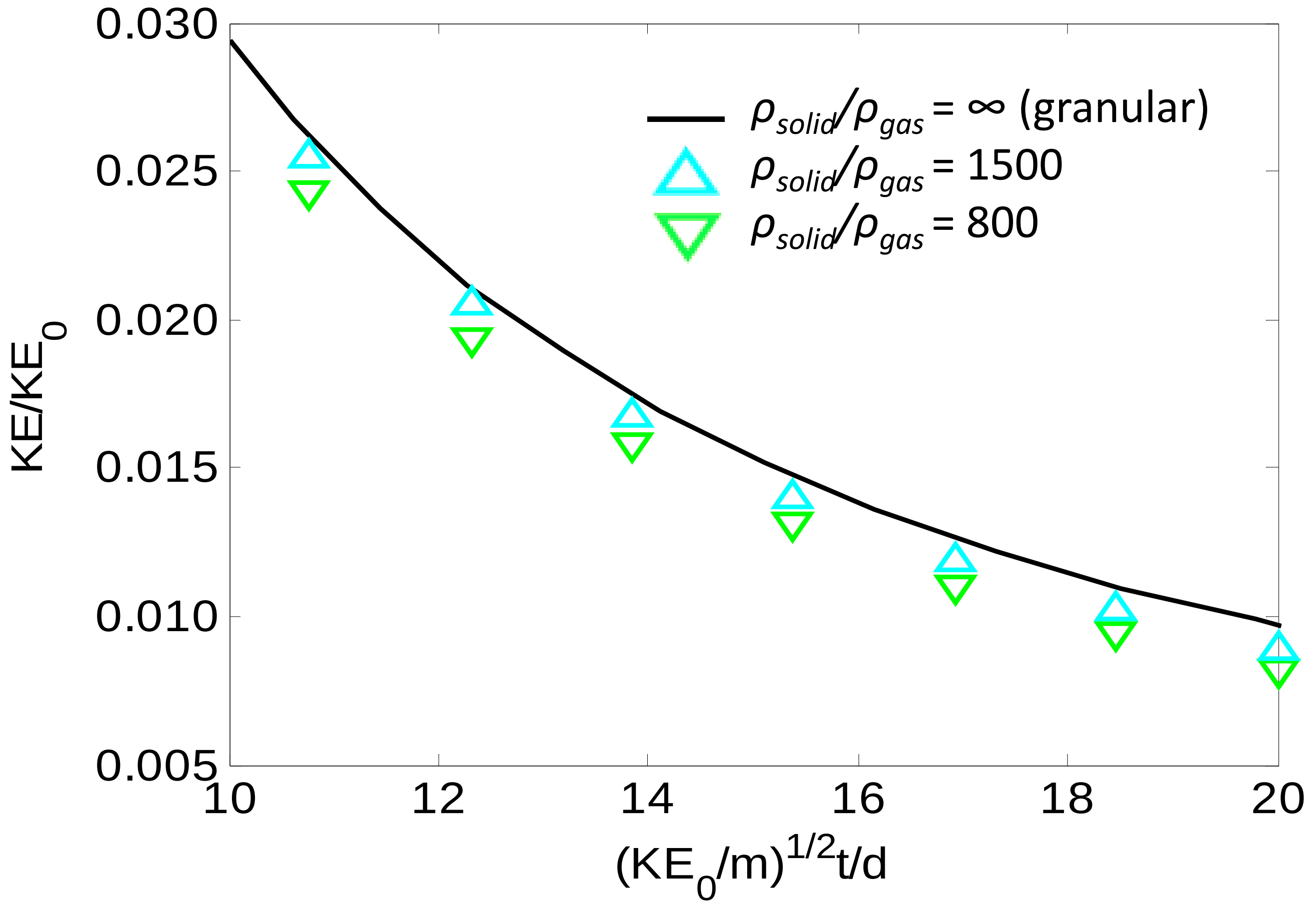
Particle Clusters



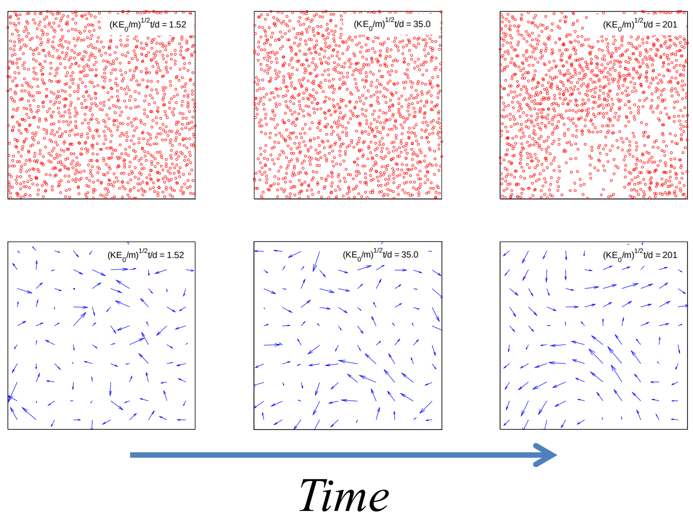
Influence of Re_T and *e*



Density Ratio

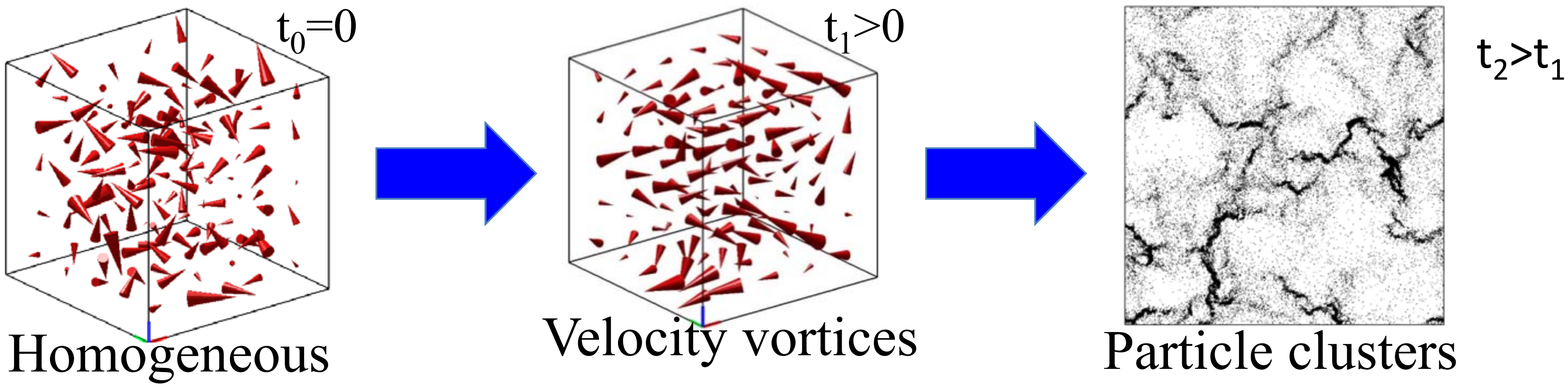


$e = 0.9$
$\varphi = 0.4$
$\mathrm{Re}_T = 30$


(KE0/m)1/2t/d = 1.52
(KE0/m)1/2t/d = 35.0
(KE0/m)1/2t/d = 201
(KE0/m)1/2t/d = 1.52
(KE0/m)1/2t/d = 35.0
(KE0/m)1/2t/d = 201
Time

Previous HCS work

Granular flow: *inelastic* solids; no gas (Goldhirsch 1993)



Gas-solid flow (Wylie & Koch 2000)

- *elastic* particles in viscous fluid flow

Focus: viscous effects