Still water
dead zone & collimated ejecta
in granular jet impact

Wendy W. Zhang
Nicholas Guttenberg, Herve Turlier,
Jake Ellowitz, Sidney R. Nagel

Physics Department & James Franck Institute
University of Chicago

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in Astrophysics and Material Science
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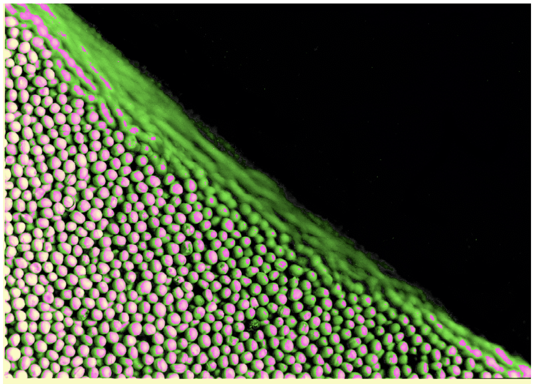
Introduction

Dense granular flow is complex

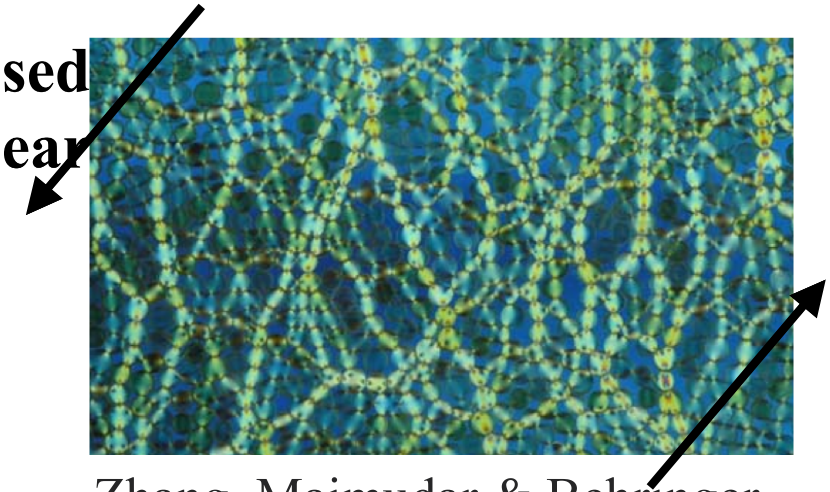
heterogeneous flow
avalanches



Jaeger, Nagel
mustard seeds

heterogeneous stress field
force networks

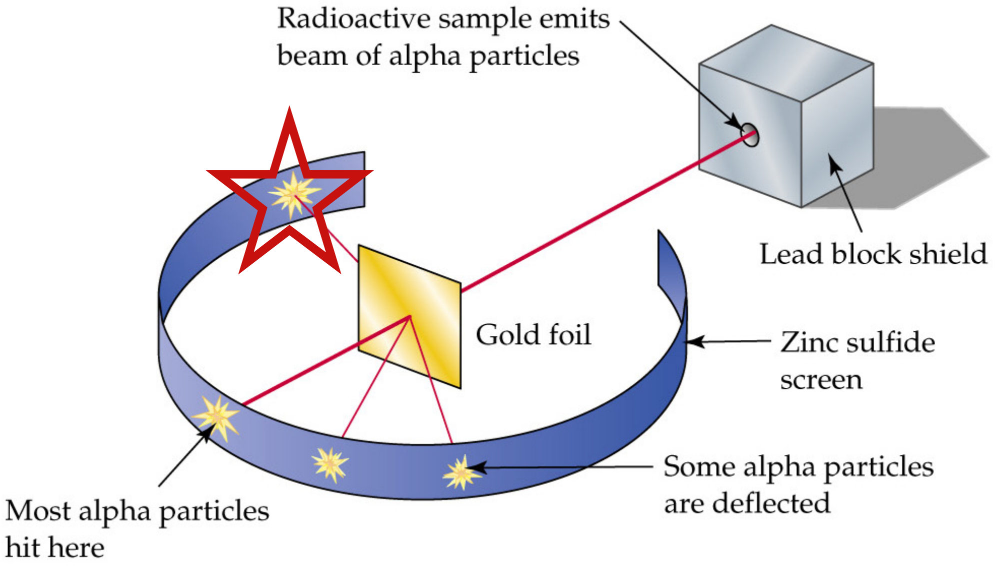
imposed
shear



Zhang, Majmudar & Behringer
photoelastic discs

Introduction

impact → scattering →structure



Rutherford's goldfoil scattering experiment
wikipedia

light scattering from infrared to x-ray
dense molecular beams in ultracold chemistry
relativistic particle beams in collider physics ...

Preview

Impact of dense granular jet

- ***Collimated (liquid-like) ejecta & interior dead zone***
- ***Different interior structure → same ejecta***
- ***Liquid-like response ← perfect fluid flow***
  dissipationless flow

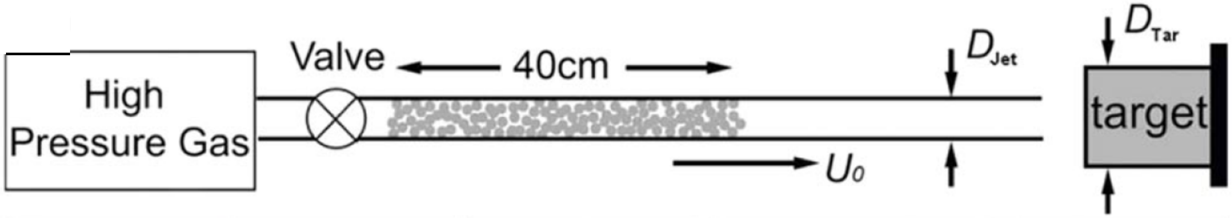
dissipation = frictional fluid

continuum flow remains non-Newtonian in limit towards dissipationless perfect fluid flow

Outline

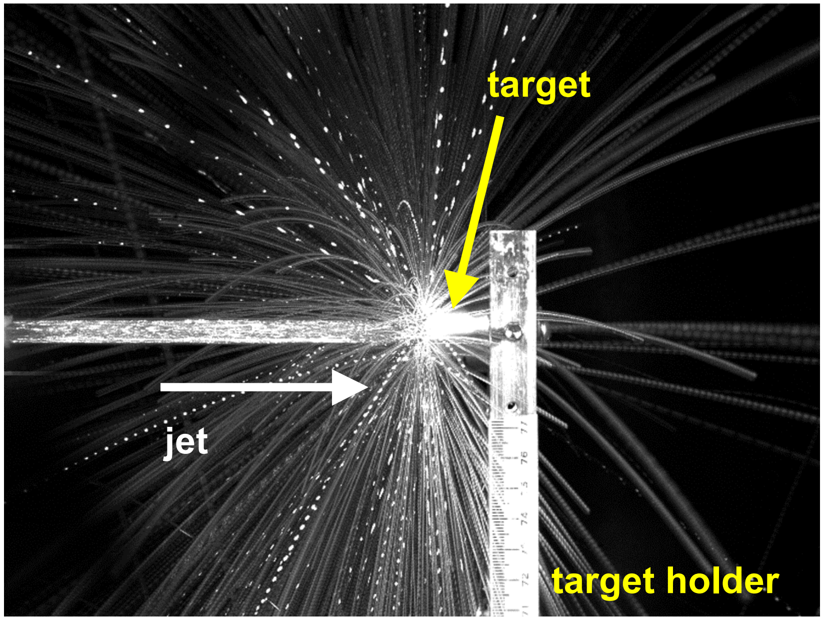
1. *Introduction*
2. *Background*
3. *Experiments & simulation*
4. *Model*
5. *Discussion & Conclusion*

Background: granular jet impact ➔collimated (liquid-like) ejecta

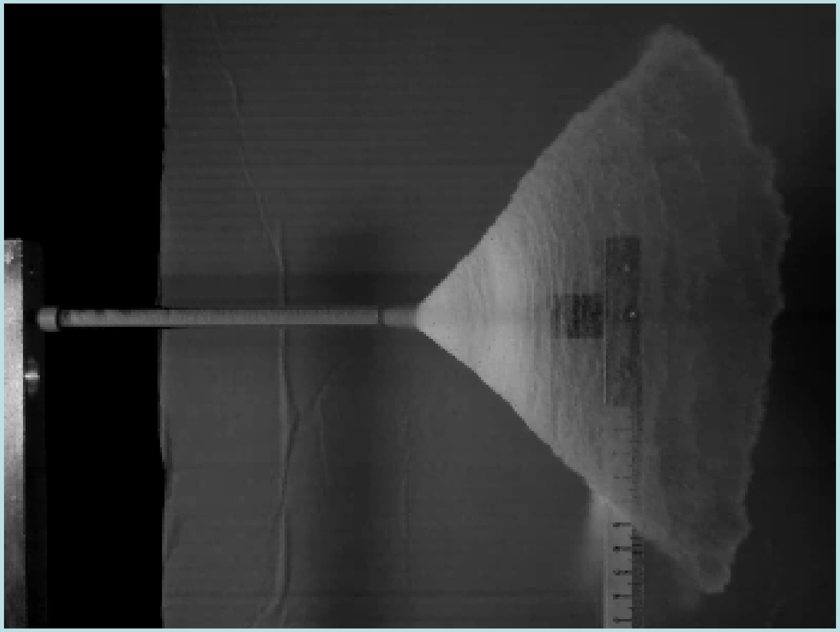


non-cohesive glass beads

Cheng et al. PRL 07

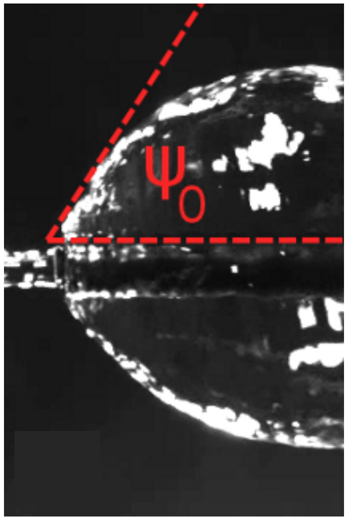


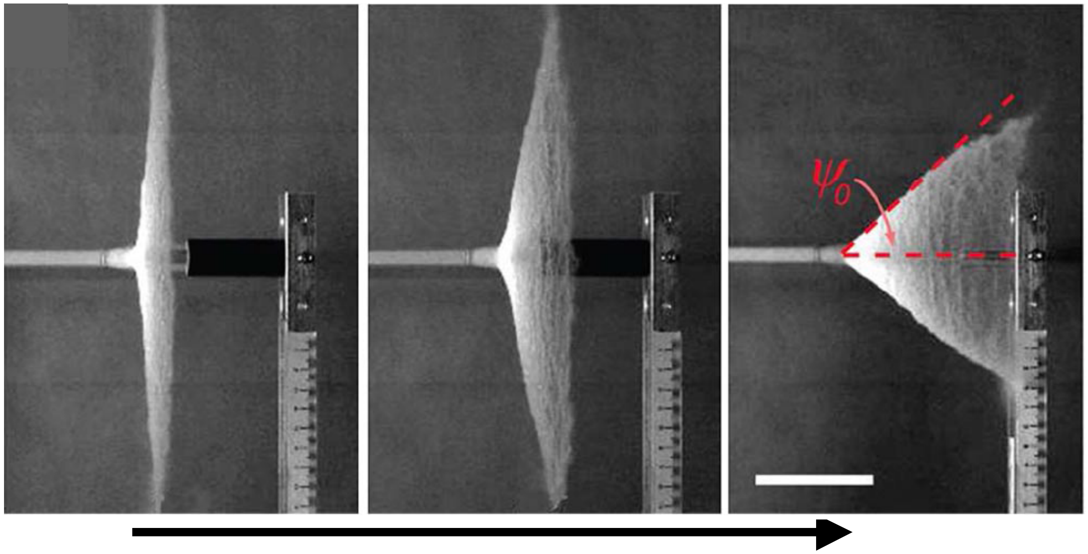
loosely packed jet
➔ shower of recoils



dense jet ➔ ejecta collimated hollow conical sheet

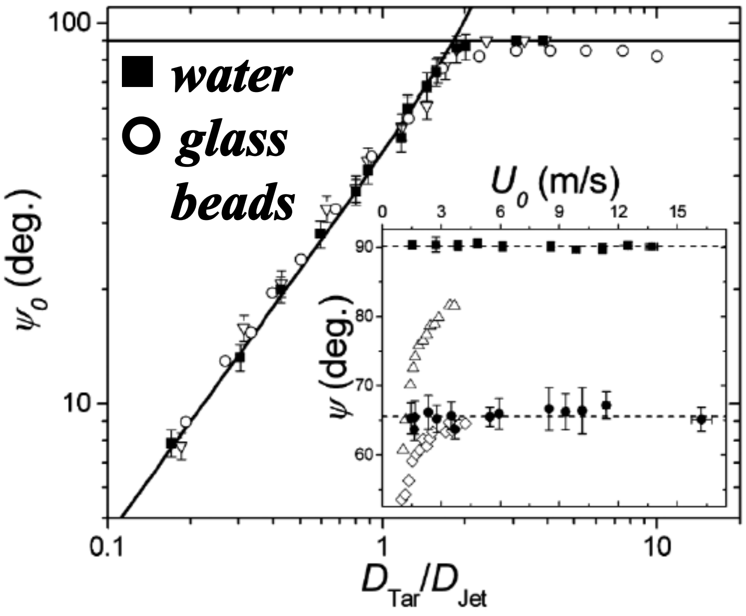
Ejecta sheet angle changes with D_{Tar}/D_{Jet}



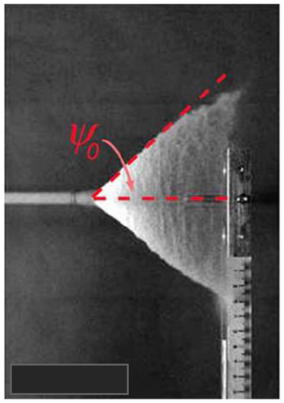


reducing D_{Tar}/D_{Jet}

Granular ejecta angle ψ_0 agree numerically with values for water jet ➔ liquid-like ejecta



Did impact create a liquid phase?

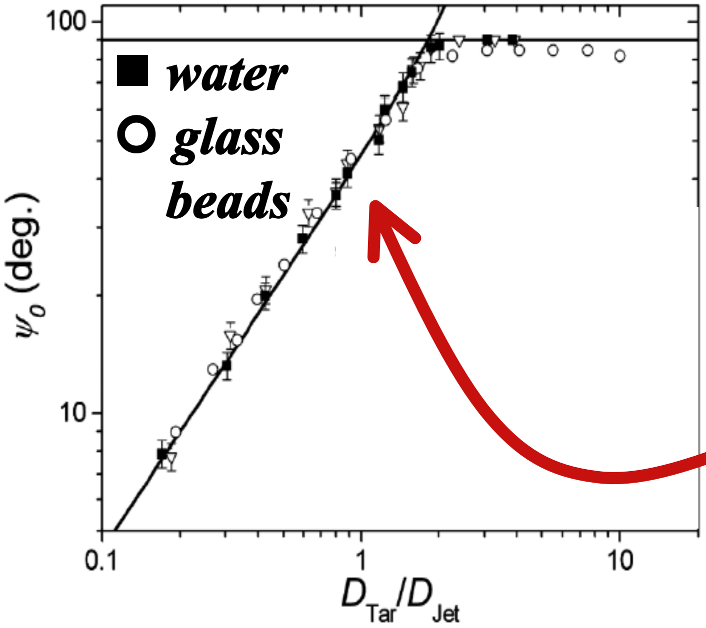


Momentum balance

dimensionless reaction force

$$\psi_0 = \frac{1 - A(D_{Tar}/D_{Jet})^2}{1 - B(D_{Tar}/D_{Jet})^2}$$

dimensionless drag force



When $D_{Tar} << D_{Jet}$

$$\psi_0 \approx 1 - (A - B)(D_{Tar}/D_{Jet})^2$$

Same ψ_0 ➔ same A-B

But individual values of A and B may differ

Context

- ***Elliptic flow: collimated ejecta from collision of gold ions at relativistic speeds ➔Liquid quark-gluon phase with Newtonian viscosity?***

- ***Formation of planetismals from dust aggregates via collisions***

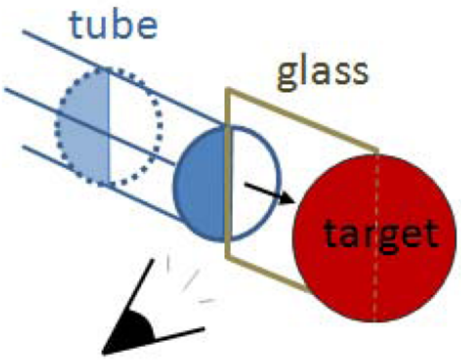
Pozkanser, Voloshin, Ritter... 2008 APS Bonner prize talk
Romatschke & Romatschke PRL 2007
Teiser & Wurm, Mon. Not. R. Astron. Soc. 2009

Outline

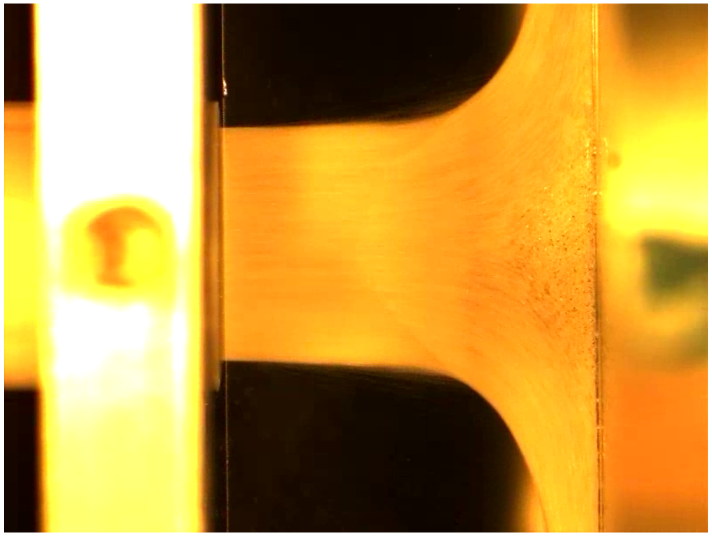
1. *Introduction*
2. *Background*
3. ***Experiments & simulation***

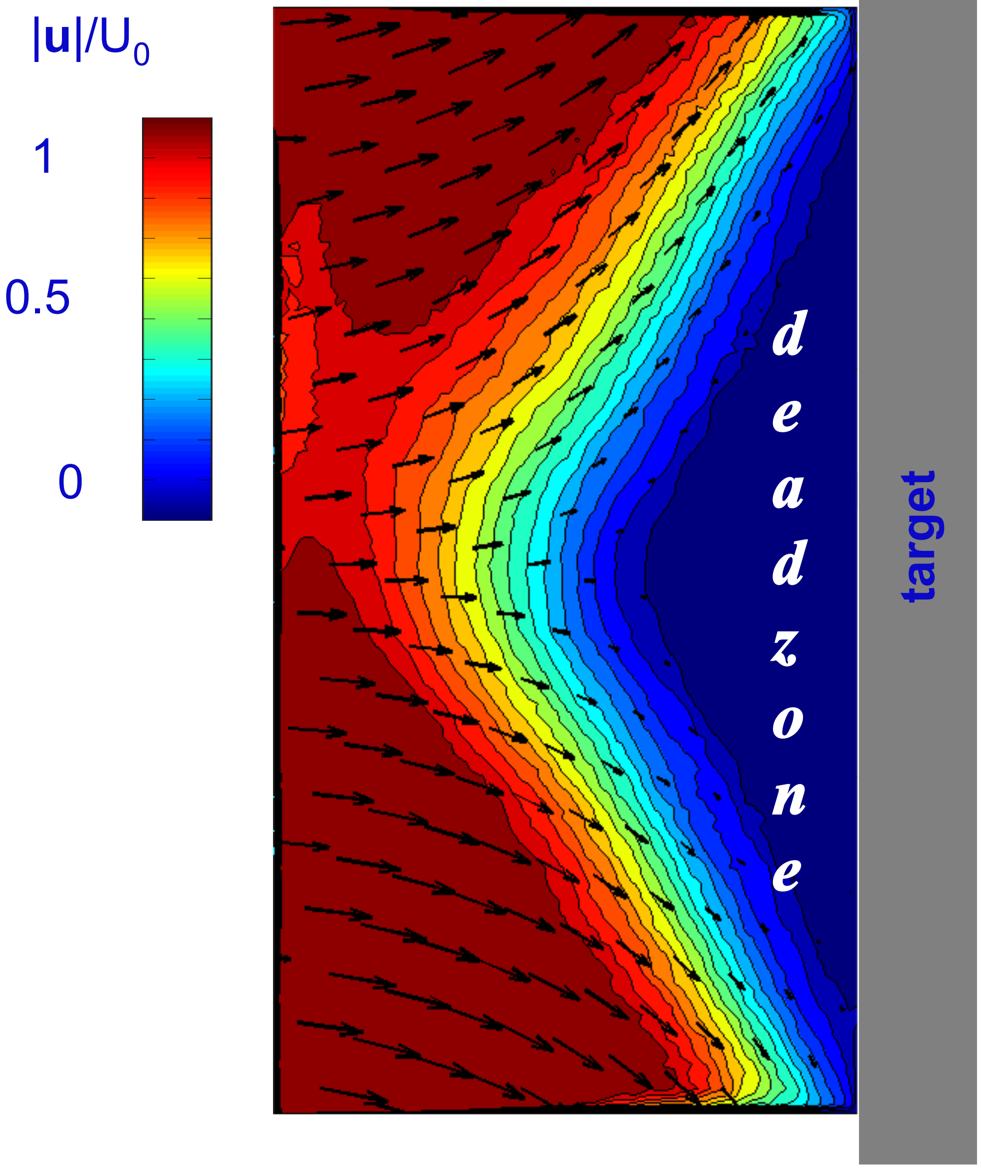
Experiment → jet interior is not liquid-like

Look at impact of half a jet pressed against glass

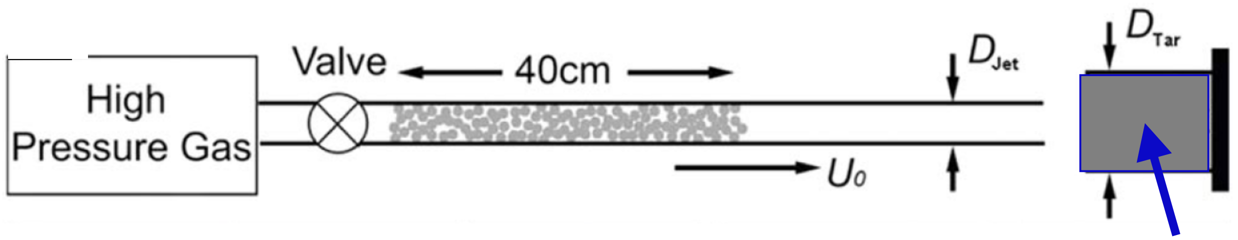


side-view of jet interior

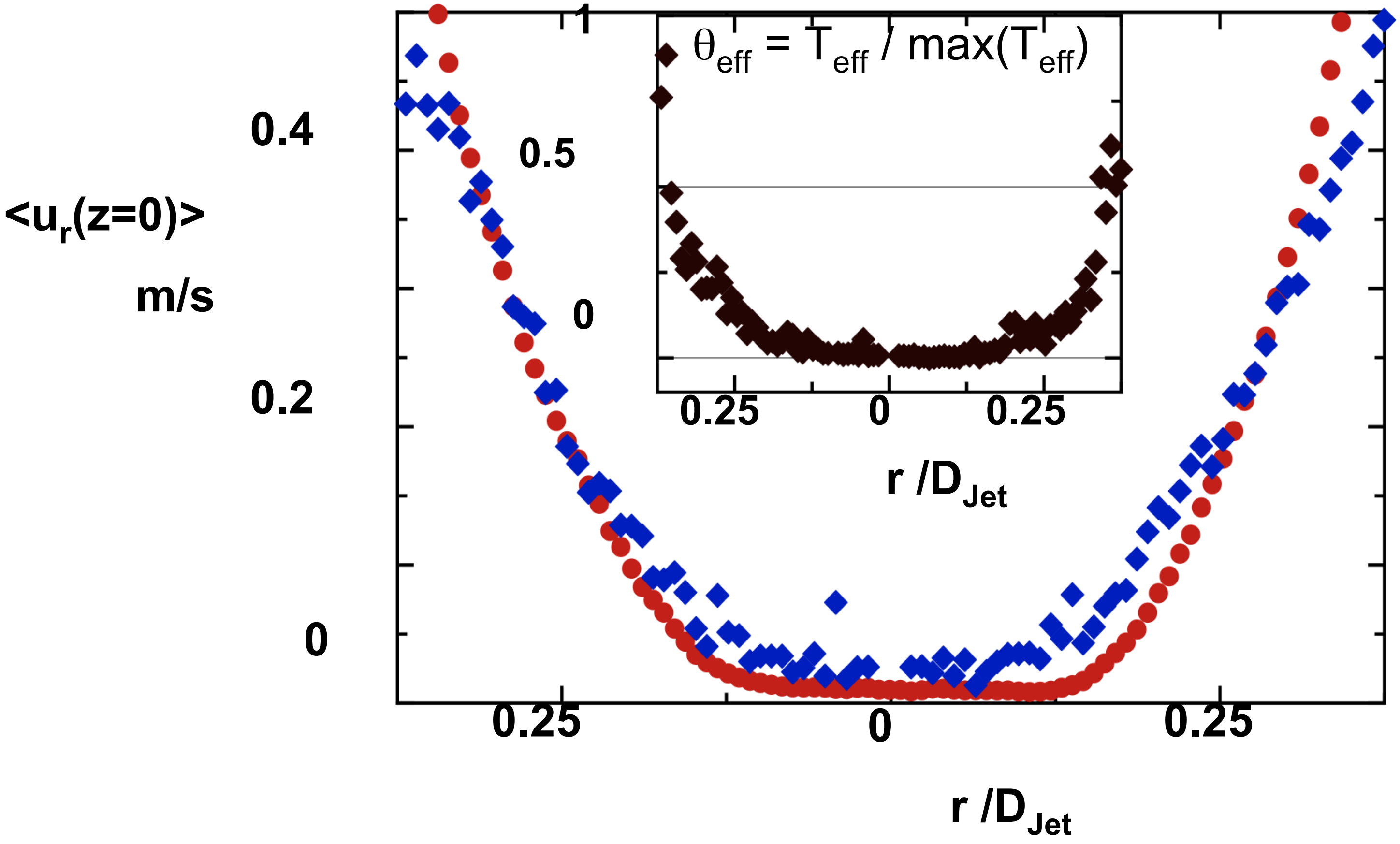


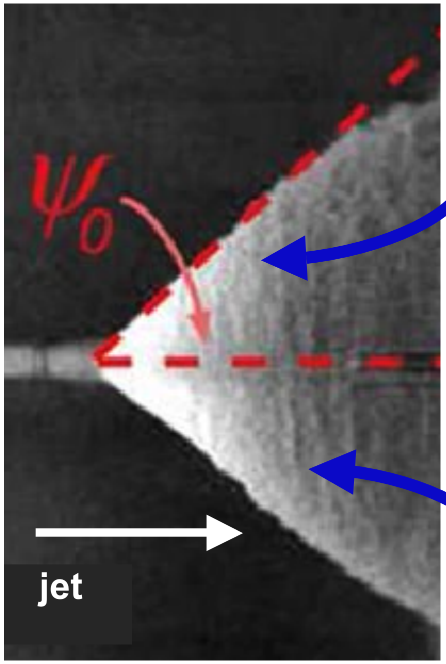


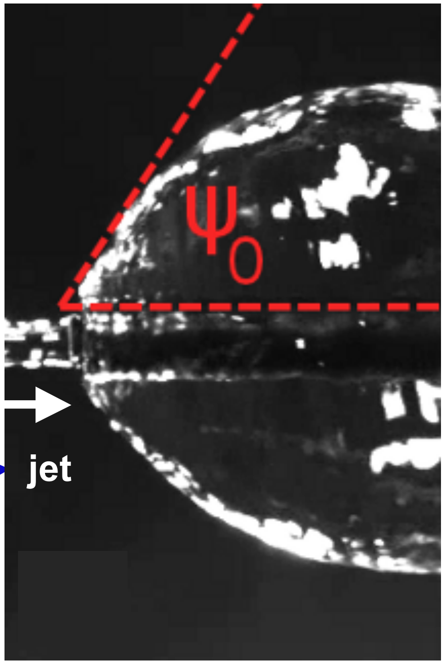
Experiment → dead zone is cold

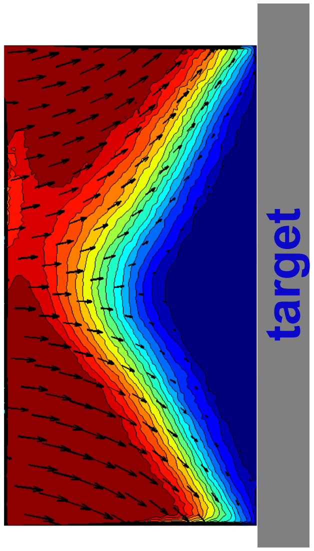


transparent target









$$\psi_0 \approx 1 - (A - B)(D_{Tar} / D_{Jet})^2$$

reaction force

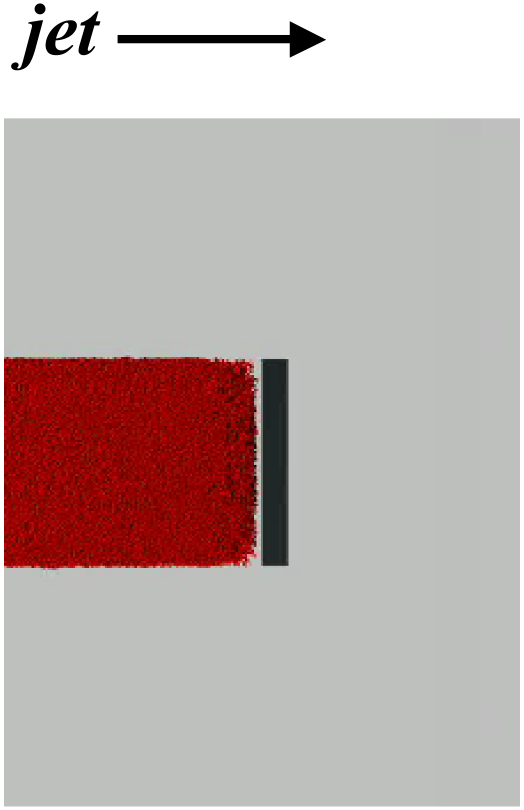
drag force

liquid-like ejecta

⇕ ?

interior structure

Simulation



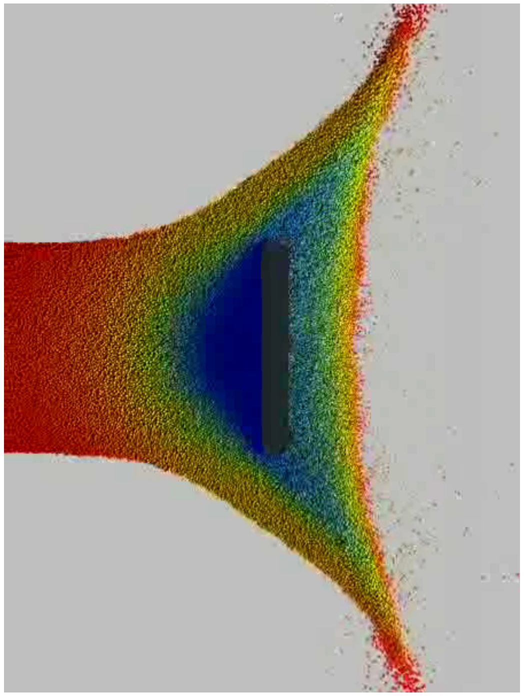
red = high speed
blue = zero speed

rigid grains
inelastic collisions
friction between grains

sticky target
    grains immobile after
    colliding with target

Simulation reproduces experiment

jet → *collimated ejecta*
dead zone



red = high speed
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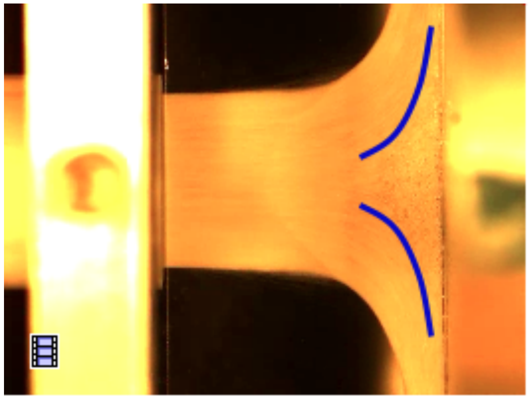
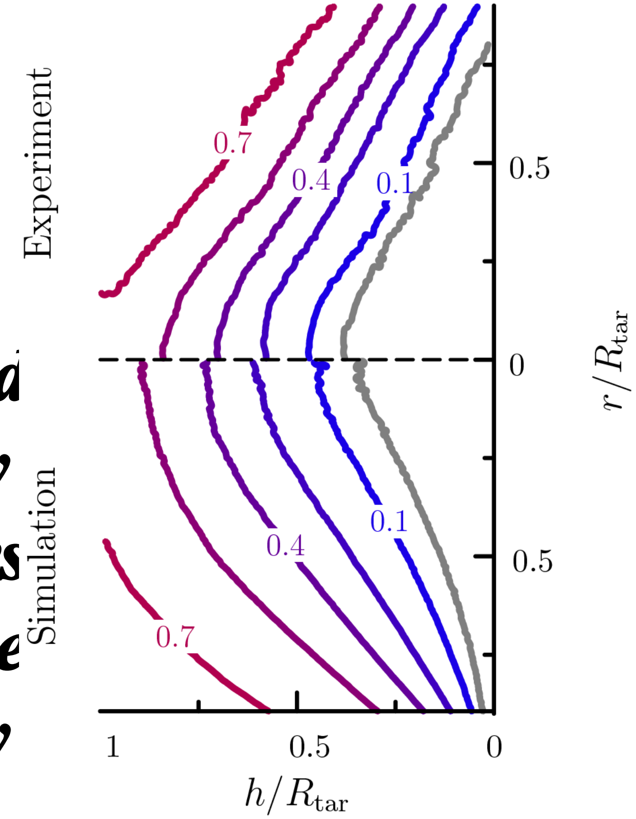
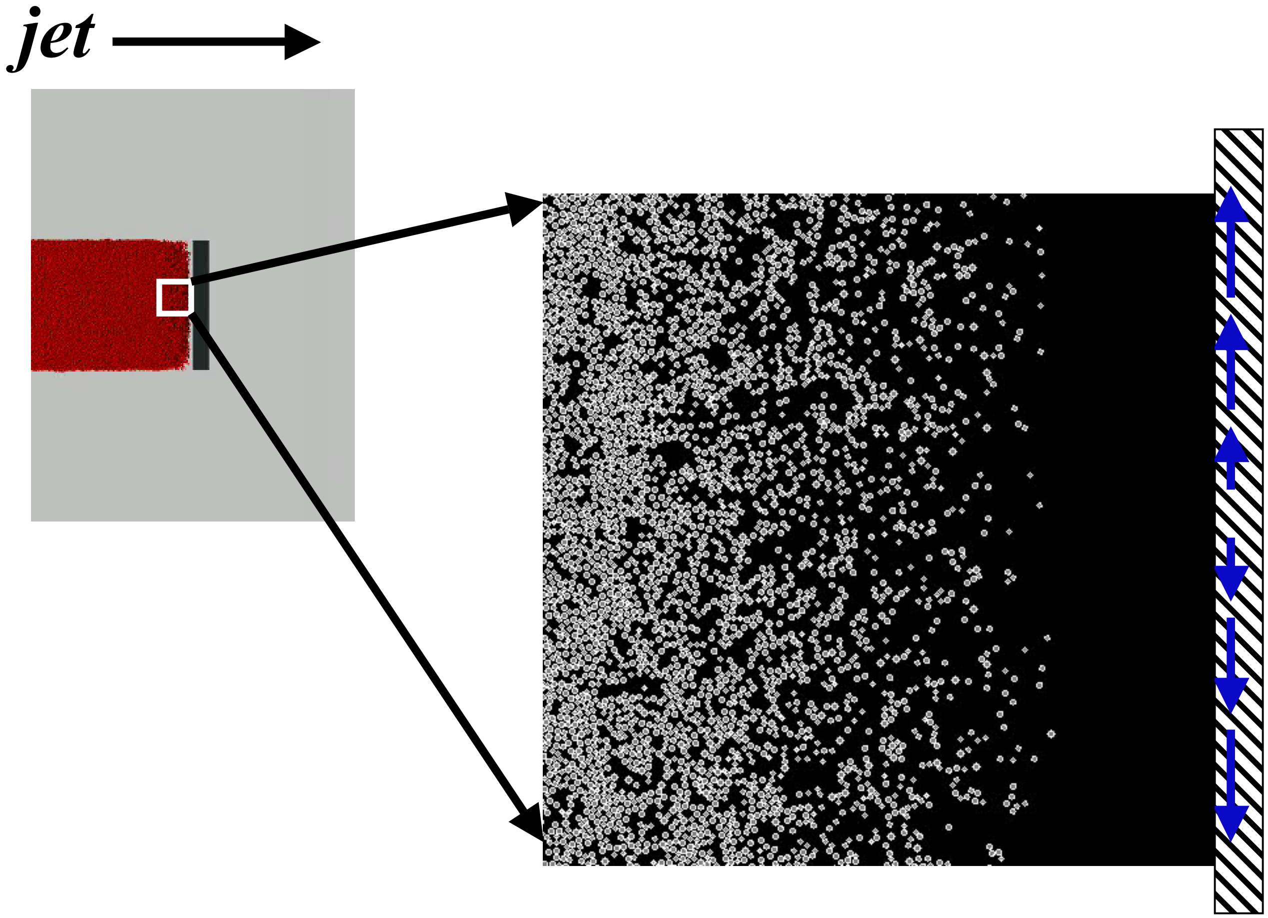




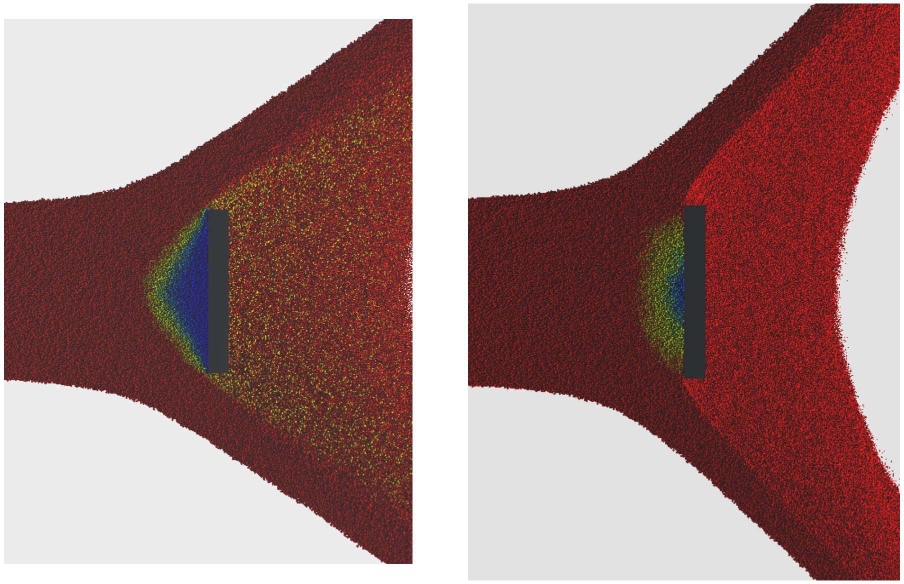
normalized velocity contours agree quantitatively

No dead zone at frictionless target

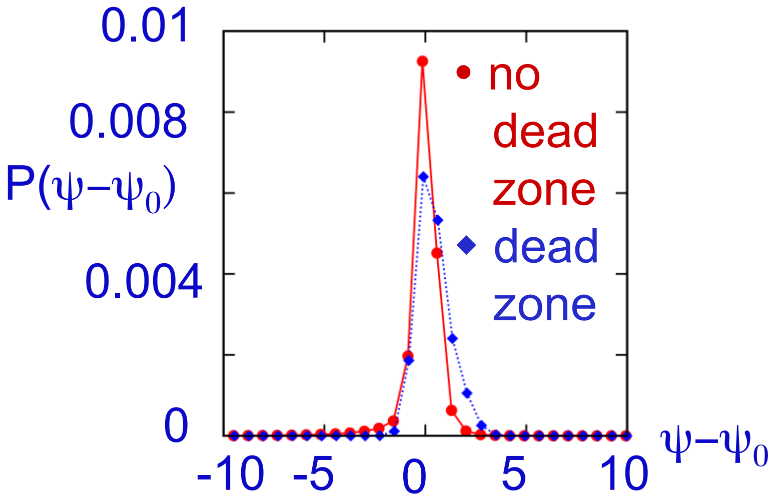


coeff. of restitution and/or friction between grains ➔ weak variation
Guttenberg (2011)

Different interior ➔Same ejecta



ejecta angle changes from
45° (with dead zone)
➔ 40° (without deadzone)



ejecta remains collimated

Outline

1. ***Introduction***
2. ***Background***
3. ***Experiments & simulation***

$$\psi_0 \approx 1 - \left(\underset{\substack{\nearrow \\ \textbf{reaction} \\ \textbf{force}}}{A} - \underset{\substack{\nwarrow \\ \textbf{drag} \\ \textbf{force}}}{B}\right)\left(D_{Tar}/D_{Jet}\right)^2$$

Same ψ_0 in granular & water jet impact

➔ liquid phase in granular jet? No

Ejecta ≠ scattering pattern (dilute regime)

Dense jet impact is different

➔ To see relevant limit, model as continuum
insted of simulating as hard spheres

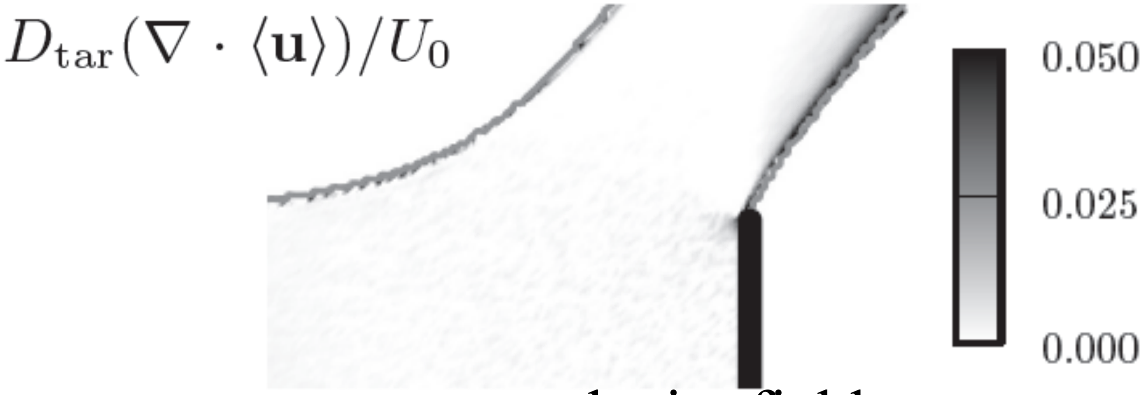
Frictionless target simulation results
➔ *continuum model of granular jet impact*

1. *Mass conservation*
2. *Energy conservation*
3. *Momentum conservation*

Not assuming hydrodynamic limit obtains
Phenomenological

Frictionless target simulation results
➔ *continuum model of granular jet impact*

1. Mass conservation



velocity field

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\mathbf{u})=0 \rightarrow \underline{\nabla\cdot\mathbf{u}=0}$$

density

incompressible flow

Frictionless target simulation results
➔ *continuum model of granular jet impact*

2. Energy conservation

granular temperature $T_{\mathrm{G}} = \rho_{\mathrm{jet}}(\langle u^2\rangle - \langle u\rangle^2)/2$

$T_{\mathrm{G}} \Big/ \rho_{\mathrm{jet}} U_0^2/2$

T_G = 0 flow

Frictionless target simulation results
➔ *continuum model of granular jet impact*

3. Momentum conservation

density × *acceleration* = *- pressure gradient* + *dissipation*

↑

$\nabla \cdot$ *(shear stress tensor)*

↑

shear stress = μ *pressure* $e_{\text{local shear direction}}$

↕

phenomenological friction coefficient

$$\rho\left(\frac{\partial}{\partial t}+\mathbf{u}\cdot\nabla\right)\mathbf{u}+\nabla p=\nabla\cdot\mu\,\frac{P}{|\dot{\gamma}^{d}|}\,\dot{\gamma}^{d}_{ij}$$

$$1/2\,(\partial_i v_j+\partial_j v_i)-1/2\,\dot{\gamma}_{kk}\delta_{ij}$$

Frictionless target simulation results ➔ continuum model of granular jet impact

1. ***Mass conservation***
2. ***Energy conservation***
3. ***Momentum conservation***

$$\nabla \cdot \mathbf{u} = 0$$

$$T_G = 0$$

$$\rho\left(\frac{\partial}{\partial t}+\mathbf{u}\cdot\nabla\right)\mathbf{u}+\nabla p=\nabla\cdot\mu\frac{P}{|\dot{\gamma}^d|}\dot{\gamma}_{ij}^d$$

Incompressible frictional fluid

Boundary conditions:

At unknown jet surface, normal stress and tangential stress both 0

At target, tangential and normal velocity both 0

Frictionless target simulation results
→ continuum model of granular jet impact

1. **Mass conservation**
2. **Energy conservation**
3. **Momentum conservation**

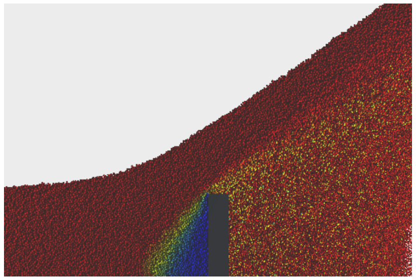
$$\nabla \cdot \mathbf{u} = 0$$

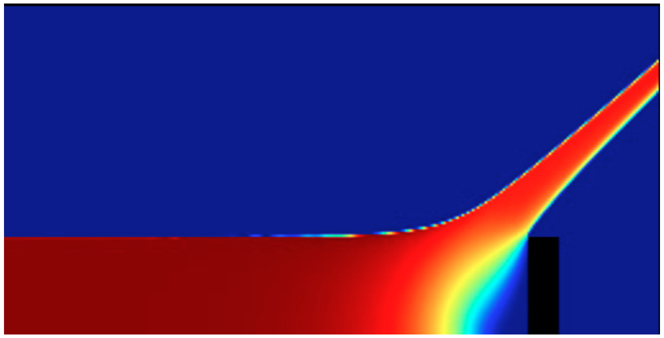
$$T_G = 0$$

$$\rho\left(\frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla\right)\mathbf{u} + \nabla p = \nabla \cdot \mu \frac{P}{|\dot{\gamma}^d|}\dot{\gamma}^d_{ij}$$

Incompressible frictional fluid

hard sphere simulation





Choose μ to fit simulated ψ_0 quantitatively reproduces u(x) & p(x) in hard sphere simulation

Frictionless target simulation results
➔ *continuum model of granular jet impact*

1. ***Mass conservation*** $\nabla \cdot \mathbf{u} = 0$
2. ***Energy conservation*** $T_G = 0$
3. ***Momentum conservation***

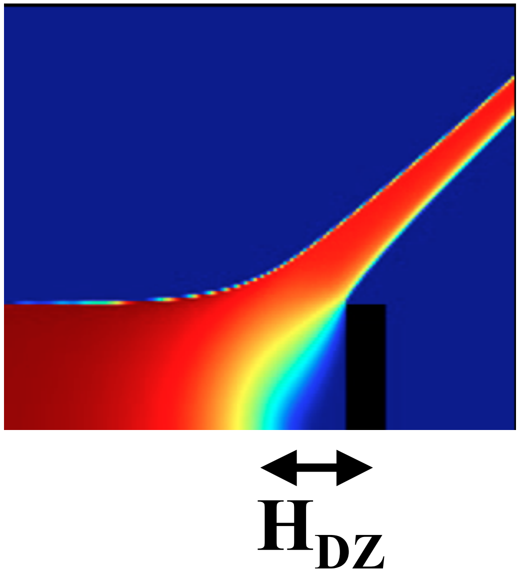
$$\rho\left(\frac{\partial}{\partial t}+\mathbf{u}\cdot\nabla\right)\mathbf{u}+\nabla p=\nabla\cdot\xcancel{\mu\frac{P}{|\gamma^d|}}\dot{\gamma}^d_{ij}$$

Dissipationless perfect fluid flow emerges when we take the limit μ ➔ 0

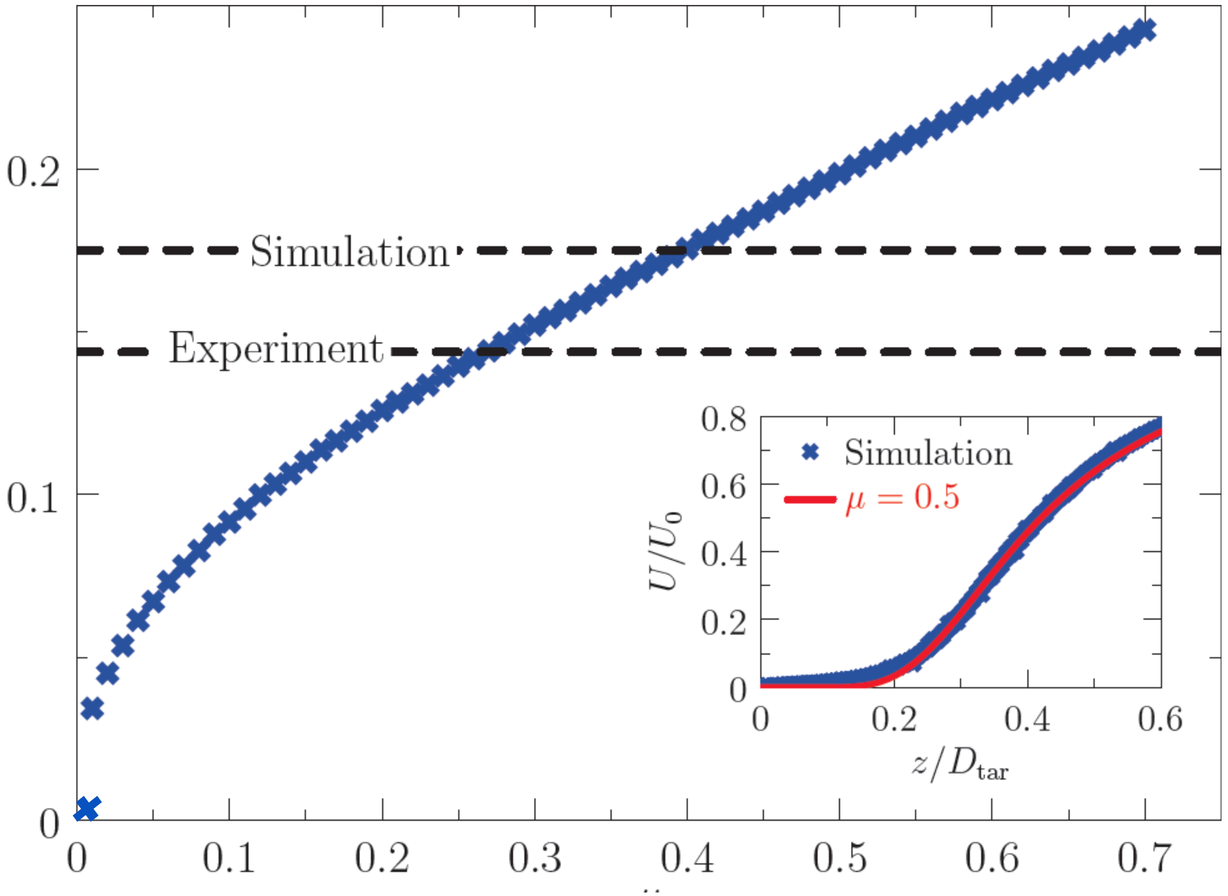
$$\rho\left(\frac{\partial}{\partial t}+\mathbf{u}\cdot\nabla\right)\mathbf{u}+\nabla p=0$$

Continuous approach instead of abrupt change

Deadzone shrinks continuously to 0 as μ → 0

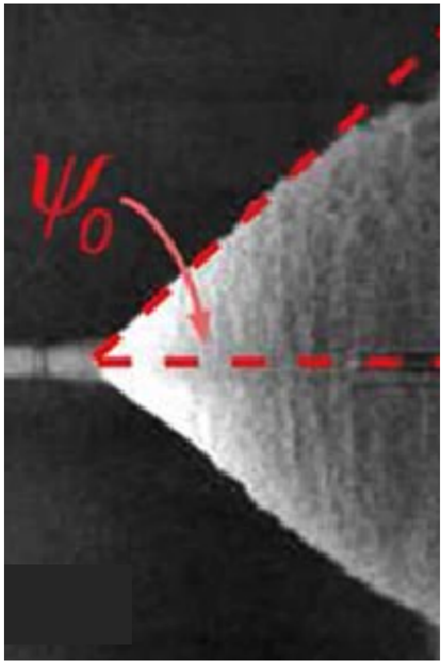


$$\frac{H_{DZ}}{D_{Tar}}$$



μ

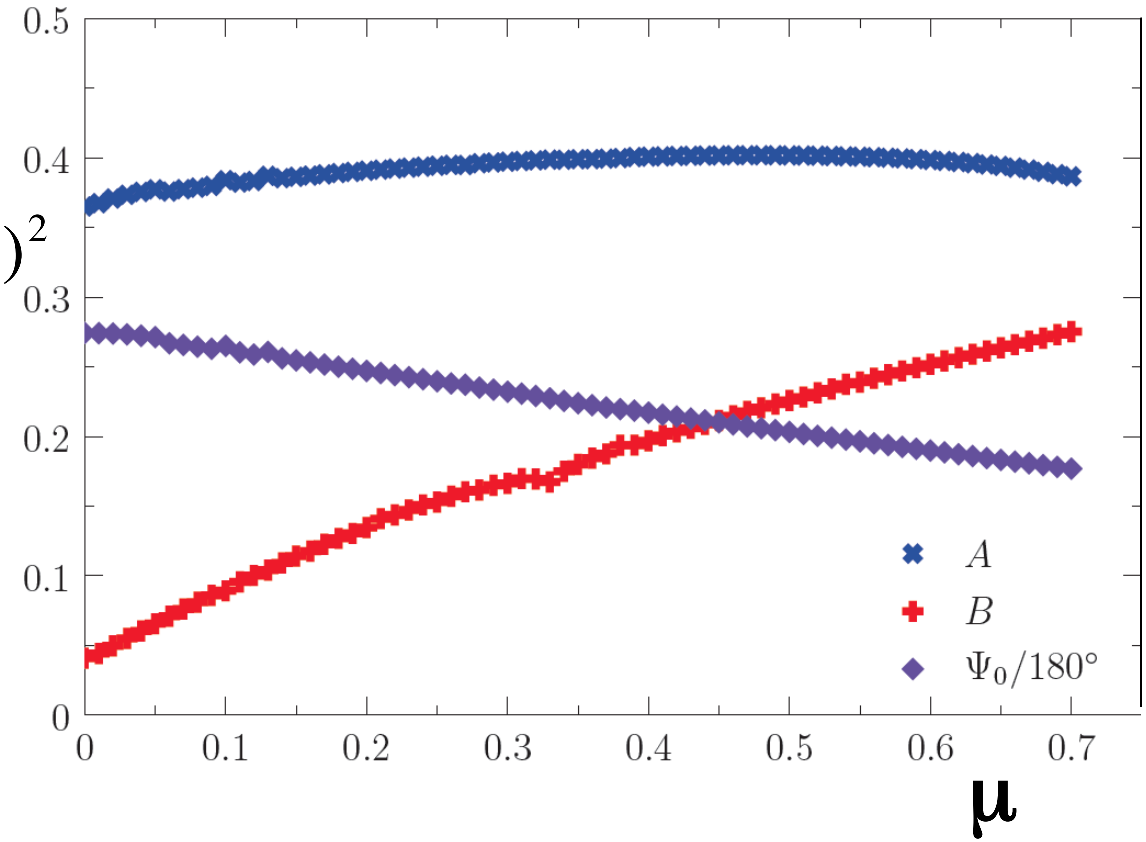
Ejecta angle dominated by contribution from reaction force A as μ → 0



$$\psi_0 \approx 1-\left(A-B\right)\left(D_{Tar}/D_{Jet}\right)^2$$

reaction force

drag force



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$$\psi_0 \approx 1-\left(\underset{\substack{\nearrow\\ \textbf{\textit{reaction}}\\ \textbf{\textit{force}}}}{A}-\underset{\substack{\nwarrow\\ \textbf{\textit{drag}}\\ \textbf{\textit{force}}}}{B}\right)\left(D_{Tar}/D_{Jet}\right)^2$$

4. Model → alternative interpretation

Same ψ_0 because small drag but same reaction force

(B << A, same A)

Different dissipation mechanisms

Same limit of perfect fluid flow as dissipation → 0

Direct demonstration that perfect fluid flow is relevant for hard-sphere jet impact?

Quantitative check

granular simulation

2D
inelastic / friction
non-cohesive

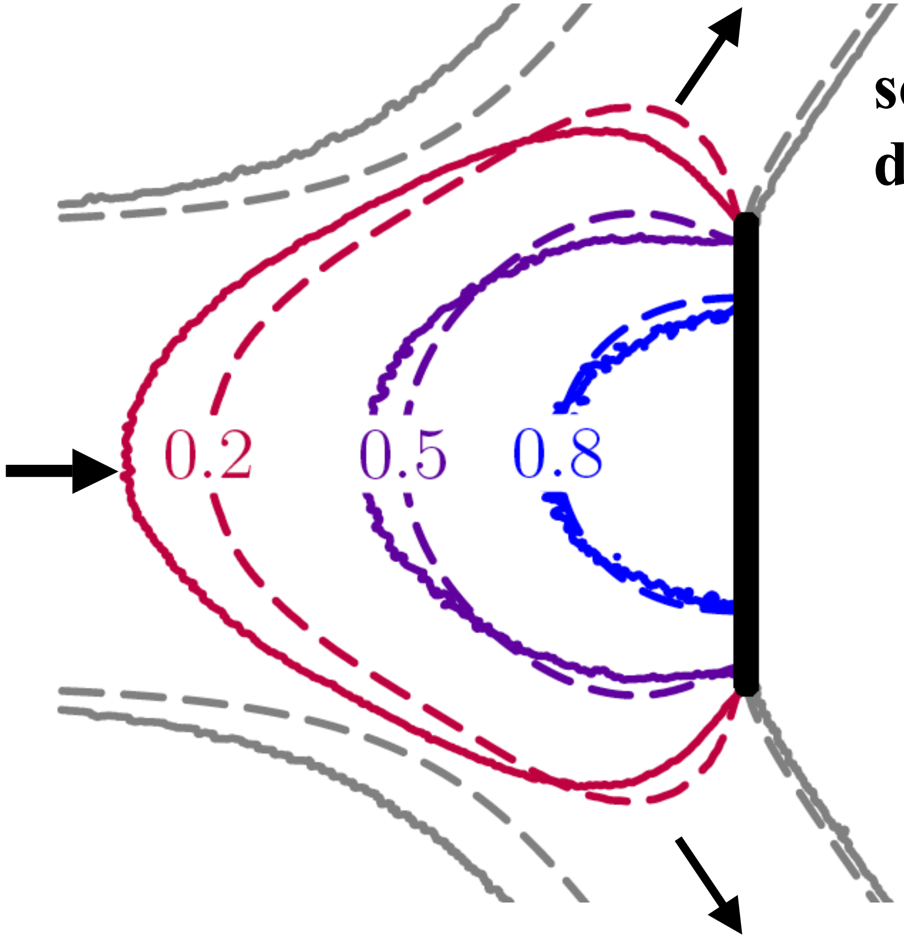
direct comparison

exact solution

2D
perfect fluid flow
zero surface tension

Pressure contours

local pressure / pressure at target center



solid line = granular simulation
dashed line = perfect fluid solution

Quantitative agreement

Discussion

- ***Elliptic flow at RHIC***

Small deviation from perfect fluid flow interpretted as very low Newtonian viscosity

-- assumes hydrodynamics

Granular jet impact

small deviation ≠ low Newtonian viscosity

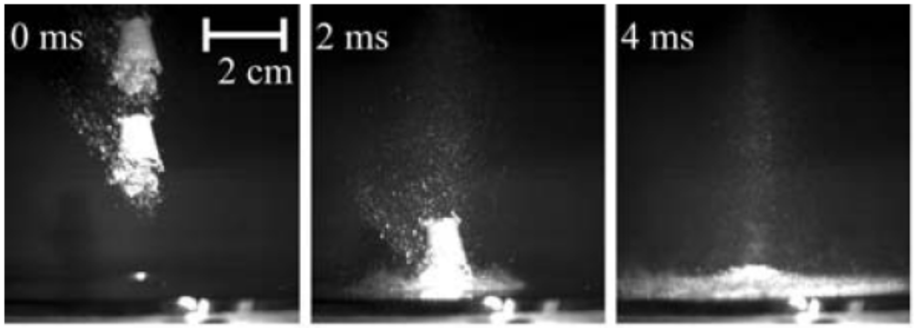
approaches perfect fluid flow as frictional fluid (always far-from-equilibrium)

Discussion

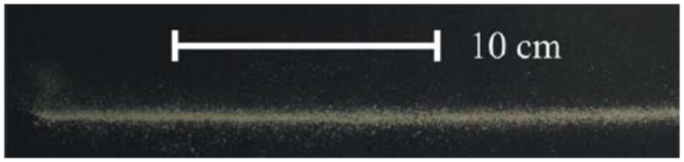
- ***Formation of planetismals from dust aggregates collisions***

Teiser & Wurm
Mon. Not. R. Astron. Soc. 2009

40 m/s



formation of dead zone during initial impact



ejecta collimated within 1

Model as frictional fluid impact?

Conclusion

Impact of dense granular jet

- ***Collimated (liquid-like) ejecta & interior dead zone***
- ***Different interior structure → same ejecta***
- ***Liquid-like response ← perfect fluid flow***

dissipation = frictional fluid

continuum flow remains non-Newtonian in limit towards dissipationless perfect fluid flow

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Thank you