Viscoelastic response of the impact process in dense suspensions

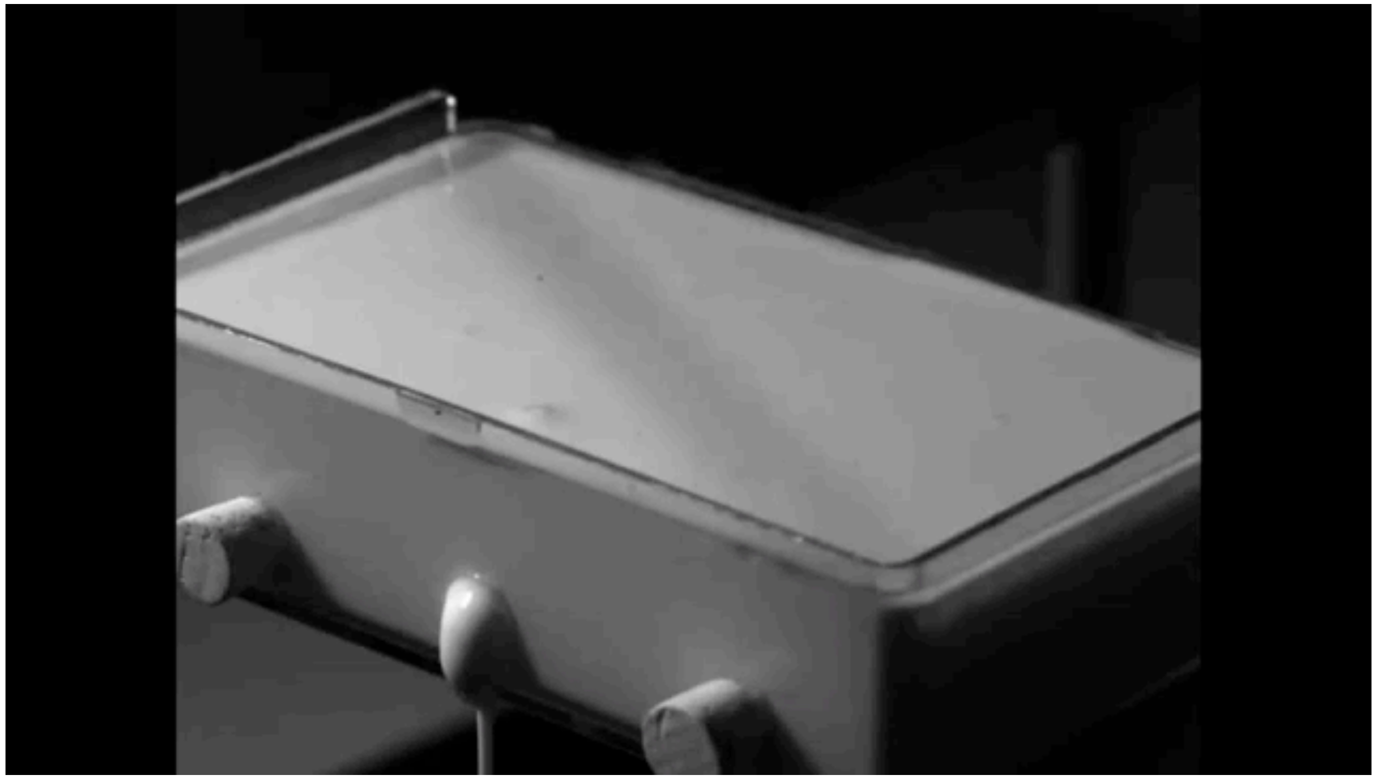
Pradipto and H. Hayakawa, Phys. Fluids **33**, 093110 (2021).

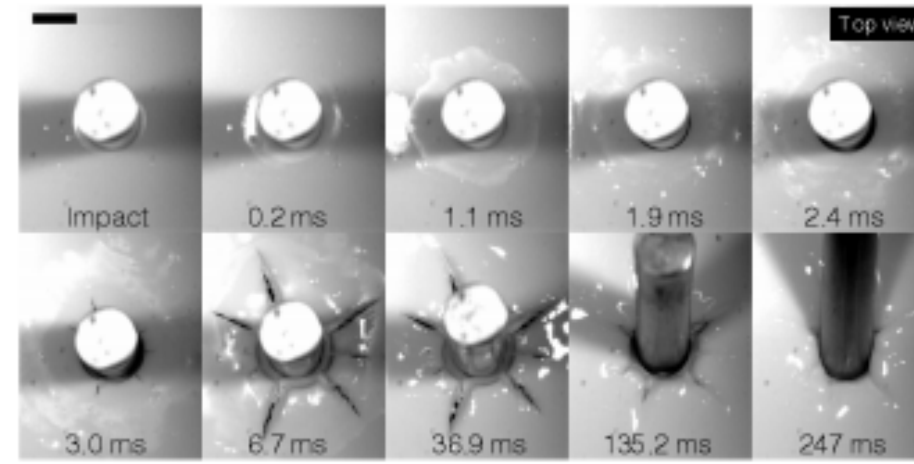
Pradipto and Hisao Hayakawa
Yukawa Institute for Theoretical Physics
Kyoto University

JPS Annual Meeting 2022

17aB11-1

Dense suspensions under impact





Fracture Roche et al, PRL 2013

Source: Itai Cohen Group on YouTube https://youtu.be/hP88C-_LgnE

Impact-induced hardening

Occurs on hard particles suspended in Newtonian solvent

Cannot be observed in fluids or granular particles alone

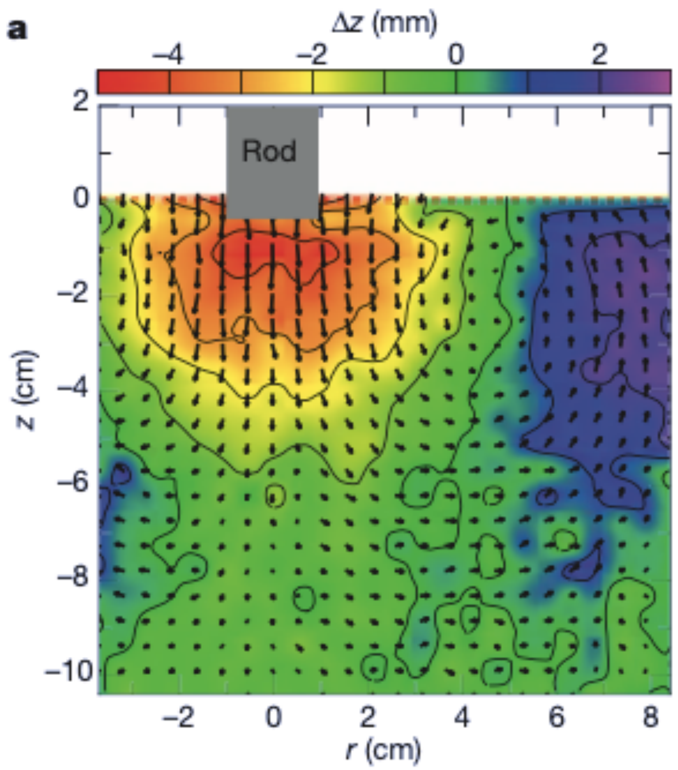
A person can run on top of dense suspensions

Physical explanations remain elusive

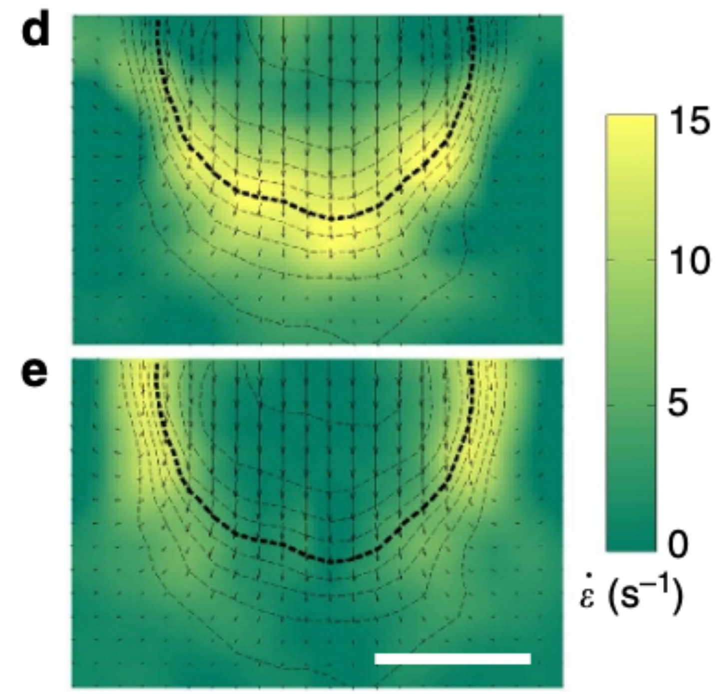
- Inherently far-from-equilibrium
- Highly dissipative —> transient

Dense suspensions under impact have stronger response than the one observed in shear thickening suspensions

Waitukaitis and Jaeger, Nature **487**, 205 (2012)



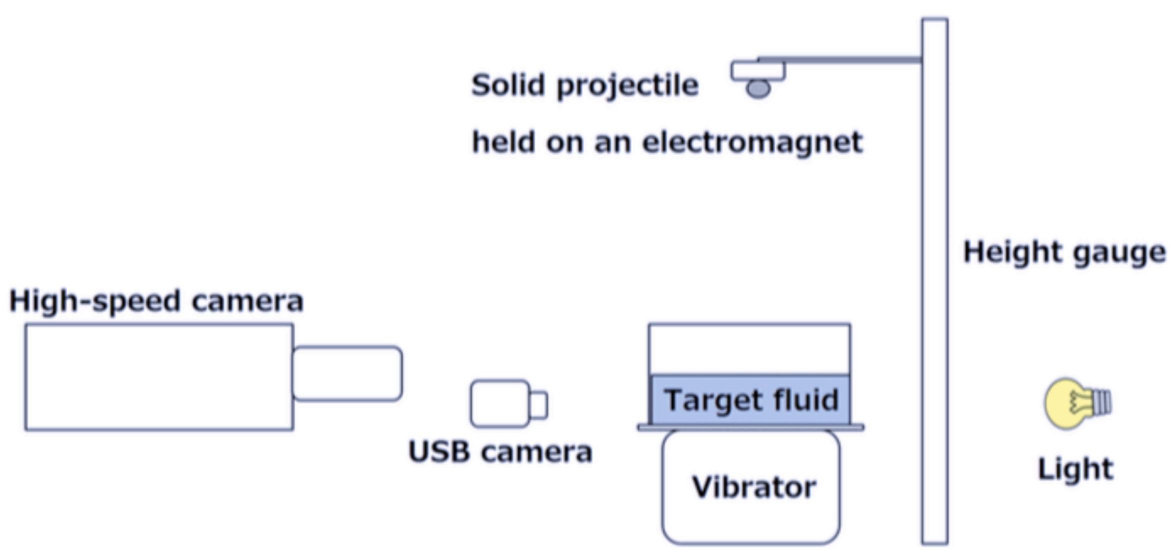
Han et al, Nat. Comms. 2016

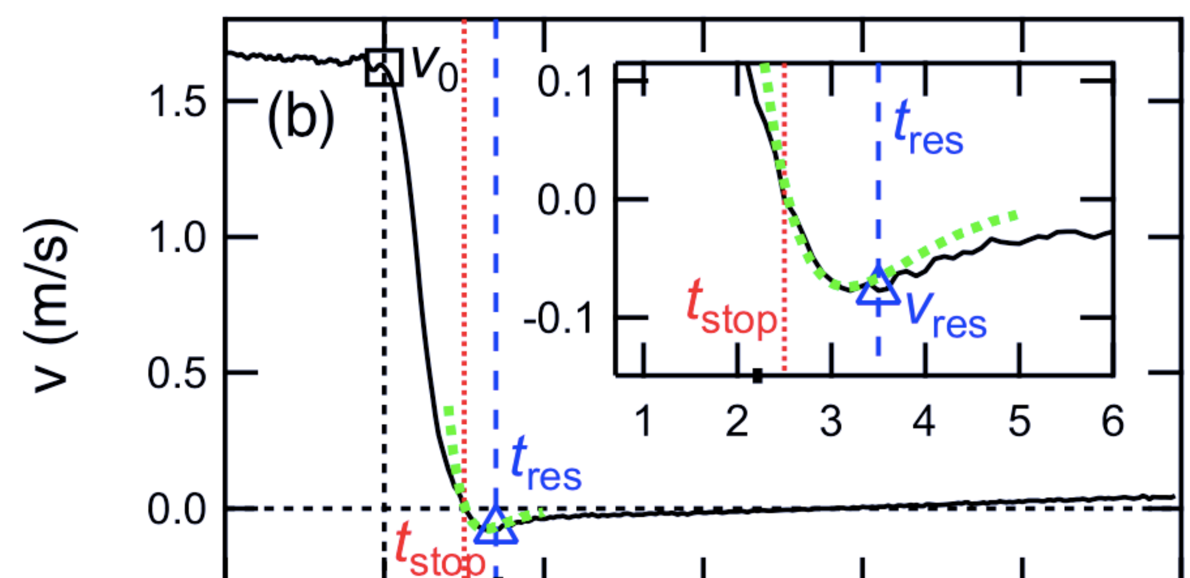


Dynamically Jammed Region

Localized and transient solid-like region beneath the impactor

Elastic rebound Egawa and Katsuragi, Phys. Fluids **31**, 053304 (2019)



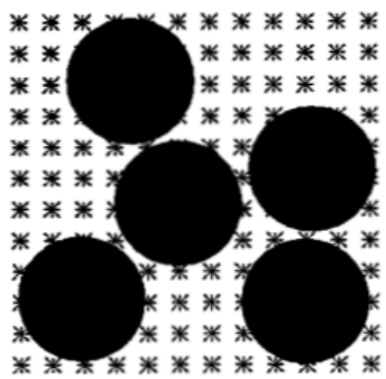


Simulation of impact-induced hardening

Pradipto and Hayakawa, Phys. Rev. Fluids **6**, 033301 (2021).

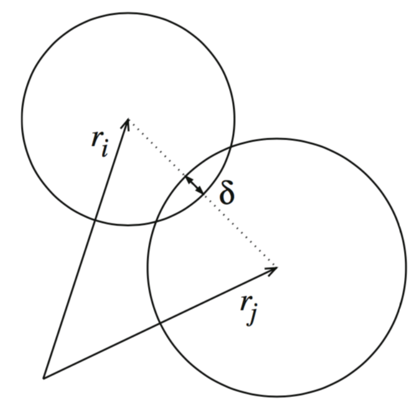
Hydrodynamic interaction

LBM + Lubrication corrections



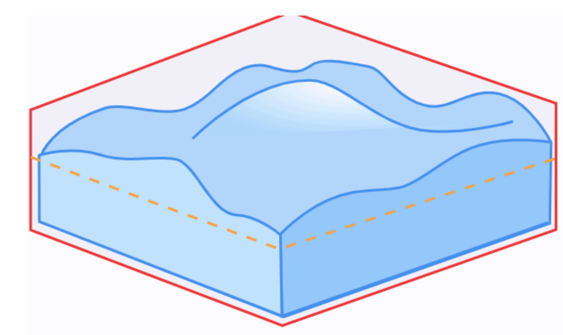
Contact between particles

DEM

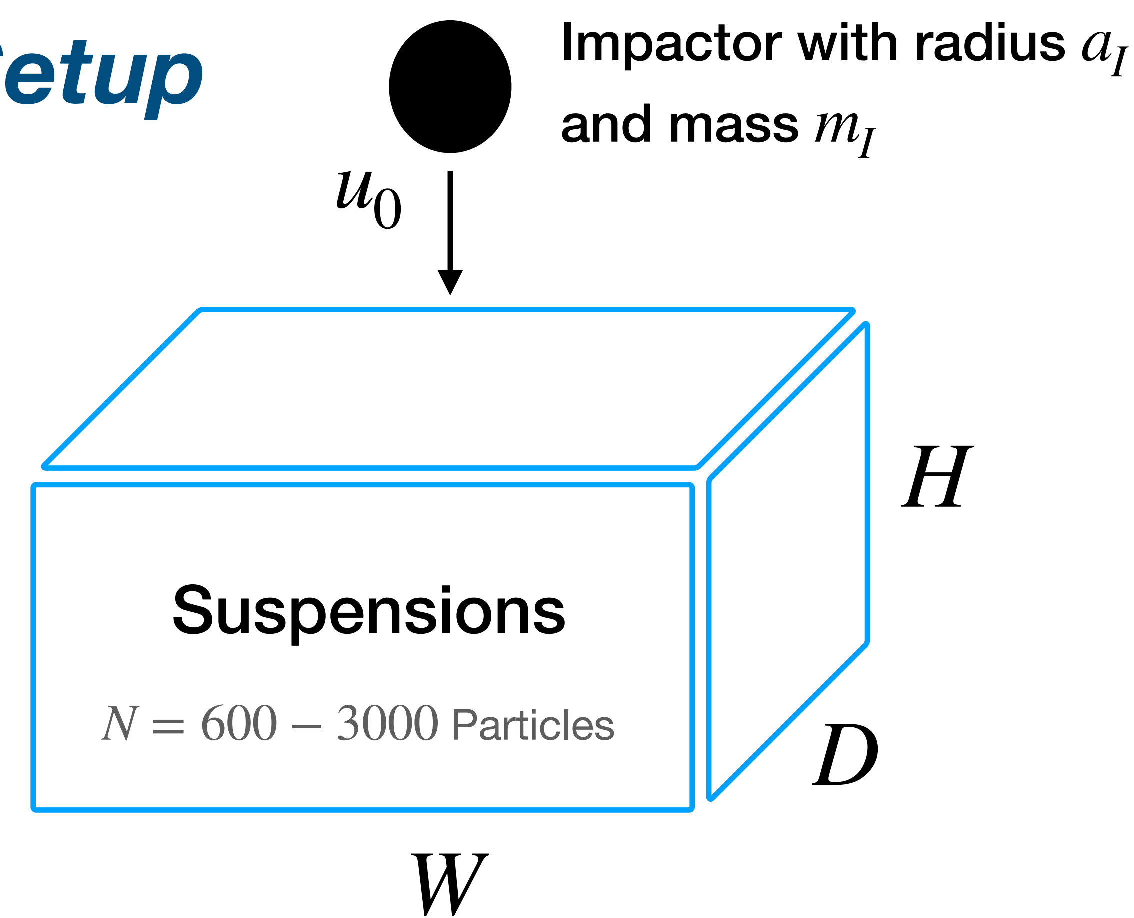


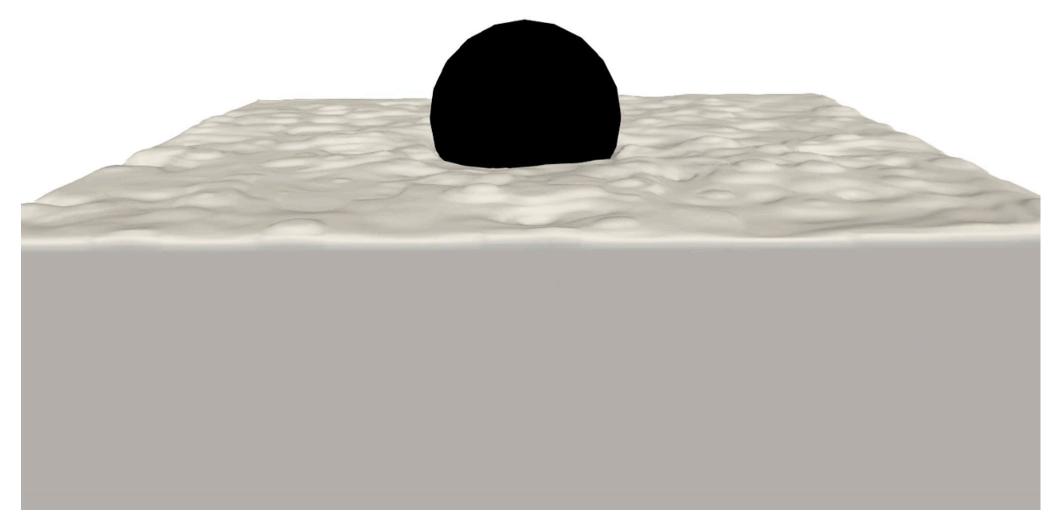
Free surface

LBM



Setup

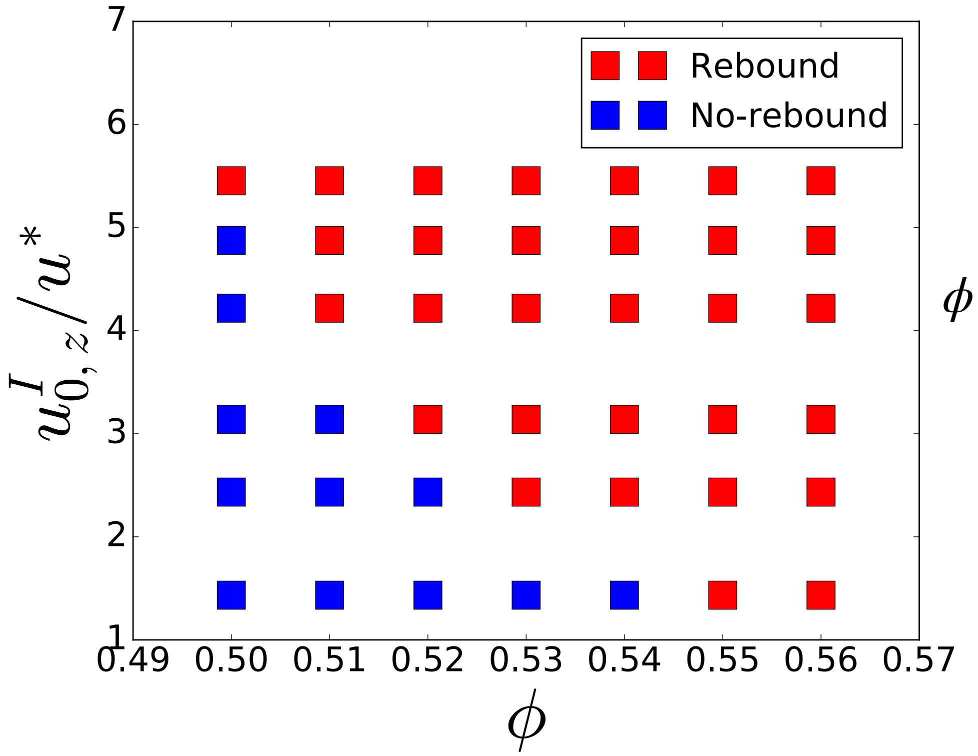




Elastic rebound depends on impact velocity and frictional interactions between particles

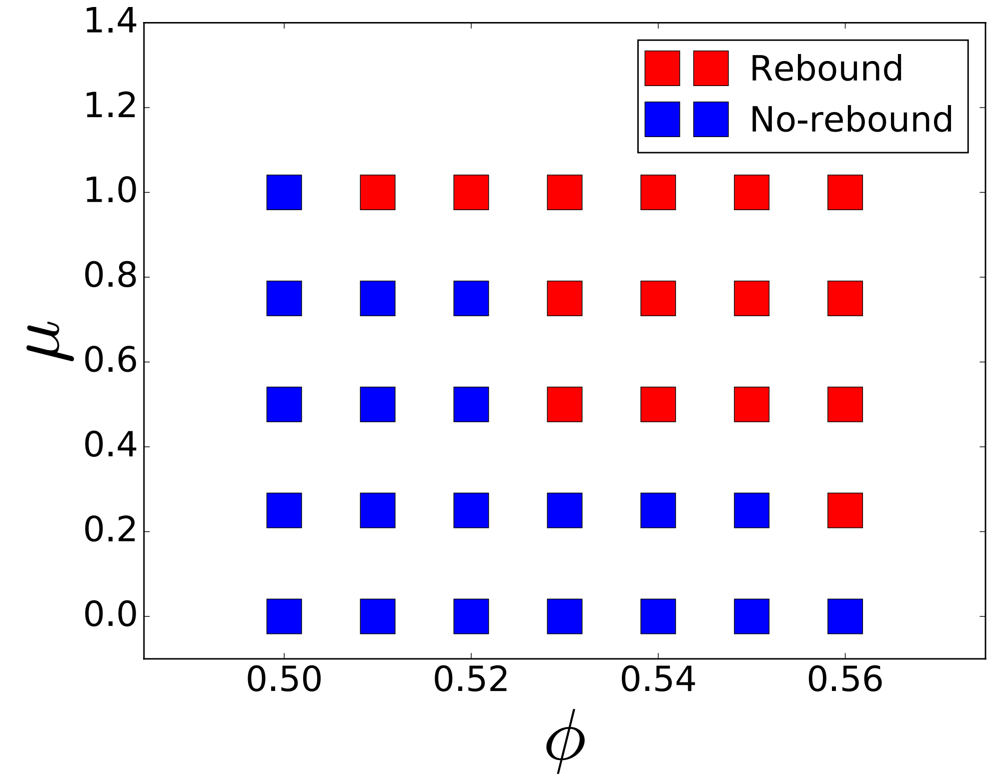
Pradipto and Hayakawa, Phys. Rev. Fluids **6**, 033301 (2021).

Impact velocity

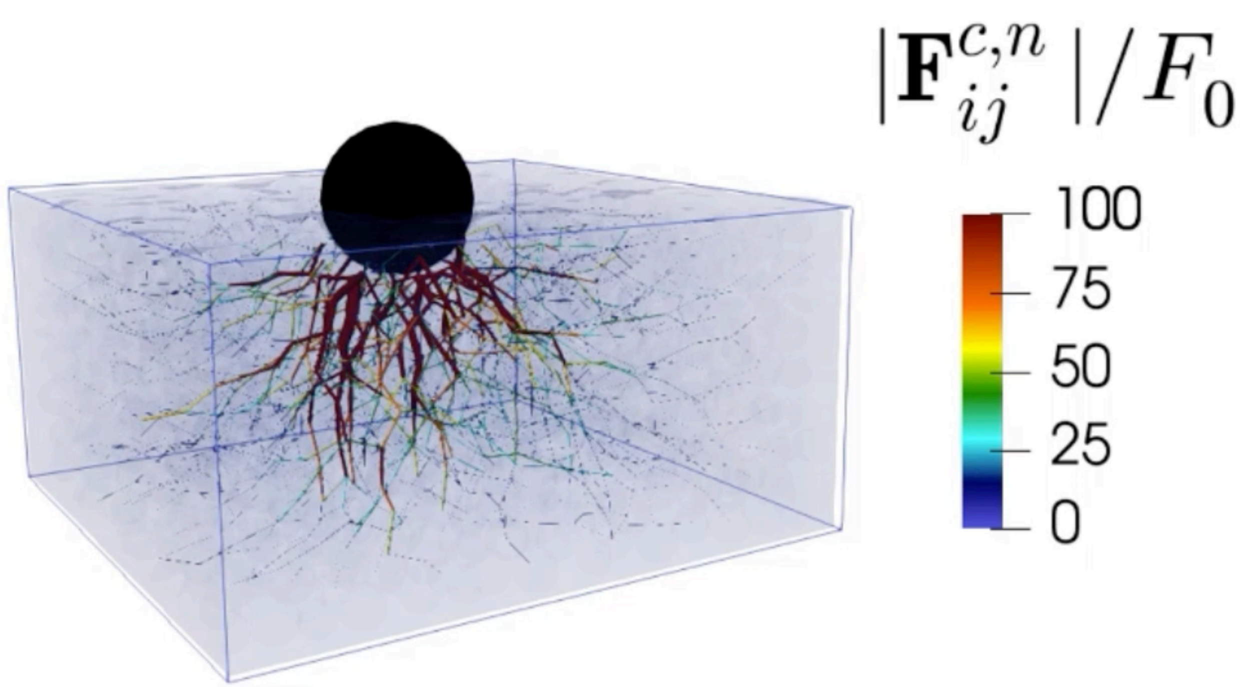


$$\phi = \frac{\text{Total solid particles volume}}{\text{Volume of the container}}$$

Friction coefficients



Inside the hardening suspension

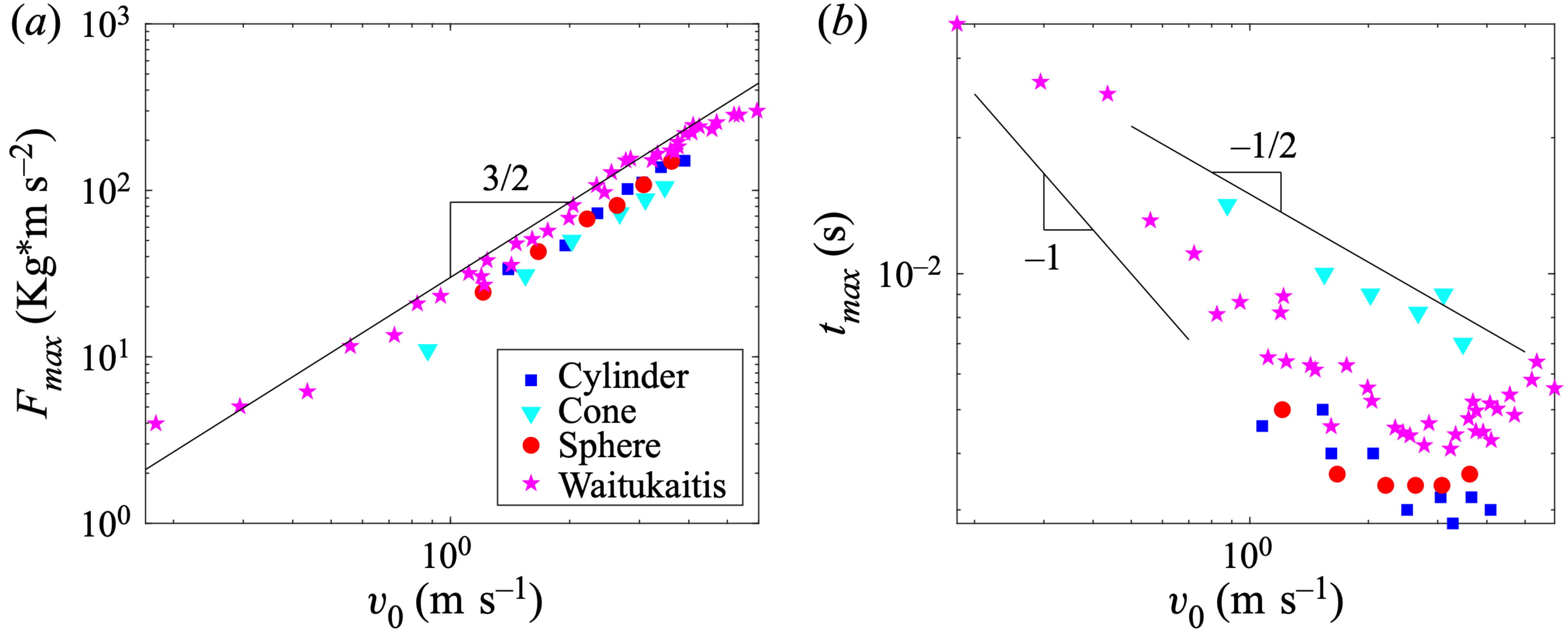


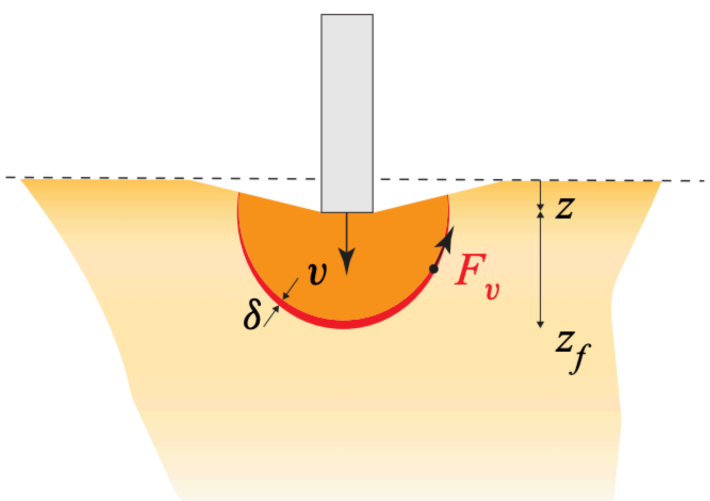
Force chains

- Formed by contacting suspended particles
- Transmitting force from the impactor to the bottom boundary
- Sustain the impactor → rebound

Power-law relations between u_0, $F_{\max}$, and $t_{\max}$

Brassard, et. al, JFM **923**, A38 (2021)





Viscous force from the dynamically jammed region

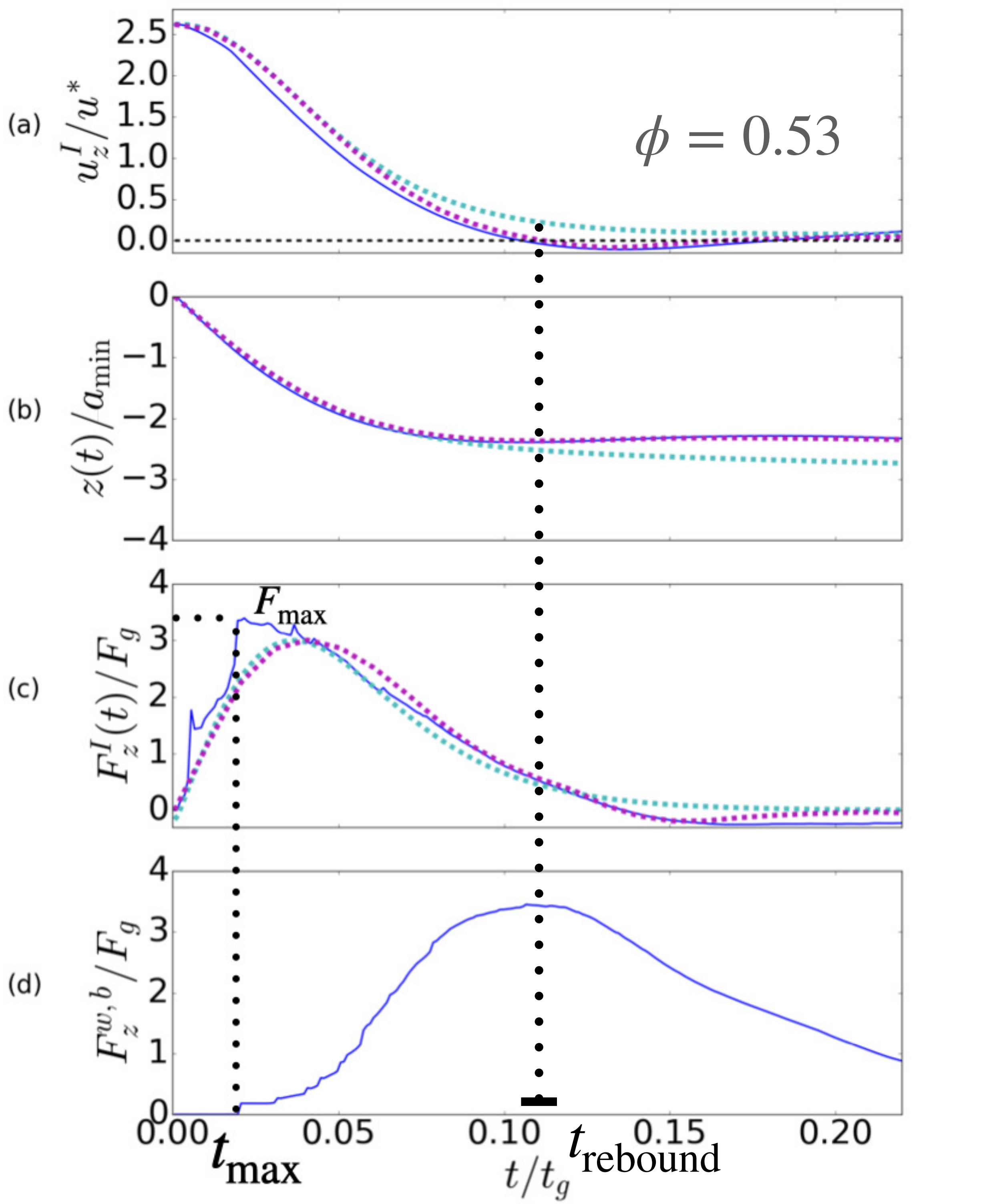
$$F_v = -C_v \pi D \eta_s k z \frac{v}{\delta}.$$

Cannot recover the elastic rebound

Purpose of this talk

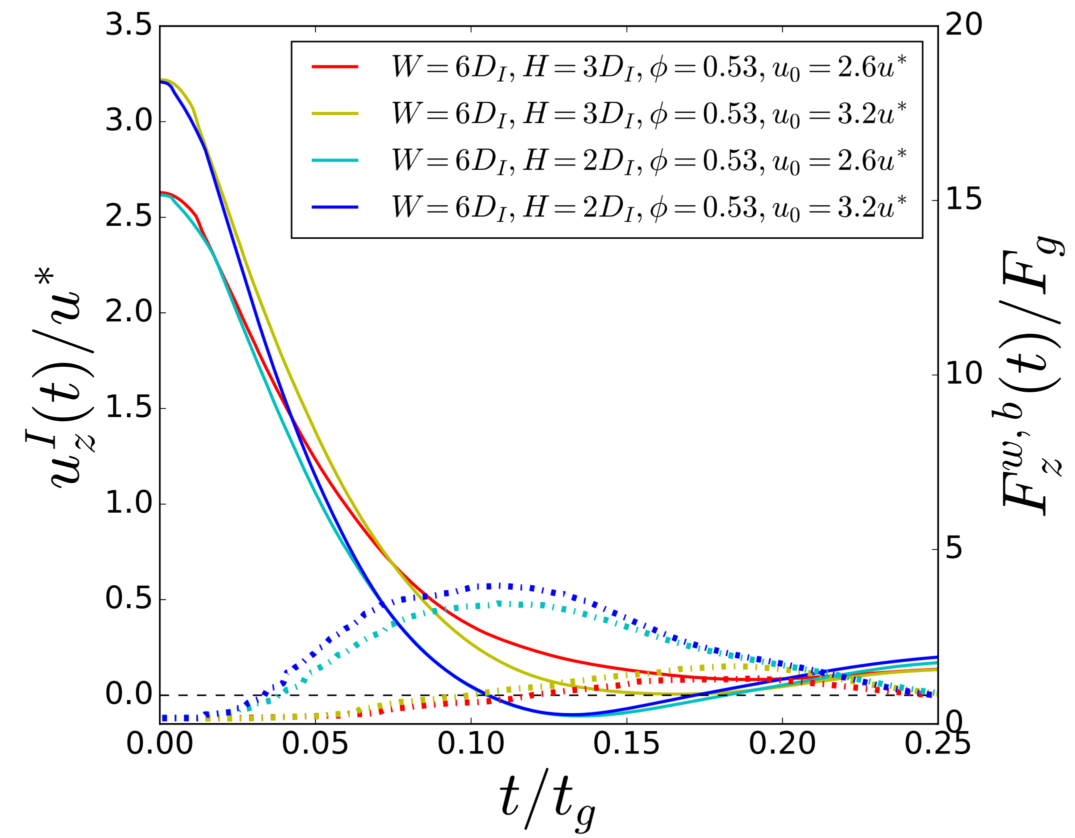
Elucidate the connection between this power-law relation and the rebound motion

Force on the impactor reach its peak before the rebound



Dyn. jammed region touch the bottom and starts accumulating

Dyn. jammed region reached its peak on the bottom and soften → impactor starts to sink



Rebound depends on the depth of the container

The origin of $F_{\max}$ is the **floating** jammed region

The origin of rebound is the transmission of force from the impactor to the bottom plate and vice versa

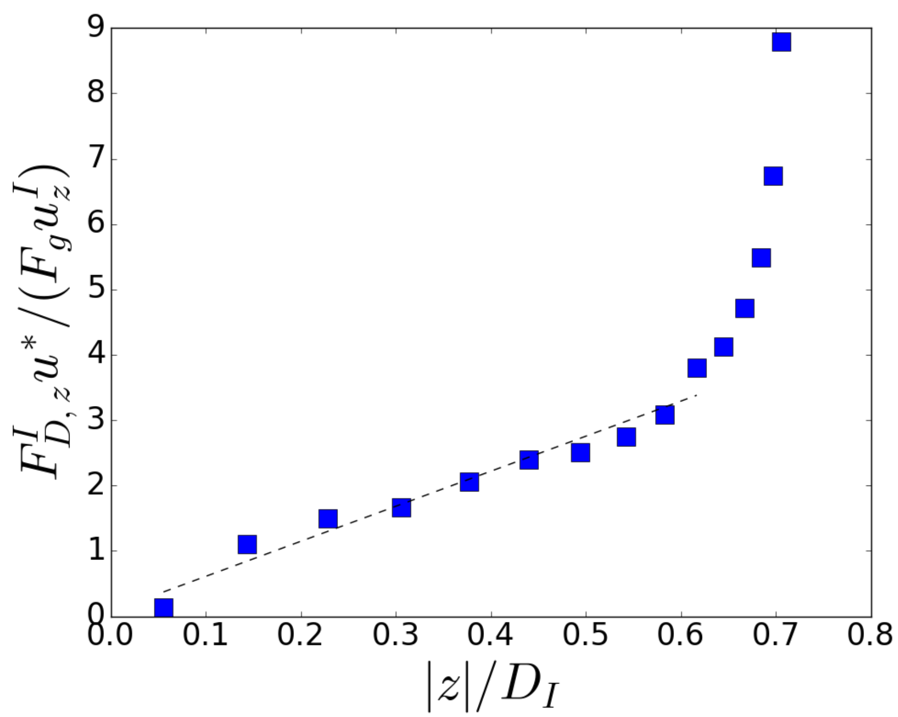
Phenomenology Floating + force chains model

Viscous Elastic

$$m_I \frac{d^2 z_I}{dt^2} = -m_I \tilde{g} + 3\pi\eta_{\mathrm{eff}} \dot{z}_I |z| + n(t) k_n z_I$$

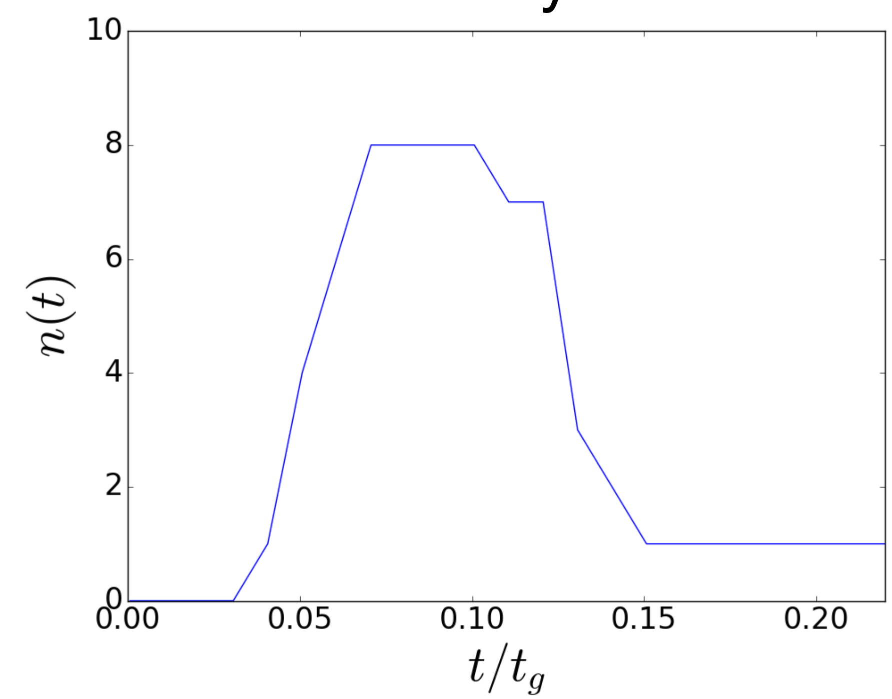
From floating jammed region

Drag on the impactor is proportional to its depth before completely immersed



From force chains

$n(t)$ → Number of percolating force chains from the impactor to the bottom boundary

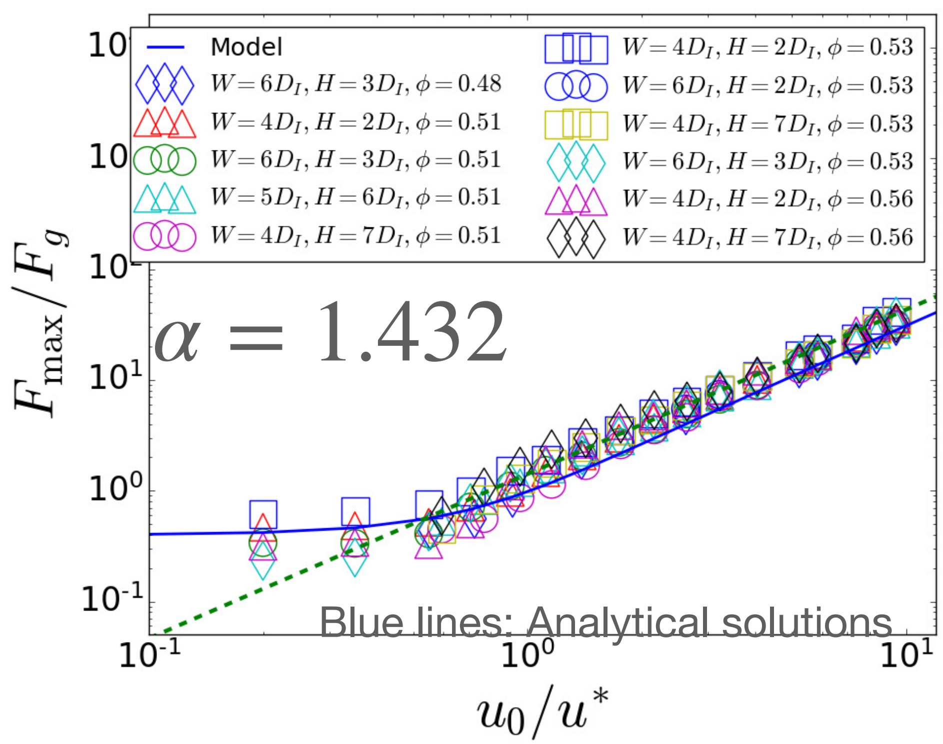


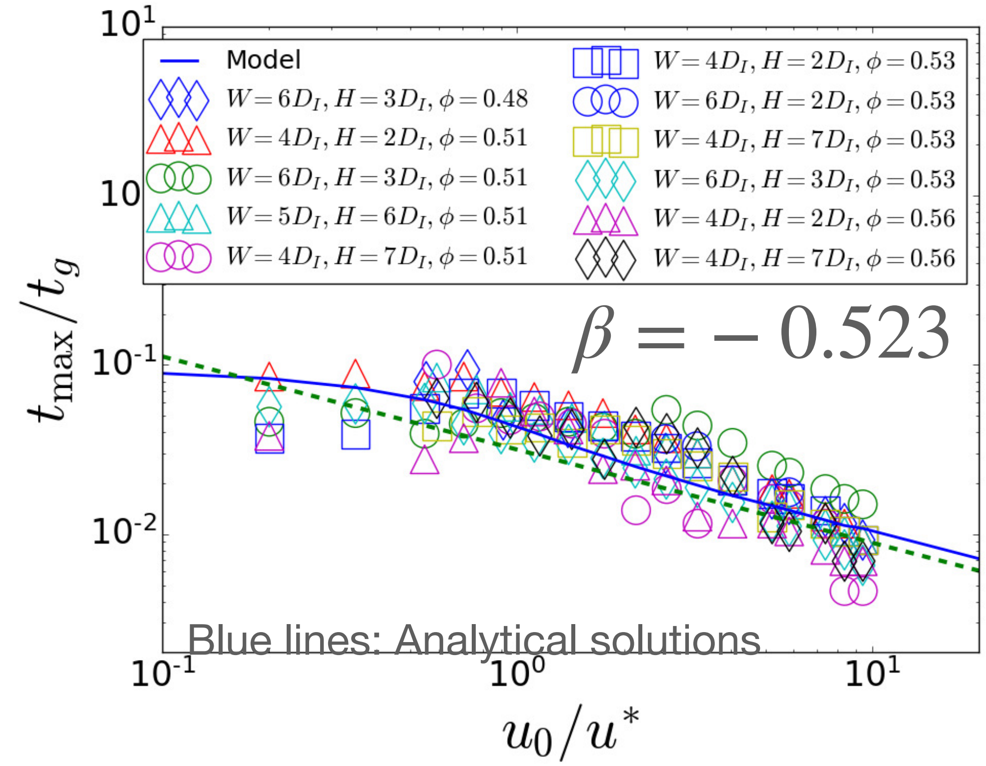
Analytical solution of floating model in $u_0 \gg 1/\eta_{\mathrm{eff}}$:

$$F_{\max} \propto u_0^{\frac{3}{2}} \text{ and } t_{\max} \propto u_0^{-\frac{1}{2}}$$

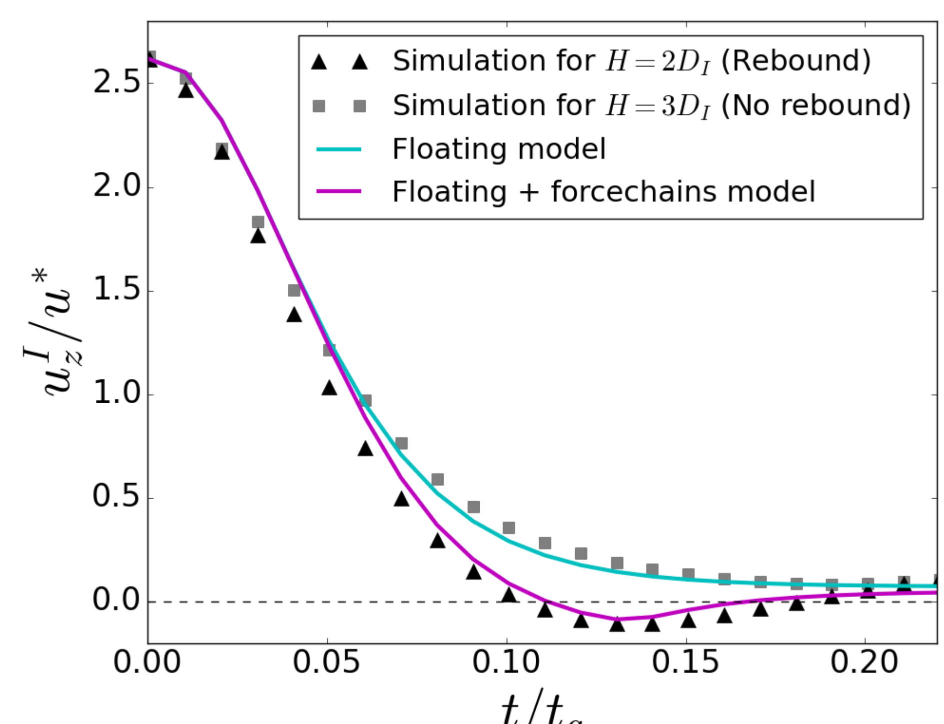
Model vs simulations Power-law relationships between $F_{\max}$, $t_{\max}$, and u_0

$$m_I \frac{d^2 z_I}{dt^2} = -m_I \tilde{g} + 3\pi \eta_{\text{eff}} \dot{z}_I |z| + n(t) k_n z_I$$





- Elastic term from percolating force chains is necessary to recover rebound



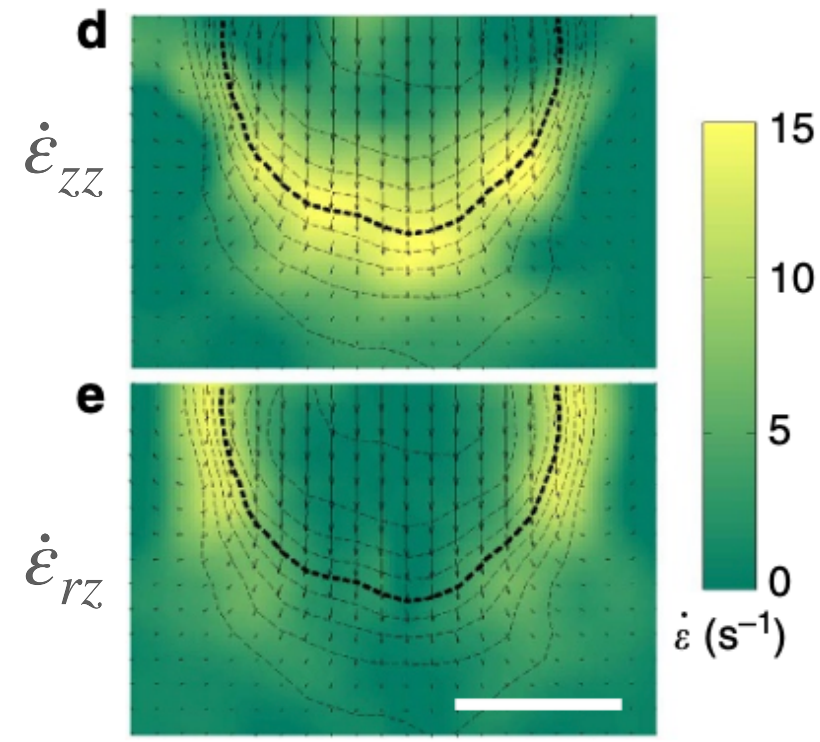
- **Crossover** from low u_0 to high u_0 regime
- High u_0 regime: $F_{\max} \propto u_0^{\alpha}$ and $t_{\max} \propto u_0^{\beta}$
  - Similar to experiments

    Brassard, et. al, JFM **923**, A38 (2021)

  - Independent of system size

Discussions and future directions

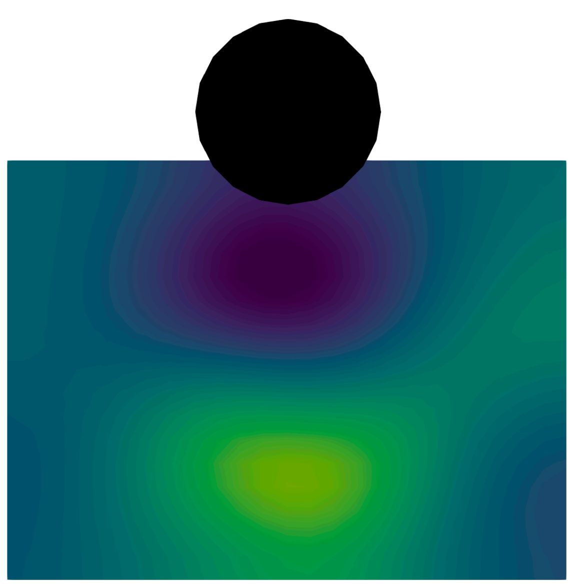
Han et al, Nat. Comms. 2016



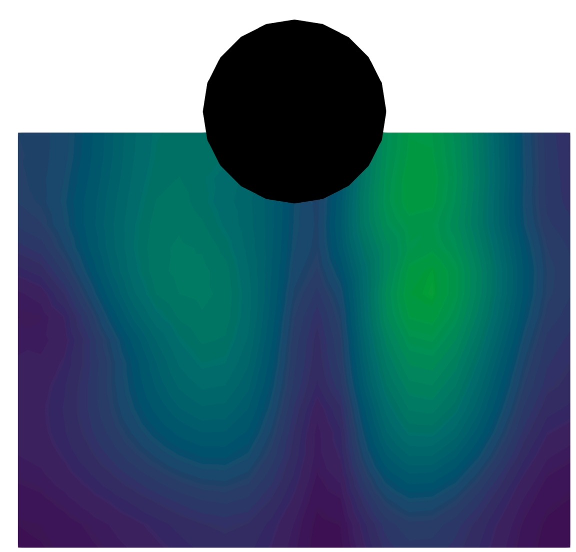
- **Current picture:** elastic response only takes place when force chains percolate
- Even before touching the boundary, dynamically jammed region is **rigid**
  - **Future task:**
    - Delineate the dynamically jammed region
    - Directly measure the elasticity of the dynamically jammed region

Coarse-grained fields

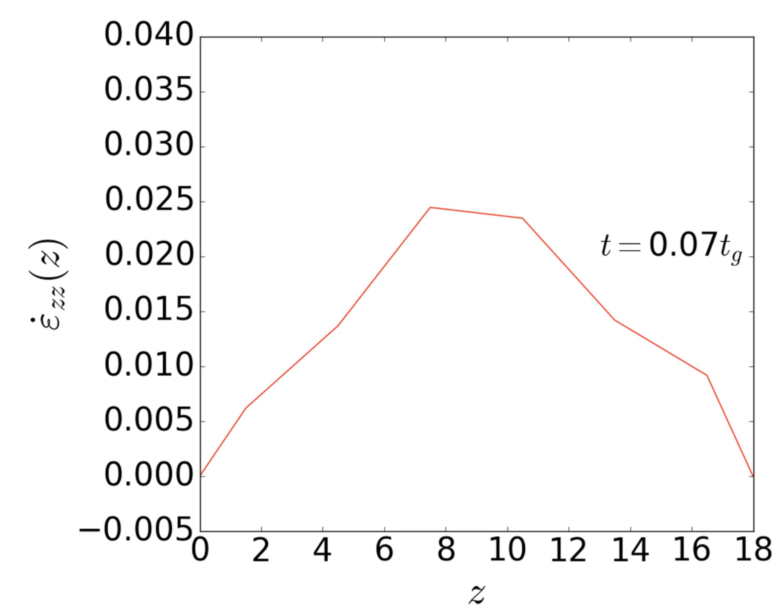
J. Zhang, R. P. Behringer, I. Goldhirsch, Prog. Theor. Phys. Supp **184**, 16 (2010)



$\dot{\varepsilon}_{zz}$



$\dot{\varepsilon}_{rz}$



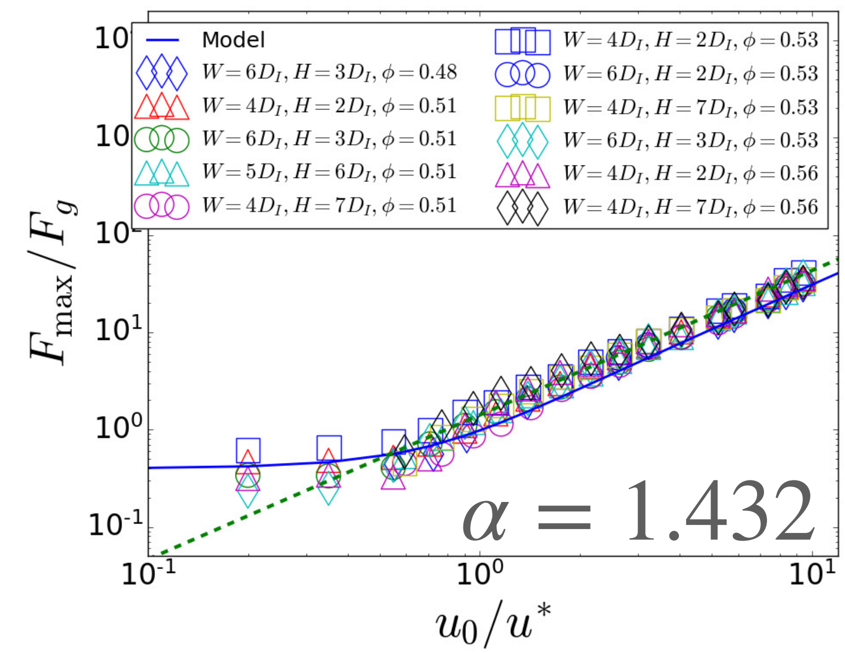
Summary

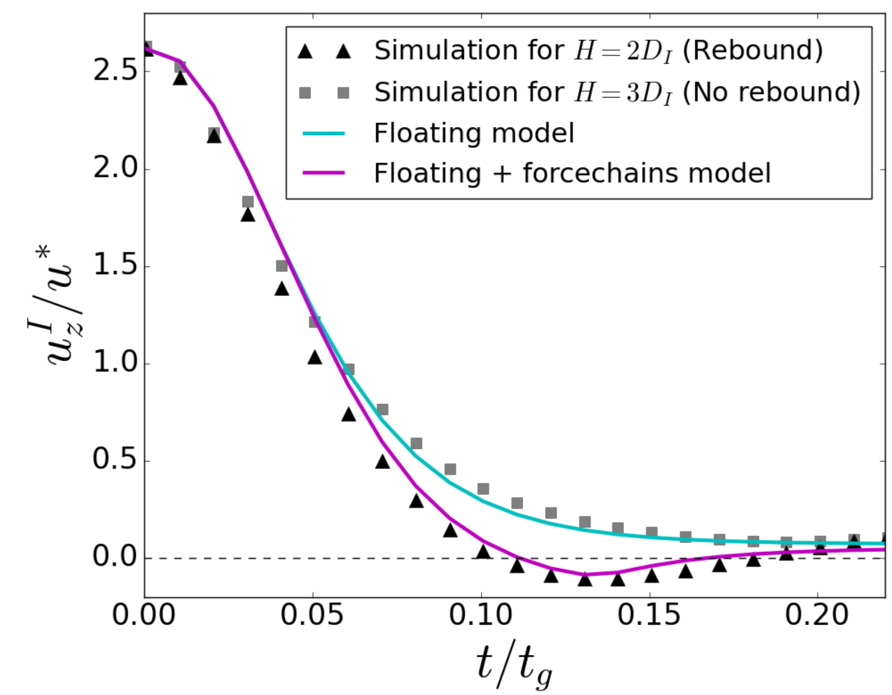
Rebound motion depends on the system size and takes place later than $t_{\max}$

Our phenomenology shows that the power-law relationship between $F_{\max}$, $t_{\max}$, and u_0 arises solely from the viscous process

(Current picture) Elastic rebound is originated from percolating force chains

Future task: Measure the elasticity of the dynamically jammed region





For more details, please check:

Pradipto and H. Hayakawa, Phys. Fluids **33**, 093110 (2021).