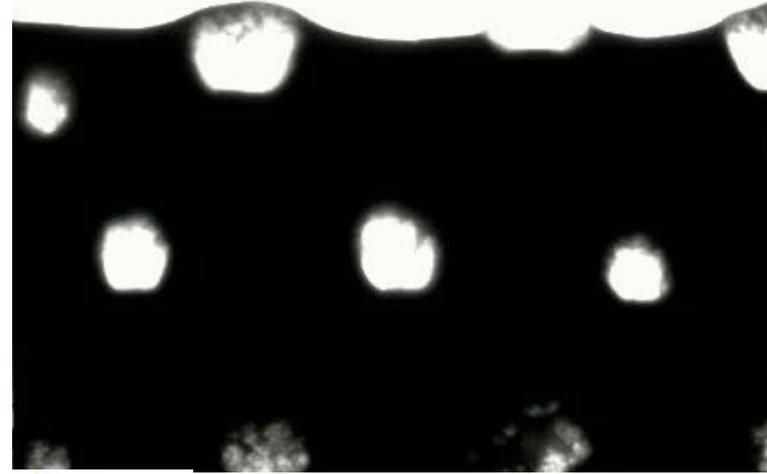


# Structured Bubbling in Vibrated Gas- Fluidized Beds with Bidisperse Particles



**Chris Boyce**

**Department of Chemical Engineering,  
Columbia University**

**Presentation at the NETL Multiphase  
Flow Workshop  
August, 2022**

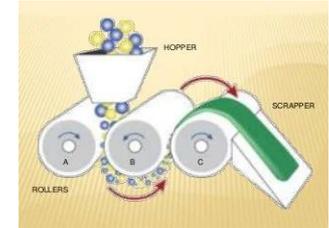
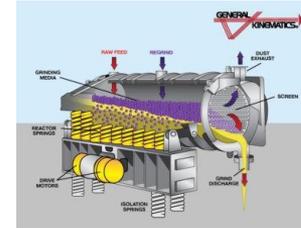
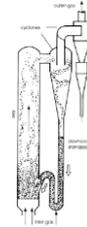


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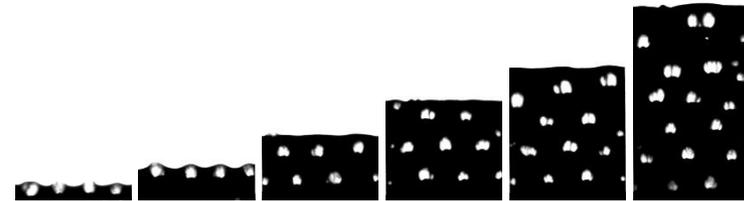


# Outline

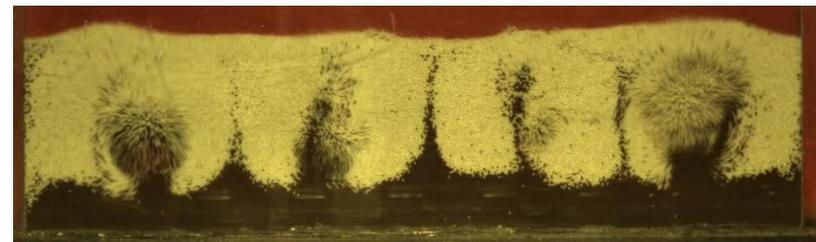
➤ Motivation



➤ Structured Bubbling in Monodisperse Systems



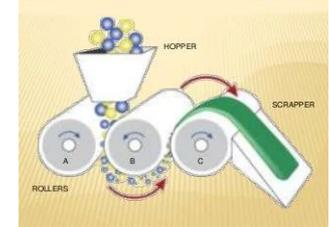
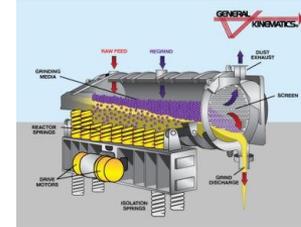
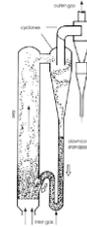
➤ Structured Bubbling in Bidisperse Systems



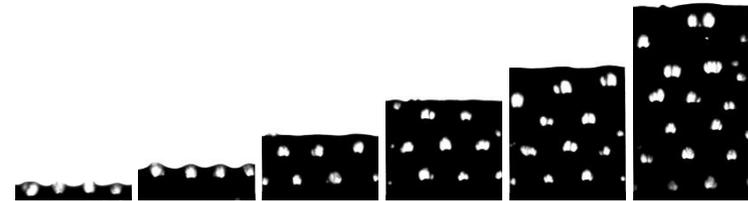
➤ Conclusions

# Outline

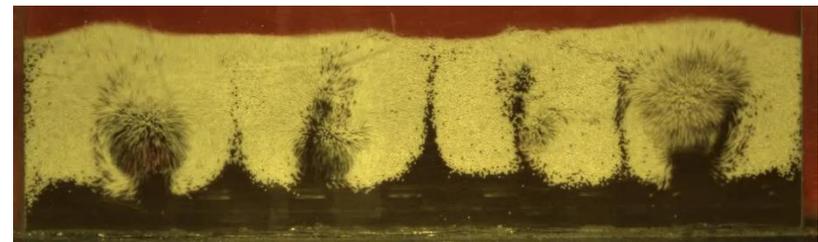
## ➤ *Motivation*



## ➤ Structured Bubbling in Monodisperse Systems



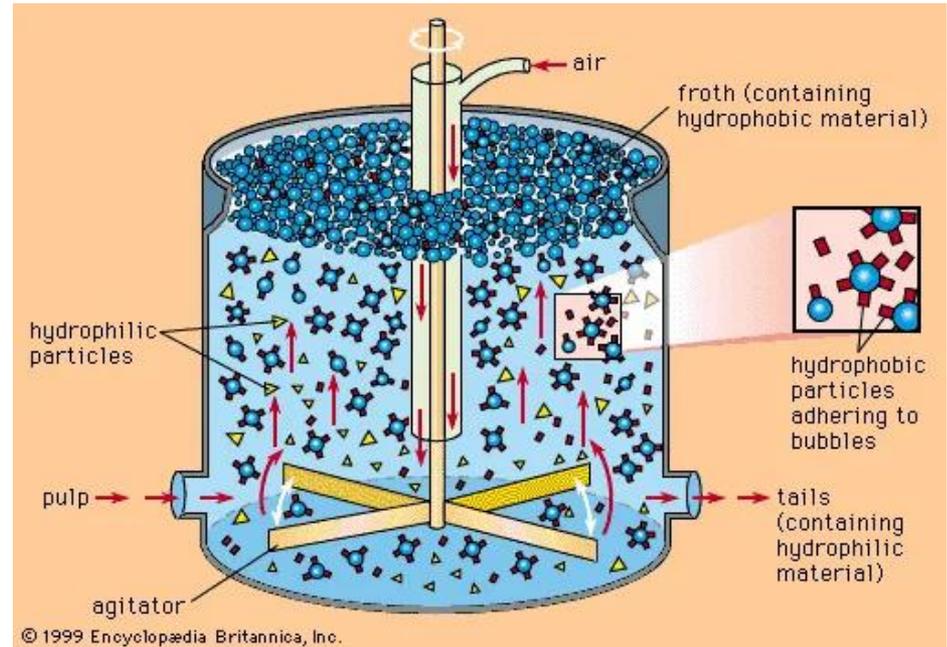
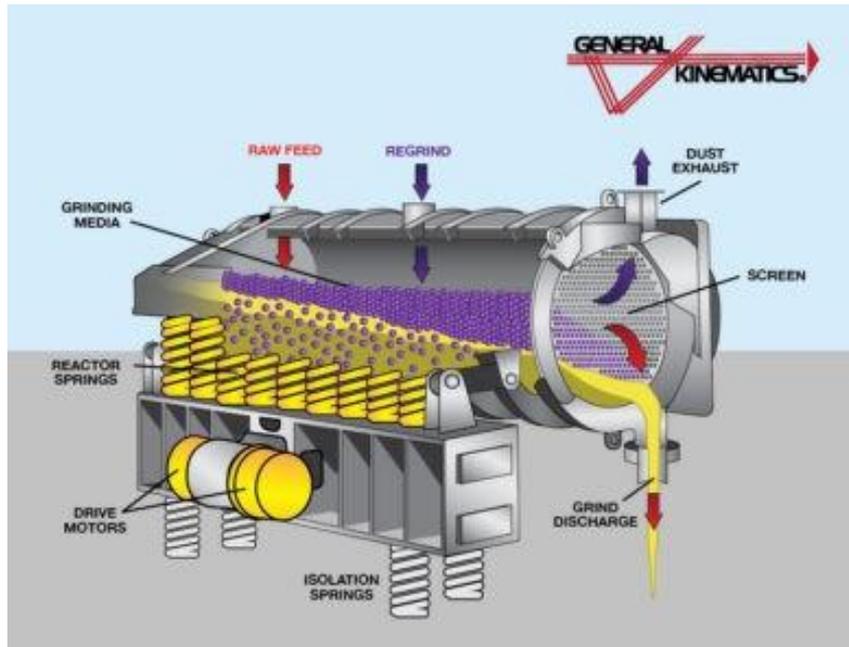
## ➤ Structured Bubbling in Bidisperse Systems



## ➤ Conclusions

# Mining Separations: Optimizing Segregation

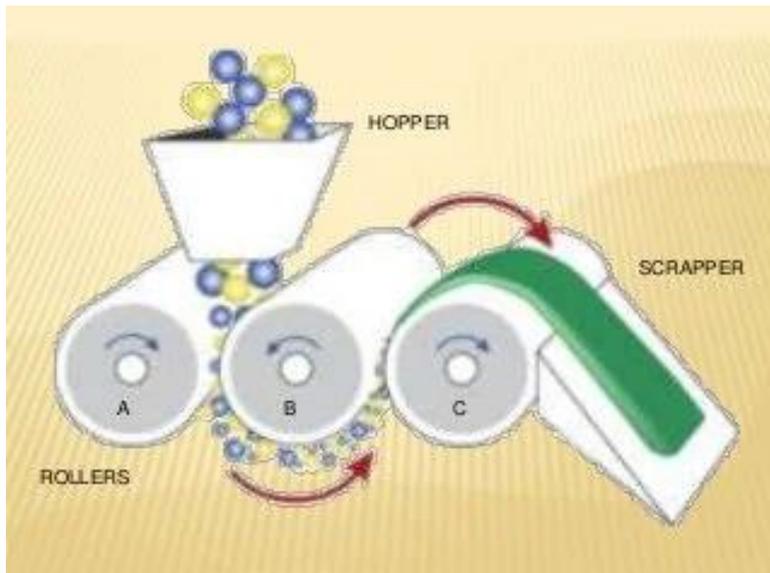
- Mining of metals, such as silicon, lithium and copper, is critical to a clean energy future
- Current techniques for segregating particles grind particles down to micron size, requiring large amounts of energy and then use chemically treated water to separate out valuable metals, requiring large amounts of water
- Dry separation of granular particles on the basis of size, density and shape can reduce water and energy input to make mining more sustainable



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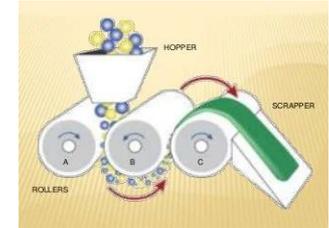
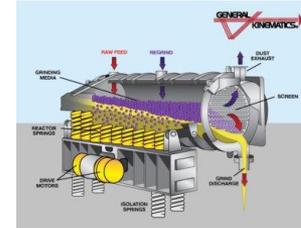
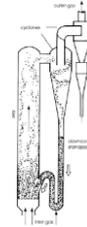
# Pharma Production: Optimizing Mixing

- Pharmaceutical tablets require exact mixing of active and passive ingredients
- A variety of devices have been designed to maximize mixing accuracy while minimizing mixing time and energy input
- Gas fluidized beds are sometimes used, but they do not always produce optimal mixing

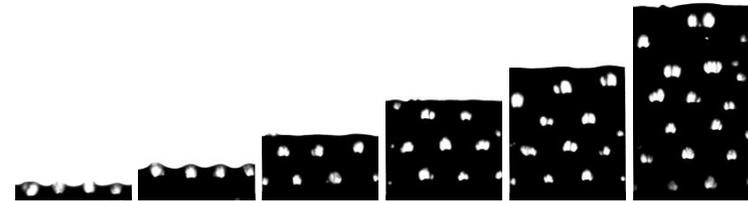


# Outline

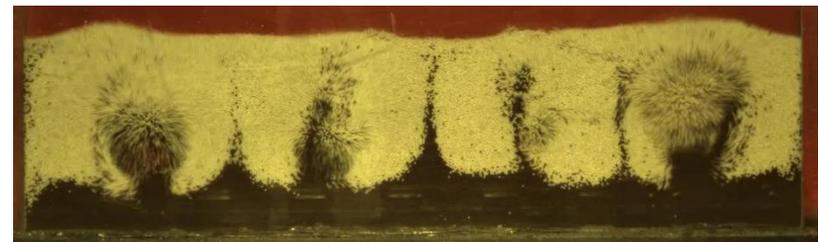
➤ Motivation



➤ **Structured Bubbling in Monodisperse Systems**

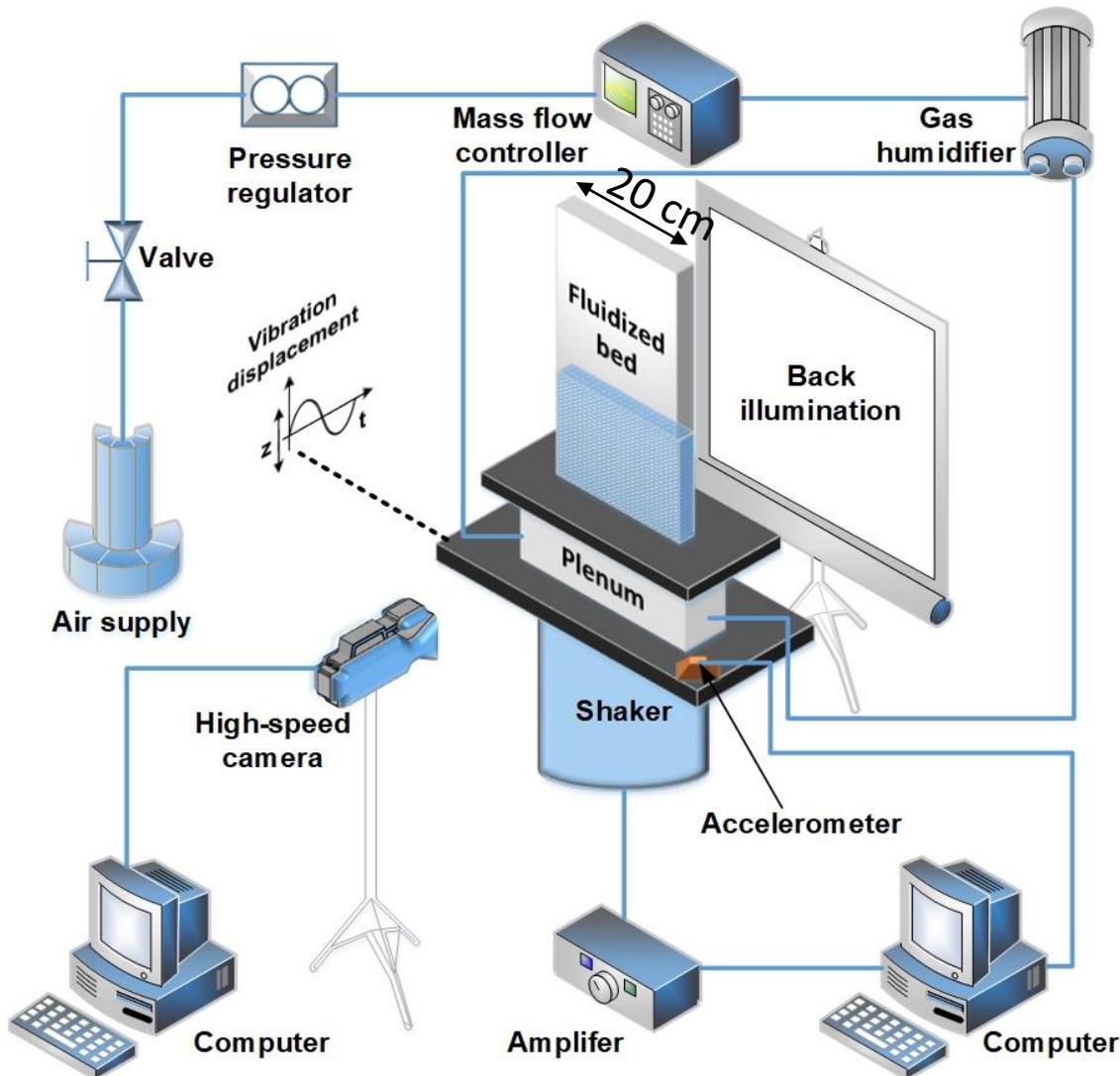


➤ Structured Bubbling in Bidisperse Systems



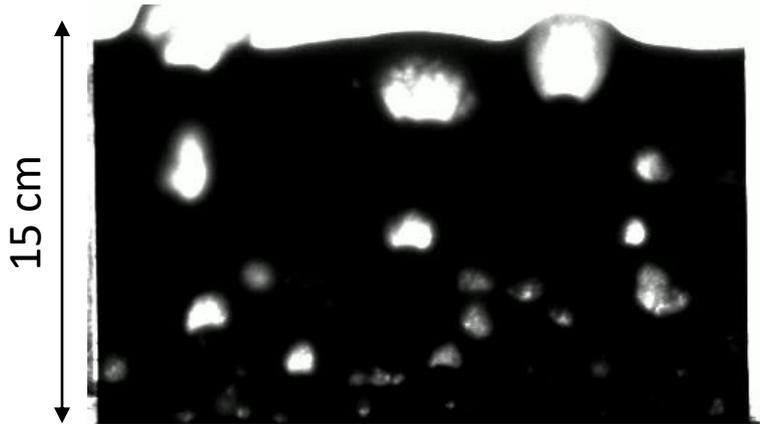
➤ Conclusions

# Experimental Setup

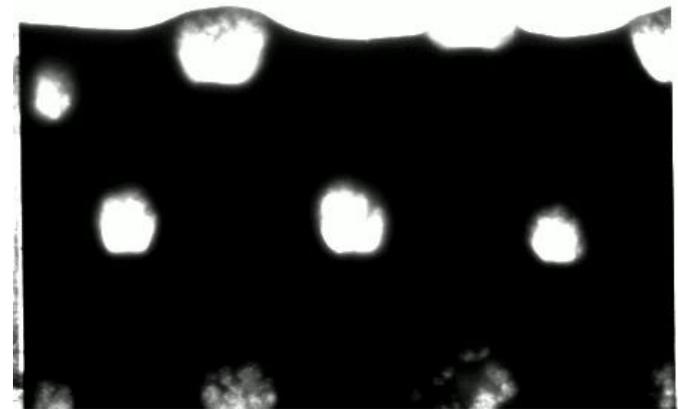


- Placing the fluidized bed on a shaker makes the entire system vibrate sinusoidally with amplitude and frequency controllable by a computer
- Back illumination makes bubbles appear white and particles appear black

# Vibration + Gas Flow: Structured Bubbling



No Vibration → Mathematically Chaotic Bubbling

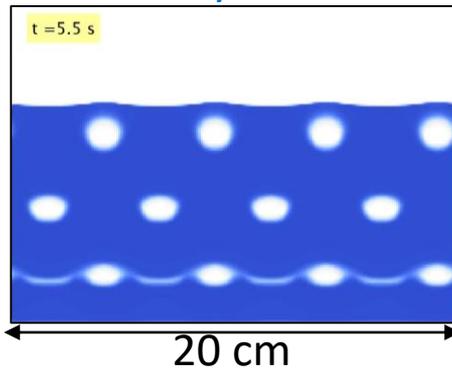


Vibration → Structured Bubbling

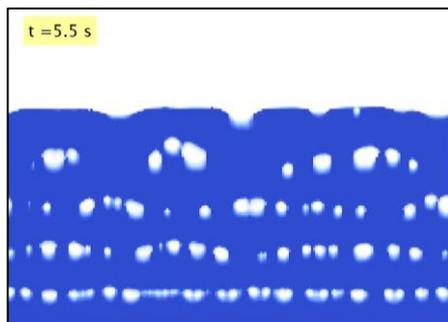
- Chaotic bubbling can lead to unpredictable reactor behavior
- Others have shown that oscillating gas velocity can create structured bubbling patterns
- We have shown that vertical vibration at a resonant frequency can also create structured bubbling
- This can create more controllable and scalable behavior in bubbling fluidized beds

# Structured Bubbling: Rheological Development (1)

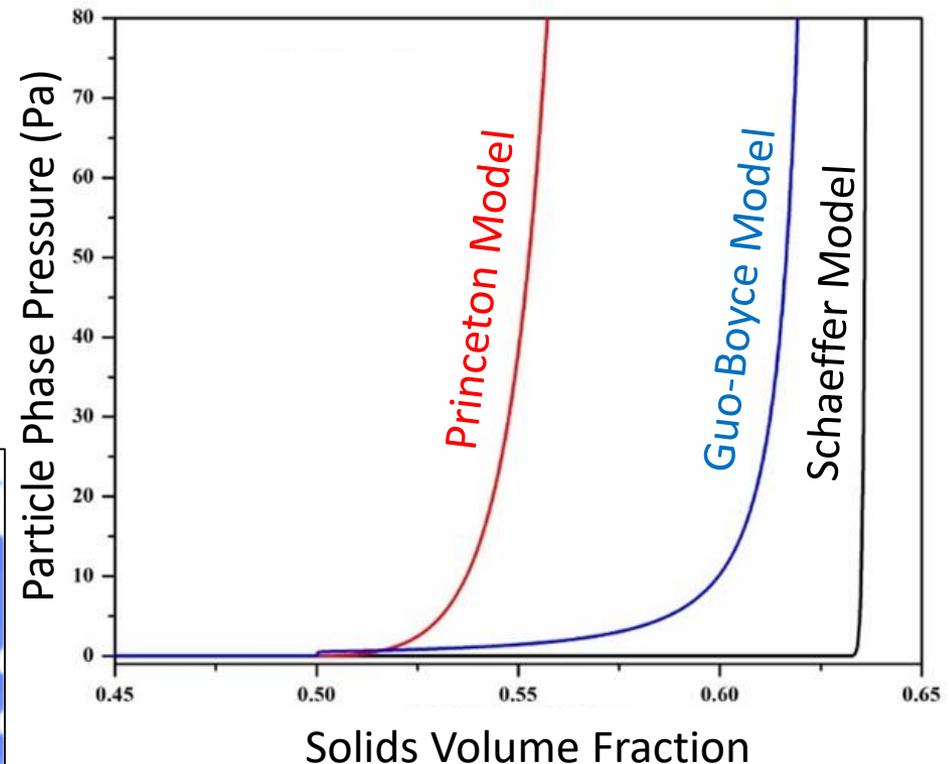
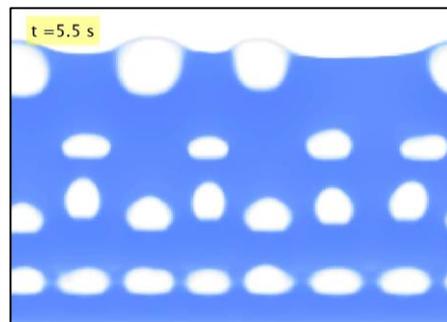
Guo-Boyce Model



Schaeffer Model



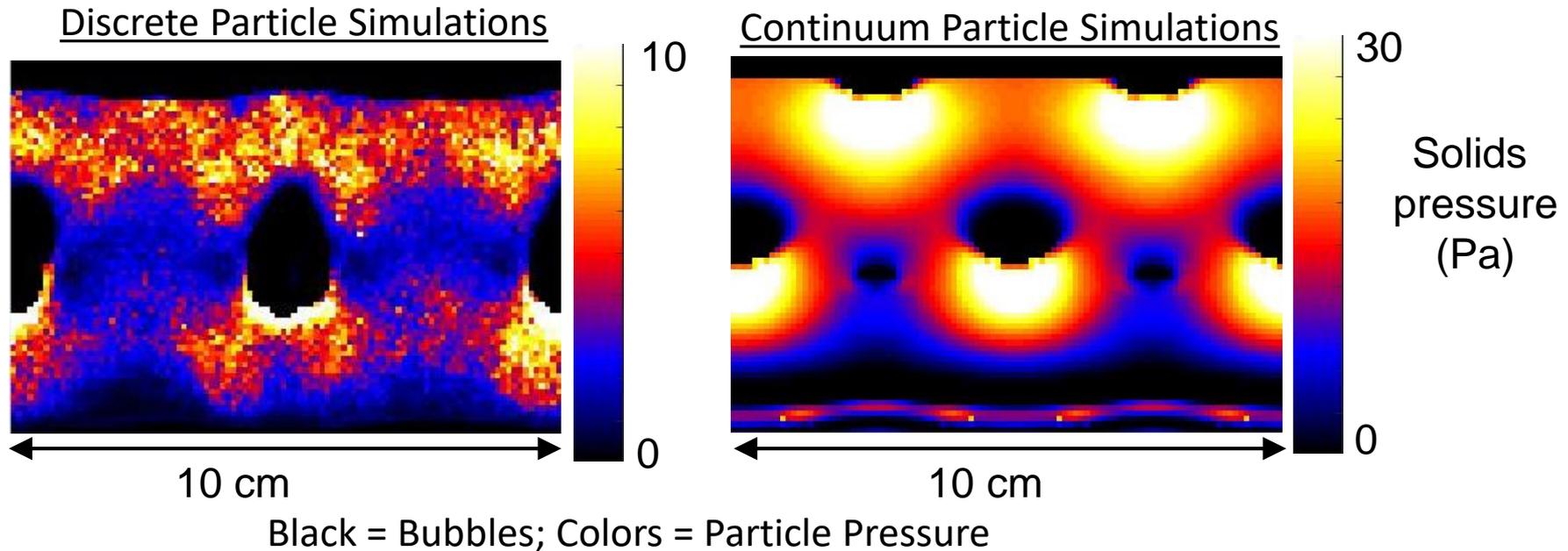
Princeton Model



- We developed a continuum model which captures the increase in particle pressure at high solids volume fractions, based on a dilation law
- This is the first model which can capture the alternating structured bubbling pattern because it can capture local solidification aspects underlying the alternating structure

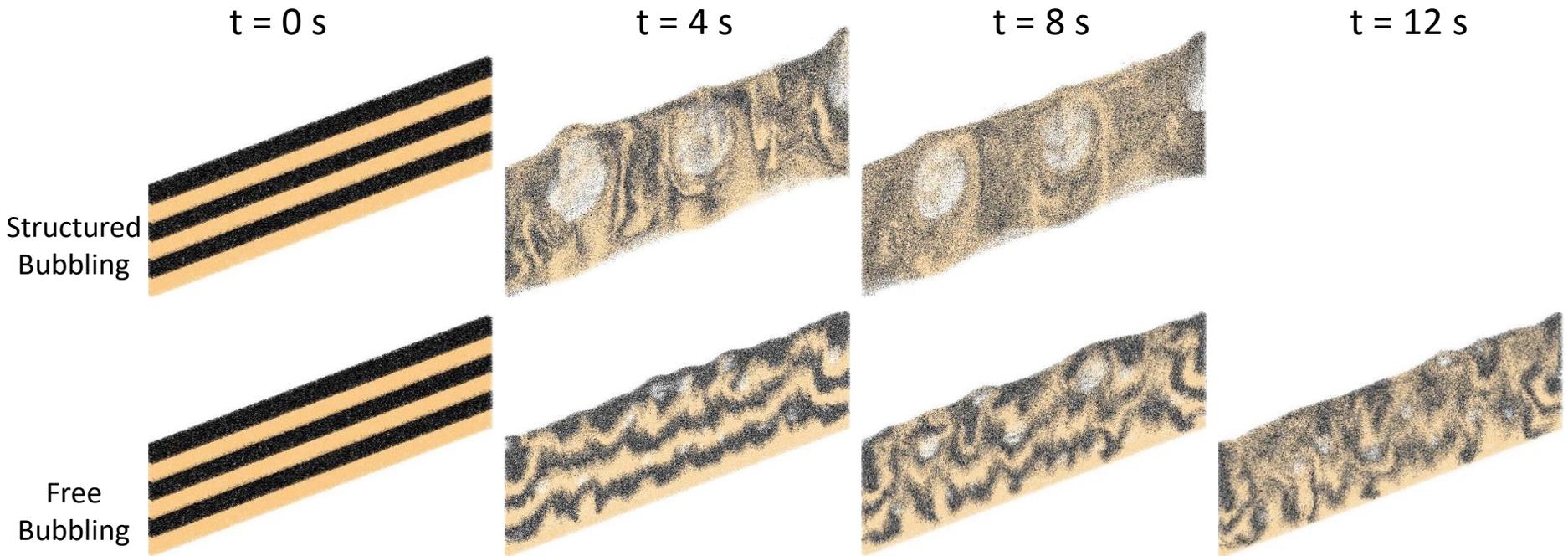
Guo, Zhang,  
Padash, Kovar, Xi,  
**Boyce**, *PNAS*, 2021

# Structured Bubbling: Rheological Development (2)



- New frictional stress model can capture solidification of particles below bubbles (shown by the high solids pressure), allowing continuum simulations to recreate the triangular structuring pattern
- This addresses the persistent challenge of capturing fluid-solid transitions in dense granular flows described by Coppens and co-workers

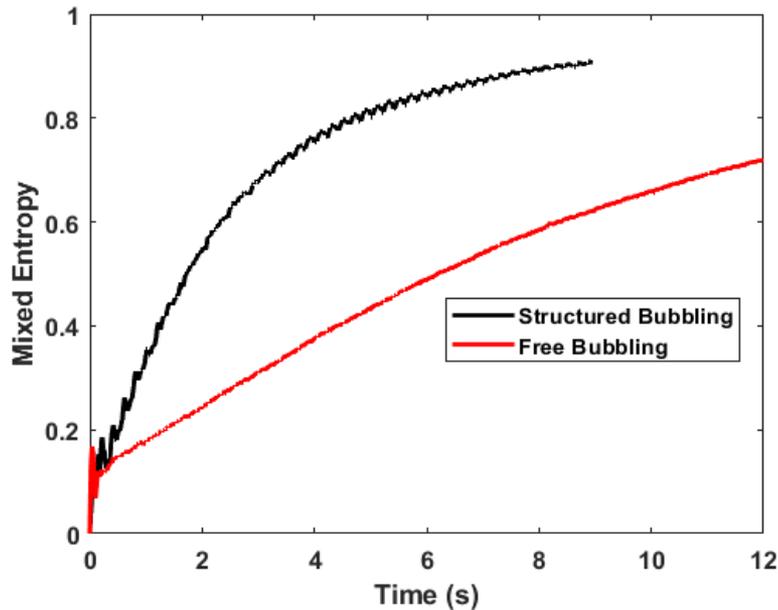
# Structured Bubbling: Mixing Amongst Like Particles



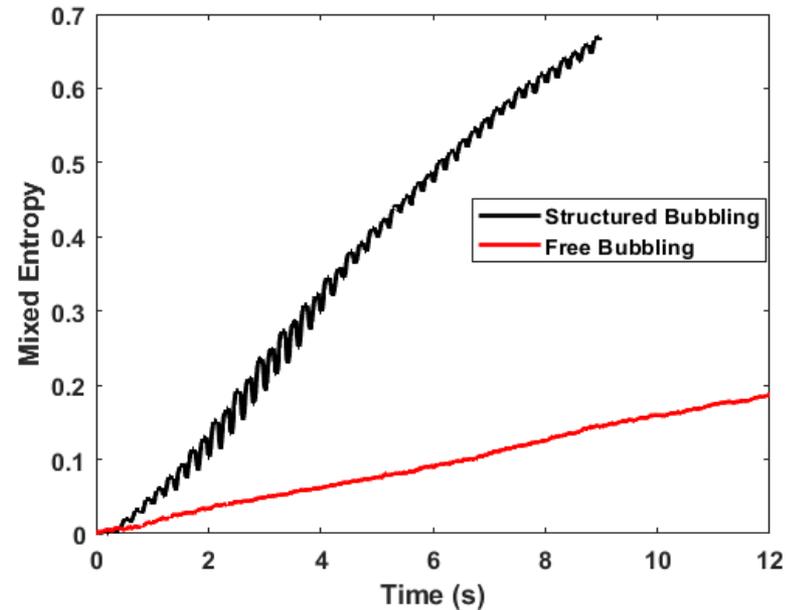
- We can visualize mixing in both simulations (here) and experiments (not shown)
- All particles are the same type, colors are just used to visualize mixing
- Mixing is better in structured bubbling fluidized beds than conventional “free bubbling” fluidized beds without vibration

# Structured Bubbling: Mixing (2)

## Vertical Mixing



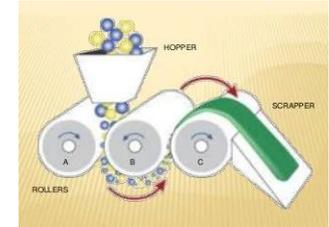
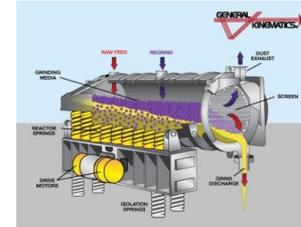
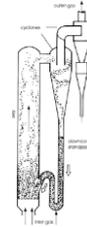
## Horizontal Mixing



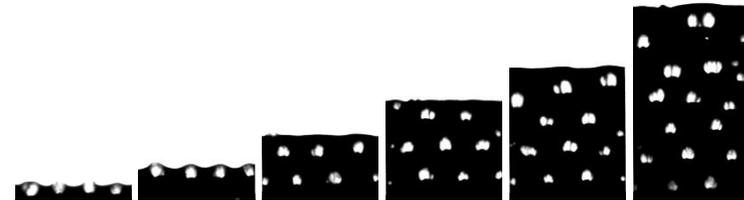
- We can quantify mixing using various methods to demonstrate quantitatively how much better structured bubbling is at mixing particles than conventional “free bubbling” fluidized beds without vibration

# Outline

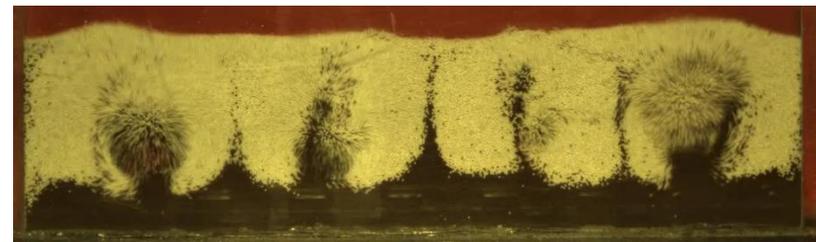
➤ Motivation



➤ Structured Bubbling in Monodisperse Systems



➤ **Structured Bubbling in Bidisperse Systems**



➤ Conclusions

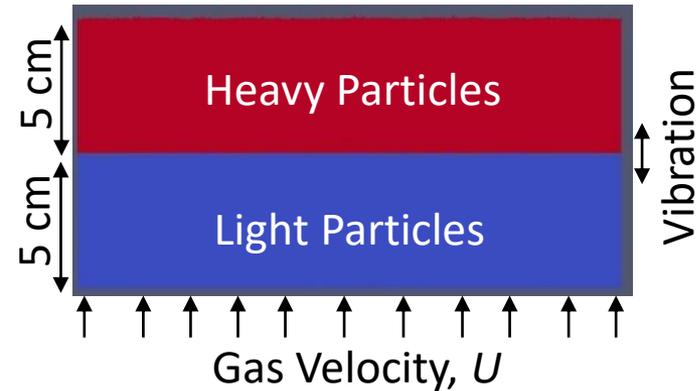
# Mixing Induced by Structured Bubbling



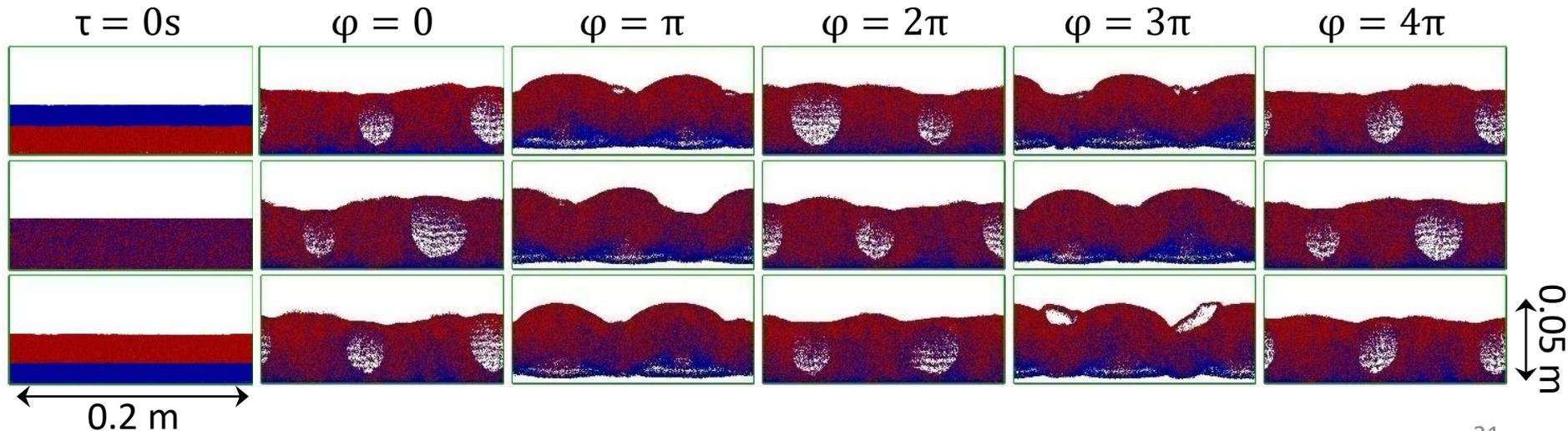
20 cm

- Playback speed: 0.5x
- Structured bubbling persists even in a mixture of heavy and light particles
- Structured bubbling mixes initially segregated particles

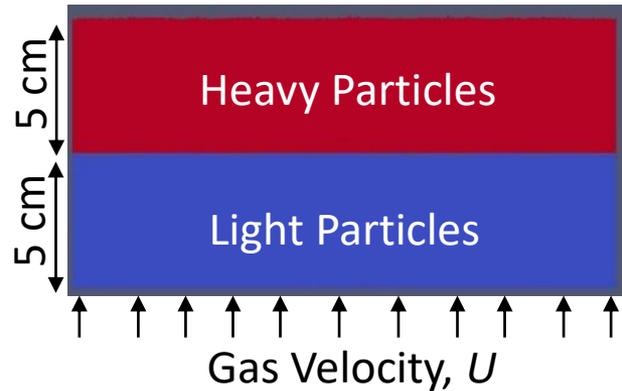
# CFD-DEM: Structured Bubbling Persists



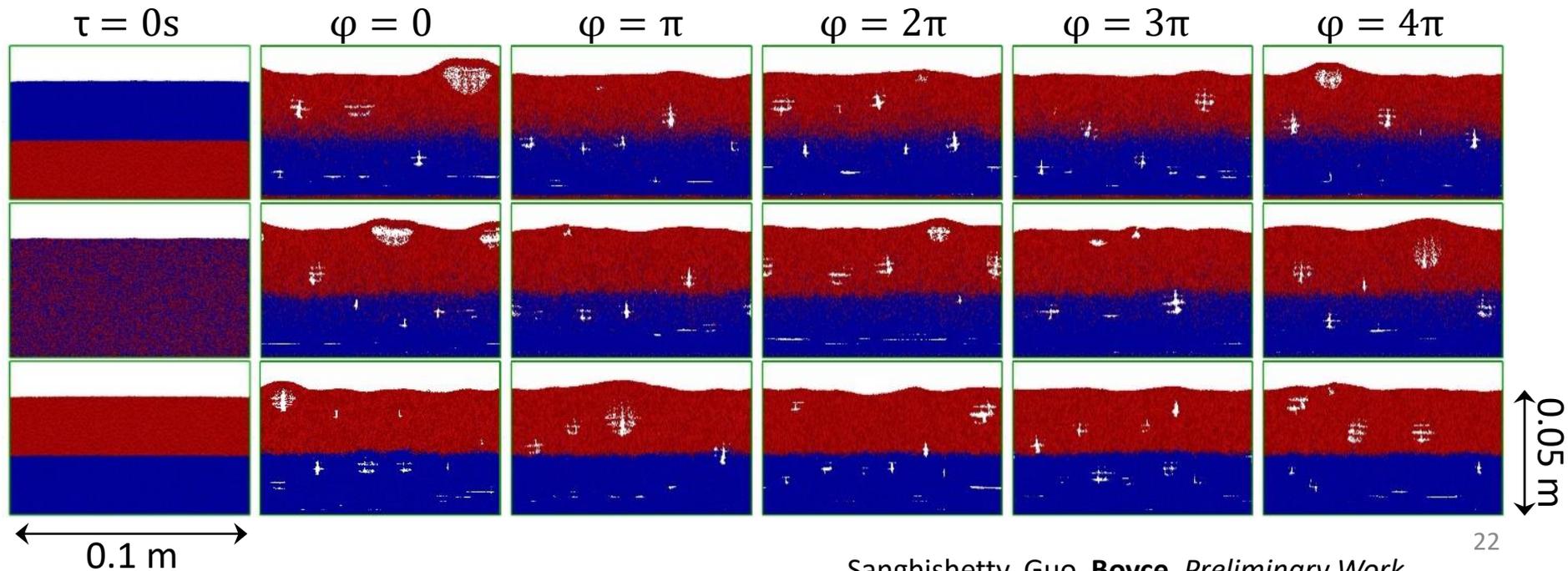
- Structured bubbling persists in a mixture of light and heavy particles
- Light particles generally rise to the surface, but vigorous motion of particles from bubbling still provides reasonable mixing of particles
- Steady-state is reached in  $\sim 10$  seconds



# CFD-DEM: Segregation in Unstructured Bubbling

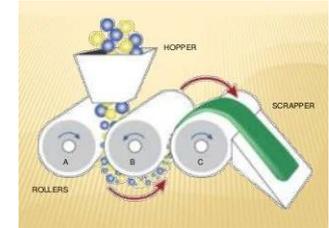
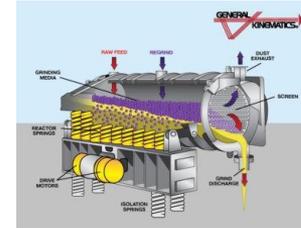
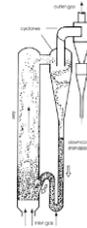


- Without vibration, we have unstructured bubbling
- Light particles generally rise to the surface and a lack of rigorous motion from large bubbles prevents significant mixing of particles

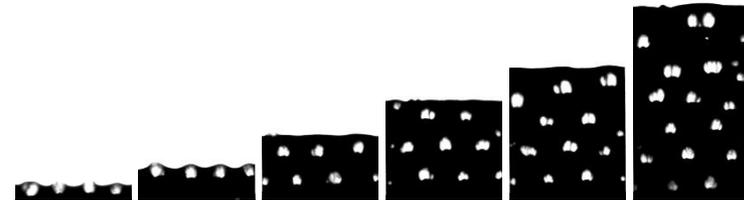


# Outline

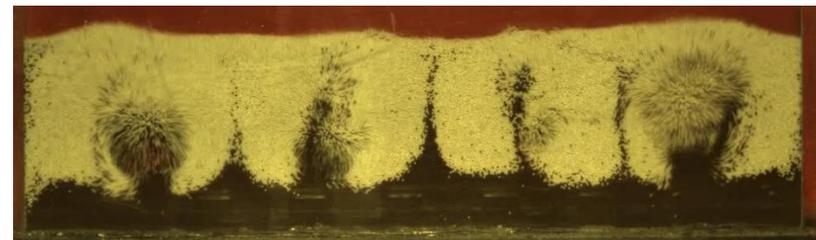
➤ Motivation



➤ Structured Bubbling in Monodisperse Systems



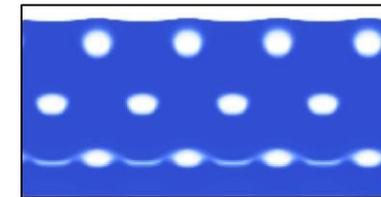
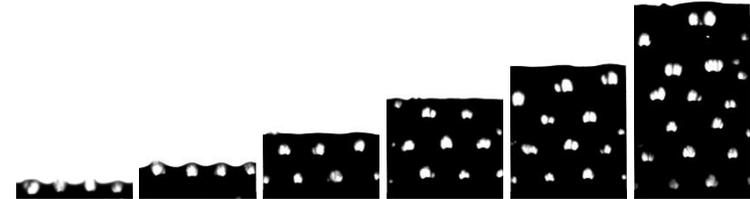
➤ Structured Bubbling in Bidisperse Systems



➤ **Conclusions**

# Conclusions

- Structured bubbles are good because they are scalable and predictable
- Dynamic, local fluid-solid transition enable structured bubbling, and a rheological model must incorporate these transitions to capture structured bubbling
- Structured bubbles work to mix particles without losing their flow structuring



Guo-Boyce Model



# Acknowledgments

## ➤ Research Group



## ➤ Funding



Pall Corporation



Structured Bubbling



Qiang Guo



Jagan Mohan



Chris Spitler