Force and velocity fluctuations in dense granular flows

What is the state of flow as jamming is approached?

- Force fluctuations
- Spatial correlations of force and velocity

Emily Gardel, Ellen Keene, N. Easwar , Smith College

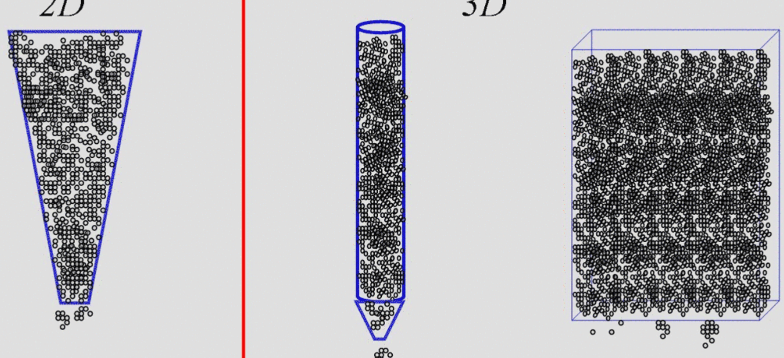
Narayanan Menon, U. Massachusetts, Amherst

NSF-DMR

Experimental flow geometry

Measure kinematics and wall forces

2D *3D*



Normal force

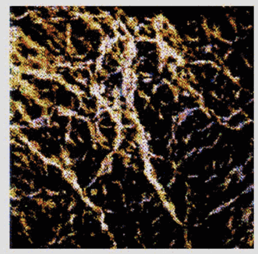
Spatial correlations of force

Vector forces and torques; DWS

Do the force fluctuations carry a signature of impending jamming?

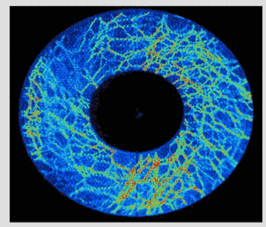
Force chains in static sand

Forces are spatially inhomogeneous in static sand …



Chicago group

… even under quasistatic shear

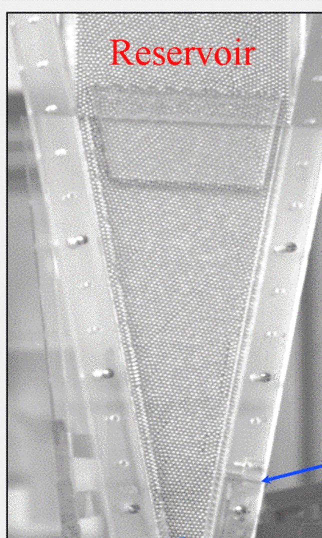


Duke group

What happens to force inhomogeneities when flow is turned on?

2-dimensional gravity driven flow

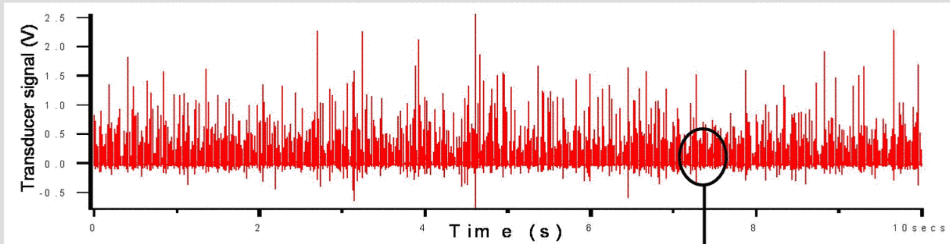
Steel beads
diameter:
d= 3mm



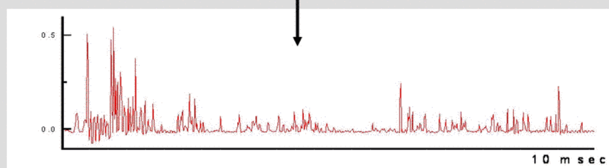
Transducer
- head size ≈ **d**
- normal forces

- opening **a** - varied from 3d to 16d
- flow velocity constant as hopper drains
- packing very dense at all flow rates

Forces on wall are collisional

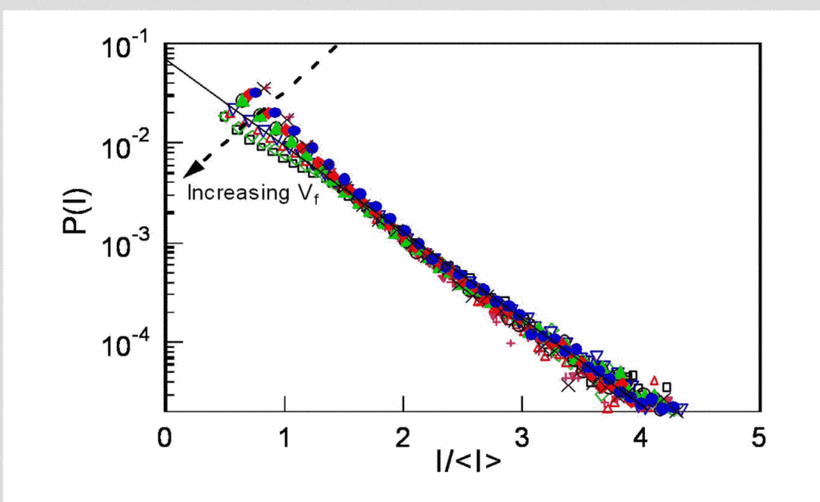


peak height ∝ impulse



Peak width	<	(Collision freq)$^{-1}$	<	Time for ball to pass transducer
20μs		500μs		5-30 ms

Histogram of impulse fluctuations

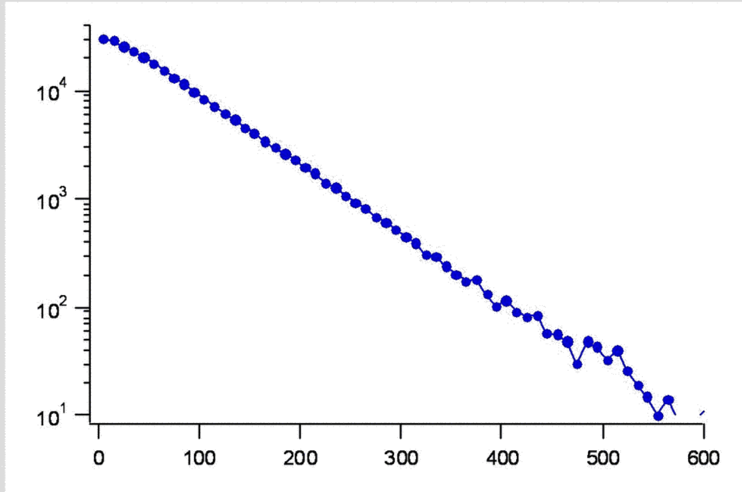


- *high force end of distribution is exponential*
- *low force end evolves with flow rate but no clear signature of the approach of jamming*

Longhi, Easwar, NM, PRL 2002

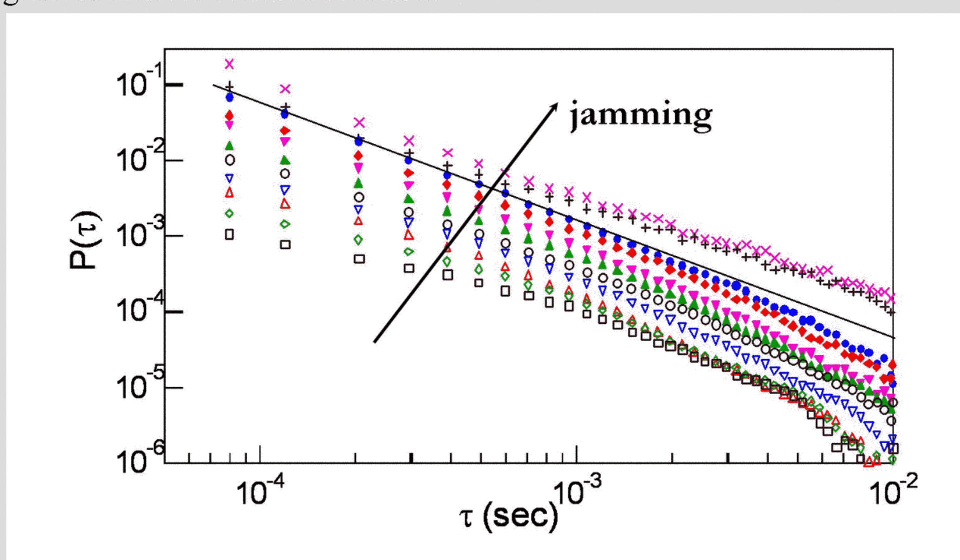
Impulse histogram

Large force tail really is exponential in 2D



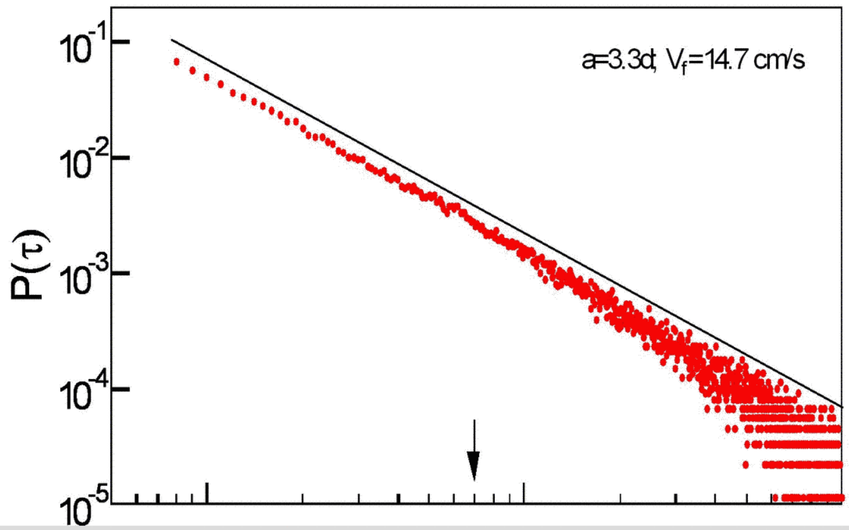
Temporal characteristics of force

- Histogram of interval between collisions -



- Distribution broadens continuously toward power law $P(\tau) \sim \tau^{-3/2}$ at jamming

Time distribution close to jamming



- Time distribution, $P(\tau) \sim \tau^{-3/2}$ close to jamming
- Average collision time diverges?

Also seen in simulations - Denniston and Li

Summary

Force fluctuations show

– Clear dynamical signature of jamming

but no static signature

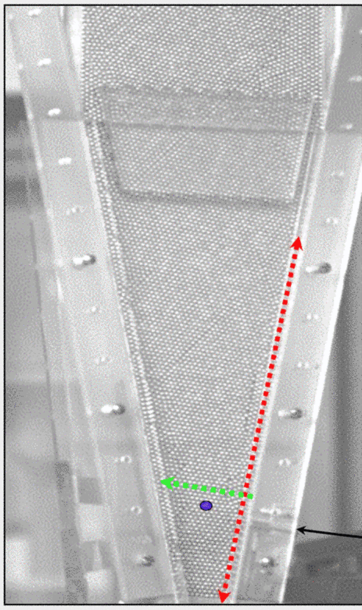
– Exponential force distribution at all flow rates

force chains?

Next:

How does this connect with kinematics?

Video measurement



Video measurement synchronized with force measurement

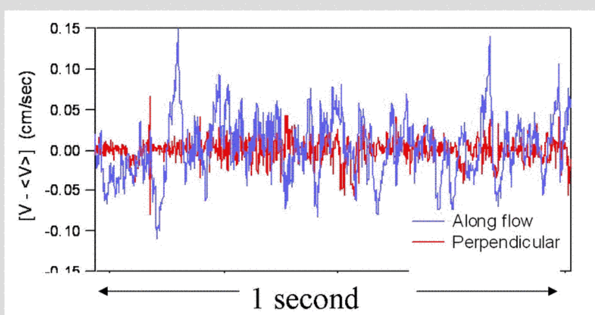
Typical frame rate = 4000 frame/sec

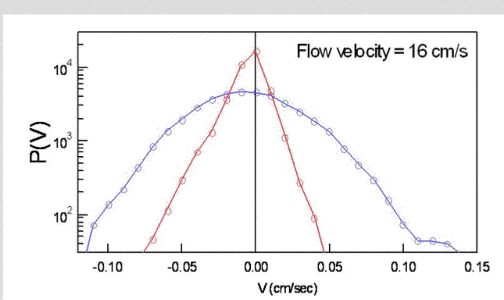
High spatial resolution: 512x512 px over ~ 2.5d x 2.5d

Measured velocities are convective velocities, not "temperature" fluctuations

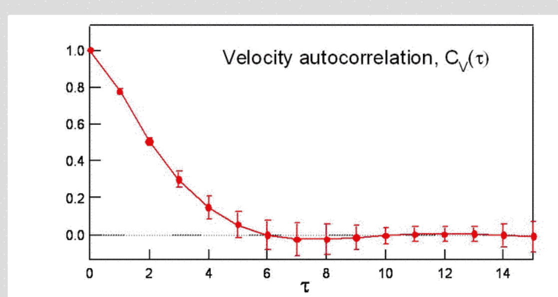
Transducer

Velocity fluctuations are large, long-lived





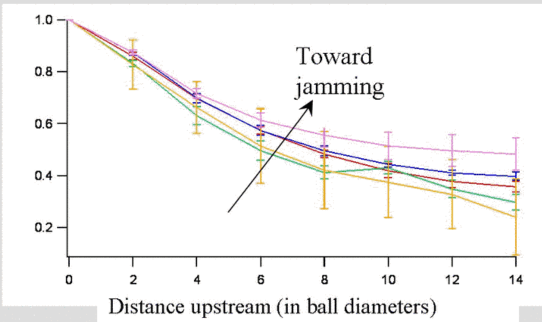
Broadly distributed along flow direction

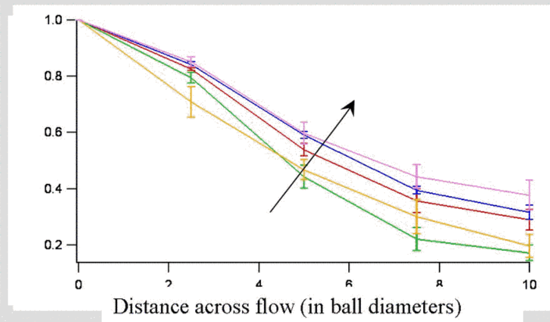


Correlation time ~ 100s of collision times

Flow is spatially correlated

Equal time spatial correlations of flow velocity

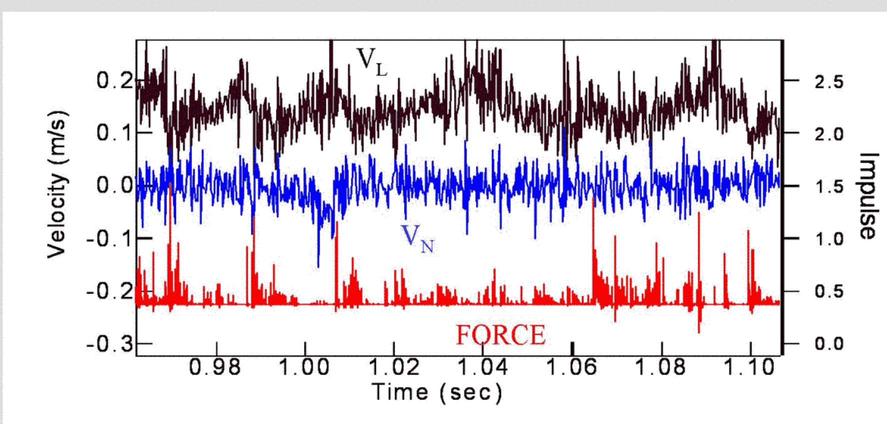




•Velocity fluctuations are very correlated, increasingly so as jamming approached

Velocity and force traces

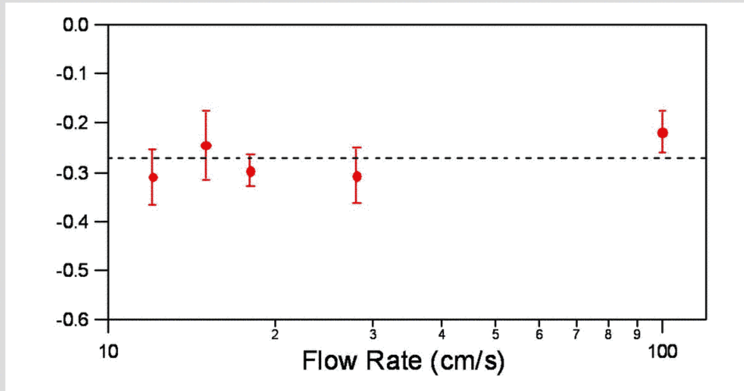
Convective velocities correlated with forces?
correlate velocity fluctuation, Δv=v-<v>
and
average force, collision frequency, magnitude of impulse



Force and velocity are negatively correlated!

Equal-time correlation of collision frequency and flow velocity

<n(t) Δv(t)>

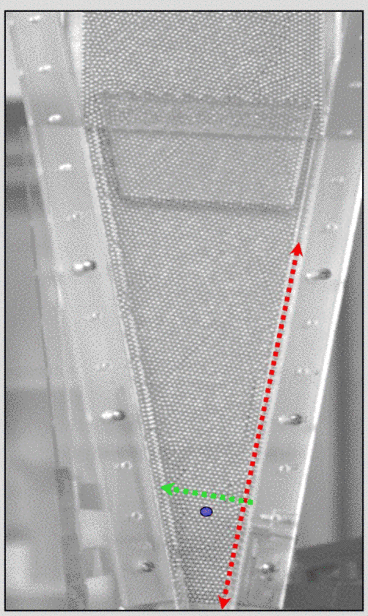


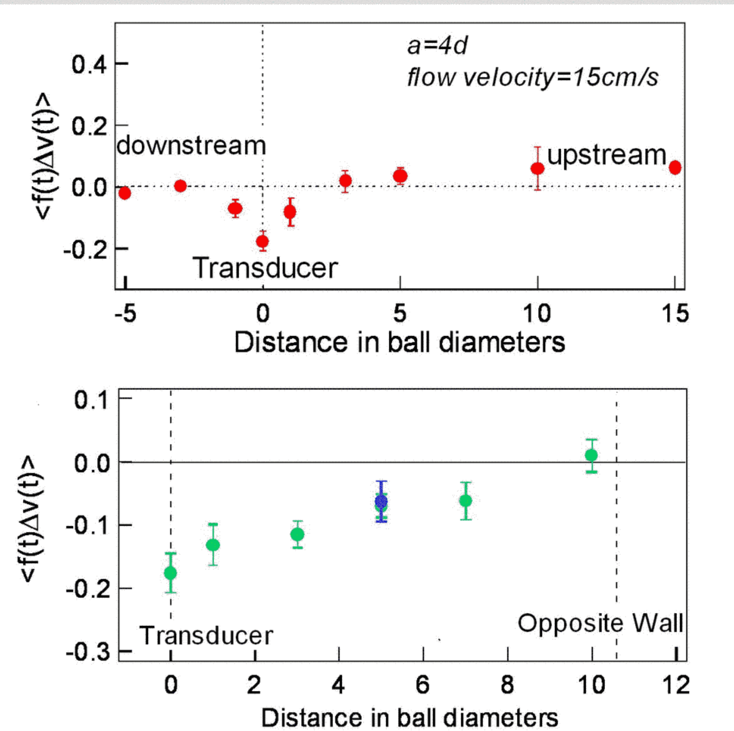
Similar trend for average force vs. velocity

cf. Luding, Duran, Clement, Rajchenbach 96

Flow at the transducer slows down when impulses are frequent and large

Spatial correlations



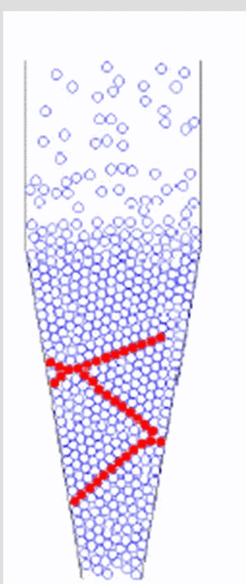


Spatial correlation between force and velocity

- In the flow direction, correlations die away on the scale of a bead diameter
- Transverse to flow, correlations die away on the scale of the channel width

Data consistent with transient "force chains" that are a few beads wide, but sometimes can span the width of the channel

Simulations

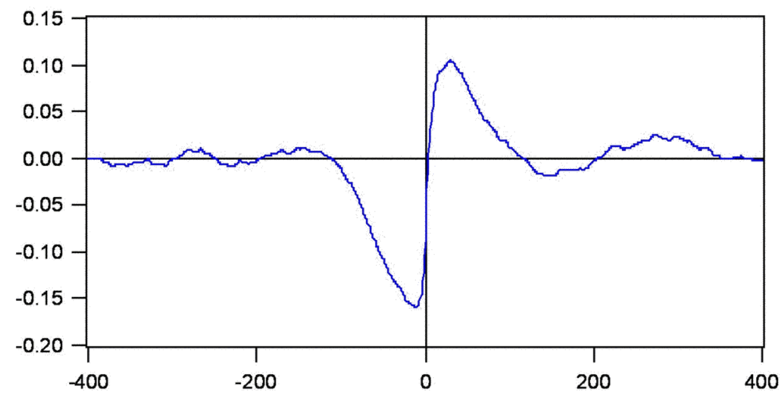


Frequently colliding particles (red) form linear chains

A. Ferguson, B. Fisher, and Bulbul Chakraborty, Europhys Lett '04

Temporal correlations – chicken/egg?

$\langle \Delta V(t) F(t+\tau) \rangle$

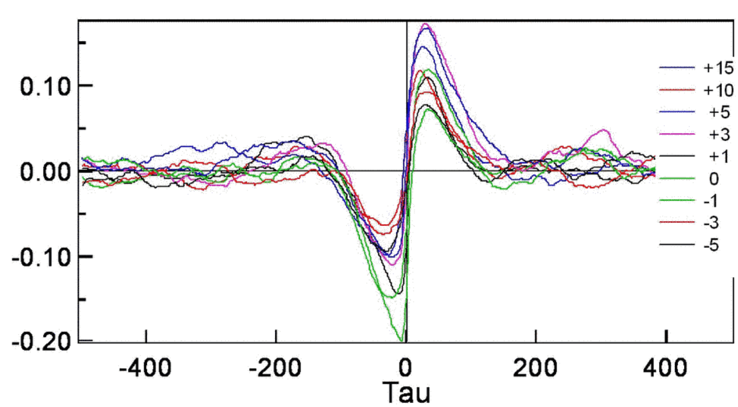


- Forces build up ~ 20 msec <u>before</u> velocity drops, die out ~30 msec later
- Time to build and break these correlations ~ 50 collision times

Temporal correlations

Cross-correlation between force at transducer and velocity elsewhere

$\langle \Delta V(t) f(t+\tau) \rangle$



- Correlations are communicated upstream rapidly coherently

  at 12 x flow speed ~ diameter x collision freq
- Amplitude of correlation diminishes very little

Summary

- Time-interval distribution shows signature of jamming but P(f) does not
- Force and velocity are anticorrelated
- Spatial correlations are very anisotropic
- Time- and space- correlations : "chains" have long-range effect

Ongoing work

- 3D flow system
  - Directly look for spatial correlations in force
  - Study crossover between collisional and frictional flows
  - Other components of force
- Connection between force fluctuations / linear response