KITP, Santa Barbara, October 20-24, 2014

Irreversible Sound-Matter Interaction in Dense Granular Media

from **acoustic probing** to **acoustic fluidization**

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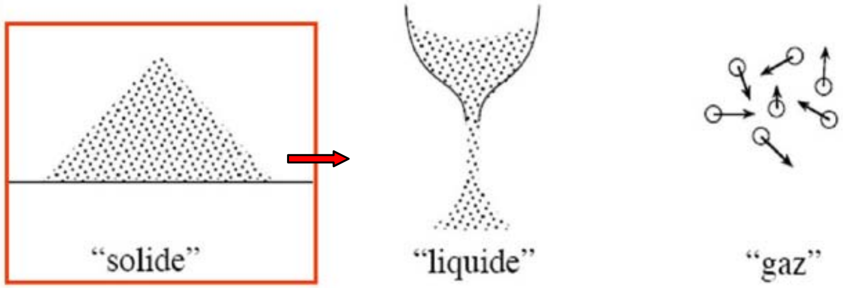
Acknowledgments: T. Brunet, J. Laurent, Y. Yang, Y. Khidas, V. Langlois, P. Mills (Université Paris-Est MLV)
J. Léopoldès (Université Paris Diderot)
P. Johnson (Los Alamos National Laboratory, USA)
S. Wildenberg, M. van Hecke (Leiden University, The Netherlandes)
J-L Genisson, M. Tanter, M. Fink, A. Tourin (Institut Langevin)

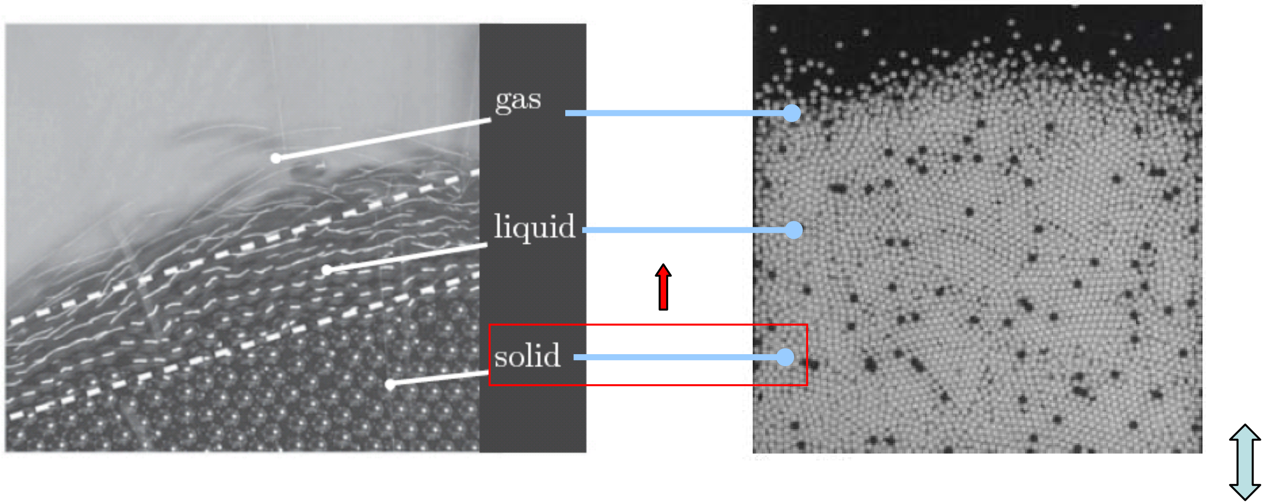
Motivation

Granular Matter (athermal)



Avalanche experiment

(Jaeger, Nagel, Behringer)



Shaking experiment

(Lohse et al)

Oscillation

Oscillatory monitoring of the **transition** from **jammed** to **(plastic) flowing states**:

- ♦ Acoustic ***probing*** and ***pumping*** **(HF)** of granular media under quasi-static shear
- ♦ Monitoring ***shear modulus (rigidity) decrease*** by high-amplitude oscillatory shear **(LF)**

  → **glassy behaviour**

Outline

I. Linear ultrasound propagation in jammed granular media

- ♦ **Coherent waves (EMT) & Multiply scattered waves**
- ♦ **Probing shear band & precursor events**

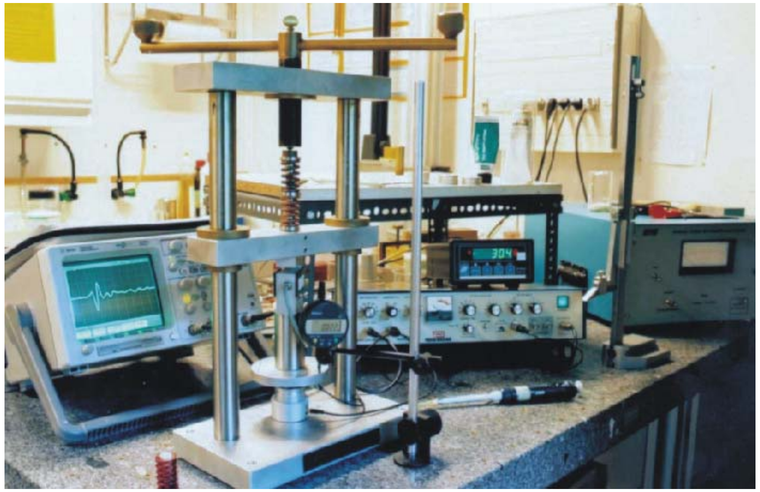
II. Nonlinear ultrasound propagation in jammed granular media

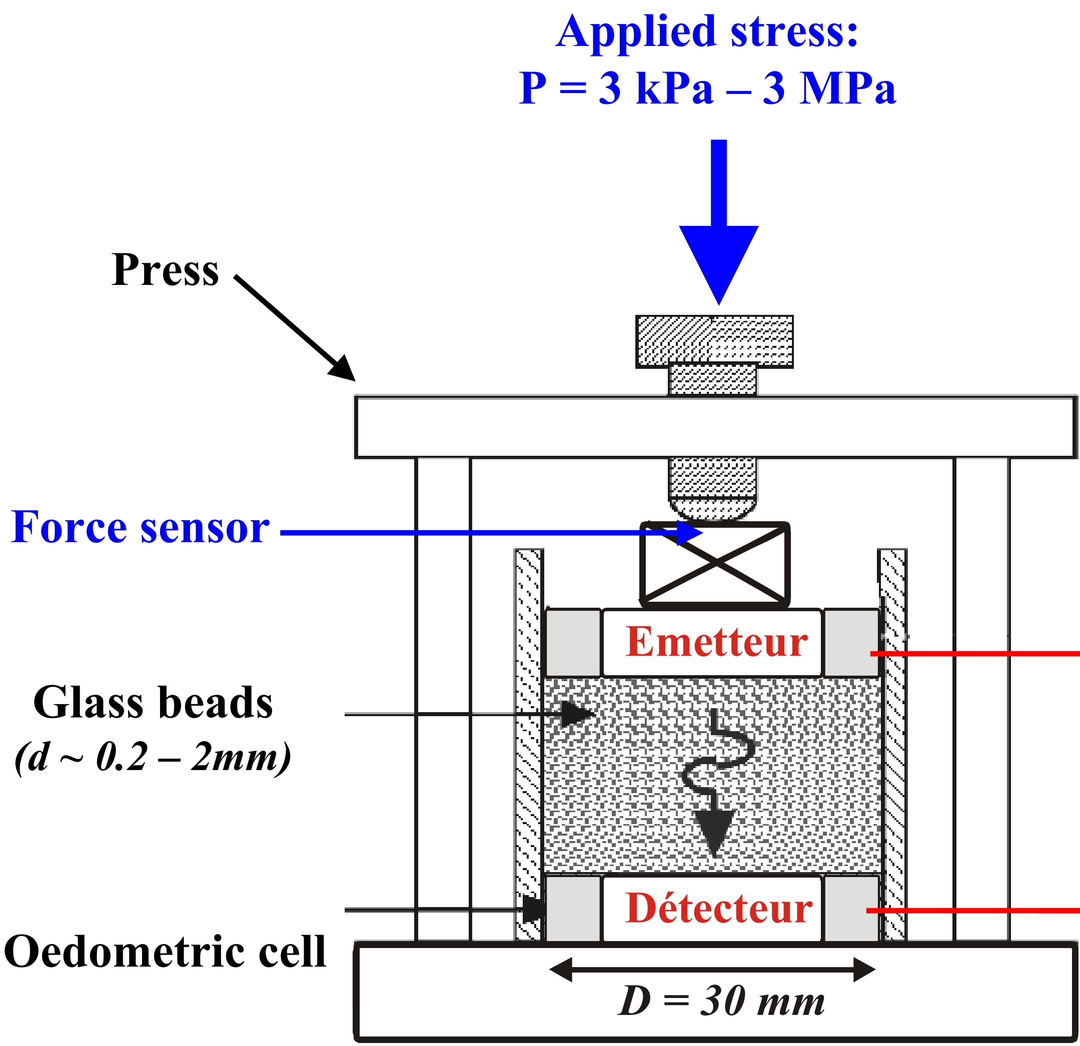
- ♦ **Hertzian and Mindlin nonlinearities: harmonics generation**
- ♦ **Wave velocity softening: reversible → irrevrsible regimes**
- ♦ **Interfacial sliding /granular flow triggered by acoustic fluidization**

III. Low-frequency nonlinear shear wave in *marginally jammed* granular media

(monitoring shear modulus softening: jammed → unjammed states)

Experimental set-up



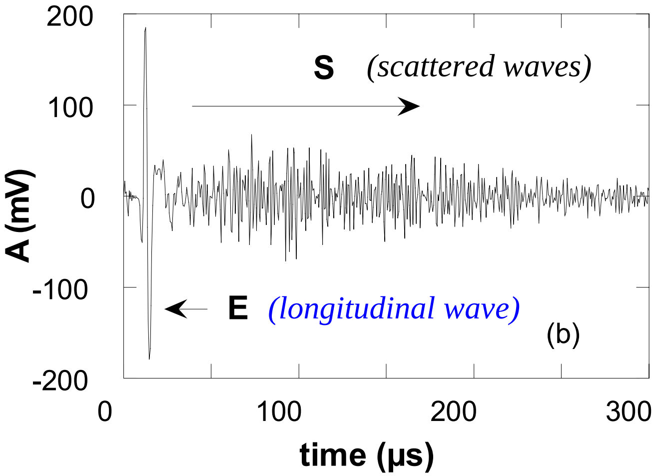


I. Linear ultrasound propagation in *jammed* granular media (1/6)

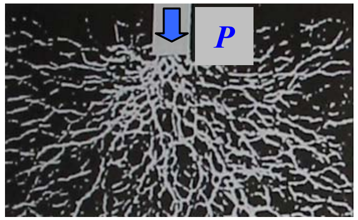
♦ Coherent waves and multiply scattered waves

Jia, Caroli, Velicky, PRL 82 (1999)

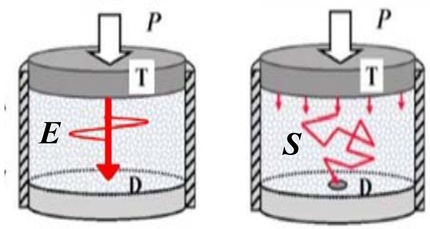
P = 0.75 MPa glass beads d=0.6-0.8mm



Contact force networks

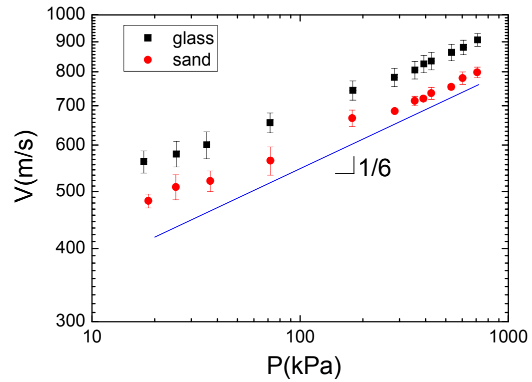


Dantu (1957)



$\lambda > 10d$ $\lambda \sim 2d$

● Compressional wave velocity *V(P)*

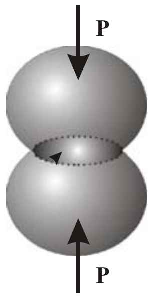


Wildenberg, Yang, Jia, Powders & Grains (2013)

$$V_P = \sqrt{(K + 4/3G)/\rho}$$

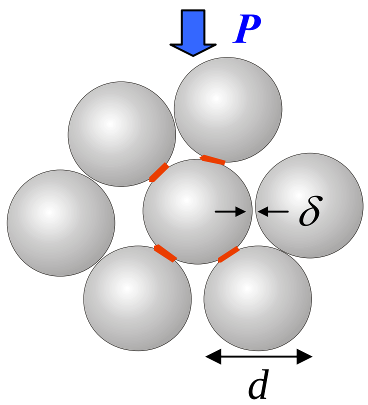
$$V_S = \sqrt{G/\rho}$$

● Effective medium theory (EMT) *(Duffty & Mindlin 1957; Digby 1981)*



Hertzian contact :
k ∝ P^1/3

$$V_{P,S}(P) \propto Z^{1/3}.\Phi^{-1/6}[k(P)]^{1/2} \propto P^{1/6}$$



Z_{mech} is the coordination number

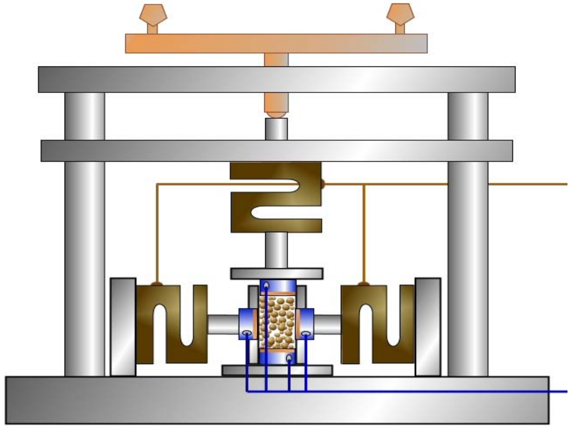
$Z_{bead} \approx 6$
$Z_{sand} \approx 4$

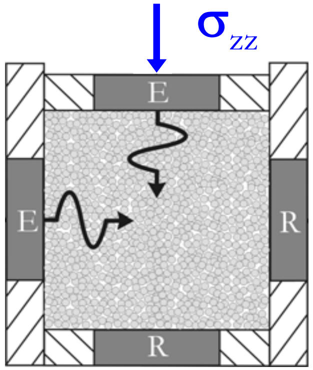
- *Goddard (1990)*
- *De Gennes (1999)*
- *Makse, Johnson, Schwartz (2000)*
- *Velicky, Caroli (2002)*
- *Coste, Gilles (2003); Roux (2000)*

Elastic anisotropy: stress-field anisotropy and fabric (2/6)

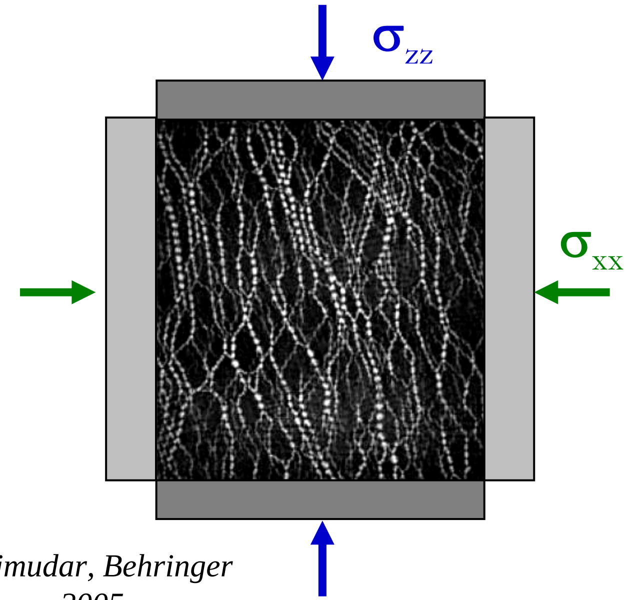
Khidas & Jia, PRE 81 (2010)

♦ **Set-up**



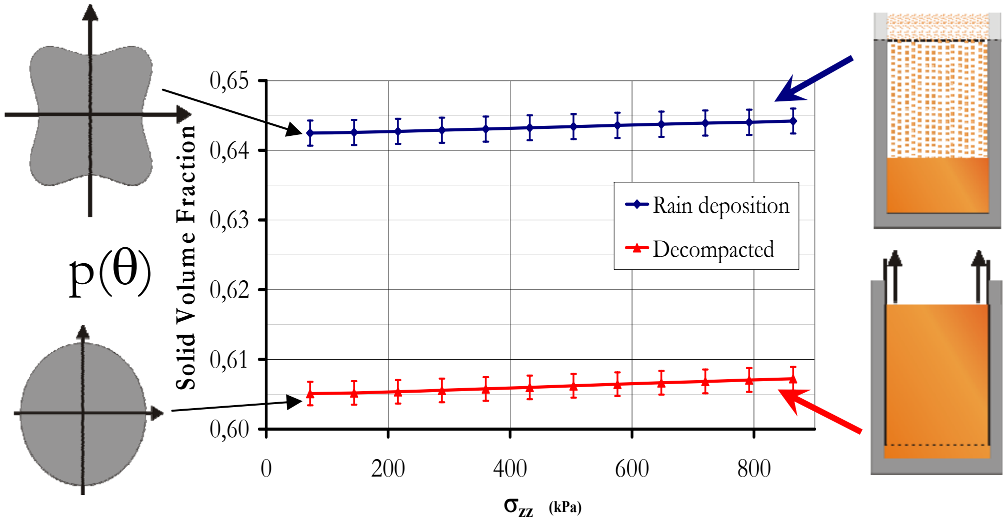


♦ **Stress-field ansiotropy**



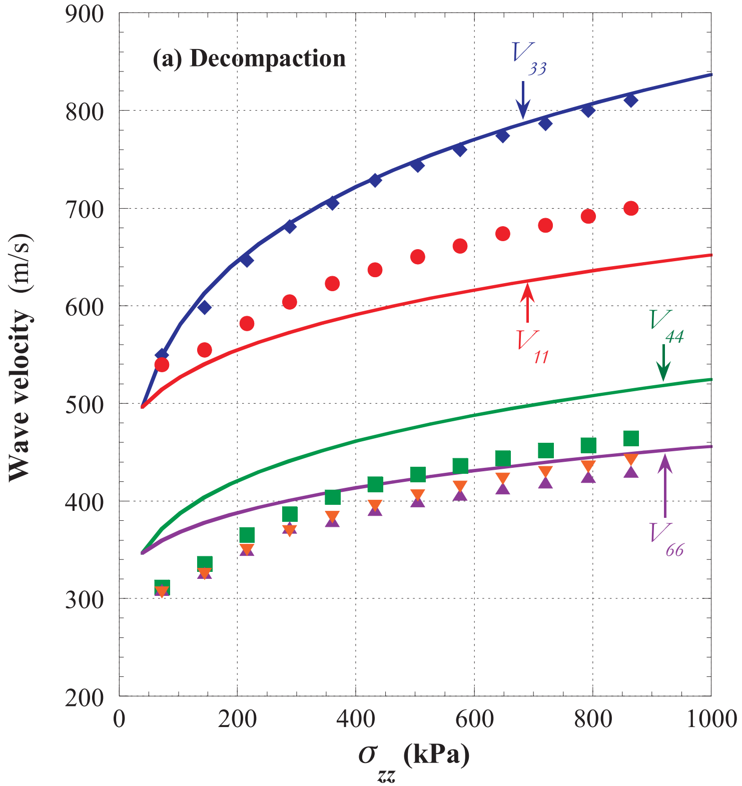
Majmudar, Behringer 2005

♦ **Sample density & fabric**



Correlation between induced elastic anisotropy and stress anisotropy (3/6)

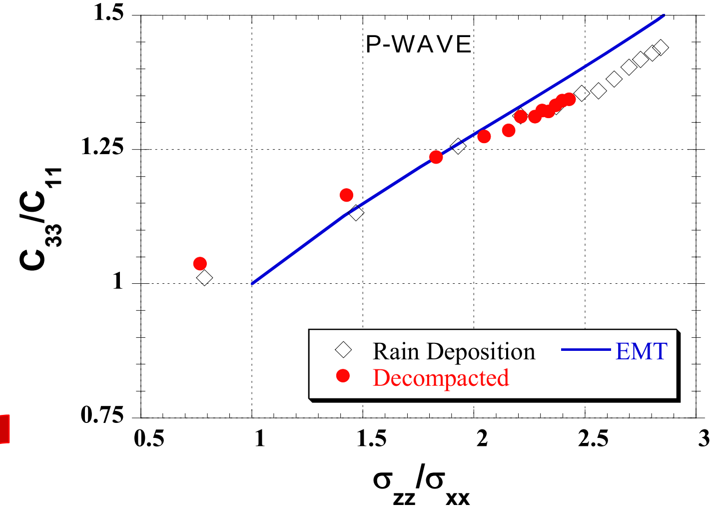
♦ **Compressional (P-) & shear (S-) wave velocities**



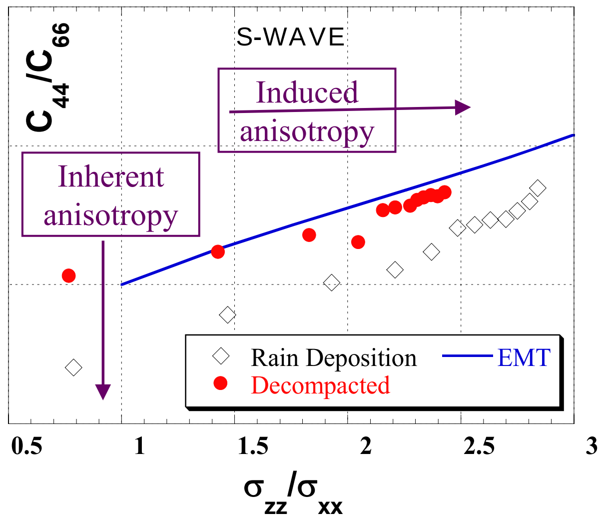
Agreement with EMT and GSH theory

- D. Johnson et al, J. Appl. Mech. 65 (1998)

- Mayer & Liu, PRE (2010)



P-wave is only sensitive to stress anisotropy



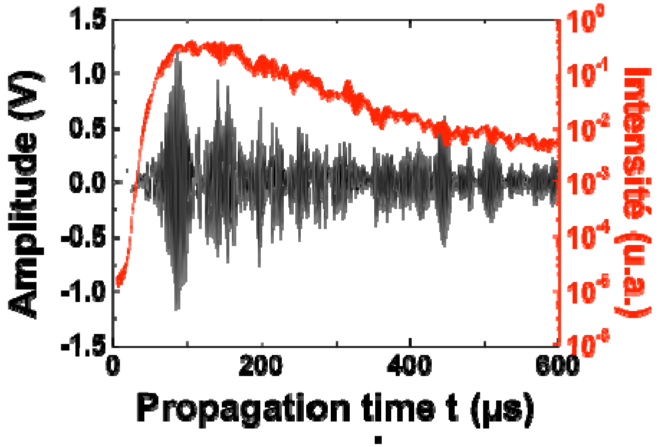
S-wave is also sensitive to fabric anisotropy

Probing the internal dissipation in *dry* and *wet* granular media with diffusively scattered waves (4/6)

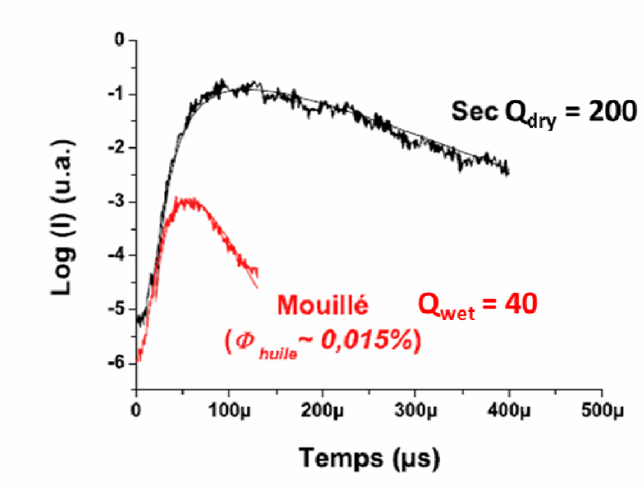
Jia, PRL 93 (2004)

♦ **Diffusively scattered shear waves:** $\partial_t I - D\nabla^2 I + I/\tau_a = \delta(z)\delta(t)$

with $D = (1/3)\, v_e\, l^*$ the diffusion coefficient and τ_a the inelastic absorption time

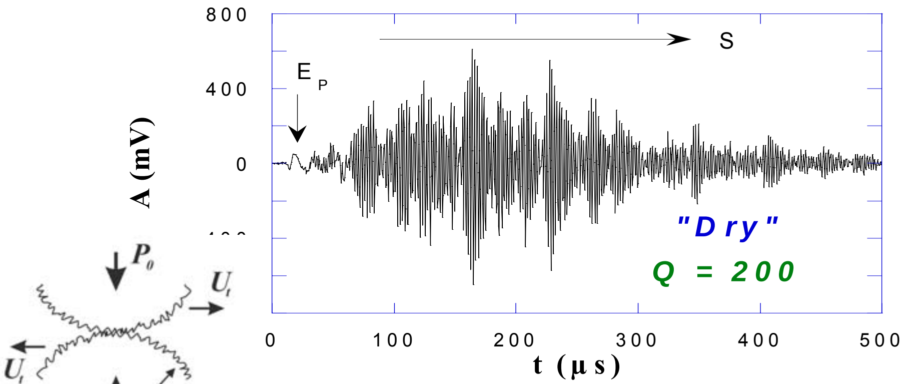


$D \approx 0.13$ mm²/µs
$\tau_a \approx 64$ µs
($Q \approx 200$)

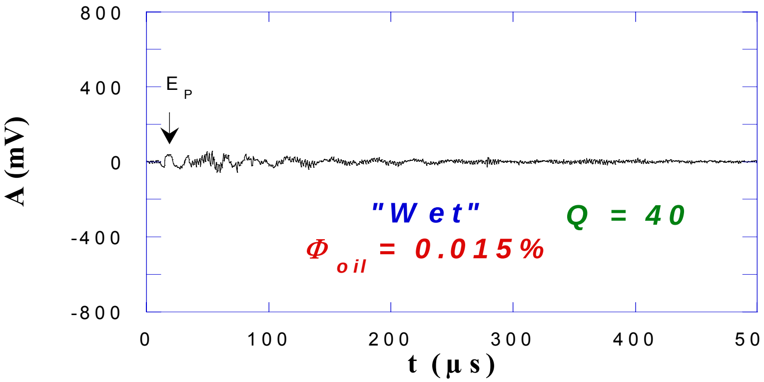


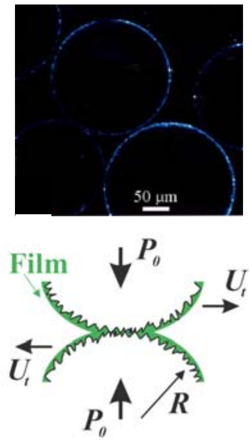
♦ **Absorption of multiply scattered waves by added liquids**

Brunet, Jia & Mills, PRL 101 (2008)



Frictional loss



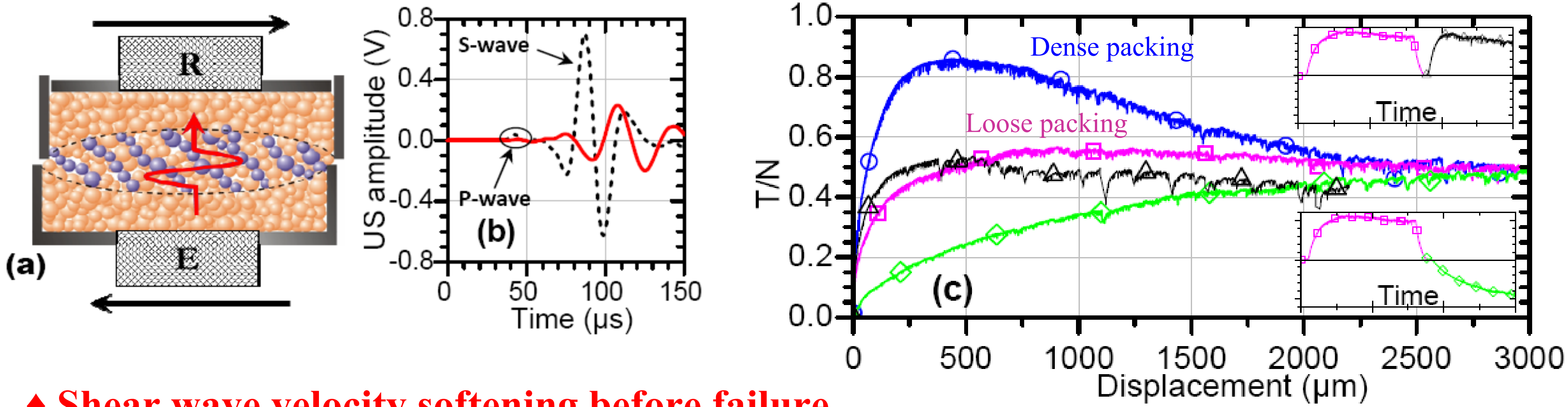


Viscous loss

Probing the shear band formation with shear wave (5/6)

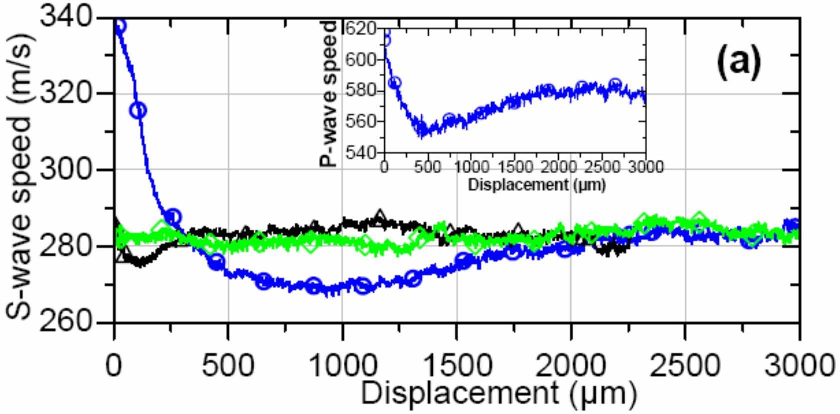
Khidas & Jia, PRE 85 (2012)

♦ **Mechanical response**

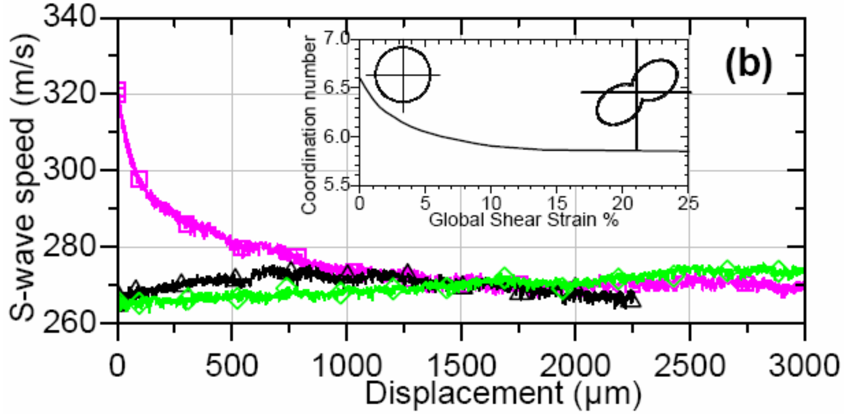


♦ **Shear wave velocity softening before failure**

Dense packing



Loose packing



$$V_S \propto z^{1/3} \cdot \phi^{-1/6} \cdot P^{1/6}$$ ➡ **Decrease of the coordination number *z***

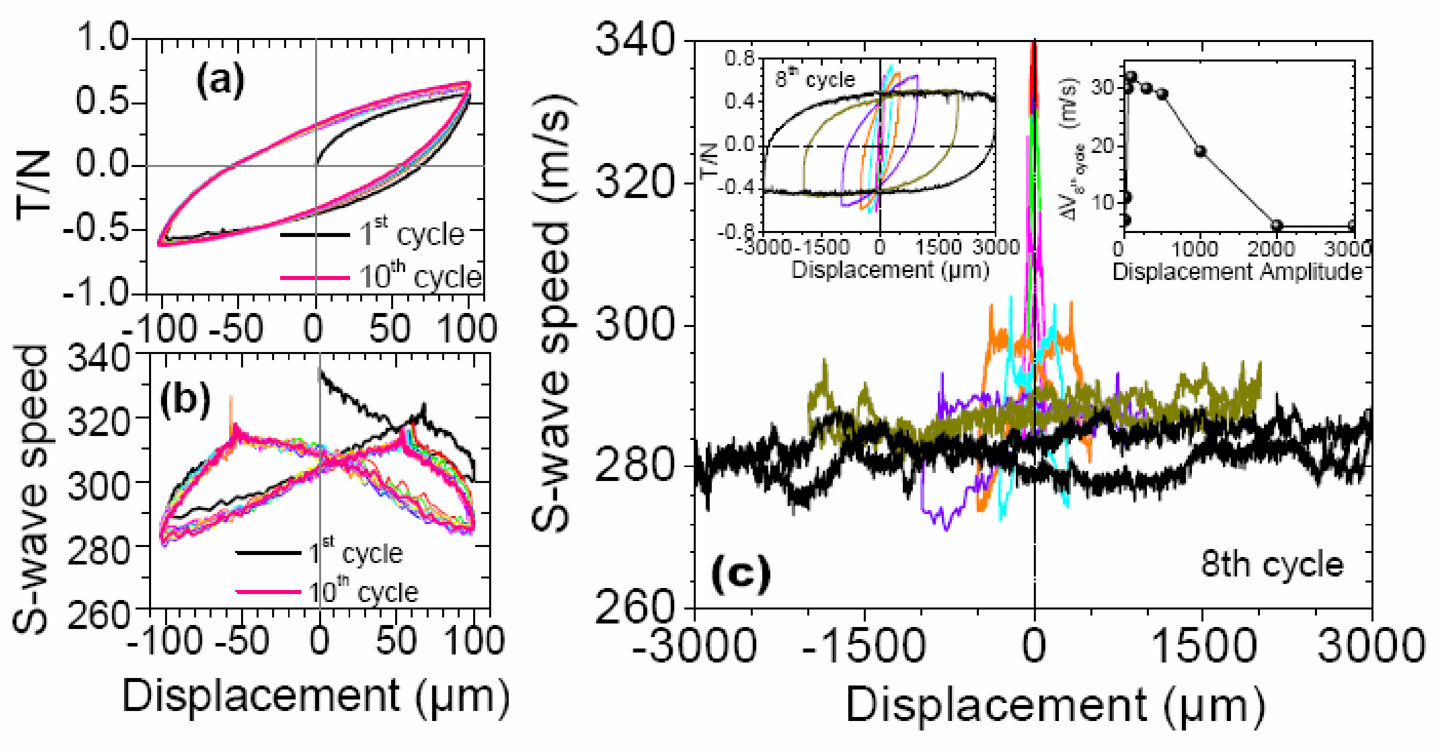
3D DEM simulations
Cui & O' Sullivan 2006

Acoustic monitoring of granular failure by cyclic shear

Khidas & Jia, PRE 85 (2012)

♦ **Cyclic loading/unloading**

Loose packing

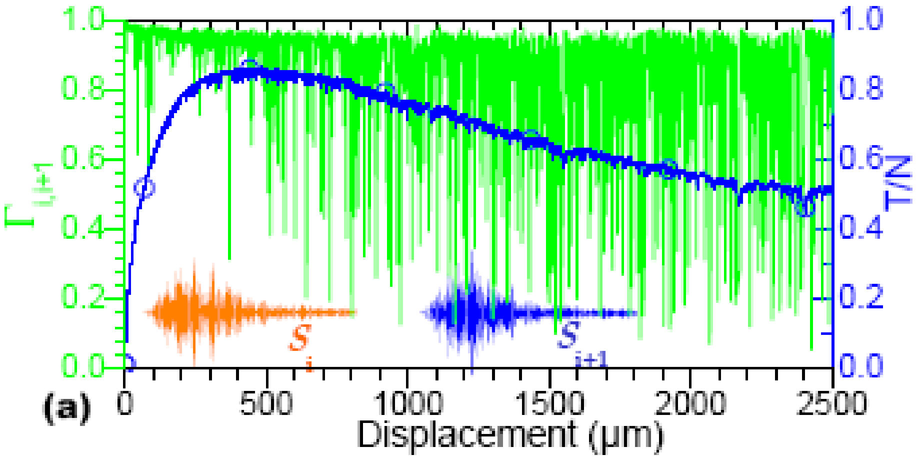


Probing **intermittent behavior** with scattered waves (6/6)

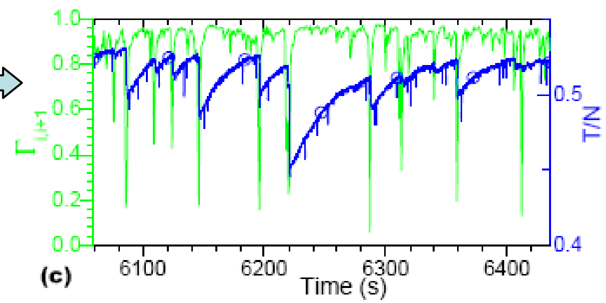
♦ **Cross-correlation of scattered waves (i.e., acoustic speckles or coda):**

$$\Gamma_{ij}(\tau=0) \propto \int S_i(t)\cdot S_j(t+\tau)\,dt$$

Dense packing

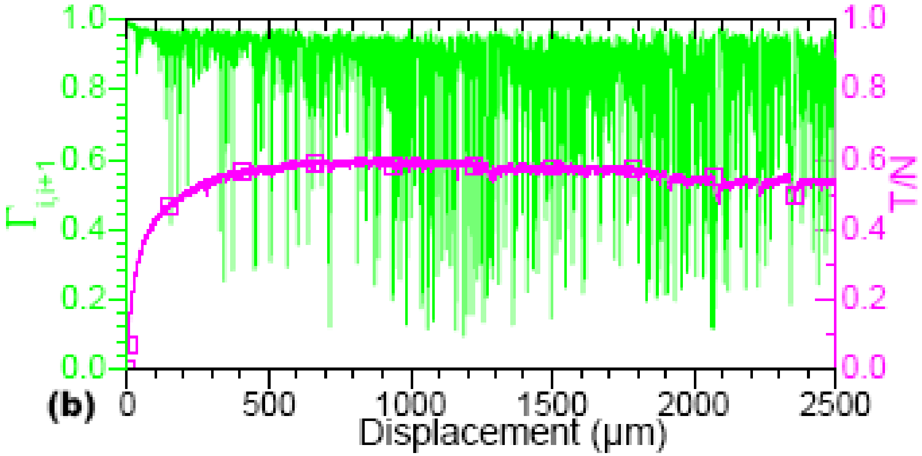


zoom



Intermittent dynamics !
("stick-slip" events)

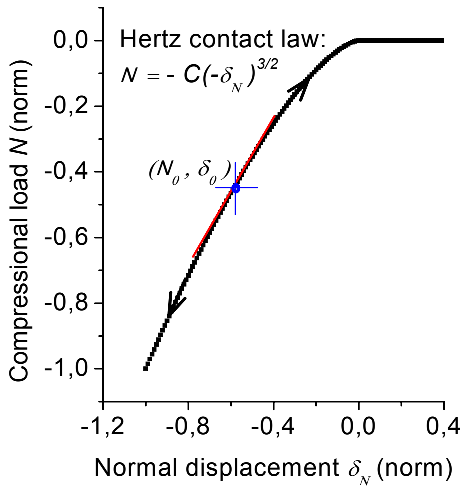
Loose packing



Monitoring the contact modification by the coda wave interferometry (Sneider, 2009)

II. Nonlinear ultrasound propagation in jammed granular media (1/6)

♦ Hertzian nonlinearity:



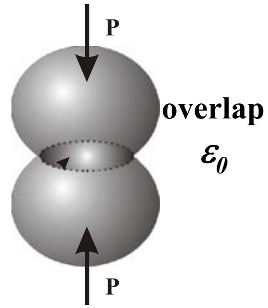
► **weakly nonlinear regime:** $\varepsilon_a \ll \varepsilon_0$

$$\sigma_a = M_0 \varepsilon_a (1 + \beta \varepsilon_a + \ldots)$$

$\beta = -1/(4\varepsilon_0)$ is third-order elastic constant

(Norris & Johnson, 1997)

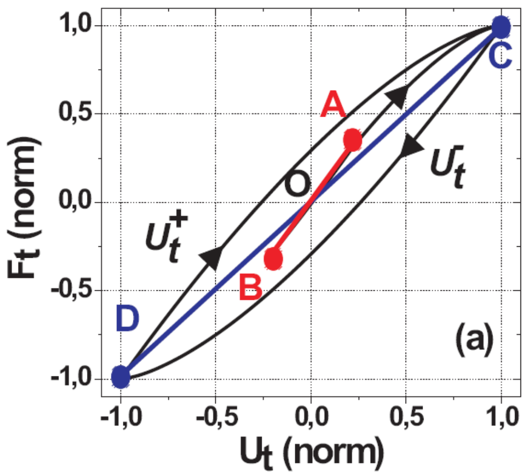
→ harmonics generation (reversible interaction)



► **strongly nonlinear regime:** $\varepsilon_a > \varepsilon_0$

Soliton-like shock waves (Nesterenko,1983; Coste, Falcon, Fauve, 1997)
(Sen et al, 2008; Dario et al, 2006; Gomez, van Hecke, Vitelli, 2011)

♦ Frictional nonlinearity:
(Mindlin model)



in weakly nonlinear regime, $\varepsilon_a < 0.1\varepsilon_0$

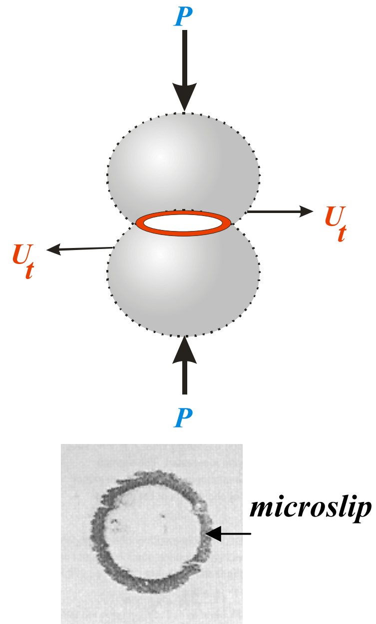
► **Frictional (hysteretic) dissipation**

Brunet, Jia, Mills, PRL 101 (2008)

► **Shear stiffness weakening**

U_t^* increases

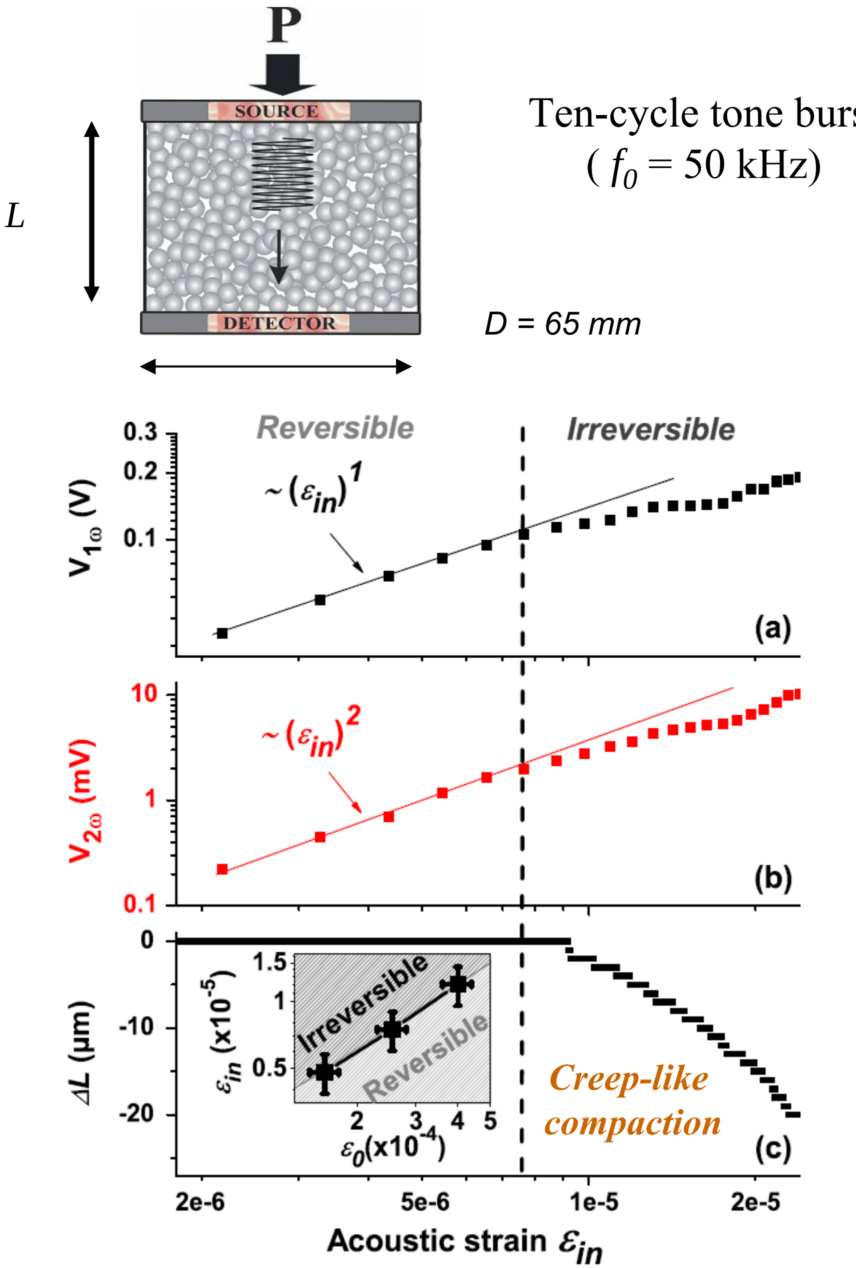
$k_t = dF_t / dU_t$ decreases

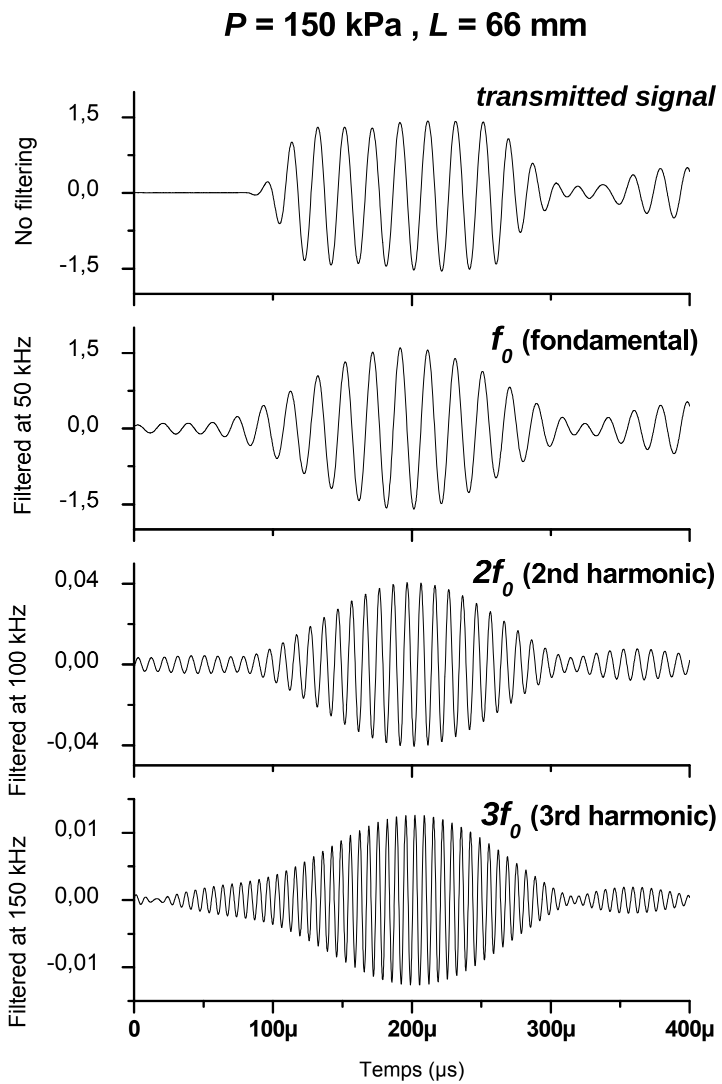


K.L. Johnson (1961)

Harmonic generation: reversible → irreversible regimes (2/6)

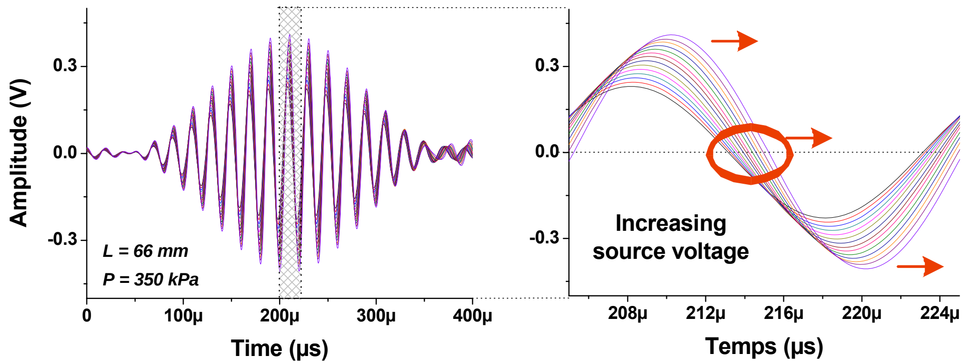
Brunet, Jia & Johnson, Geophys. Res. Lett. 35 (2008)





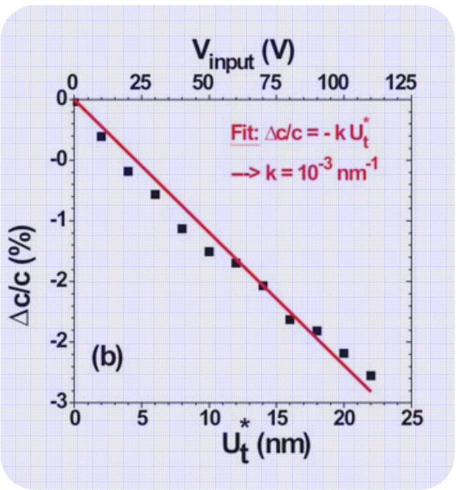
Compressional wave velocity softening: reversible → irreversible (3/6)

Jia, Brunet, Laurent, PRE 84 (2011)

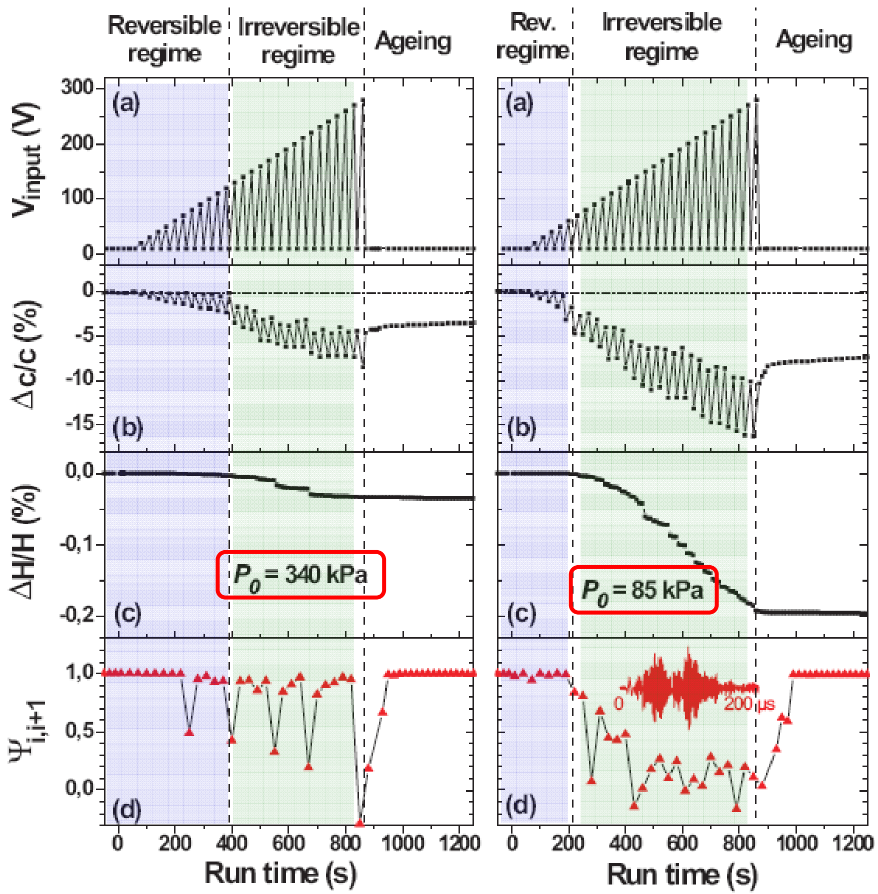


Δc/ c ~ 1-10 % (softening)

♦ Mindlin model



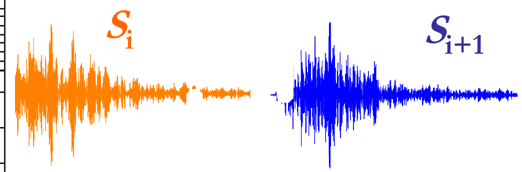
$$\Delta c / c_0 \propto \Delta k_t / k_t \propto -\varepsilon_a$$



♦ Correlation function

$$\Gamma_{i,i+1} = \frac{C_{i,i+1}(\tau = 0)}{\sqrt{C_{i,i}(0) C_{i+1,i+1}(0)}}$$

$$C_{i,i+1}(\tau) = \int S_i(t) \cdot S_{i+1}(t+\tau)\, dt$$



$$c_L \propto (Z / R\rho_0)^{1/2} (k_n + 2k_t / 3)^{1/2}$$

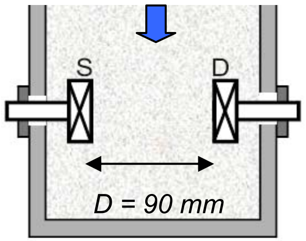
with Z decreased !

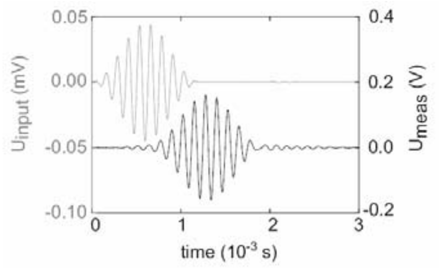
Olson, Lopatina, Jia, Johnson arXiv: 1406.4529 (2014)

Oscillation between softening and hardening (4/6)

Wildenberg, van Hecke and Jia, EPL 101 (2013)

Weakly compressed media:
under gravity



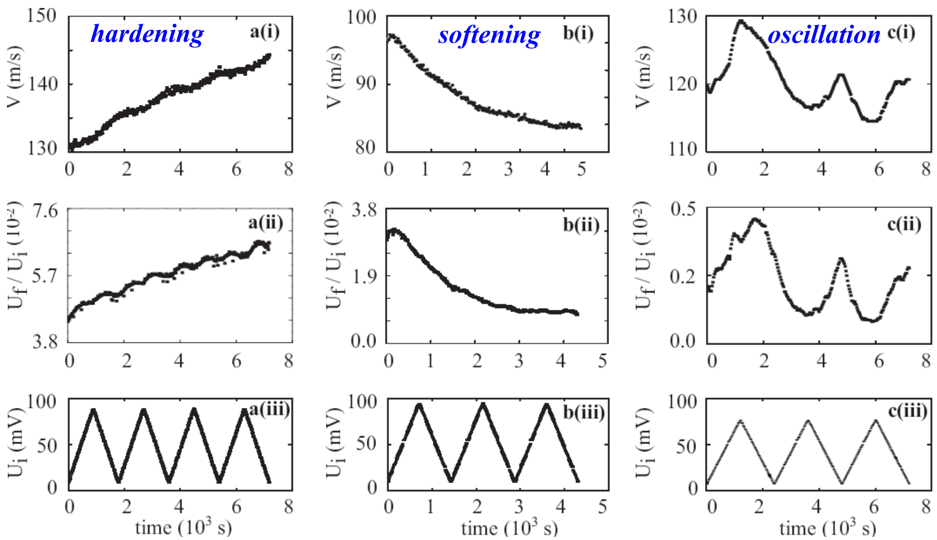


Excitation by Gaussian tone burst $f = 8$ kHz

Longitudinal velocity V →

Amplitude transmission t →

Input amplitude →



$\Delta V_L / V_L \sim 10\%$

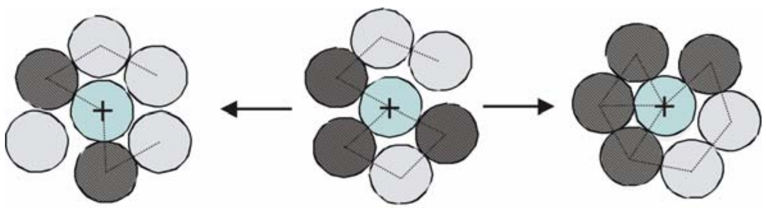
♦ Little change in packing ϕ :
$\Delta\phi < 0.1\%$

♦ **Amplitude vs Velocity :**

$t = t_{piezo} t \approx 4z / z_{piezo} \propto V$

♦ Sound-induced breaking and making of contacts via slippage : $V_L \propto (Z / R\rho_0)^{1/2} (k_n + 2k_t / 3)^{1/2}$

Z decreases
via fludization



Z increases
via bucliking

EMT qualitatively applies
but quantitatively fails !

$(\Delta V_L / V_L \sim 10\% \rightarrow \Delta Z / Z > 25\%)$
unreasonable !

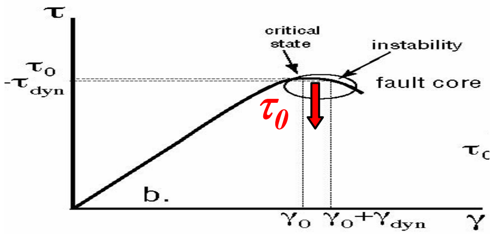
Unjamming transition by acoustic fluidization / T_{eff}

(*cf* threshold rheology perturbed by high-amplitude ultrasound)

→ Earthquake triggering / dynamical weakening

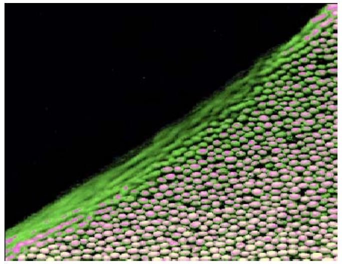
- *Melosh, Nature 379 (1996)*
- *Johnson, Jia, Nature 437 (2005)*
- *Johnson, Gomberg, Marone et al, Nature 451 (2008)*

San Andreas fault



→ Avalanche/rheology of vibrated granular media

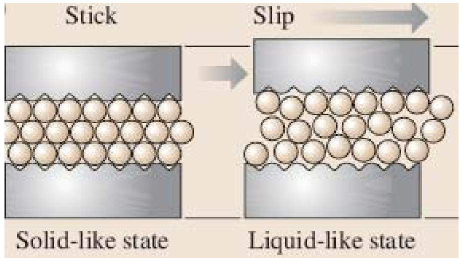
- *Jaeger, Liu, Nagel, PRL 62 (1989)*
- *Dijksman, Dauchot, van Heck et al, PRL 107 (2011)*



Lowing the yield stress!

→ Sliding triggering of a glassy interface

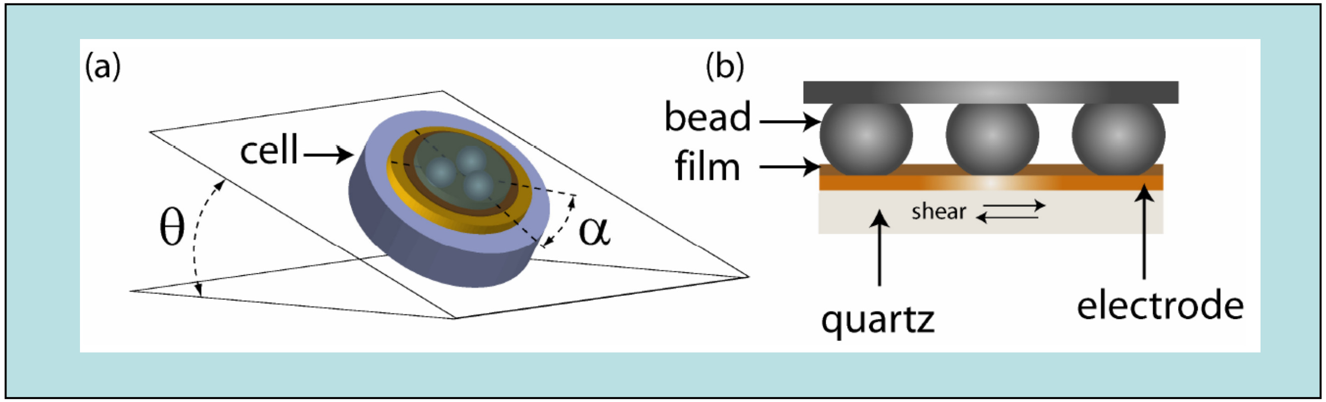
- *Bureau, Baumberger, Caroli, PRE 64 (2001)*
- *Heuberger, Drummond, Israelachvili, J. Phys Chem. B 102 (1998)*
- *Léopoldès, Conrad, Jia, PRL 110 (2013)*



Israelachvili, Gee, McGuiggan, Thompson, Robbins (1990)

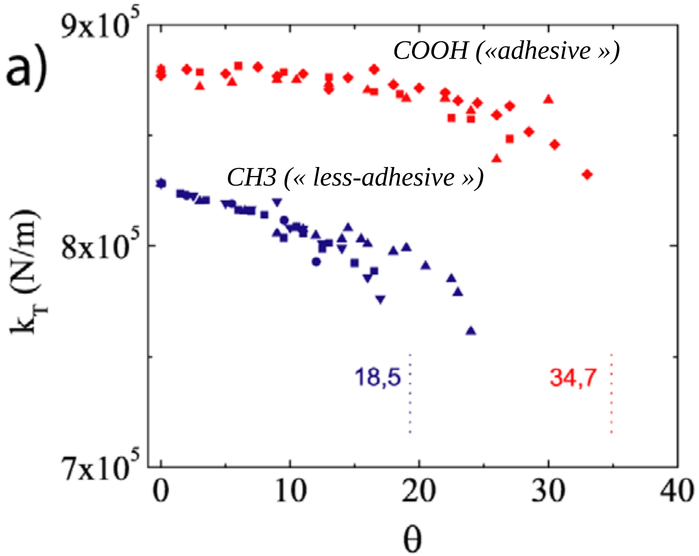
Sliding at amorphous interfaces triggered by shear NL ultrasonic oscillation (5/6)

Léopoldès, Conrad & Jia, PRL 110 (2013)

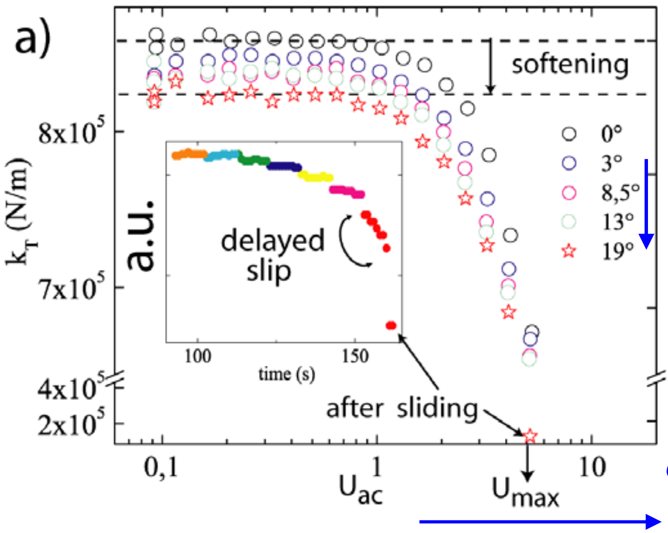


Monolayers (~ 1 nm)

♦ **Elastic softening k_T (interfacial stifness) under *static* shear**

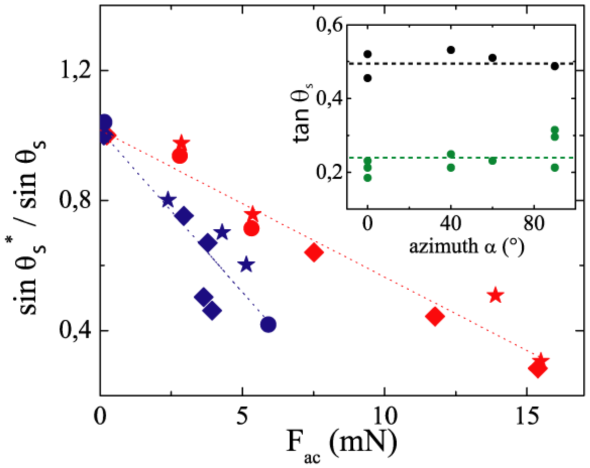


♦ **k_T softening under *oscillatory* shear and triggering of sliding**



Acoustic probing/pumping of sheared interfaces up to failure (6/6)

♦ **Decrease of the static friction coefficient by shear acoustic fluidization/lubrication**

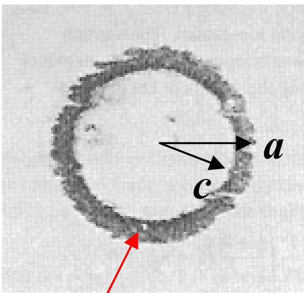


$f_{HF} \gg f_0$

with f_{HF} ~ 5 MHz

f_0 ~ 1 kHz (slider-interface)

→ no macro-sliding !



Micro-slip annulus
within non-cohesive contact

$$\sin\theta_s^* / \sin\theta_s = F_s^* / F_s \approx c^2 / a^2$$

$$\approx 1 - (2/3) F_{ac} / \mu_s F_N$$

where $F_s = \sigma_s \Sigma_s$

with $\Sigma_s : \pi a^2 \searrow \pi c^2$

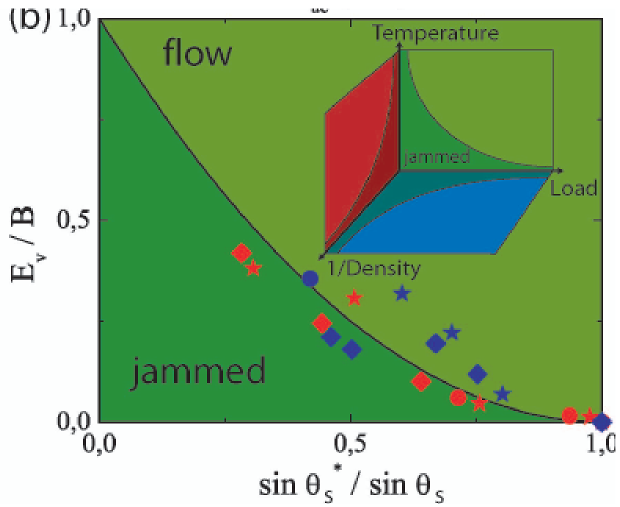
$f_{HF} \gg 1/\tau_{relax}$

τ_{relax} ~ 1-10 ms

→ in fluidized state

♦ **Jamming transition diagram**

Liu & Nagel (1998)

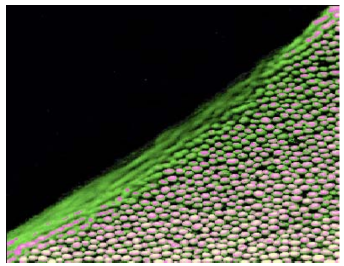


$$E_v / B \approx [1 - (\sin\theta_s^* / \sin\theta_s)]^2$$

E_v vibration energy → 'effective temperature'

♦ **Triggered flow in granular layers by shear ultrasound**

Jia and Léopoldès
(in progress)

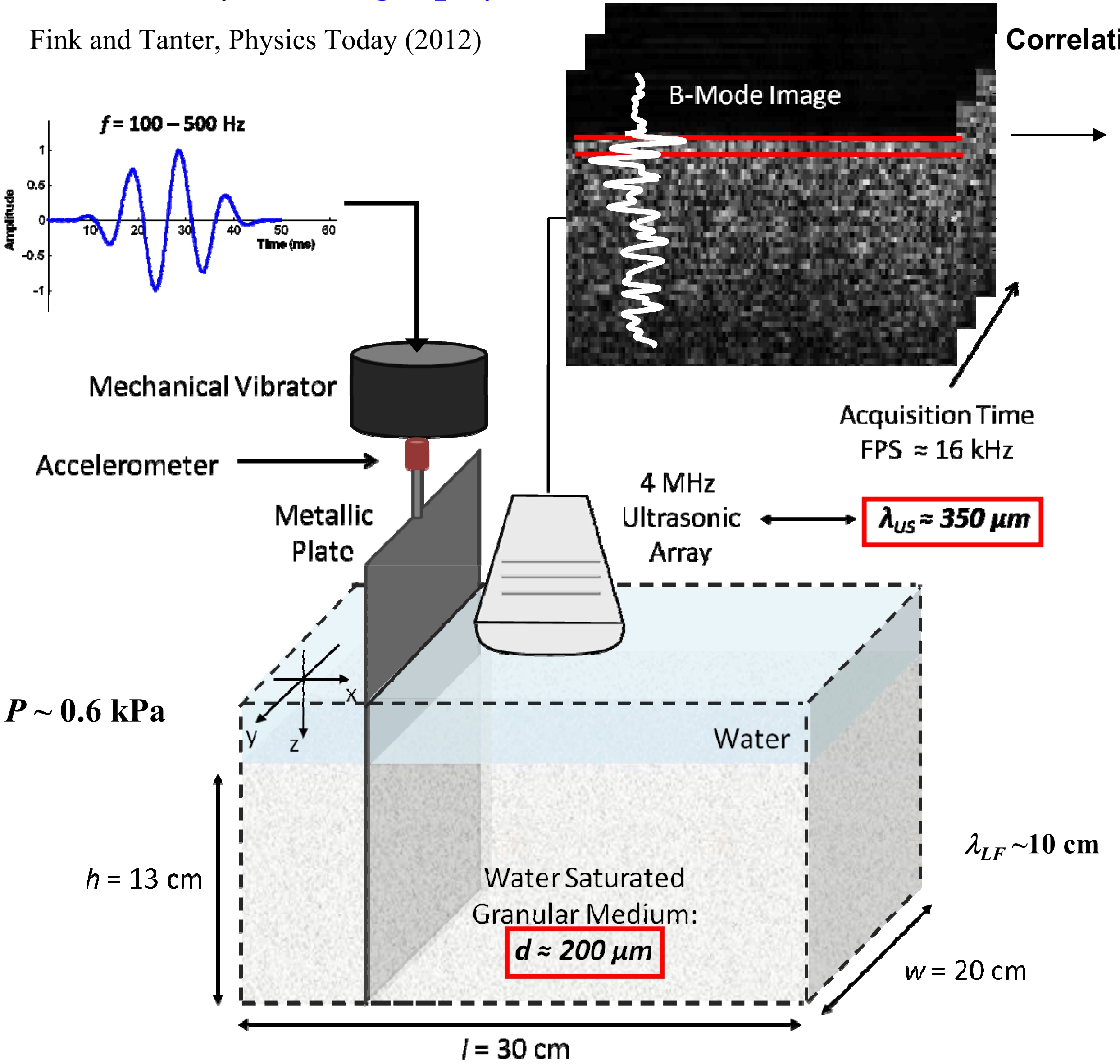


3. LF shear wave propagation in marginally jammed granular media (1/4)

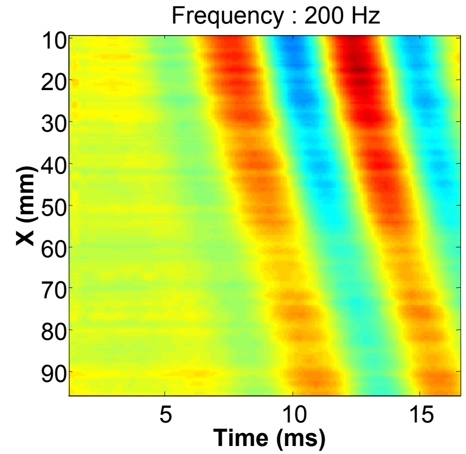
♦ **Detection of shear waves using ultrasonic speckle interferometry (elastography)**

Brum, Genisson, Tourin, Fink, Tanter, Jia (2014)

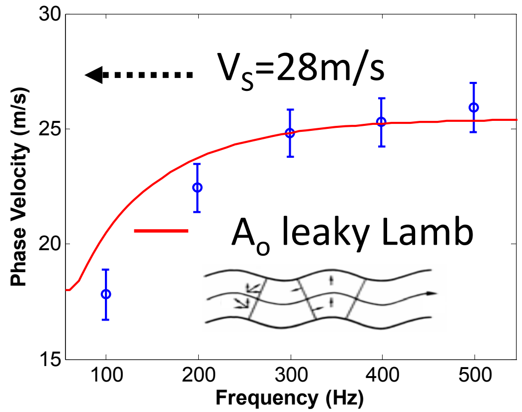
Fink and Tanter, Physics Today (2012)



● **Out-of-plane *surface vibration* in the linear regime**

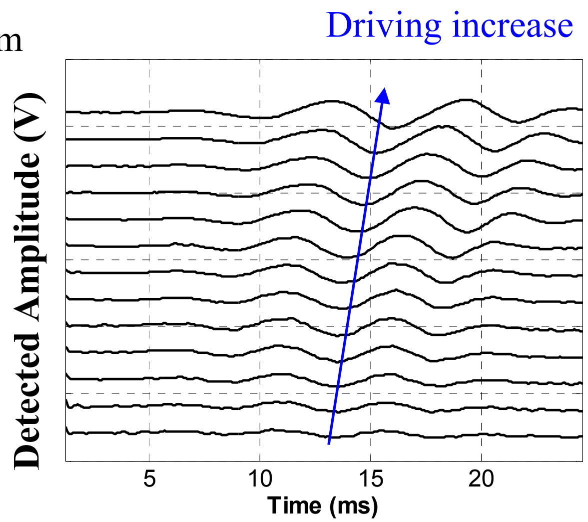


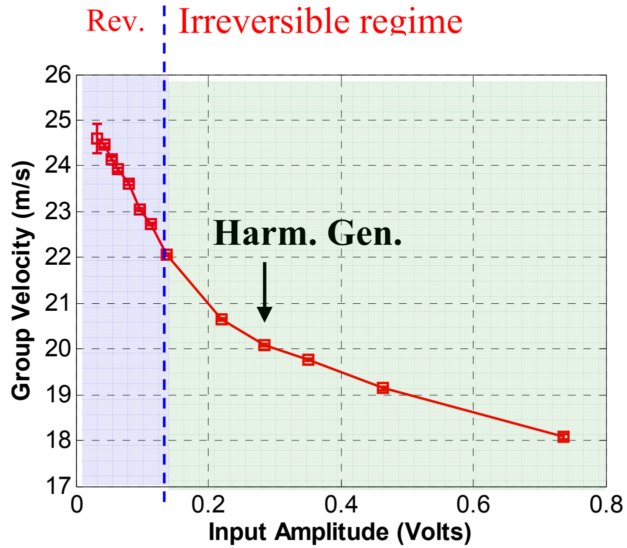
● **Dispersion of the phase velocity**



Softening of shear wave velocity from **jammed** to **unjammed** states (2/4)

Distance:
$x = 95.5$ mm

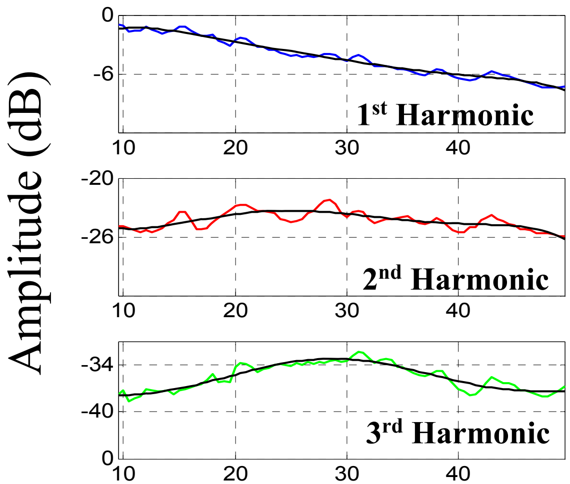




Frequency:
$f_{LF} = 200$ Hz

Softening up to
$\Delta V_S / V_S \approx 30\%$
$\sim 3\ \Delta V_P / V_P$!

● In the irreversible nonlinear regime, $\Delta V_S/V_S > 10\%$,
the EMT qualitatively applies, e.g. harmonic generation, but quantitatively fails.



Indeed, the coordination number change would be:

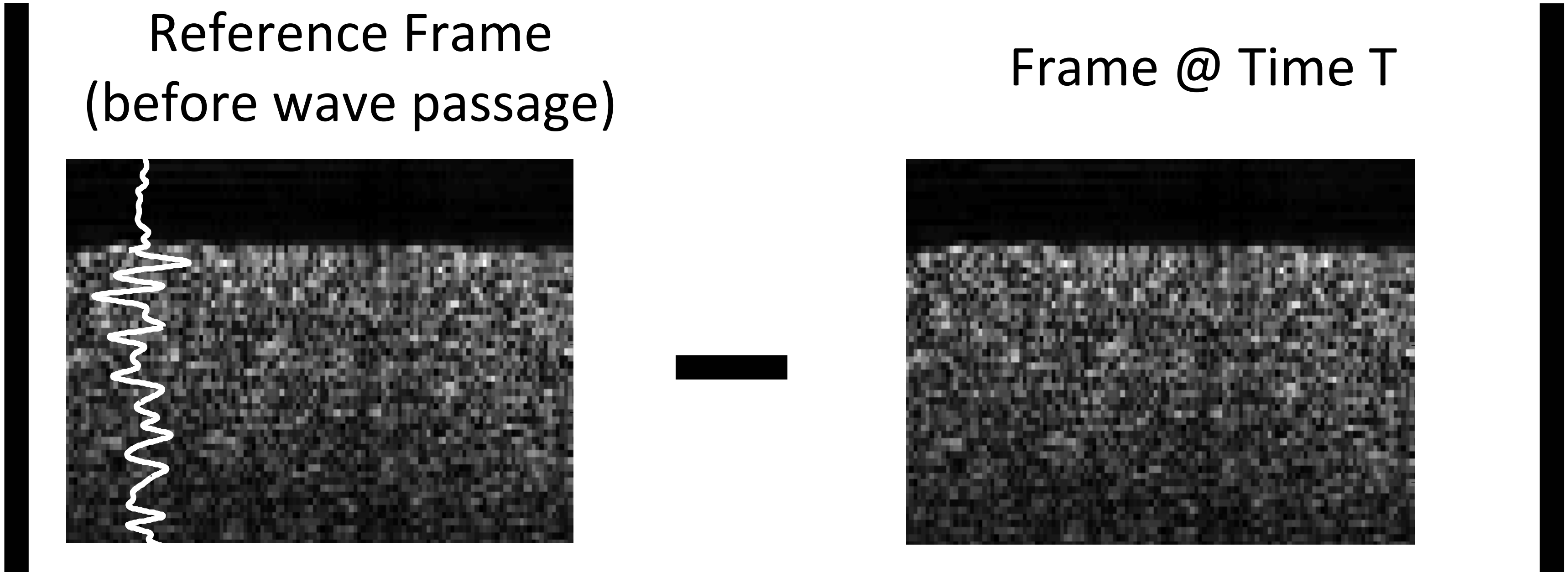
$$V_S \propto (Z / R\rho_0)^{1/2} (k_n + 3k_t / 2)^{1/2}$$

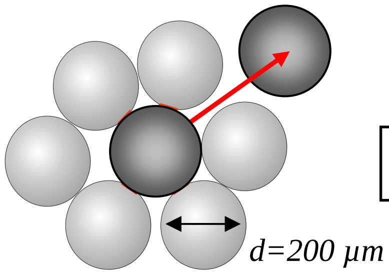
$\Delta V_S/V_S \approx 30\% \rightarrow \Delta Z/Z$ $(\sim 2\Delta V_S/V_S)$ $\sim 40\%$!

This huge, irrevelant change implies the EMT breaks down
due to the rearrangement of the contact network
without visible grain motion (jammed → unjammed states!)

Softening of shear wave velocity in unjammed flowing states (3/4)

We investigate the plastic granular flow (with grain motion!) using the change of ultrasonic speckles patterns ($\lambda_{US} \approx 350$ µm for $f_{US} = 4$MHz).





Grains escape from the cage (dilatancy) at unjammed flowing state.

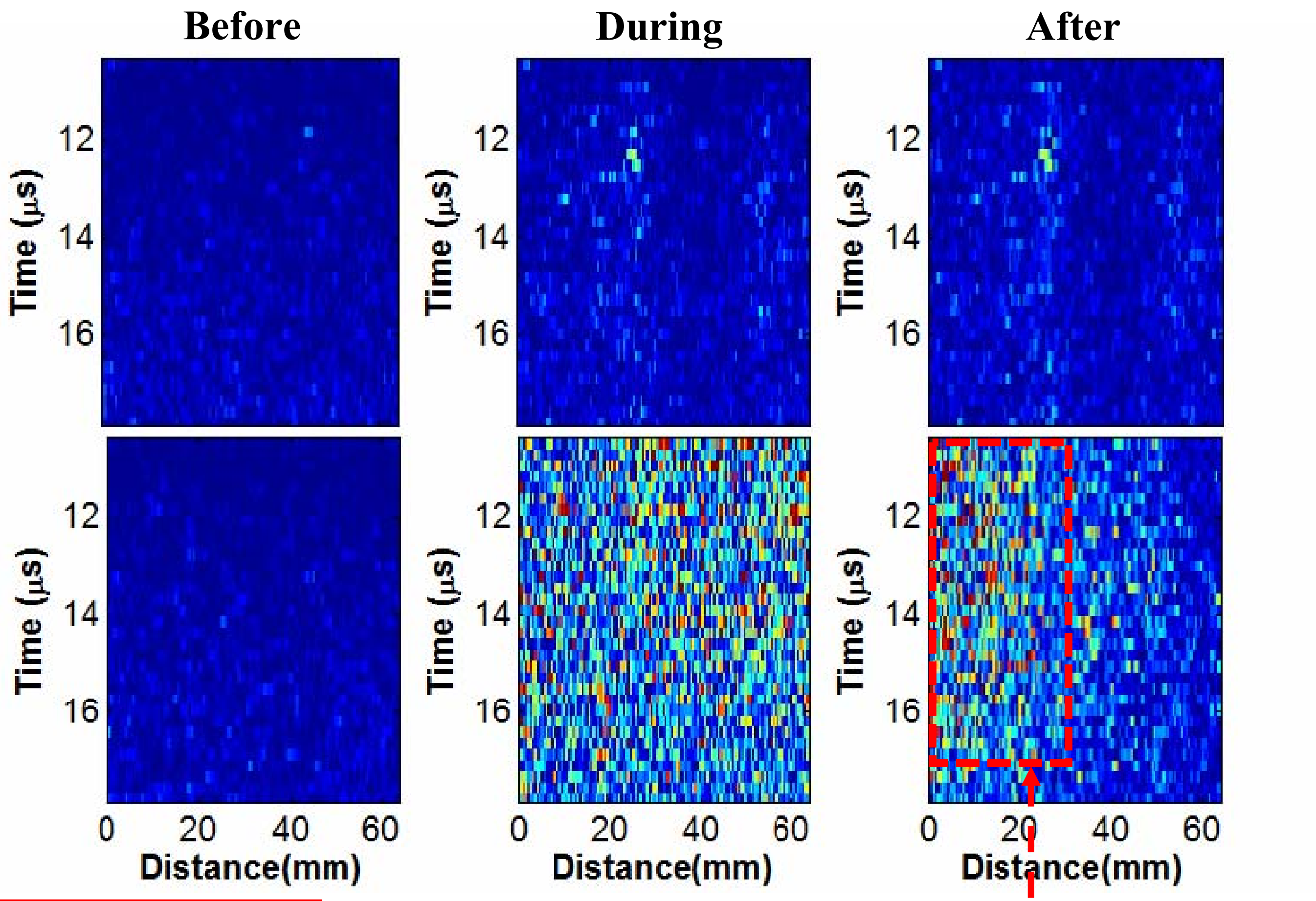
Grain motions ~ d ($\geq \lambda_{US}/2$) are detectable by US speckles !

Softening of shear wave velocity in unjammed flowing states (4/4)

$f_{LF} = 100\ Hz$

Low oscillation:
$F_{LF} \approx 0.03\ N$

High oscillation:
$F_{LF} \approx 2.7\ N$



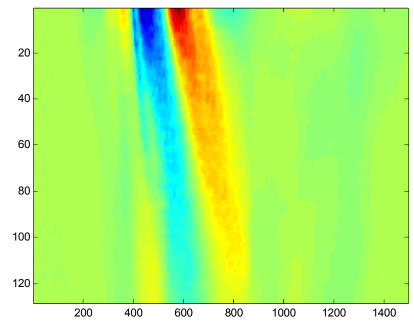
The shear velocity is $V_S \approx 6.8\ m/s$

→ $\Delta V_S / V_S$ (≈ 10/17) ≈ 55%

→ the shear modulus

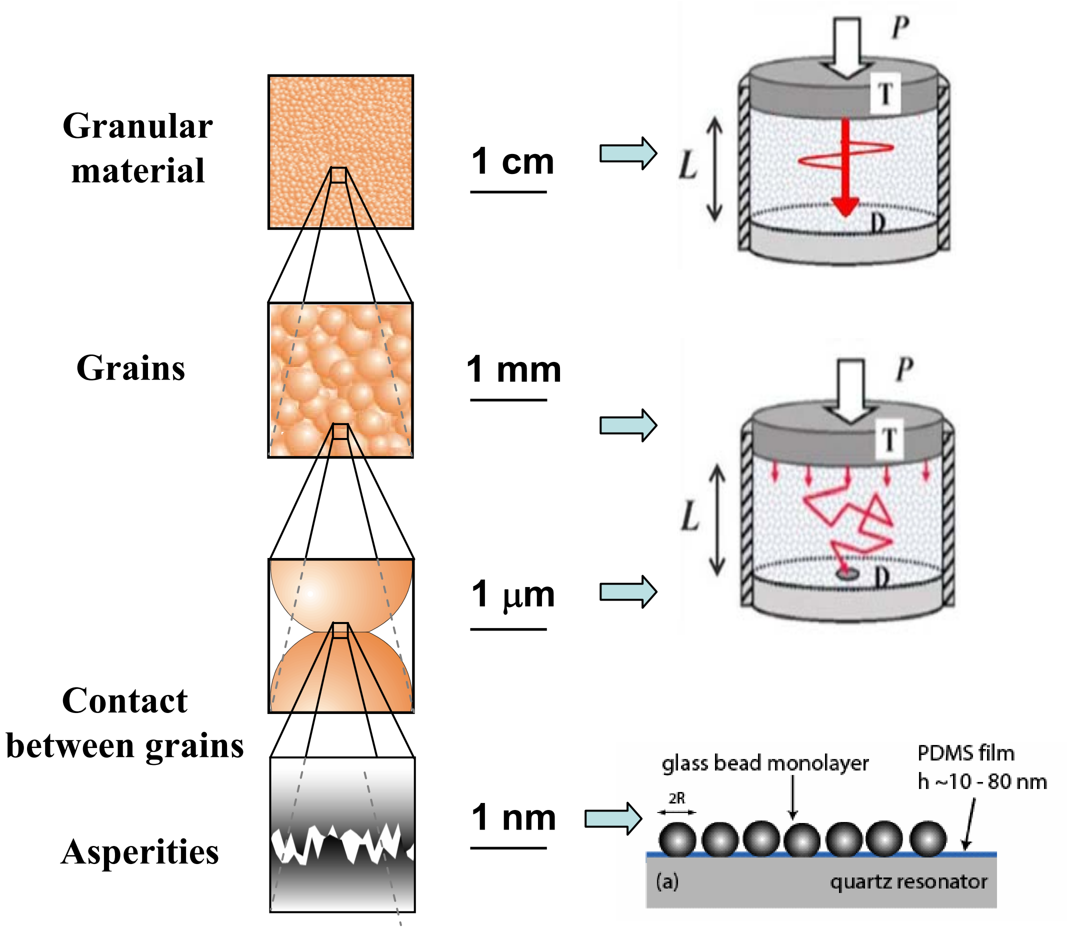
$\Delta G/G$ ~ 85% !!

during **unjamming transition !**



Plastical granular flow
(STZ-like ?)

Multiscale Acoustics of Granular Media



♦ $\lambda_E \geq 10\ d$: coherent elastic waves

- Compressional & shear velocities
  → material elastic moduli K & G

Jia, Caroli and Velicky, PRL 82 (1999)

♦ $\lambda_S \sim d$: multiply scattered waves

- *Q*-factor → dissipation at the contact
- Mean free path l^* → rearrangements

Jia, PRL 93 (2004); Brunet, Jia and Mills, PRL 101 (2008)

♦ Ultrasonic interfacial rheology

shear resonator & a bead layer

- Resonance peaks and width
  → interfacial stiffness & dissipation

Léopoldes & Jia , PRL 105 (2010)

Acoustic Probing & Pumping !