Jamming Meets Experiments

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IFPRI
International Fine Particle Research Institute

Boulder School 2017: Frustrated and Disordered Systems

Jamming Meets Experiments

Overview

① Grains have friction - different from colloids/emulsions/foams/glasses

② friction matters: it changes the allowed configs

③ we can measure what happens at the particle level (with caveats)

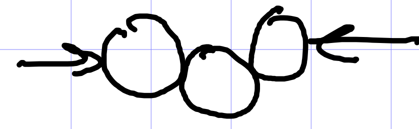
④ forces matter

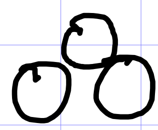
⑤ experiments + frameworks for understanding the implications

- network science techniques
- Edwards-like ensembles
- Gardner (?)

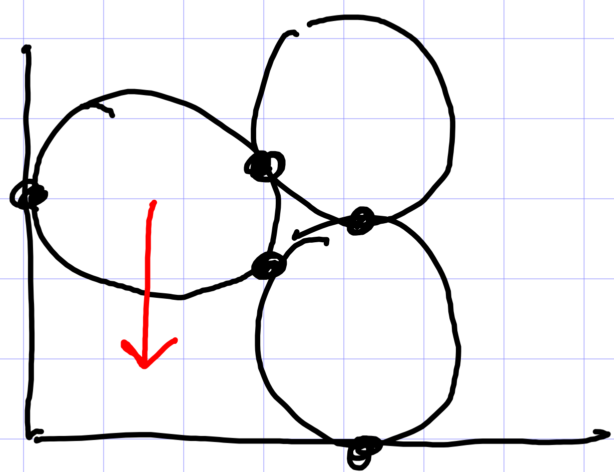
Caveats about
Real
Granular Materials

Inspiration Demos

Matthias's 3-balls demo 

also:  stable on table

A very mean intro-physics problem:



↓ mg is supported by friction at walls + contacts

$\sum \vec{F} = 0$ + $\sum \vec{\tau} = 0$

2 eqn | particle   1 eqn / particle = 9 eqn

5 contacts × 2 components = 10 unknowns

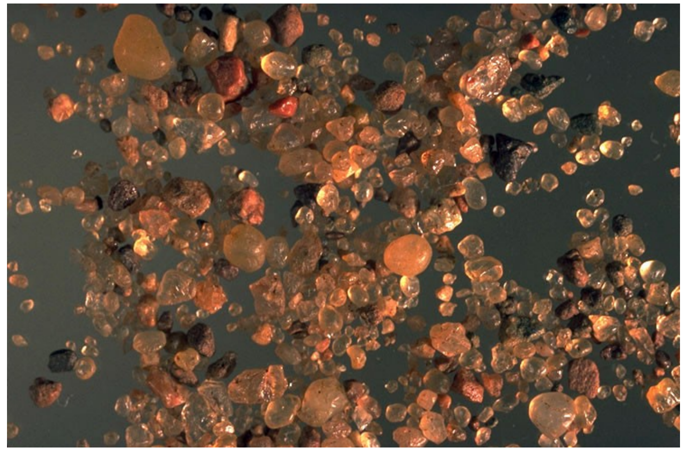
<u>missing info:</u> history of frictional contacts

Photo elastic demo: sensitivity of forces

show: force chains in crystalline vs. disordered

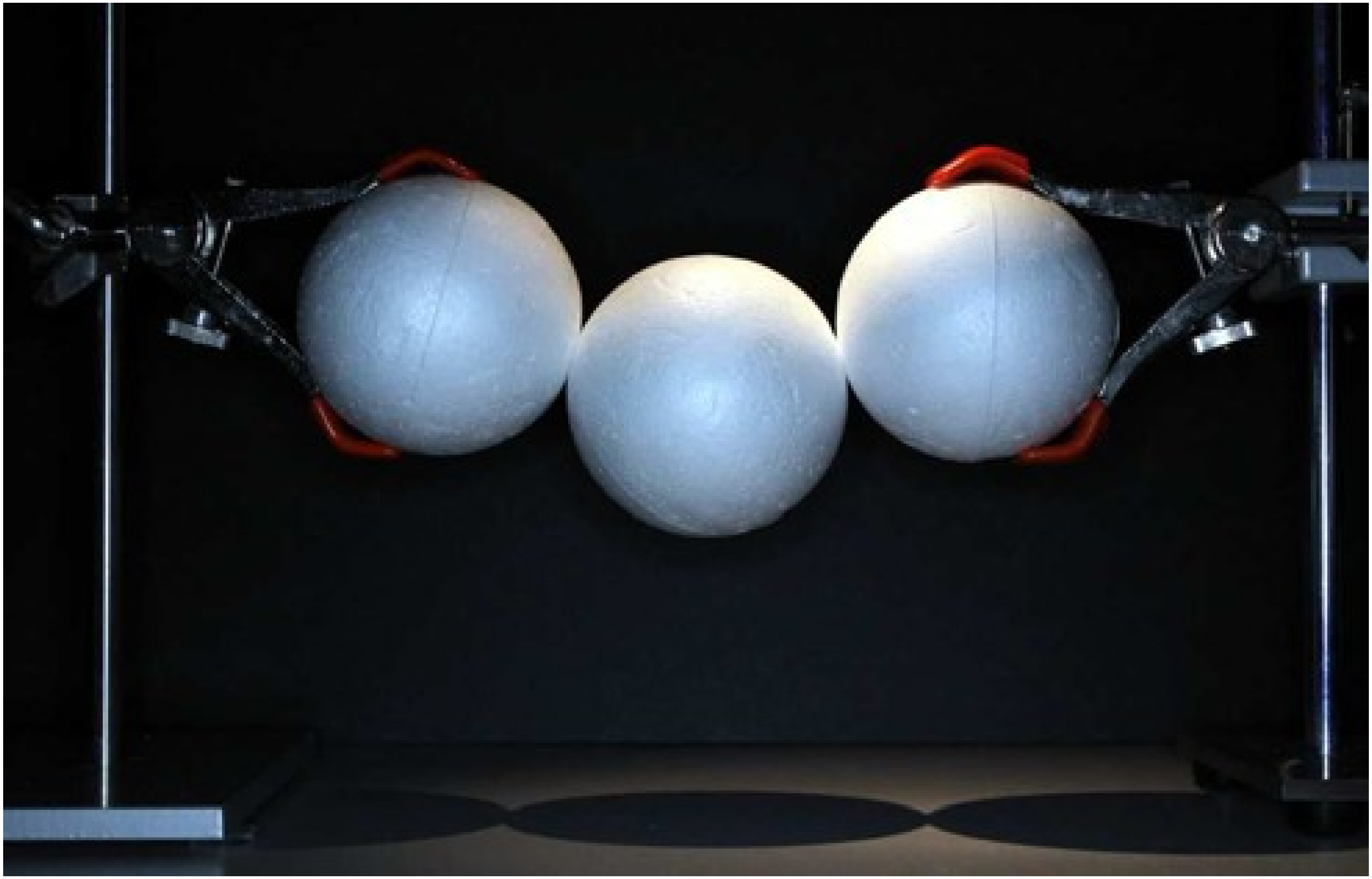
history matters: tube + cup demo

Too Real?



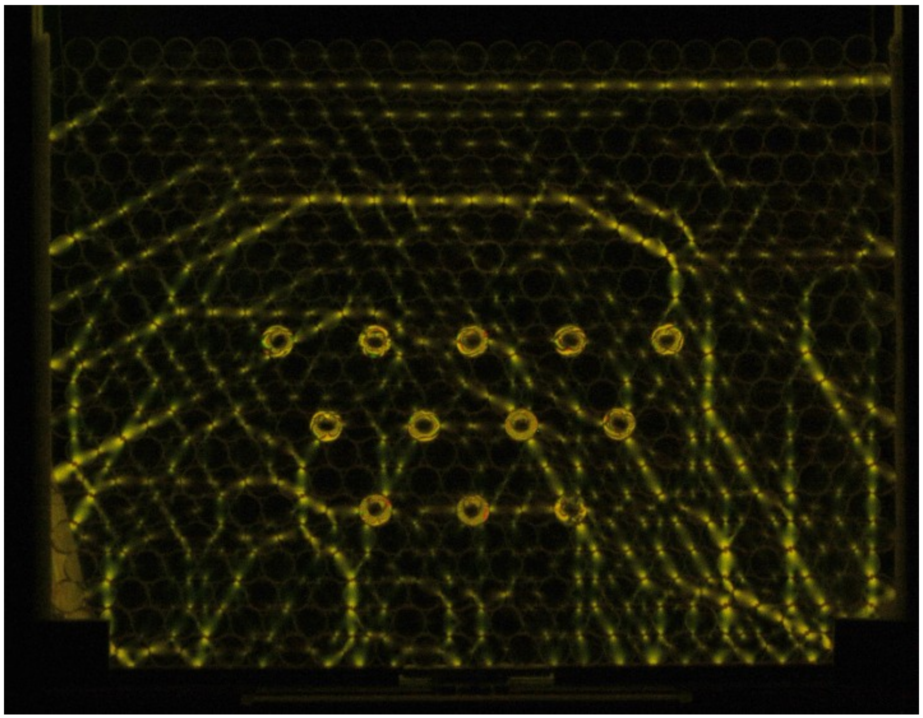
http://www.sandgrains.com

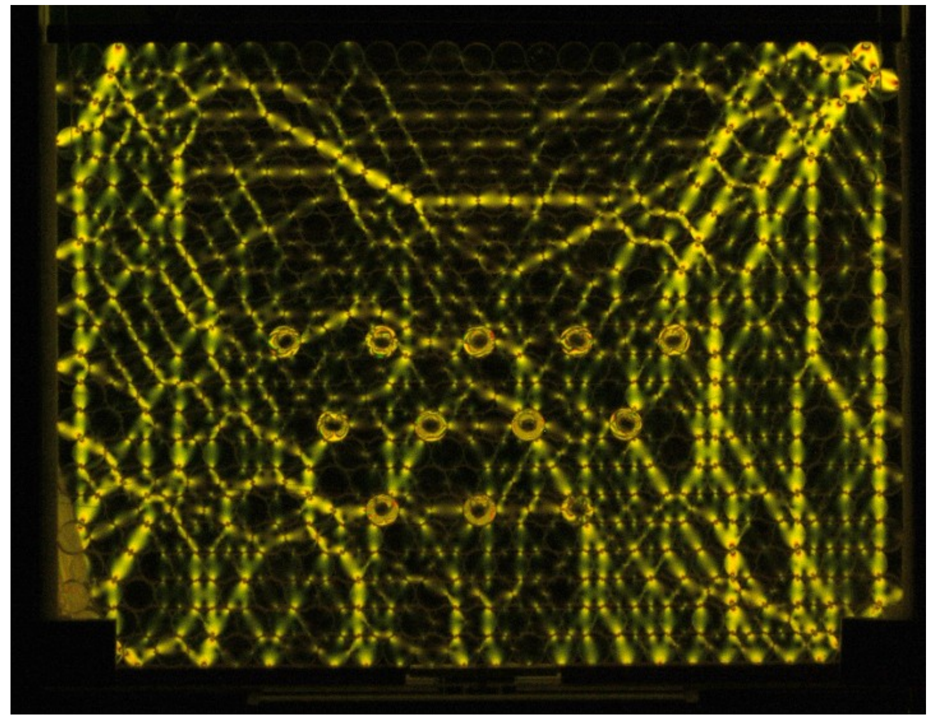
Friction Matters



Schröter, *Powders & Grains 2017* (EPJ Proceedings 140, 01008)

Ordered Particles ≠ Ordered Forces

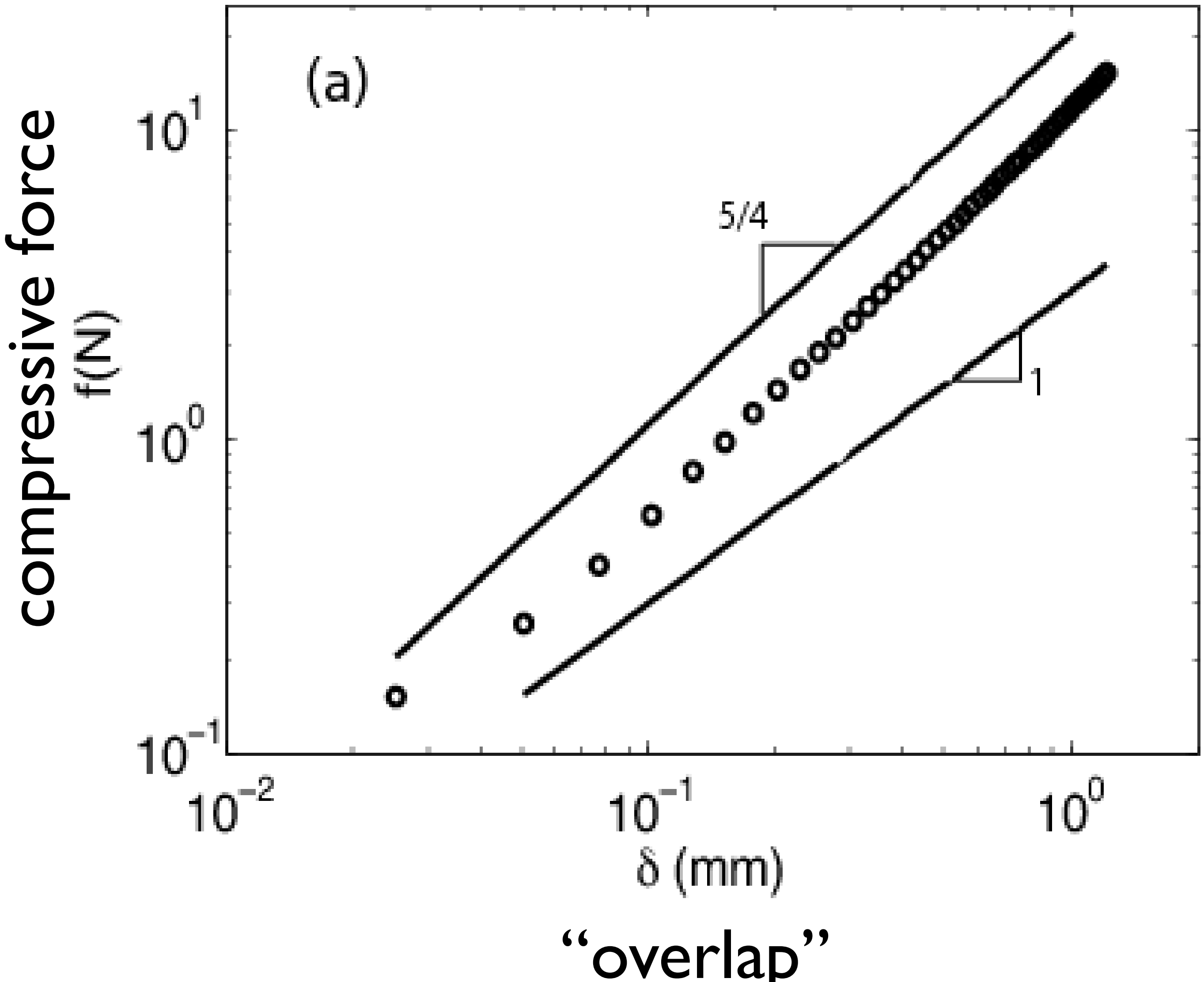




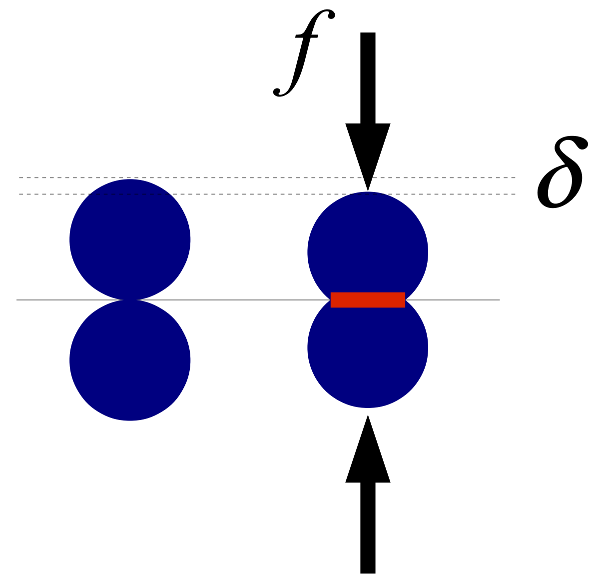
Pressure = 2.7×10^{-4}E vs. 6.9×10^{-4}E

Owens & Daniels. *Soft Matter* (2013)

Are real particles Hertzian contacts? (1)



$$f \propto \delta^{5/4}$$
$$area \propto f^{2/5}$$



Owens & Daniels, *EPL* (2011)

Are real particles Hertzian contacts? (2)

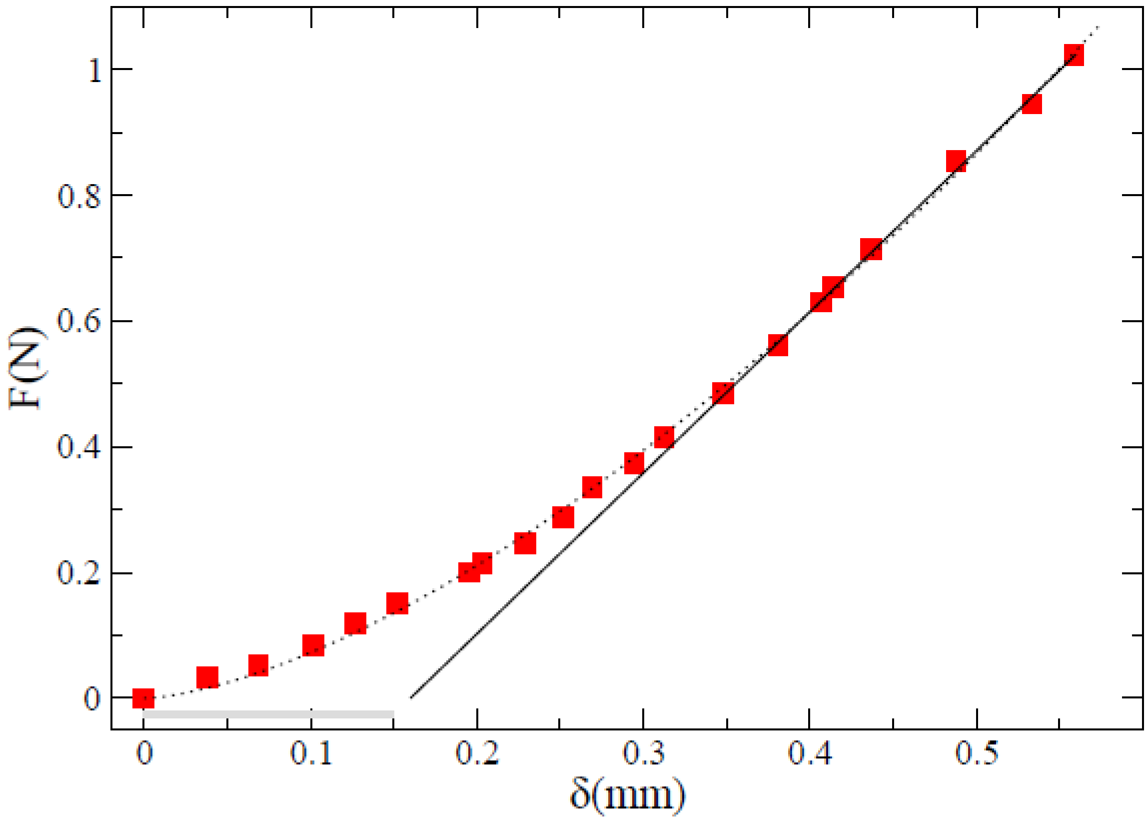
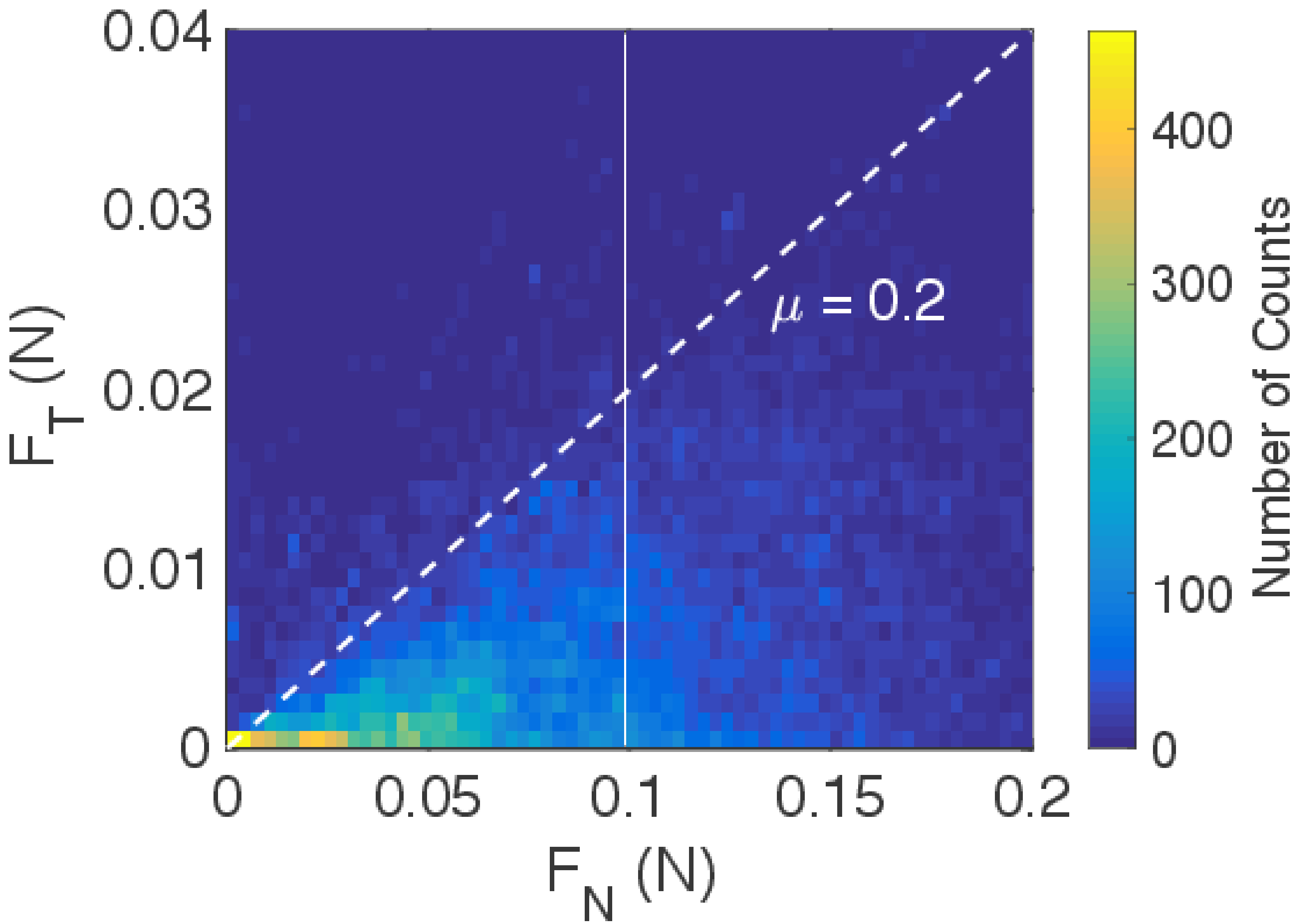


FIG. S1: Calibration of the contact force F for a representative disk pushed against a hard surface by a displacement δ. The experimental data (squares) are fitted by the power law $F = 2.52\text{N}\ (\delta^{1.54})$ (dotted) and by the linear law $F = 2.56\text{N}\ (\delta - 0.16)$ (full curve). Here, all lengths are given in mm. The gray bar indicates the roughness of the cylinder surface. Photoelastic response is reliably detectable to the right of this bar.

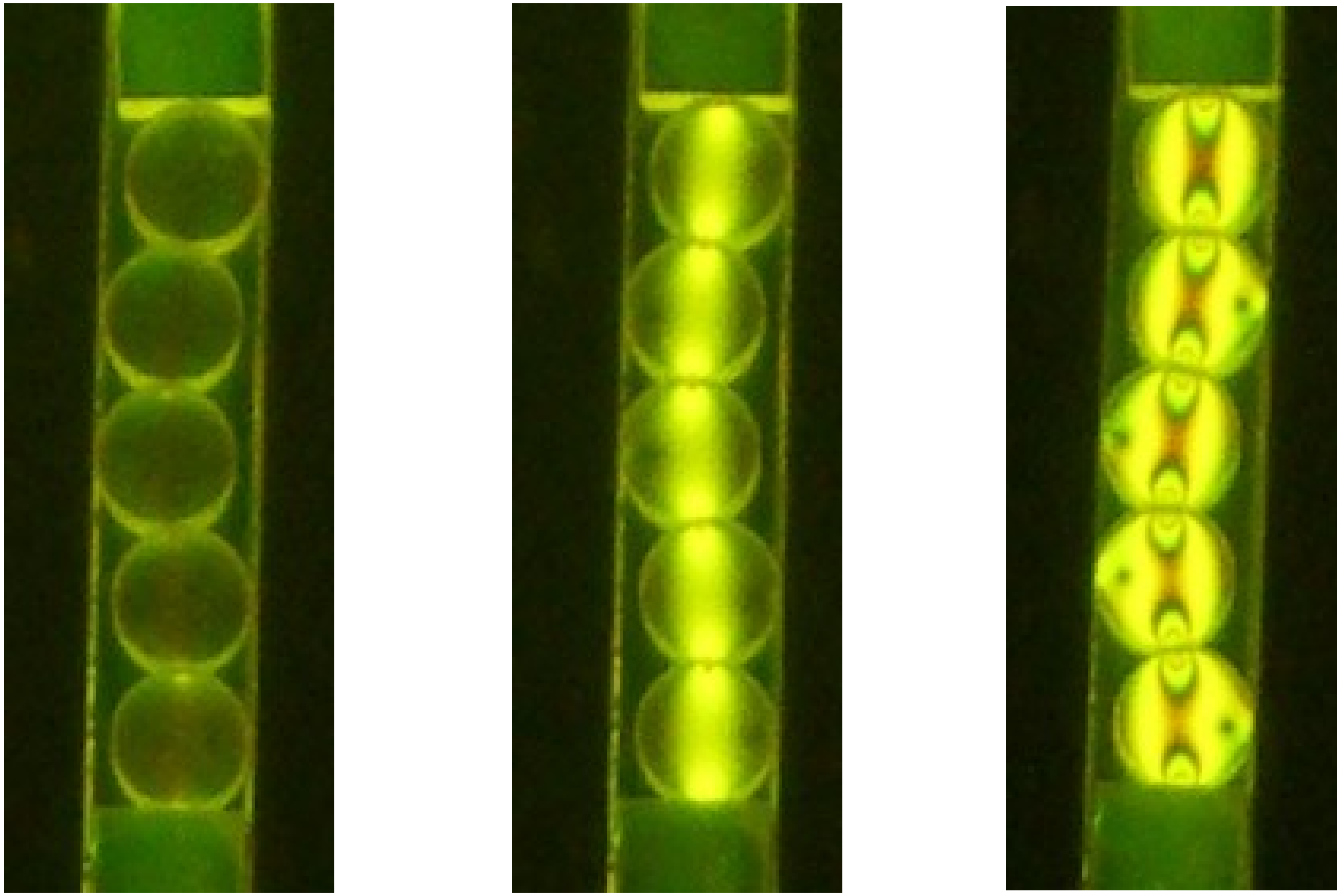
Majmudar, Sperl, Luding, Behringer PRL (2007)

Normal and Tangential Forces



Kollmer & Daniels (just a quick sample plot, not published)

Photoelastic particles are <u>soft</u>



large contact area

low force

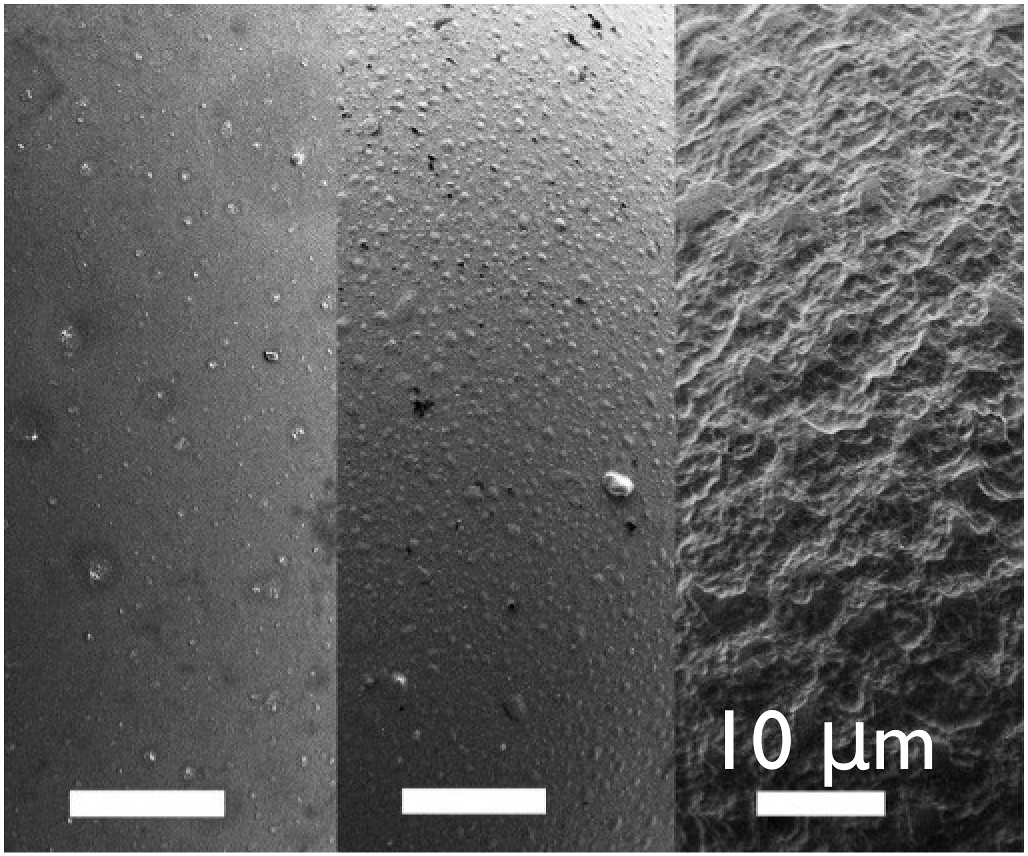
medium force

high force

Kollmer & Daniels (in prep)

Roughness ≠ Friction

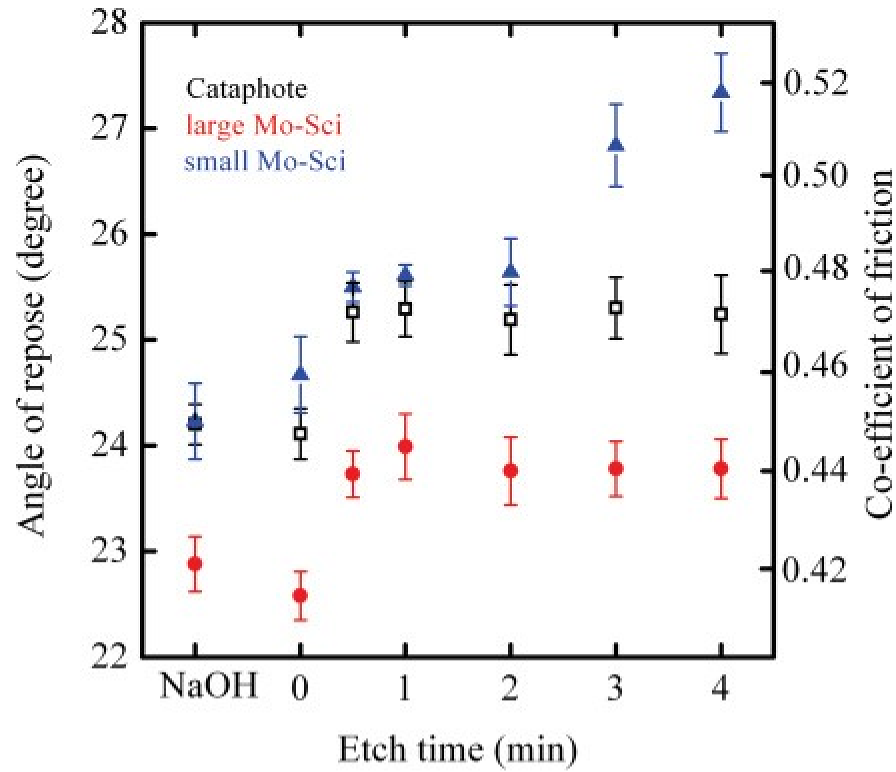
SEM images of glass sphere surfaces



↑ Smoothed in NaOH

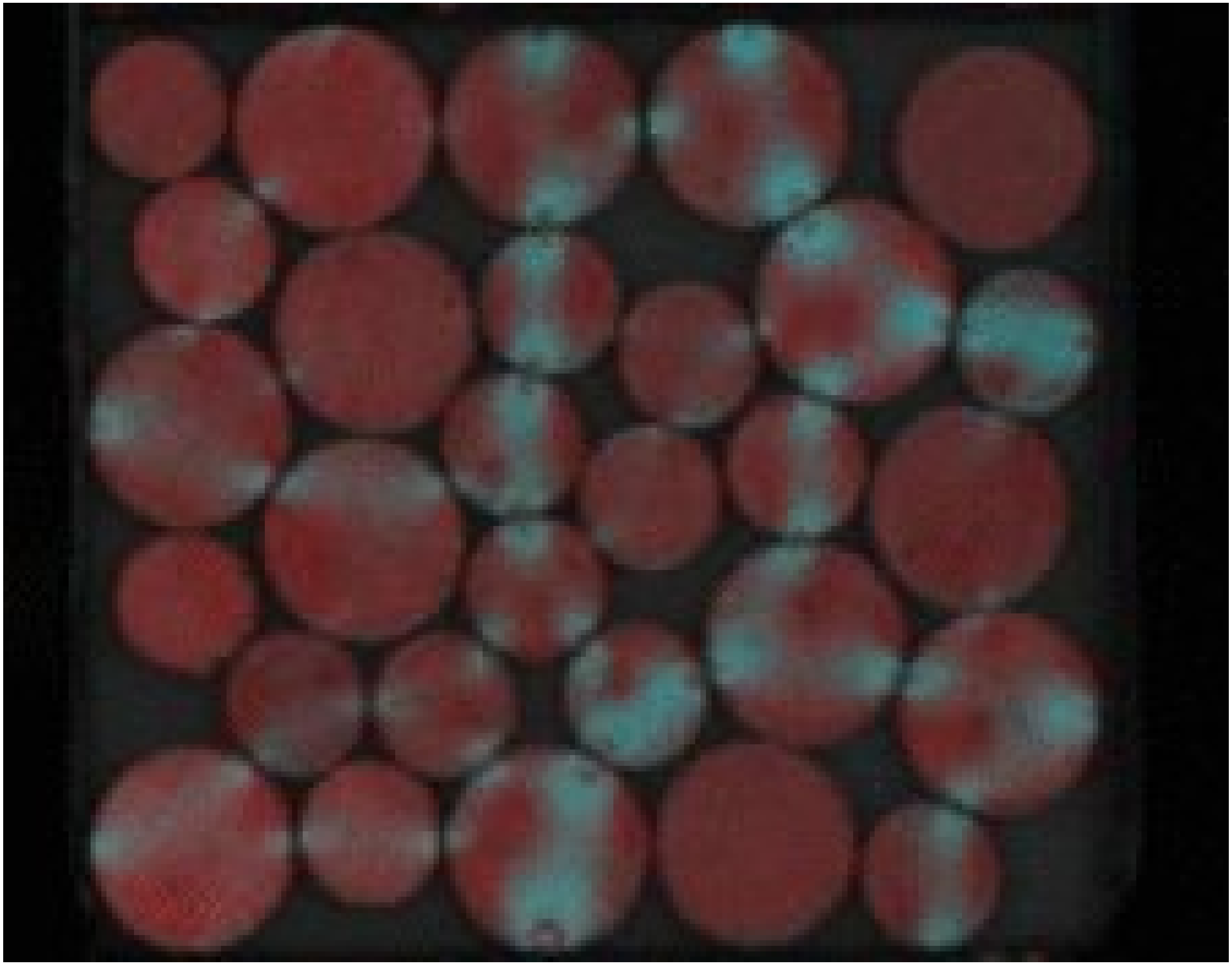
Untreated

↑ Etched in HF



Utermann, Aurin, Benderoth, Fischer, Schröter. *PRE* (2011)

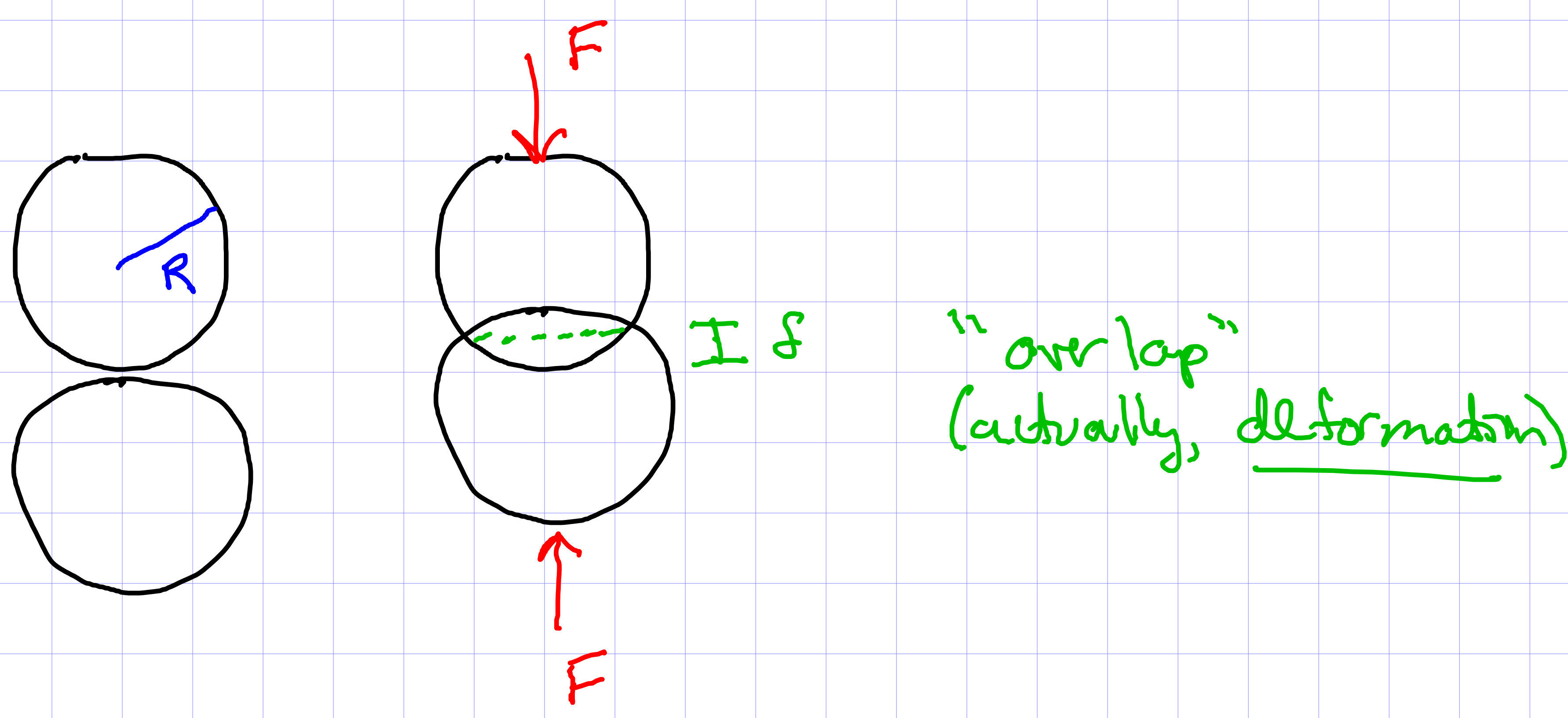
Athermal, Sensitive to Initial Conditions



Kollmer & Daniels, *Powders & Grains 2017*

Granular Contact Forces

Normal forces: Hertzian contacts
(see Landau + Lifschitz)
Johnson "Contact Mechanics" (1987)



for linearly-elastic spheres: $F \propto \delta^{3/2}$

$$F = \frac{2}{3} \frac{4G}{1-\nu} \sqrt{R}\, \delta^{3/2}$$

disks: $F \propto \delta$

show experimental $F(\delta)$ data - it's not quite as clean as that

Tangential forces: Coulomb friction

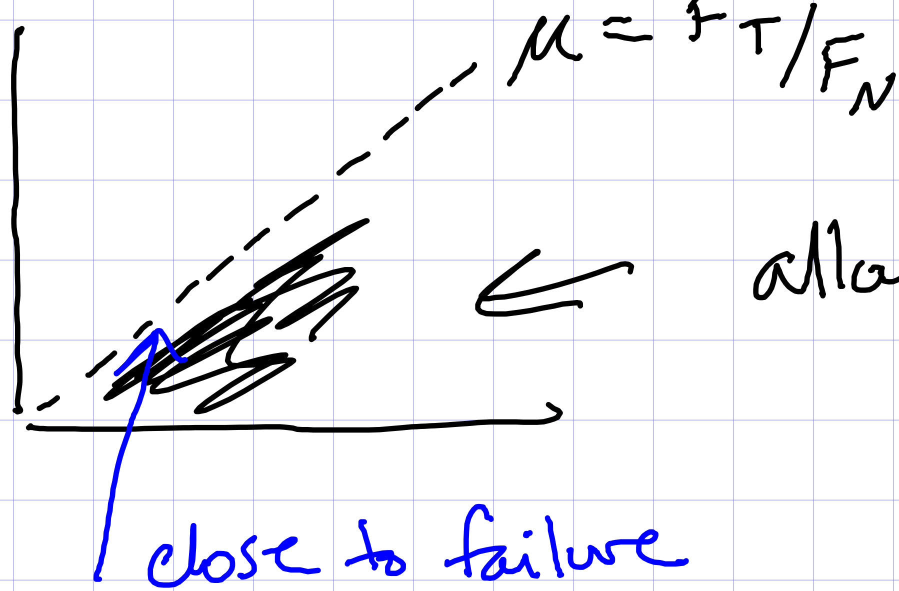
$|F_T| \le \mu |F_N|$

↑ material property, poorly-known

direction is set by history of loading the packing

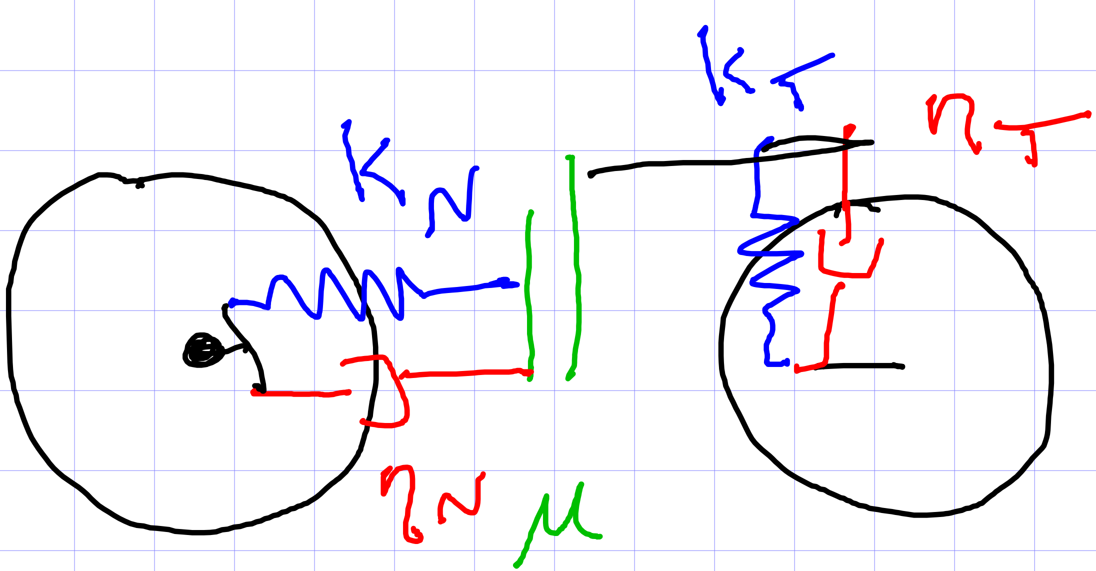
contacts need not be <u>at</u> failure

show Jonathan's scatter plot of (F_T, F_N)



← allow contacts

what do simulations do? "Hertz-Mindlin"

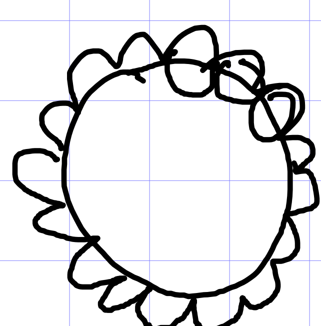


K: stiffness

η: damping

μ: friction

vs. O'Hern | Papanicholaou



← glued spheres → roughness

Brainstorm with neighbors:

What properties of a packing are <u>hard/easy</u> (or known/unknown) for <u>experiments vs. simulations</u>?

Motivational Brainstorming:

What's [Hard vs. Easy / Known vs. Unknown] in Experiments vs. Sims

	exp	sim
contact exists	hard	easy
location (centroid) of particle	hard	easy
interparticle force	very hard	easy
potential / force law	unknown, hard to measure	imposed
friction	difficult to measure	several options (none are "correct")
deformation of particles	real	replaced by overlap
roughness	quantifiable	usually ignored
ensembles	can't restart/redo	can
boundary conditions	finite	periodic

Many of you are theorists, why tell you all these experimental details?

theories that require contacts are <u>hard</u> for experimentalists to validate

a few ± 1 is a <u>big</u> error

How Particle Position Data is Collected

Determining contacts + positions

① methods of data collection

2D vs. 3D (show pics)

advertise special issue bit.ly/2uejRC4

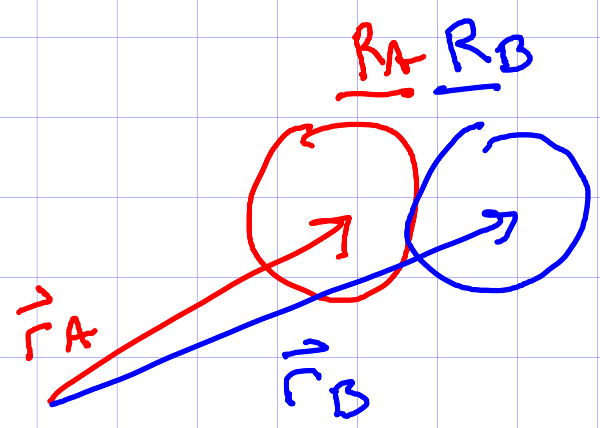
② how particles are found (centroid location)

convolutions, Hough transform

show plot of quantifying resolution (Eric)

.1 pixel = easy .01 pixel = hard

③ how contacts are identified



Deformation / forces present wherever

$$|\vec{r}_A - \vec{r}_B| < R_A + R_B$$

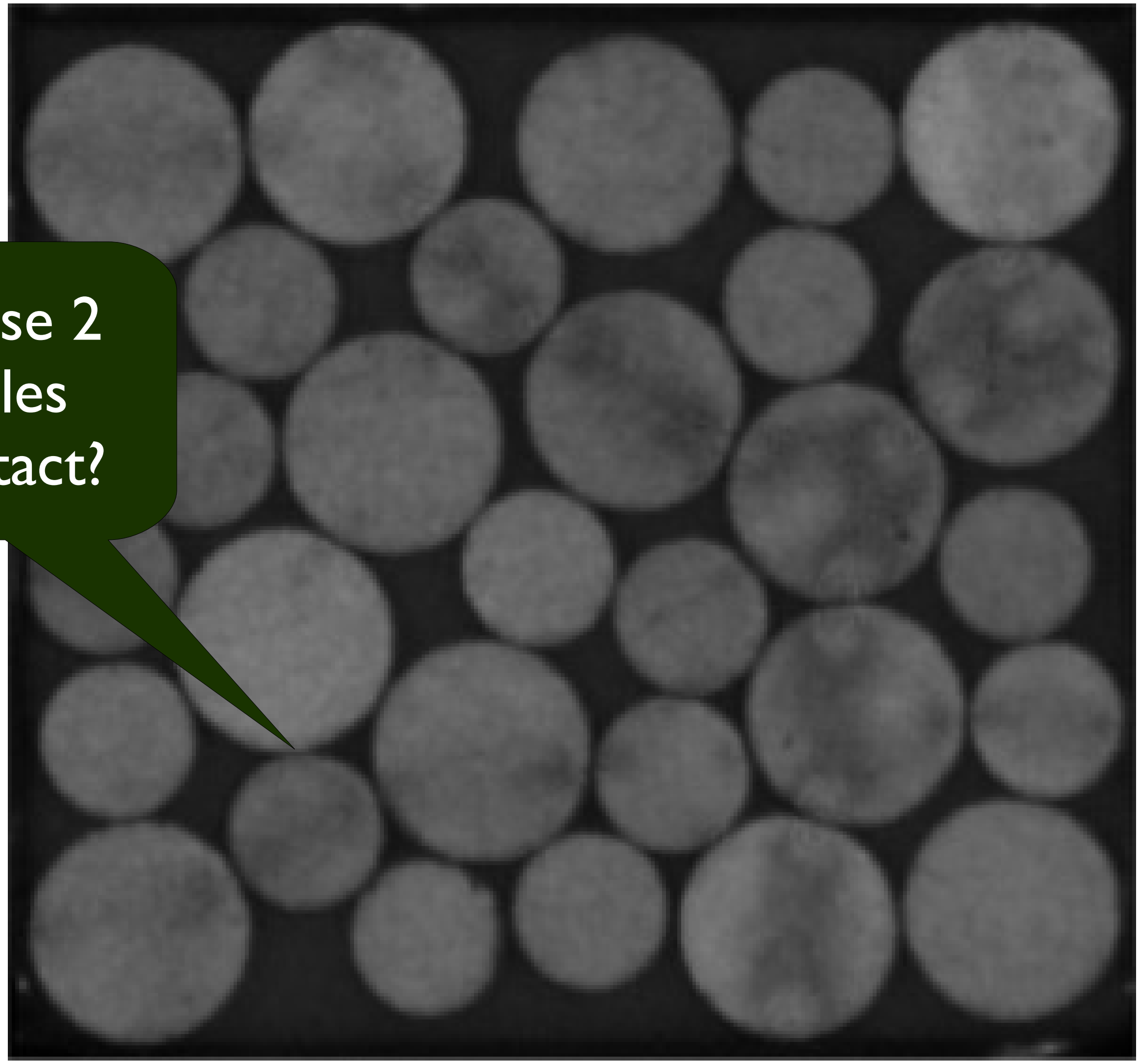
errors in $\vec{r}_i$ ⇒ errors in contacts

④ If you know positions + radii, easy to get

ϕ (local or global)

↳ via radical Voronoi or nav map

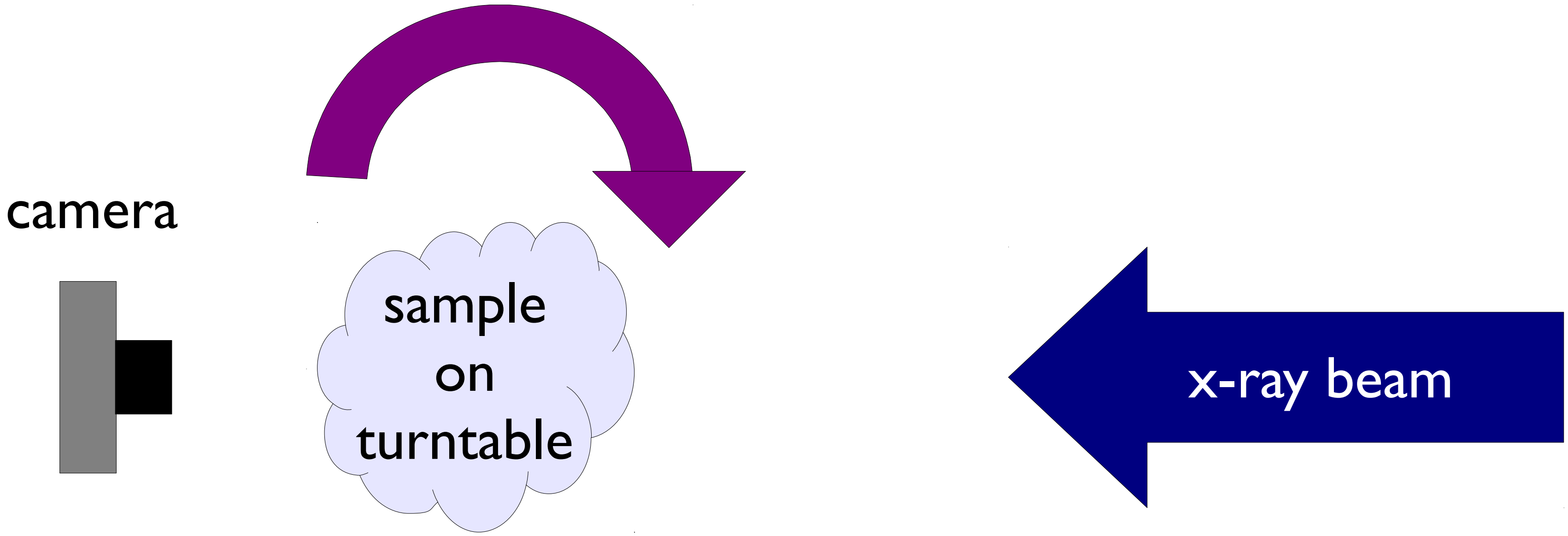
Direct Imaging (2D)

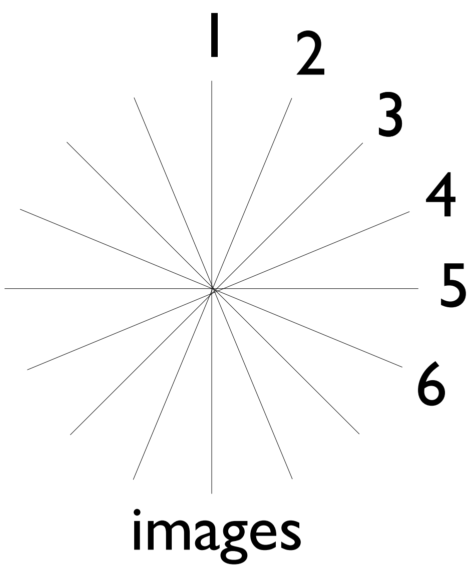


are these 2 particles in contact?

Daniels, Kollmer, Puckett. *Rev. Sci. Inst. (2017)*

X-ray Computed Tomography (CT)



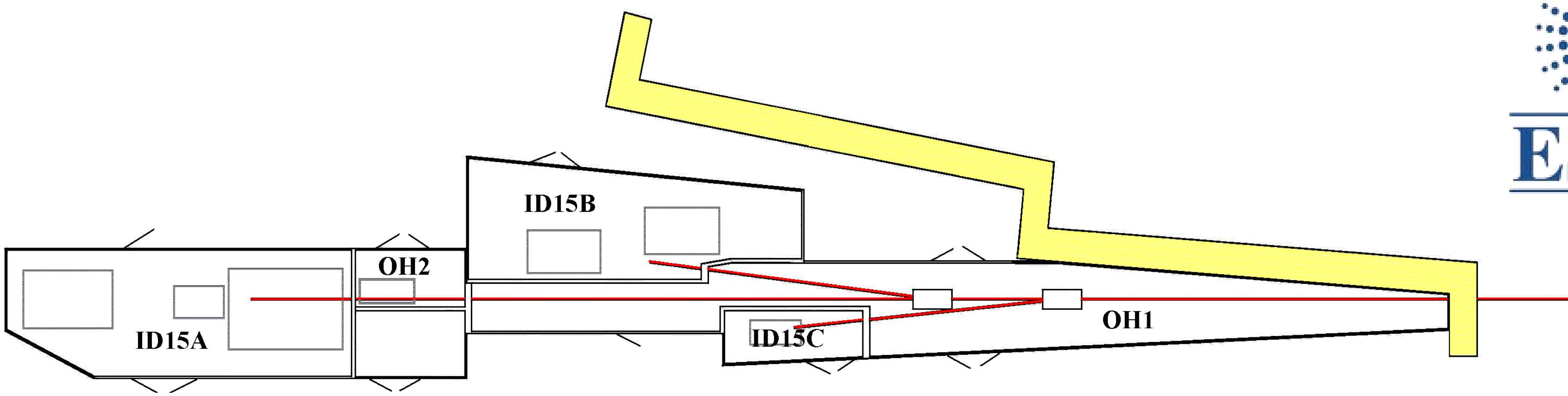


Matthias Schröter:

https://www.youtube.com/watch?v=76Z1Bbj7CtQ

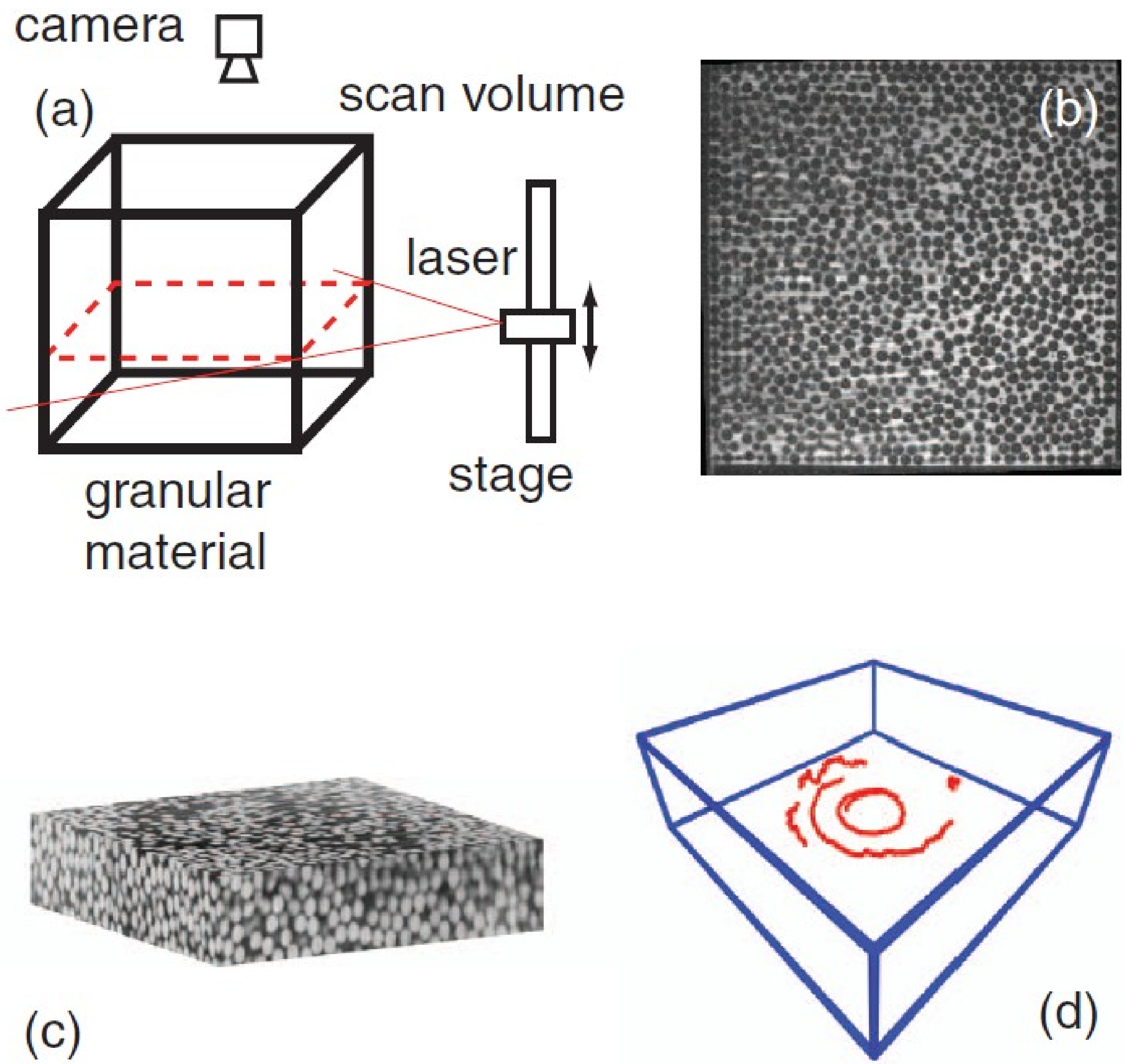
Weis & Schröter. *Rev. Sci. Inst.* (2017)

Performing Tomography



ESRF

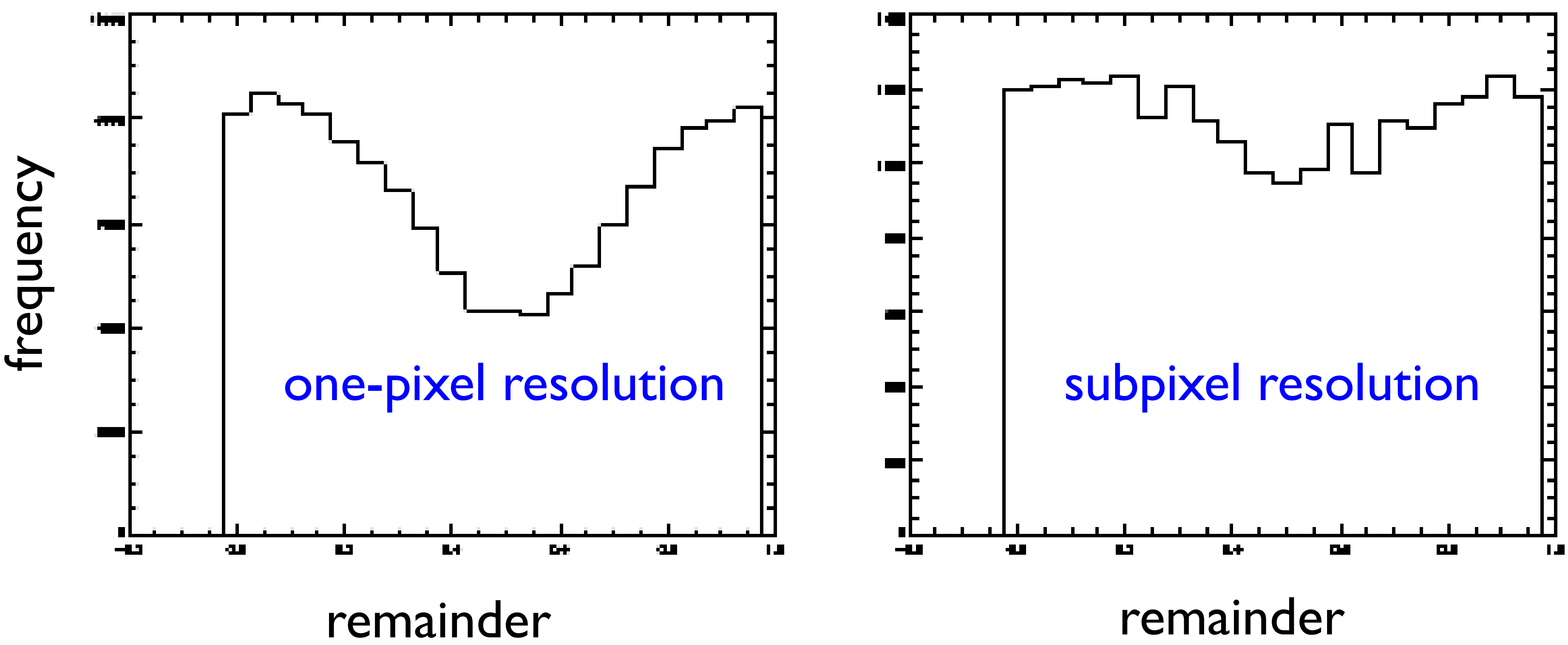
Index-Matched Laser Scanning



Dijksman, Rietz, Lörincz, van Hecke, Losert. *Rev. Sci. Inst.* (2012)
Dijksman, Brodu, Behringer. *Rev. Sci. Inst.* (2017)

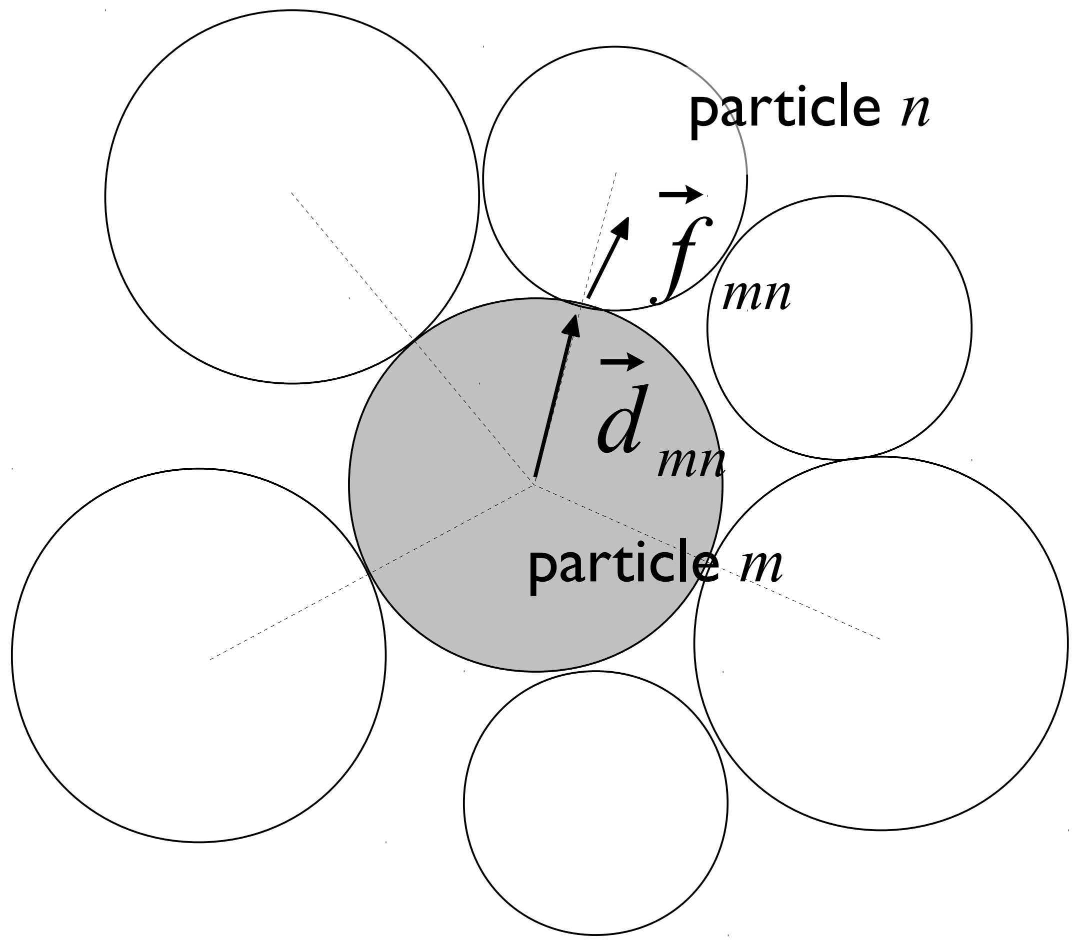
Sub-Pixel Resolution & Pixel Biasing

x coordinate = 10.234 → remainder = 0.234



http://www.physics.emory.edu/faculty/weeks/idl/

Measuring Interparticle Forces



Determining Interparticle Forces

① how data is collected (2D vs. 3D slides)

- deformation
- photoelasticity

} → indirect measures

rely on particles being <u>soft</u>

Photoelasticity (Froch 1941, Daniels | Kollmer | Puckett)

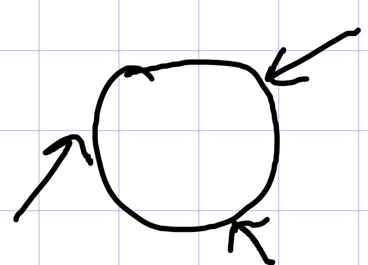
fringe intensity $= I = I_0 \sin^2 \frac{\pi (\sigma_1 - \sigma_2) h C}{\lambda}$

$\sigma_1 - \sigma_2$ = principle stress
found via classical elasticity
spatially-varying

h = thicknes λ = wavelength
C = stress-optic coefficient (λ-dependent)

finding forces:

guess set $\{f\}$ of forces acting on disk

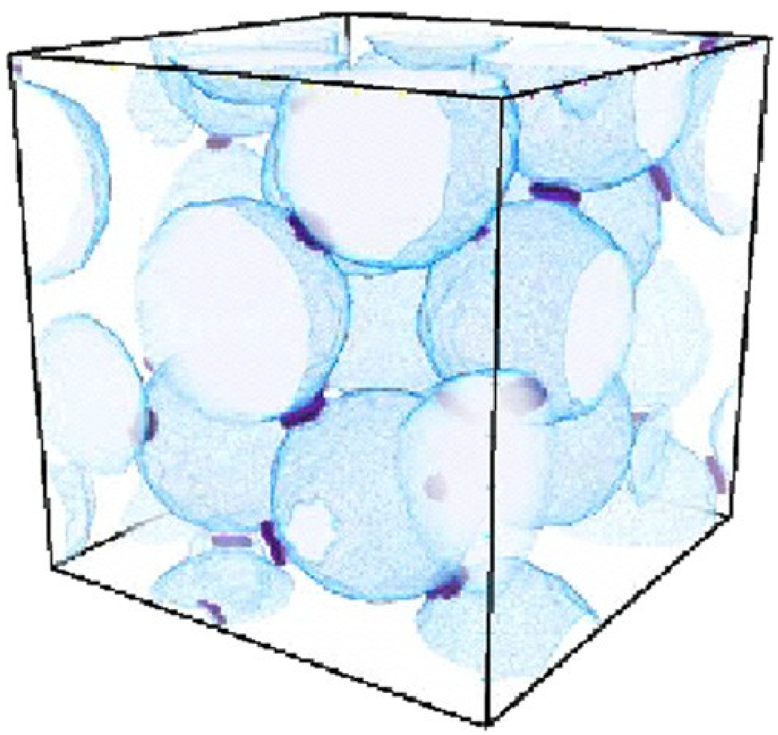


calculate analytical $(\sigma_1 - \sigma_2)(x, y)$ and then $I(x, y)$

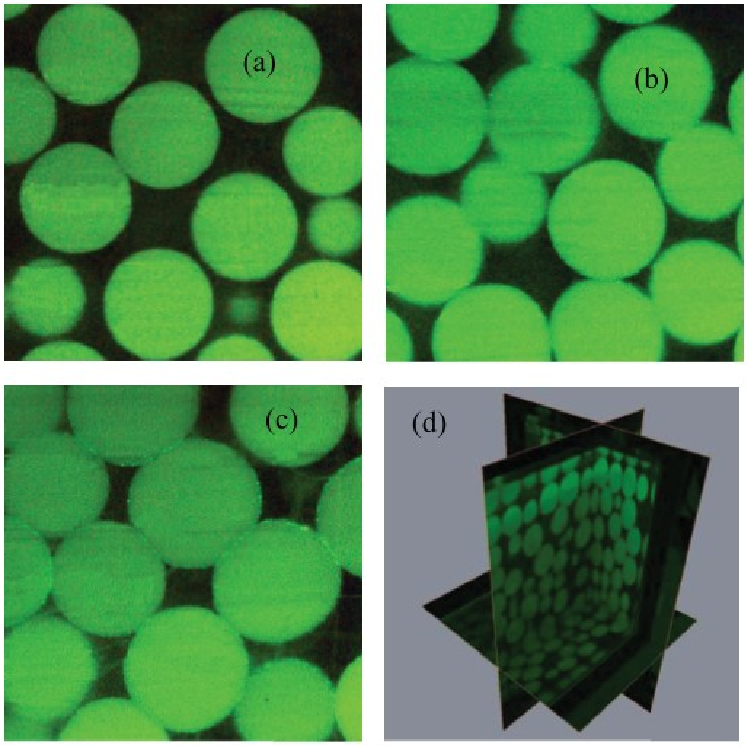
vary $\{f\}$ to optimize I to match target image, while maintaining force balance

Forces in 3D

X-ray tomography



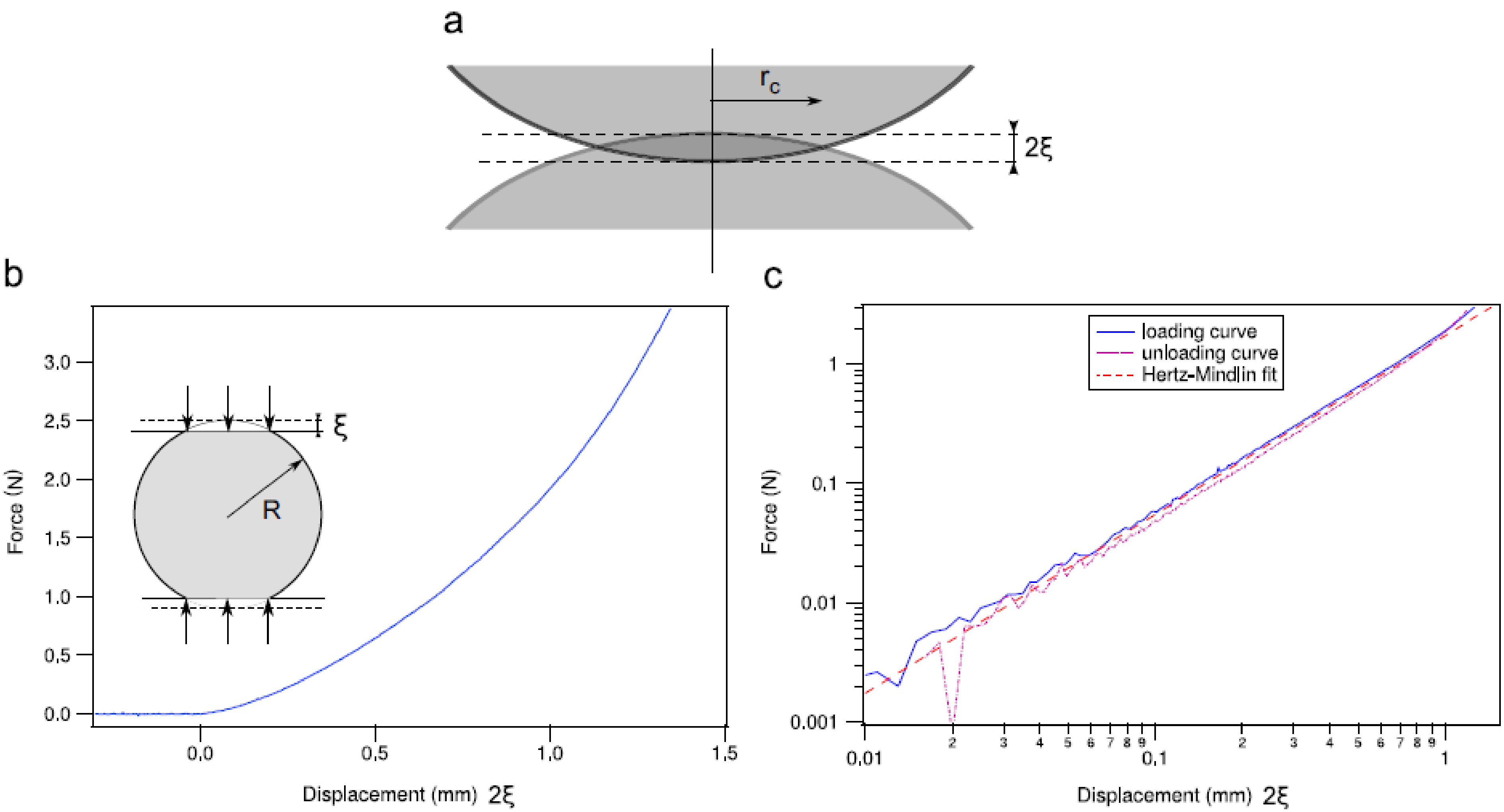
laser sheet illumination



obtain normal forces from fitting area of deformation at contacts

Saadatfar, Sheppard, Senden, Kabla, *J. Mech. Phys. Solids* (2012)
Mukhopadhyay & Peixinho. *PRE* (2011)
Dijksman, Brodu, Behringer *Nature Comm.* (2015); *Rev. Sci. Inst.* (2017)

Force Measurement via Deformation

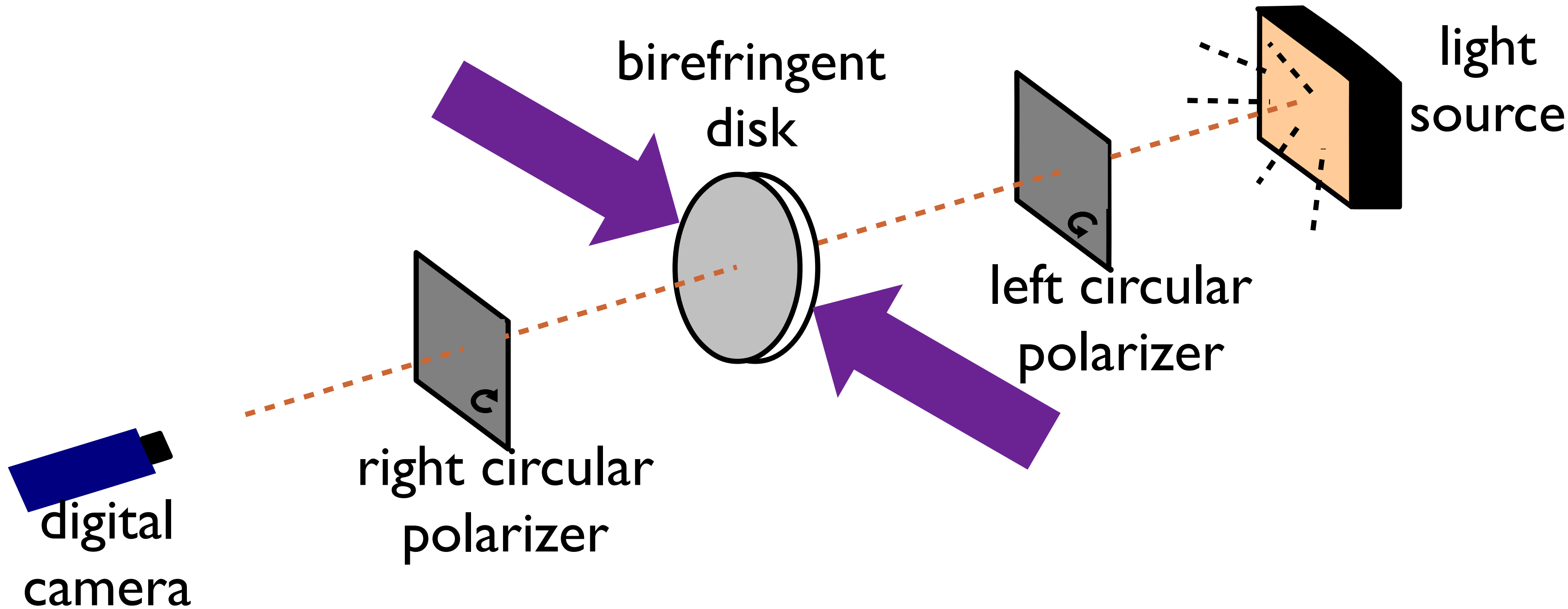


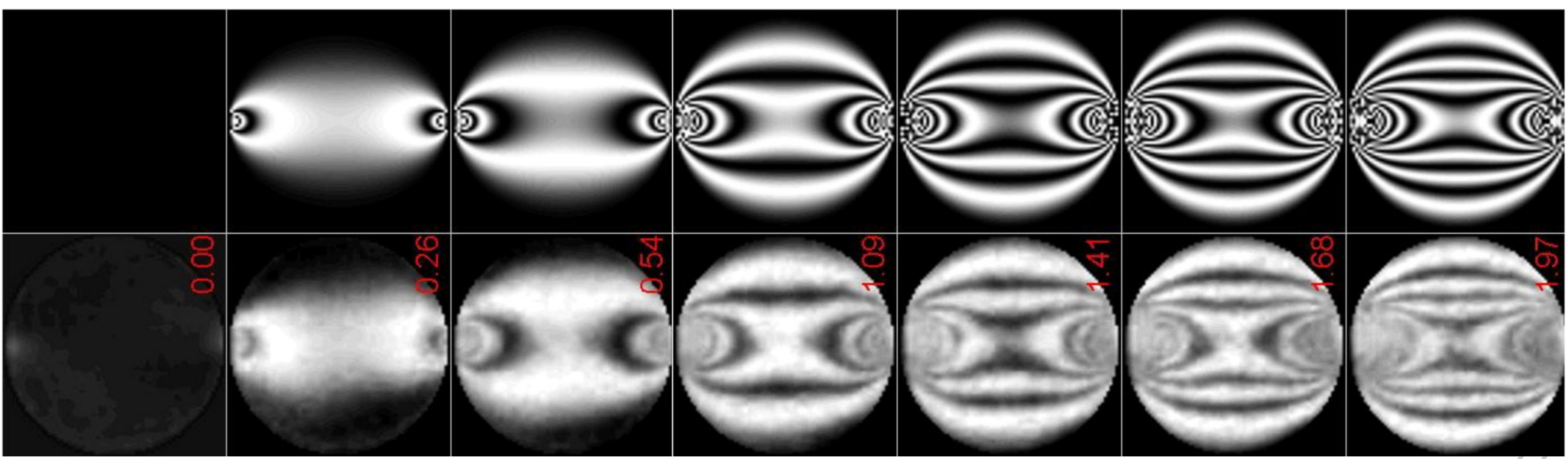
$$f_{mn} = \frac{2}{3}\frac{4G}{1-\nu}R^{1/2}\xi_{mn}^{3/2}$$

Hertzian contact force

Saadatfar, Sheppard, Senden, Kabla, *J. Mech. Phys. Solids* (2012)

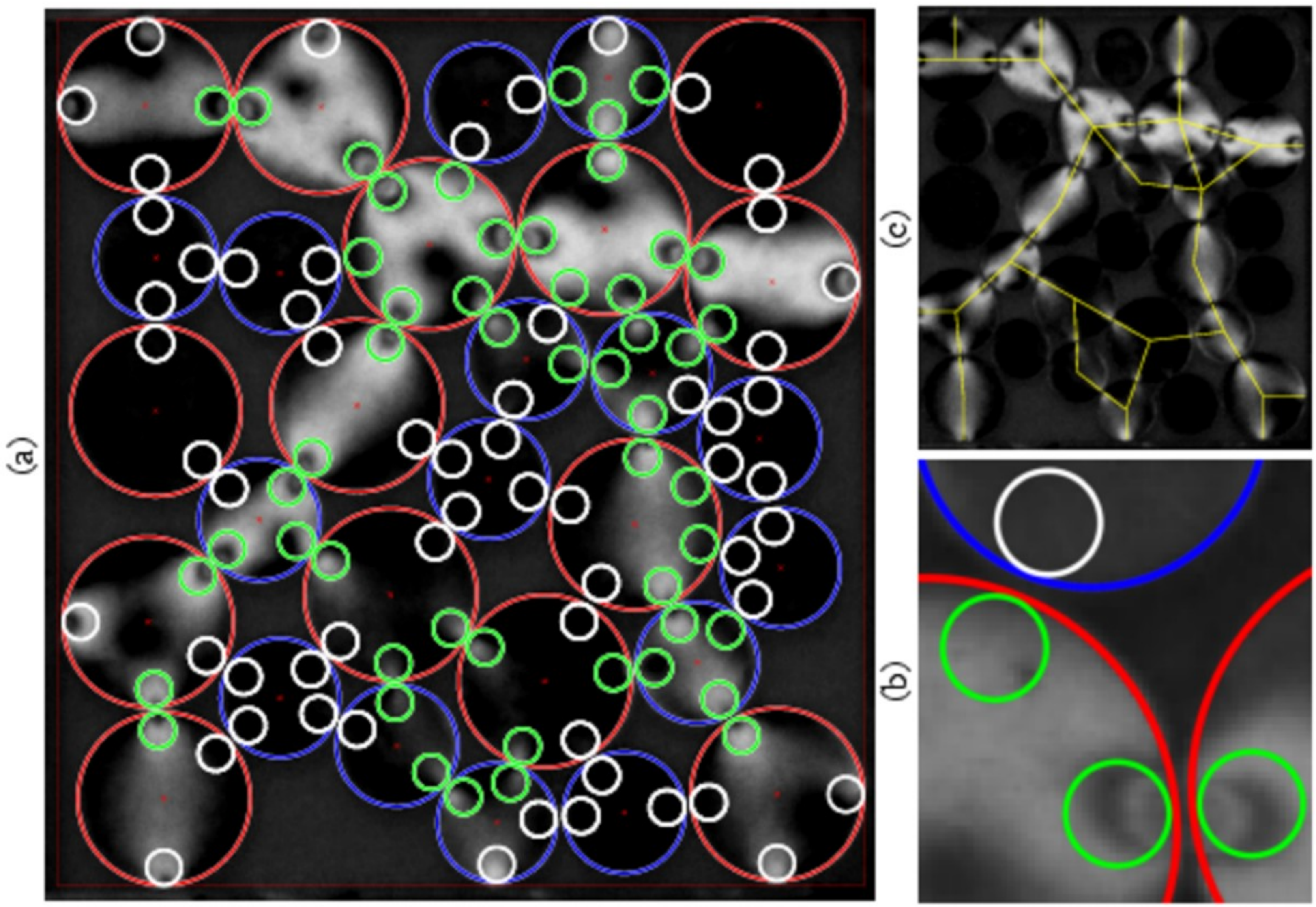
Measuring Interparticle Contact Forces





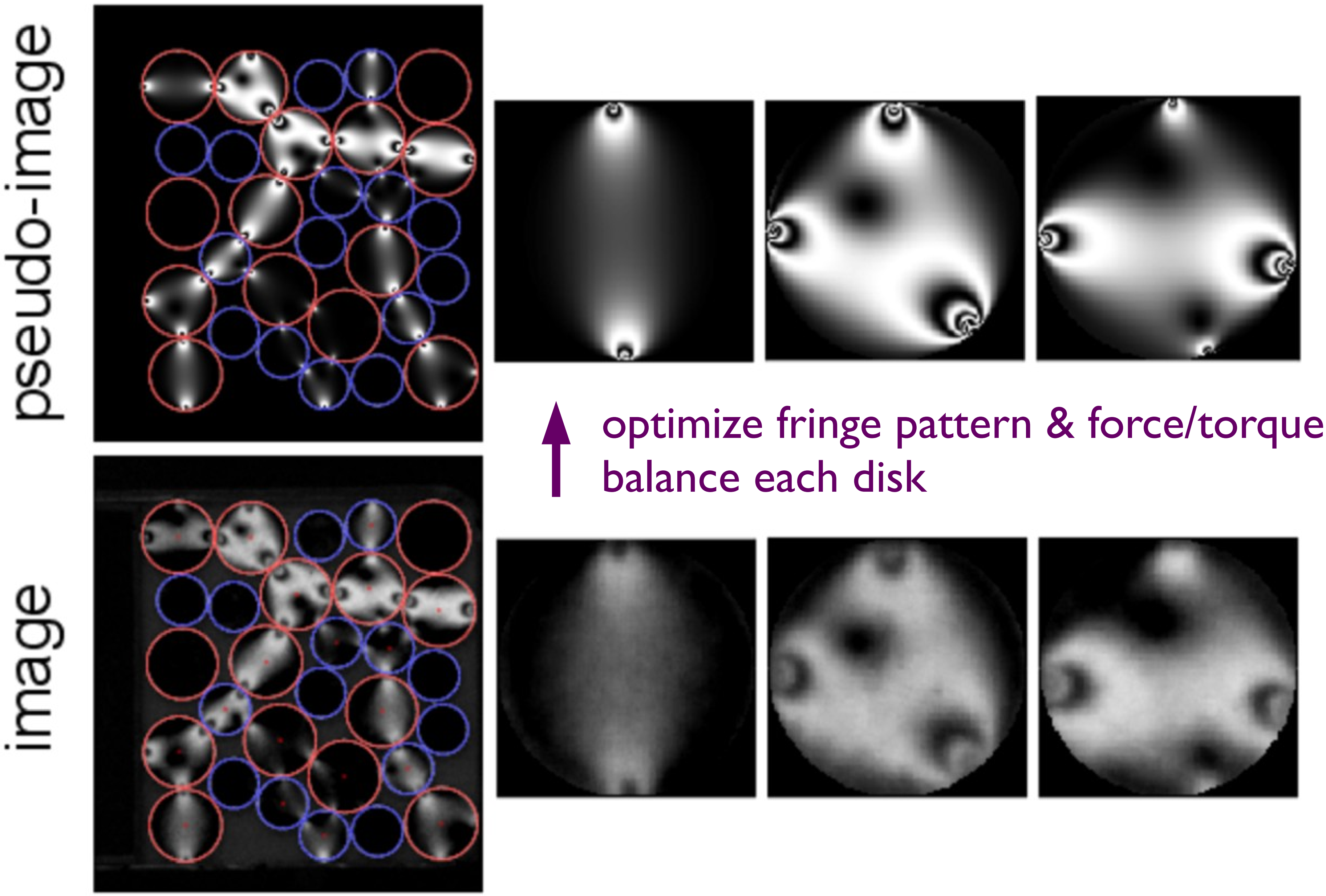
Daniels, Kollmer, Puckett. *Rev. Sci. Inst. (2017)*

Photoelastic Inversion (1)



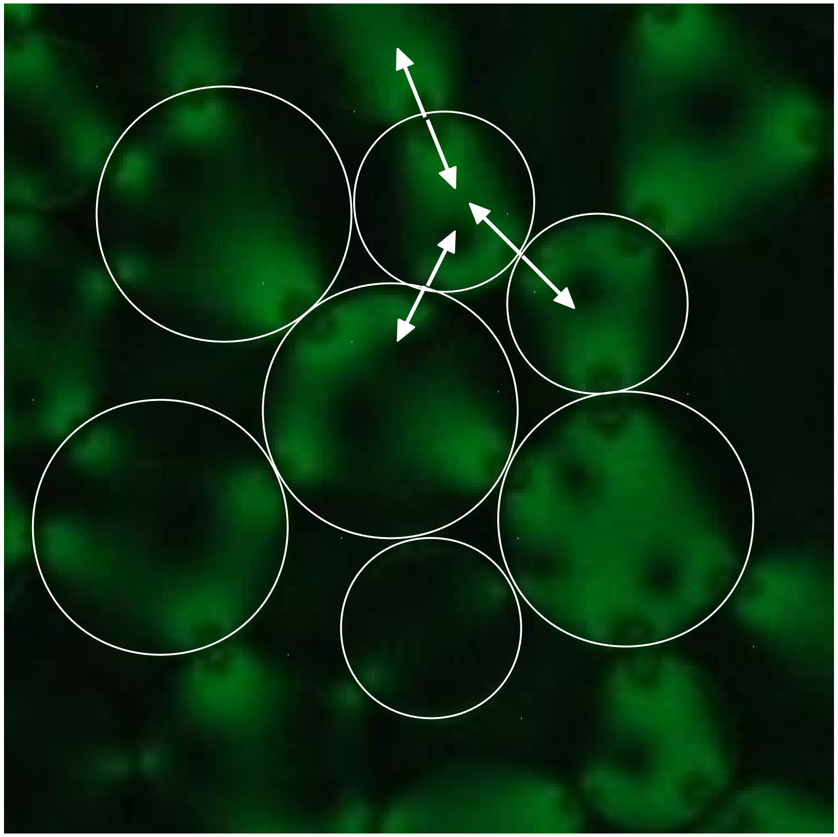
Daniels, Kollmer, Puckett. *Rev. Sci. Inst. (2017)*

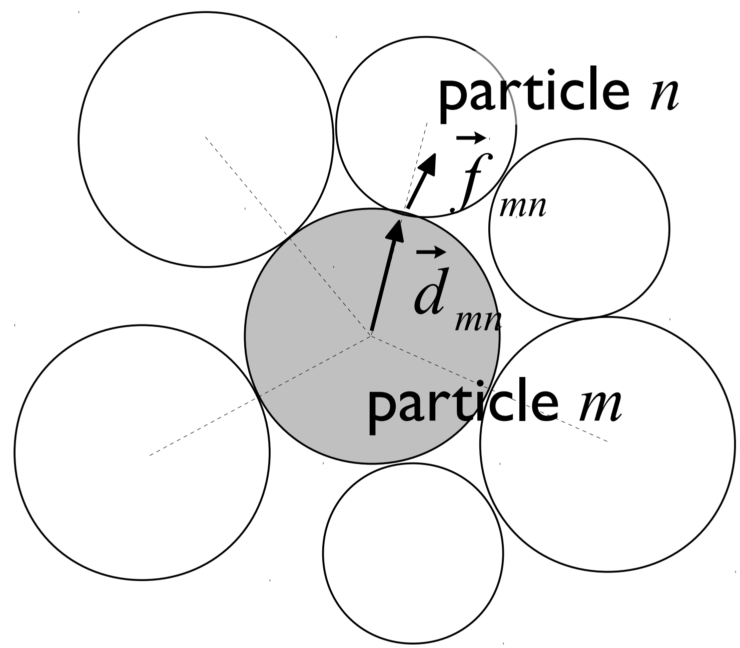
Photoelastic Inversion (2)



Daniels, Kollmer, Puckett. *Rev. Sci. Inst. (2017)*

Quantifying Interparticle Forces





Bi, Henkes, Daniels, Chakraborty.
Ann. Rev. Cond. Matt. (2015)

force-moment tensor

$$\hat{\Sigma} = \sum_{m,n} \vec{d}_{mn} \vec{f}_{mn}$$

stress tensor

$$\hat{\Sigma} = V \hat{\sigma}$$

pressure

$$\Gamma = Tr \hat{\Sigma}$$

② quality of data / working with data

evaluating quality – force balance on particle?
contact?

data analysis can be optimized for either
(but <u>both</u> is an interesting computational
problem)

Do Forces Matter? (YES!)

- sound propagation depends on contact area + pattern of heterogeneity

  DEMs ("overlap") don't capture this

  is this also important for vibrational modes? thermal conductivity?

- force network encodes a record of how the system was loaded

  tangential forces are particularly sensitive (F_T opposes direction of motion)

- for flow, fluctuations in force chains are maximum near the yield condition → susceptibility

  → need to understand ensemble of valid forces for one packing

Do the forces matter?

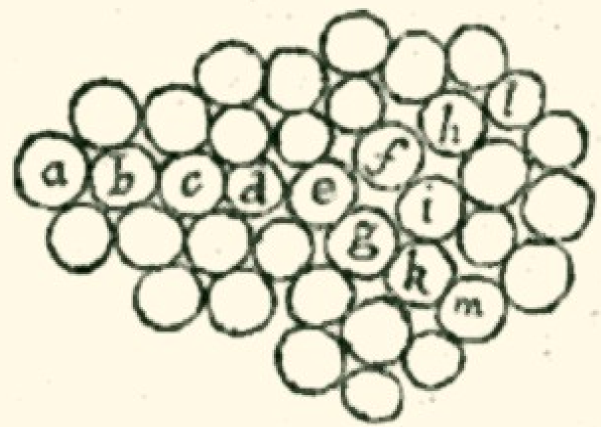
SECT. VIII.

De Motu per Fluida propagato.

Prop. XLI. Theor. XXXI.

Preſſio non propagatur per Fluidum ſecundum lineas rectas, niſi ubi particulæ Fluidi in directum jacent.

Si jaceant particulæ *a*, *b*, *c*, *d*, *e* in linea recta, poteſt quidem preſſio directe propagari ab *a* ad *e*; at particula *e* urgebit particulas oblique poſitas *f* & *g* oblique, & particulæ illæ *f* & *g* non ſuſtinebunt preſſionem illatam, niſi fulciantur a particulis ulterioribus *h* & *k*; quatenus autem fulciuntur, premunt particulas fulcientes; & hæ non ſuſtinebunt preſſionem niſi fulcian-

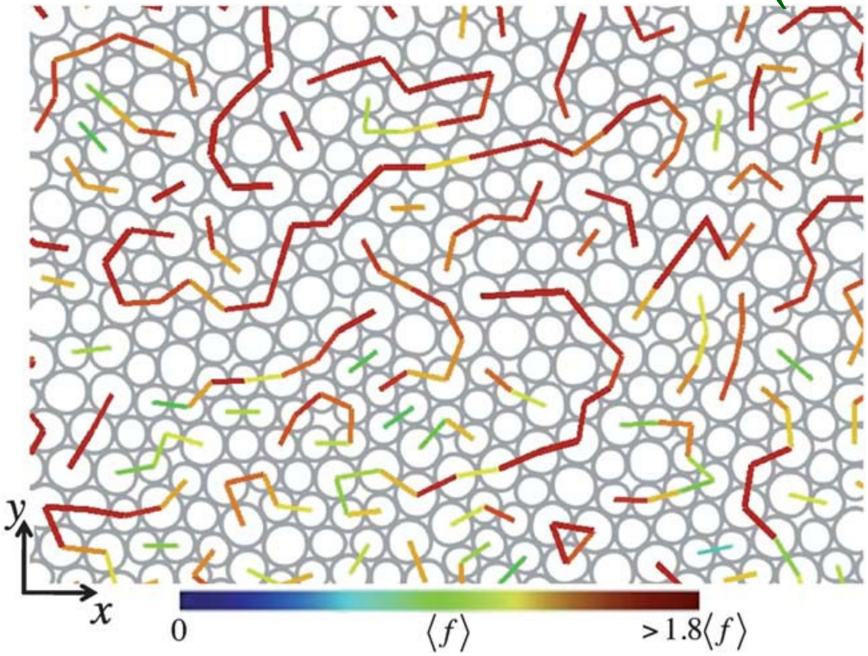


tur

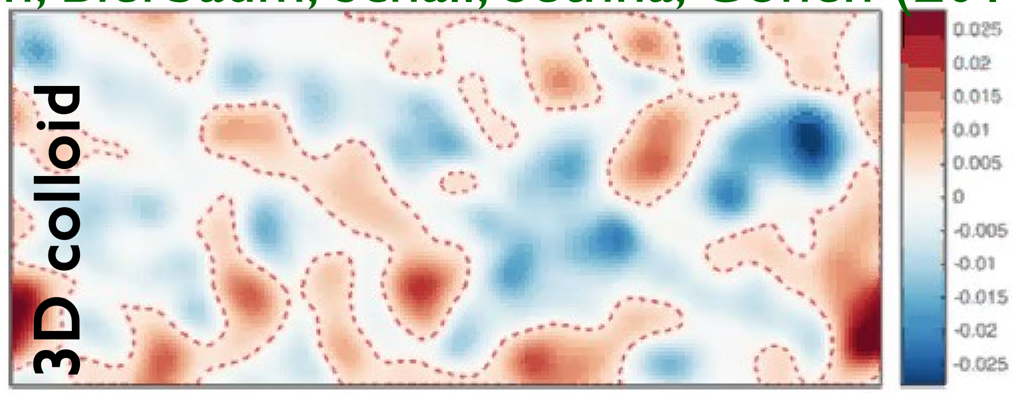
Generality of Force Chains?

Desmond & Weeks. *Soft Matter* (2013)

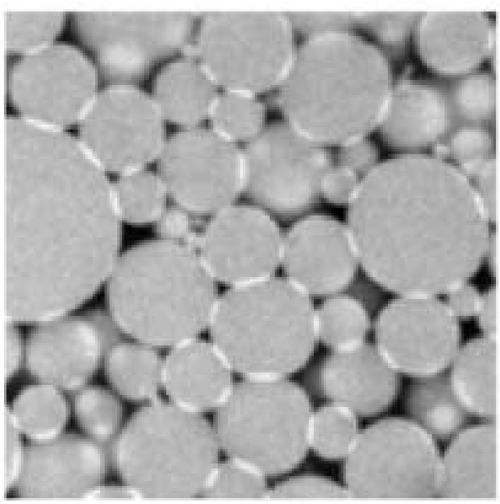
2D emulsion



Lin, Bierbaum, Schall, Sethna, Cohen (2016)

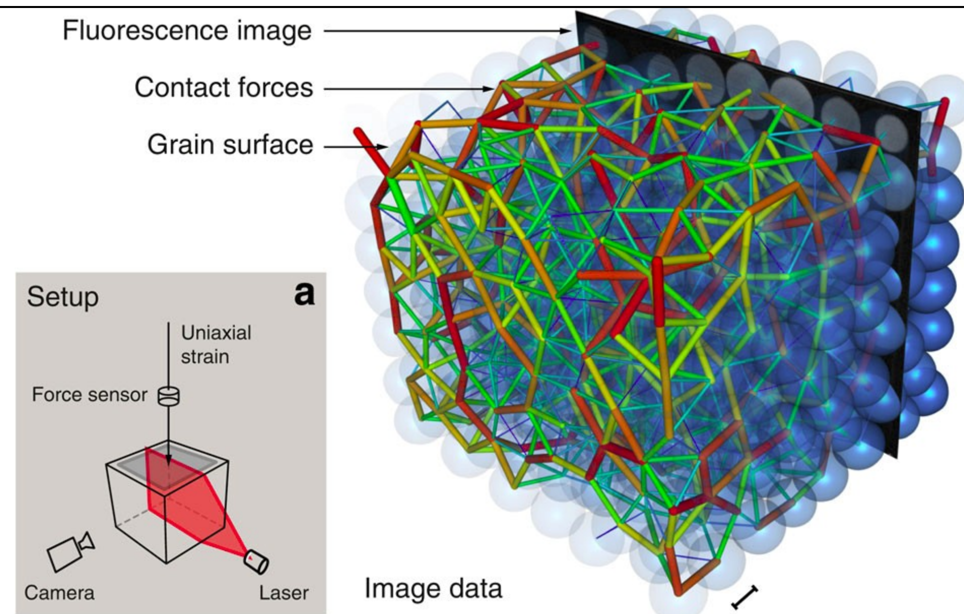


3D emulsion



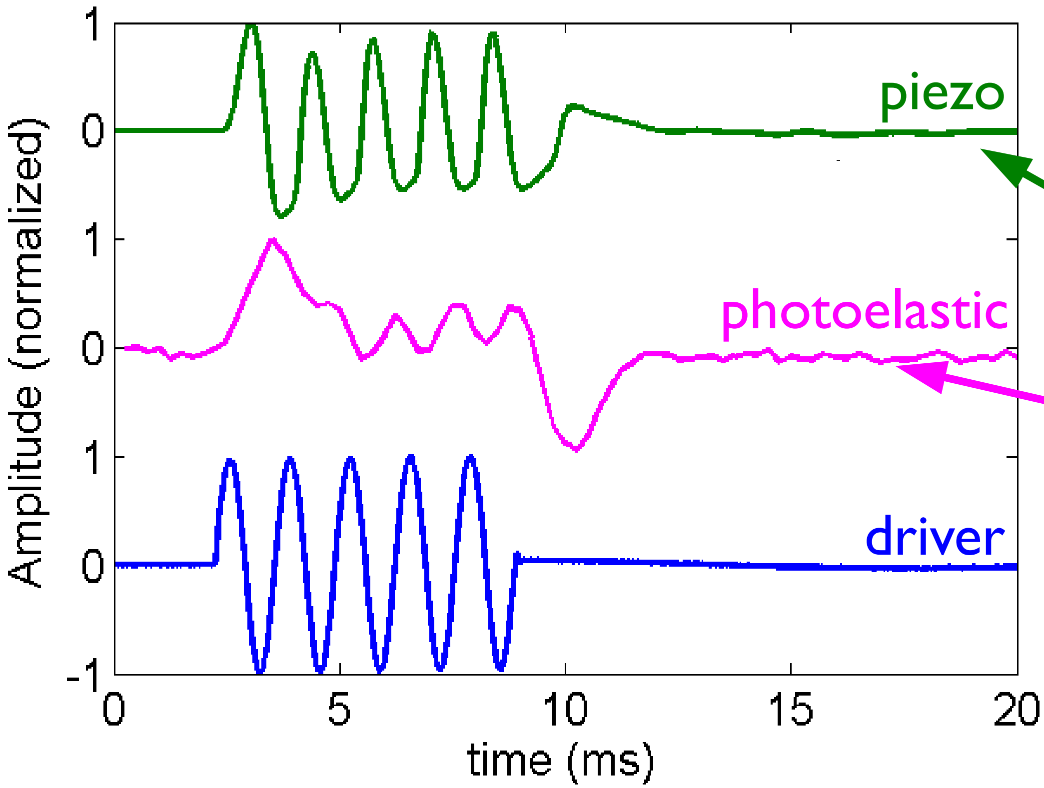
Brujic et al. *Physica A* (2003)

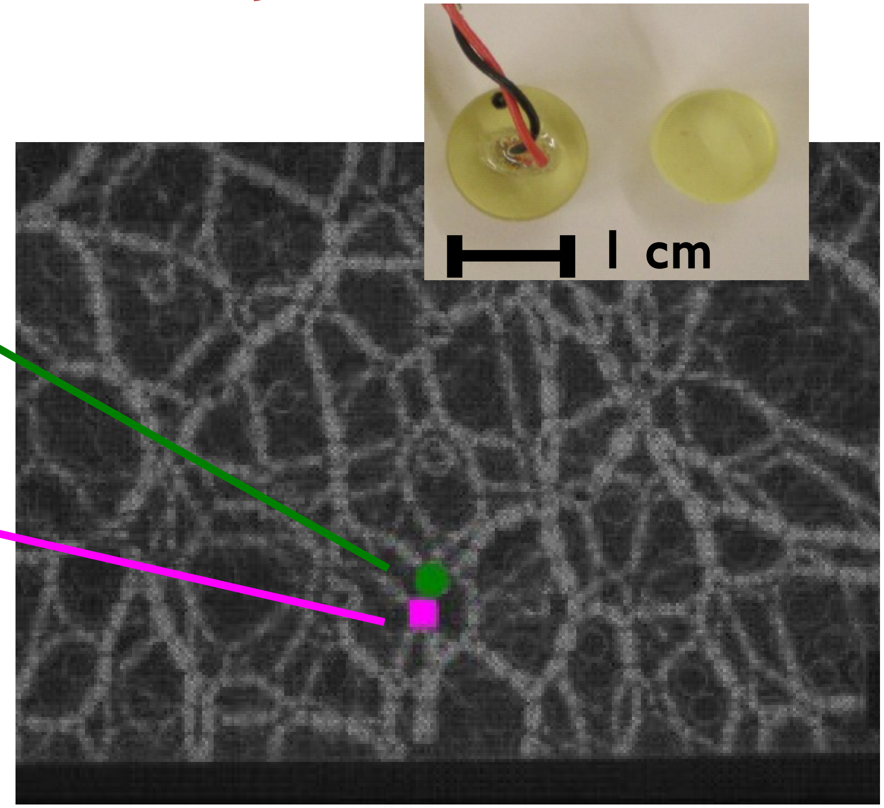
3D gel beads



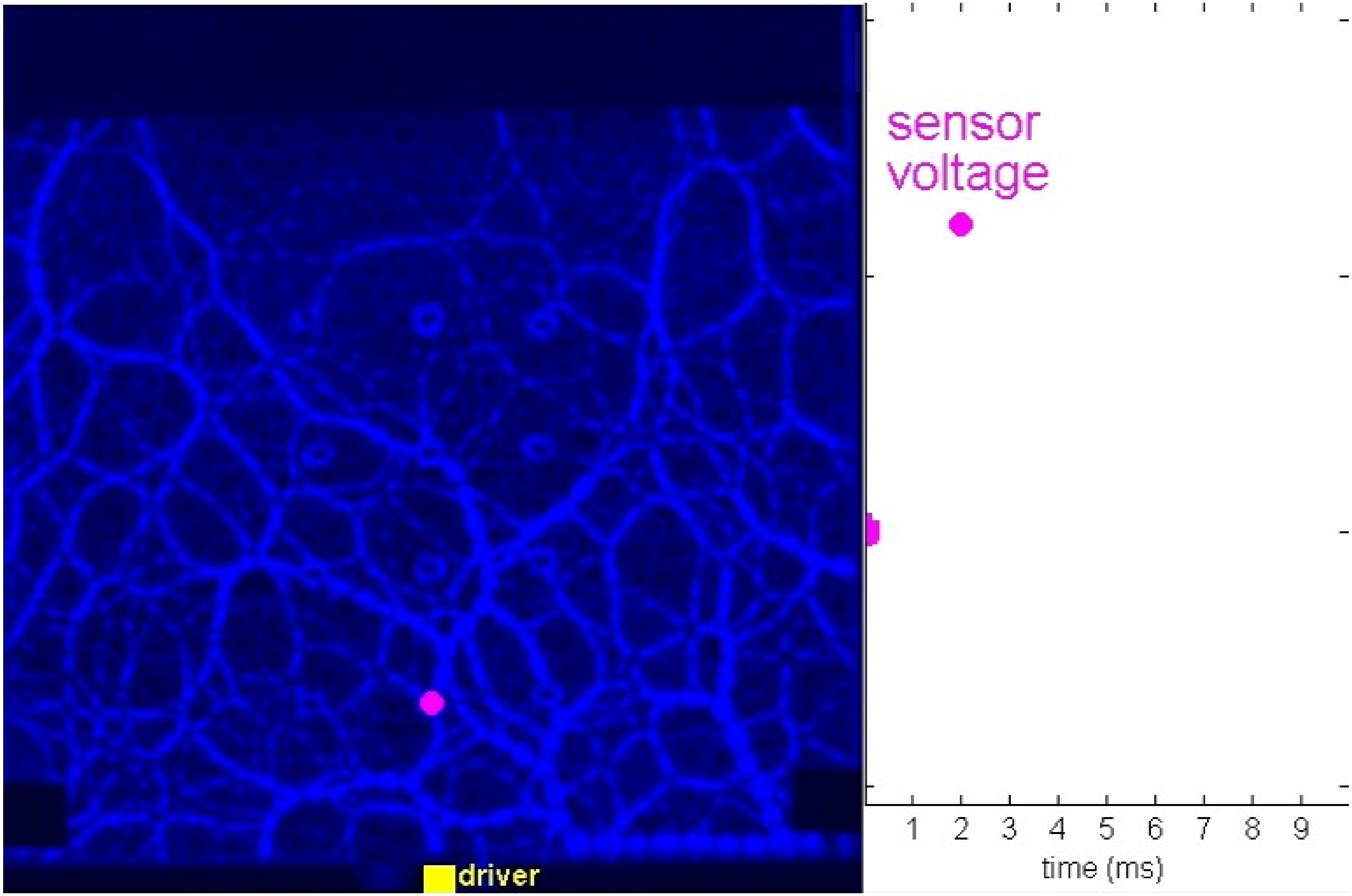
Brodu, Dijksman, Behringer.
Nat Comm. (2015)

Seeing and Hearing





- photoelastic particles: measure amplitude (hundreds)
- piezo particle: measure temporal dynamics for each (~10)
- show same features, and are on average proportional



Blue: Original Force Chains

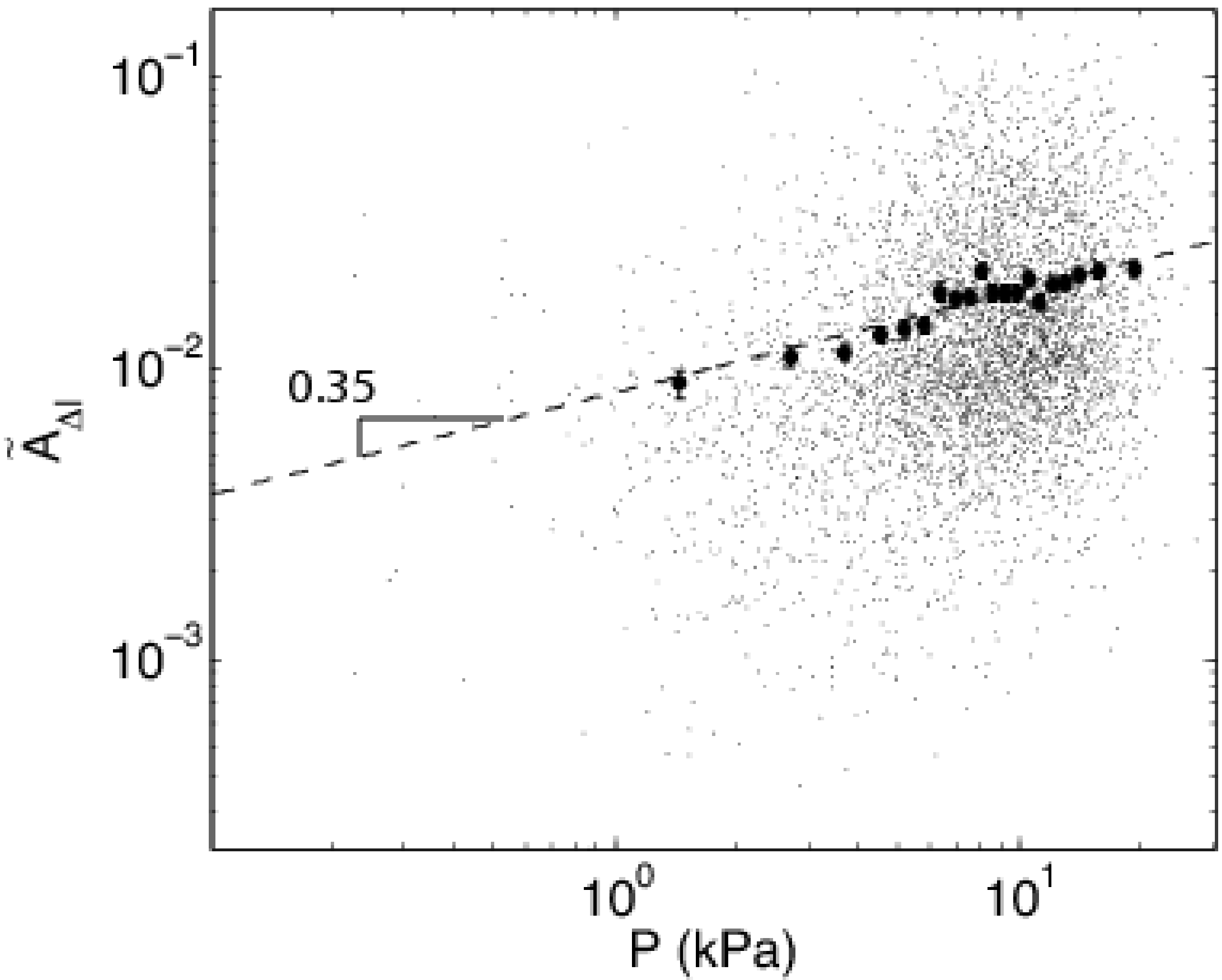
Green: Changes in Force Chains

Local force (on average) sets amplitude

high speed movies

measure maximum sound amplitude

correct for exponential decay



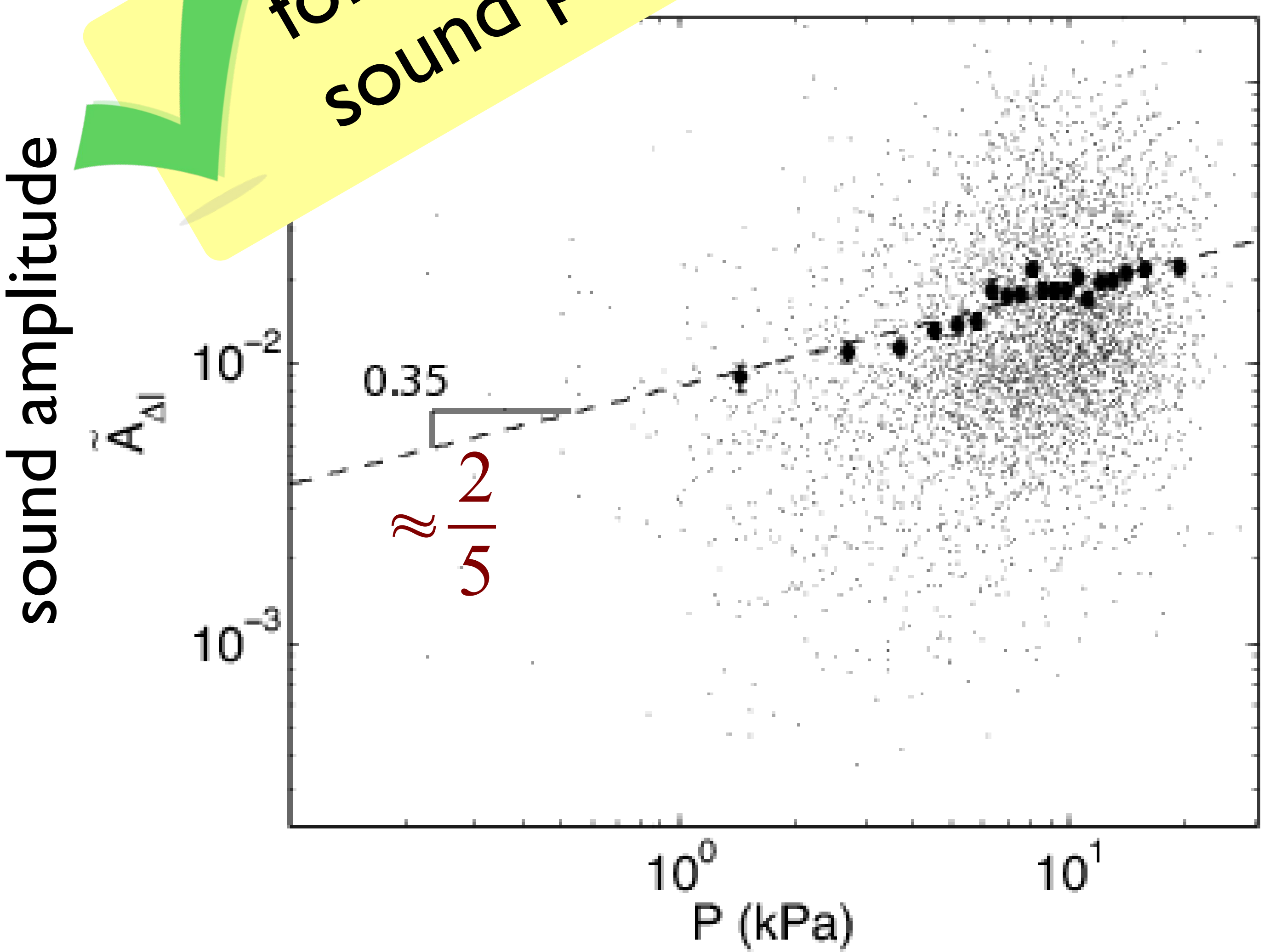
high resolution images

locate all particles, calculate pressure

Owens & Daniels, *EPL* (2011)

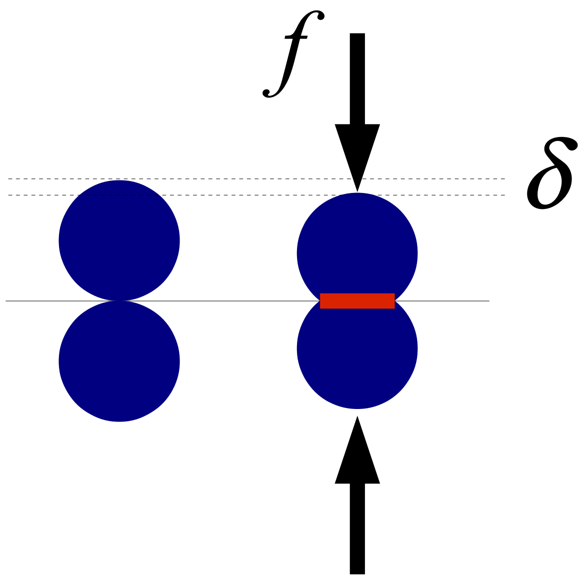
(modified) contacts

force chains affect sound propagation



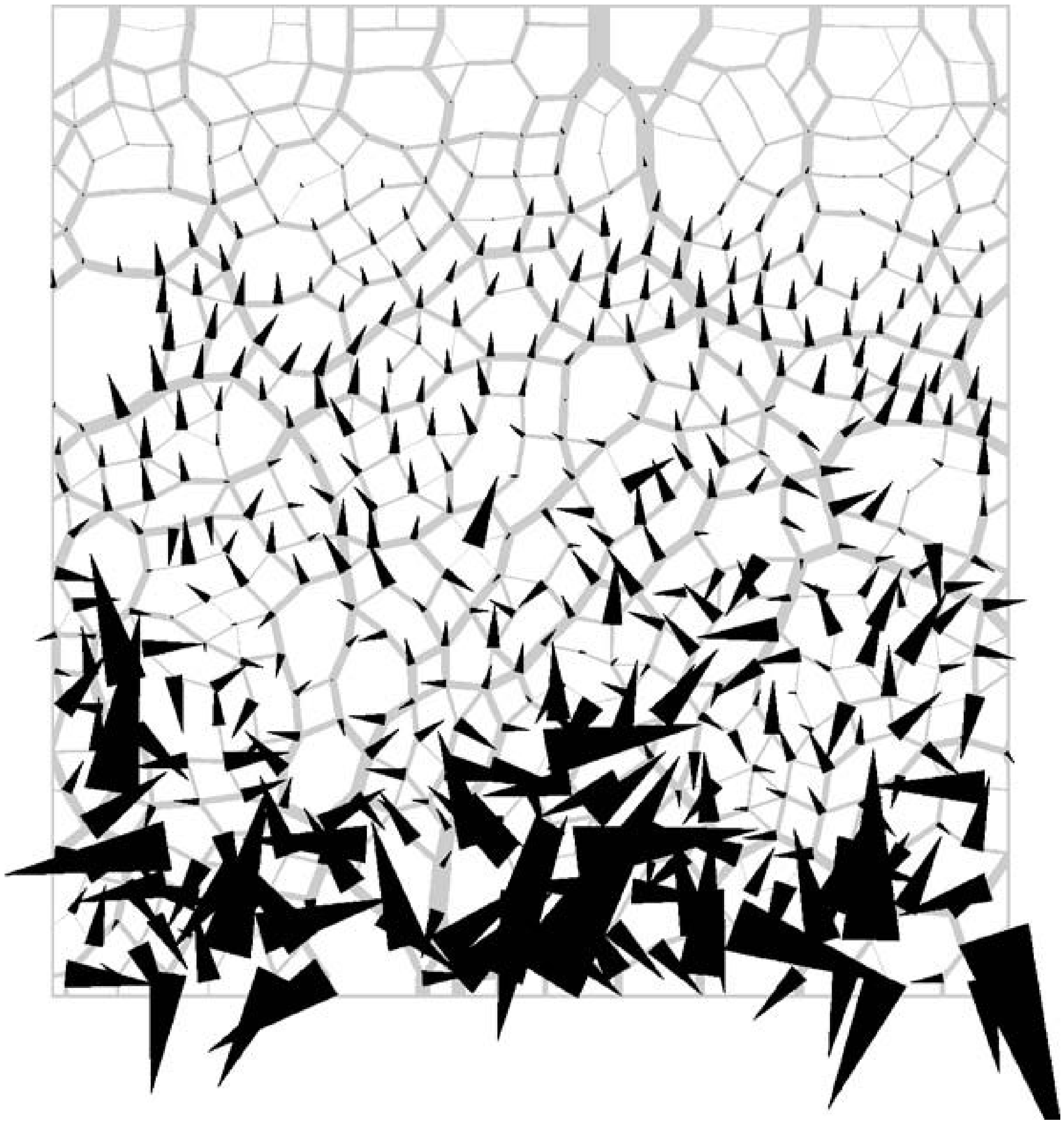
$f \propto \delta^{5/4}$

$area \propto f^{2/5}$



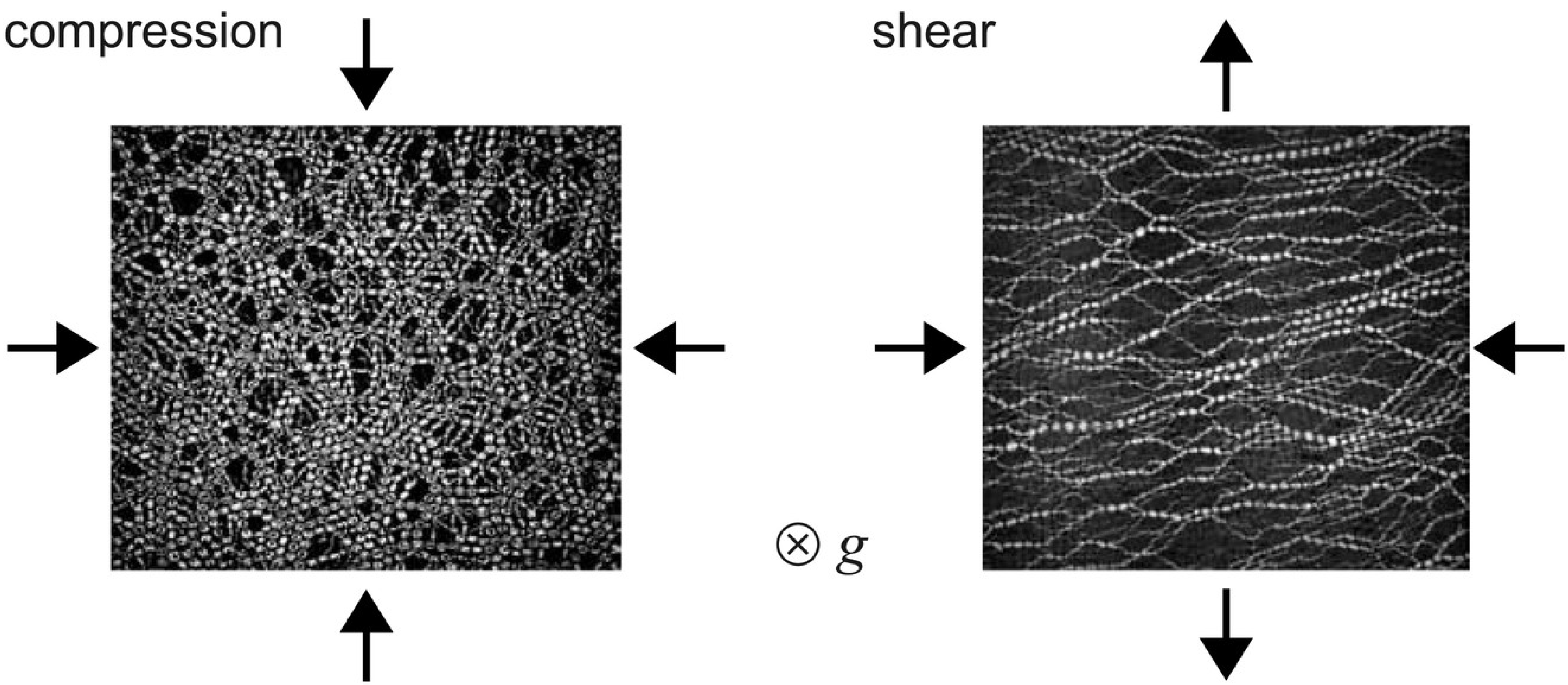
Owens & Daniels, *EPL* (2011)

DEM Simulations



Somfai et al PRE (2005)

History Matters

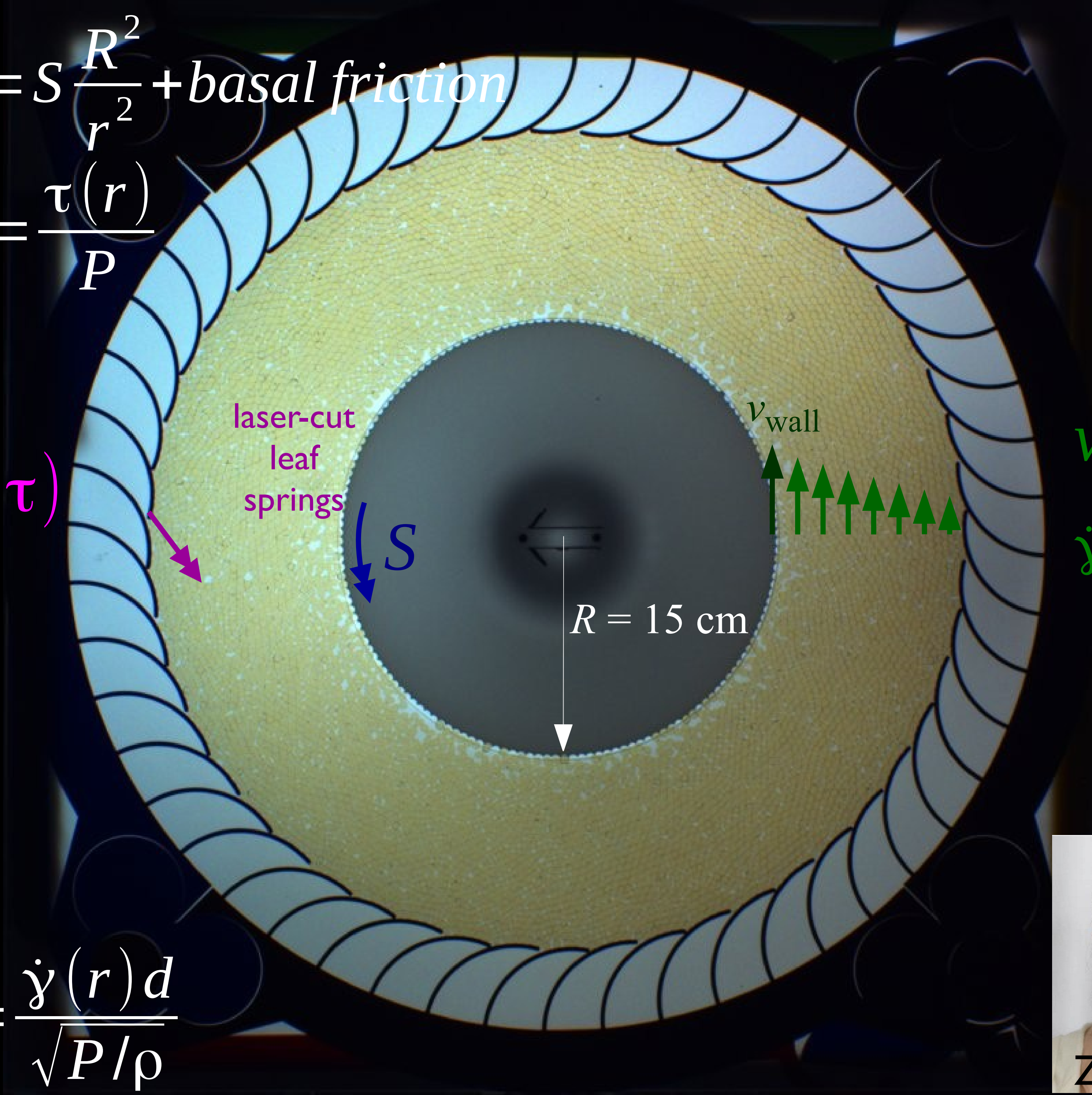


Majmudar & Behringer *Nature* (2005)

$$\tau(r) = S\frac{R^2}{r^2} + basal\ friction$$

$$\mu(r) = \frac{\tau(r)}{P}$$

(P, τ)



$v(r)$

$$\dot{\gamma} = \frac{\partial v}{\partial r}$$

$$I(r) = \frac{\dot{\gamma}(r)\,d}{\sqrt{P/\rho}}$$

Nonlocal Rheology

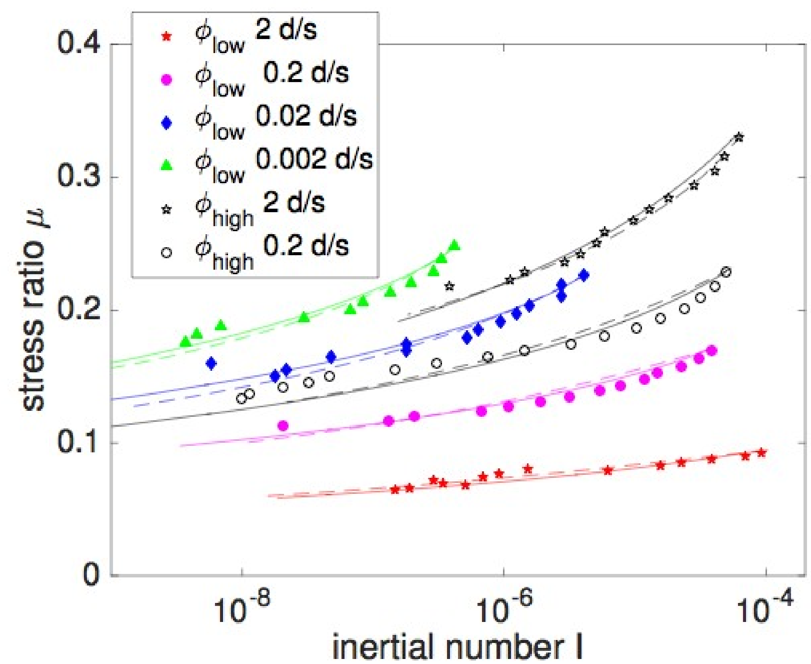
granular fluidity field $g \equiv \frac{\dot{\gamma}}{\mu}$ $\mu \equiv \frac{\tau}{P}$

$$\xi^2 \nabla^2 g = (g - g_{loc})$$

$$g_{loc}(\mu, P) = H(\mu - \mu_s)\frac{\mu - \mu_s}{b\mu T}$$

$$\xi = A\sqrt{\frac{1 + H(\mu_s - \mu)}{|\mu - \mu_s|}}d$$

– Kamrin, Koval, Hennan
- - Bouzid, Claudin



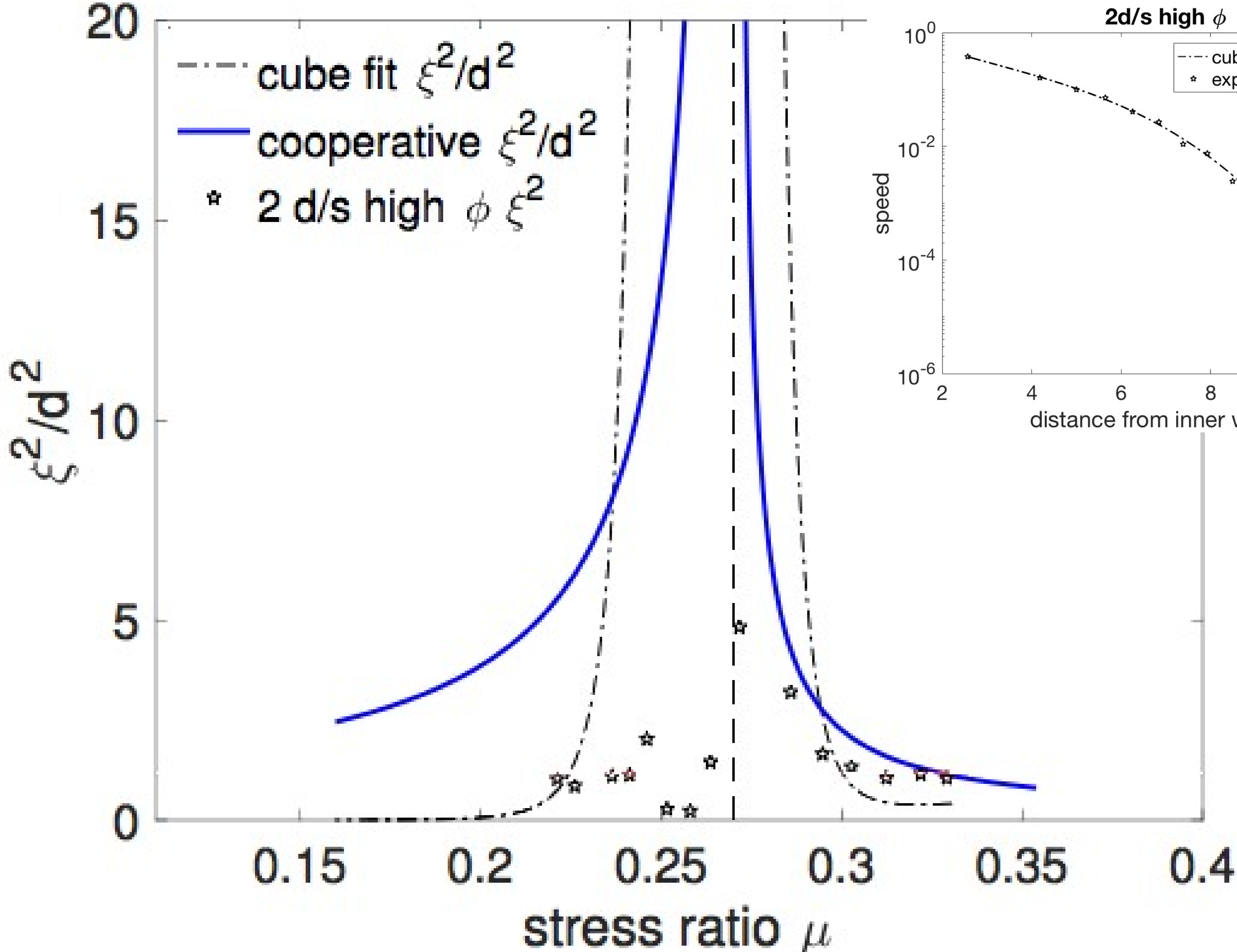
outer edge

inner edge

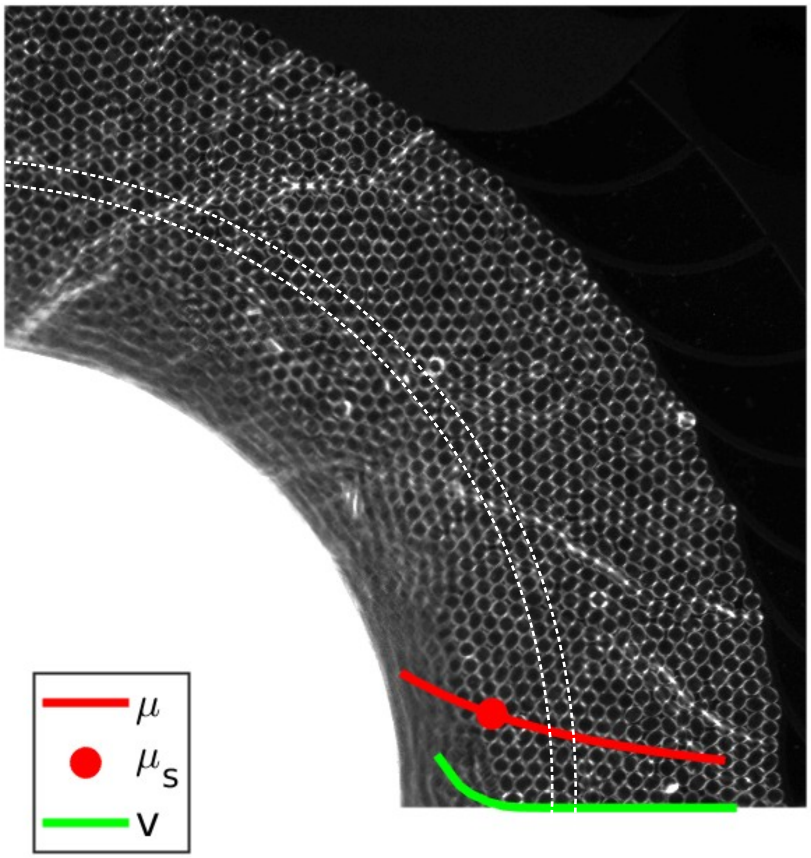
- length scale ξ diverges at μ_s
- fit parameters: A, b, μ_s should be a property of the particles only (not geometry or driving)

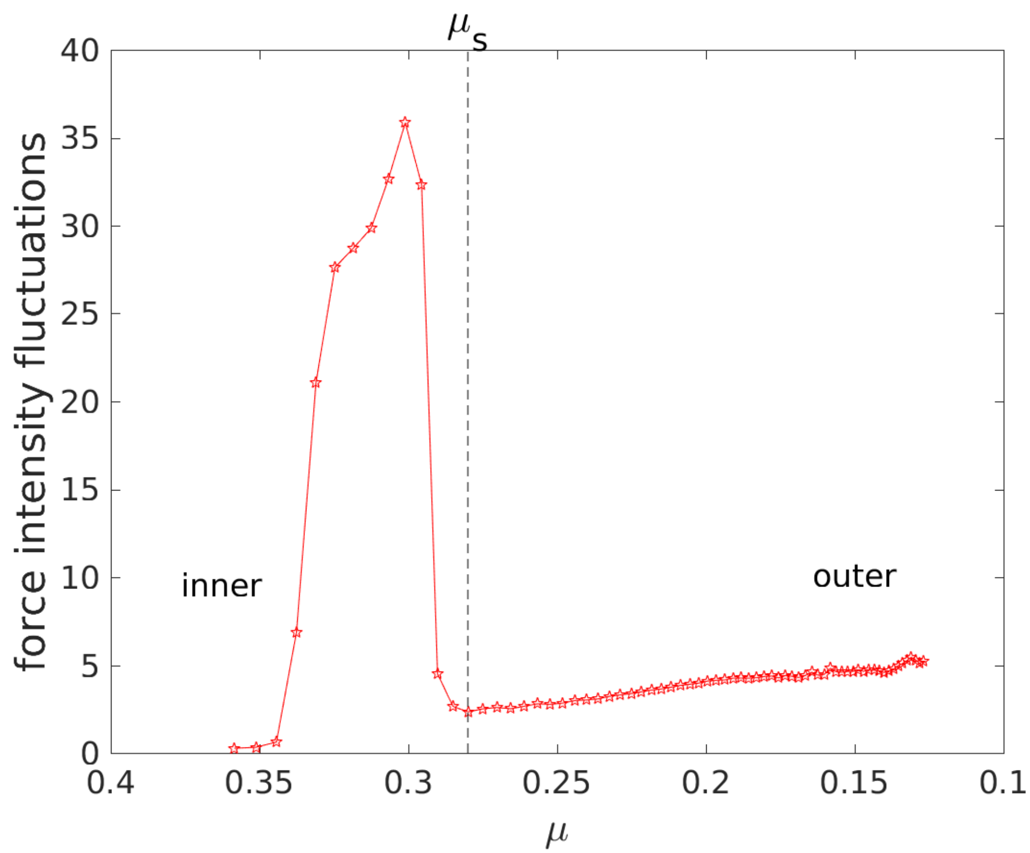
Kamrin & Koval (PRL 2012)

Growing cooperative length ξ



Force fluctuations drop below μ_s





Where do I find data to test my model?

Sharing data between theory, experiments, and simulations

Vines Current Biology (2014)

→ data gets lost over time

where to get data?

Data Dryad slide

short list of experimentalists who have data:
(befriend them)

longer list of simulators

why publish your data?

- you weren't going to do every possible thing with it anyway

- increase the impact of your research with (minimal) extra work

- make new friends (collaborators) + get new perspectives when others reuse this

http://bit.ly/2uejRC4

AIP | Review of Scientific Instruments

SPECIAL TOPIC:
Focus on Imaging Methods in Granular Physics

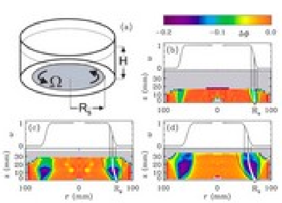
About the Focus on Imaging Methods in Granular Physics Special Topic

"This Focus Issue reviews methods for acquiring microscopic particle properties and for connecting them to the macroscopic physics of granular media. A variety of methods are presented, utilizing electromagnetic waves ranging from x-rays to radio waves. These methods provide information in the form of images, scattering, tomographic reconstruction, and the tracking of phase shifts. Each approach and probe has specific demands on sample material, instrumental investments, and computational efforts and offers different sensitivities and spatiotemporal resolutions. [The] introductory article aims to assist the reader in selecting the most appropriate techniques for their particular research." (Read More)

Review of Scientific Instruments has been in circulation since 1930, providing foundational papers, progressions of development, as well as newly emerging papers covering experimental methods, techniques, and instrumentation.

Preface

openaccess



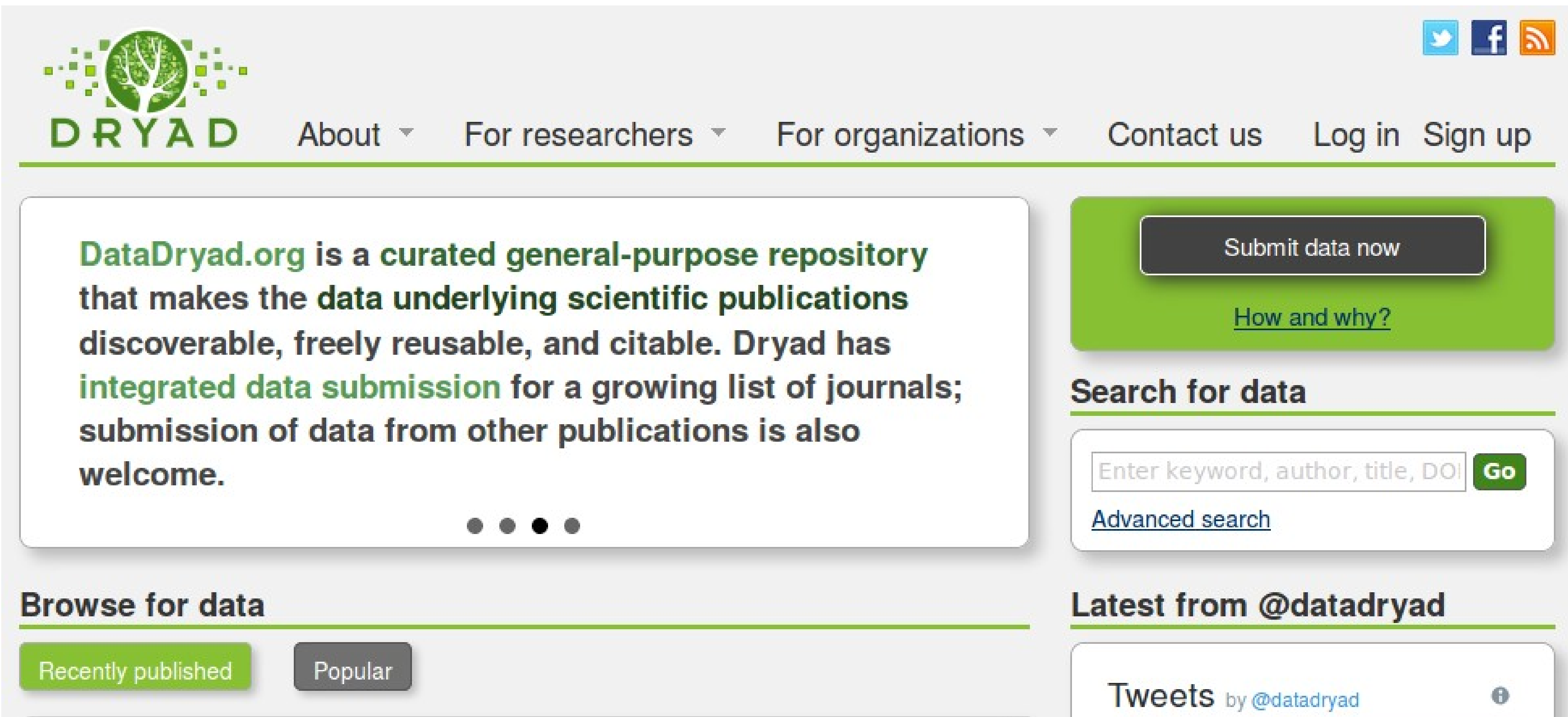
Preface: Focus on imaging methods in granular physics
Axelle Amon, Philip Born, Karen E. Daniels, Joshua A. Dijksman, *et al.*
Read More

- 10 articles from a 2016 Spring School (Erlangen)

DataDryad.com

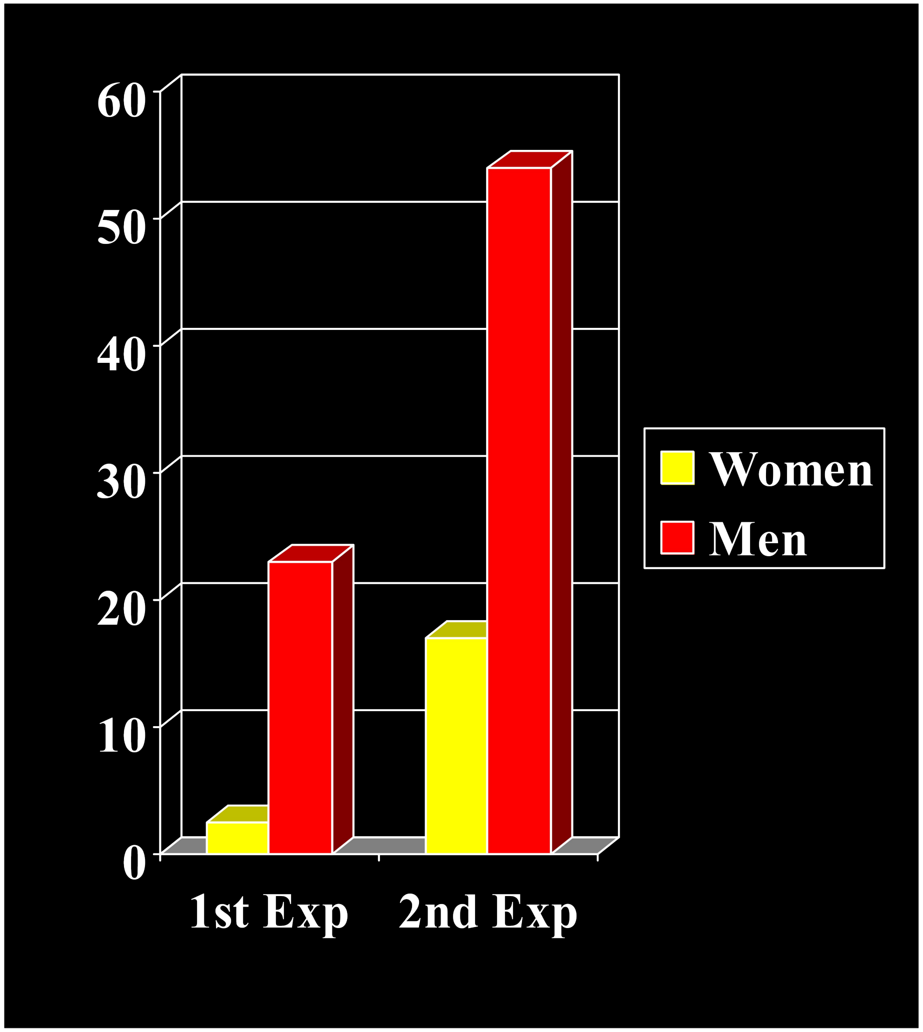
Neudecker, Ulrich, Herminghaus, Schröter. *PRL* (2013)

paper DOI: 10.1103/PhysRevLett.111.028001
data DOI: 10.5061/dryad.qv331.



What's the Monday Workshop about?

- https://www.nature.com/news/inequality-quantified-mind-the-gender-gap-1.12550
- https://www.aps.org/programs/women/workshops/skills/seminars.cfm
- "Women Don't Ask" (Babcock and Laschever)



Frustrated and Disordered Homework

- check out volleyball from Buckingham front desk
- go to sand court near Smith Hall
- perform a granular experiment/demo that illustrates a phenomenon talked about this week
- send me photo/movie

tweet it to me:
@karenedaniels
#frustdistHW

or email a link:
kdaniel@ncsu.edu

- play volleyball