

# Granular Matter

Pictures: [s98589497.onlinehome.us](http://s98589497.onlinehome.us)  
Bob Behringer's home page



Sand



Sand

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Sand



Silo collapse

# Granular Matter

Pictures: [www.castrol.com](http://www.castrol.com)  
Nature

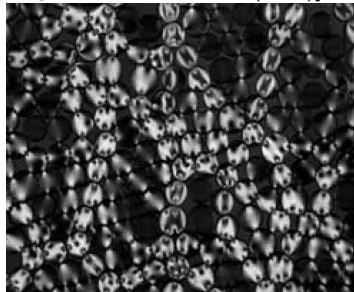
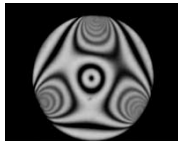


Ball bearings



Ball bearings

[Majmudar, Behringer; Nature **435**, 1079 (2005)]



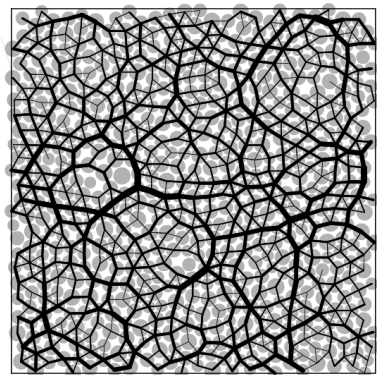
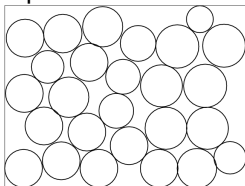
Photoelastic disks

# Spatial structure of force networks

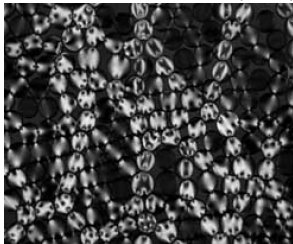
[Nature **439**, 828 (2006)]

- force network

elastic spheres confined in a box



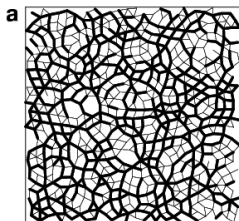
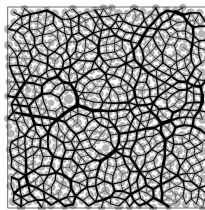
[Majmudar, Behringer; Nature **435**, 1079 (2005)]



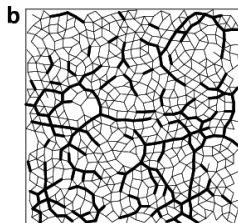
# Spatial structure of force networks

[Nature **439**, 828 (2006)]

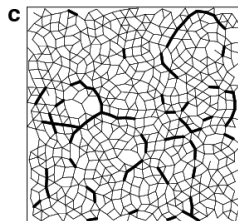
- force network
- links stronger than threshold  $f$



$$f = 0.5f_c$$



$$f = f_c$$



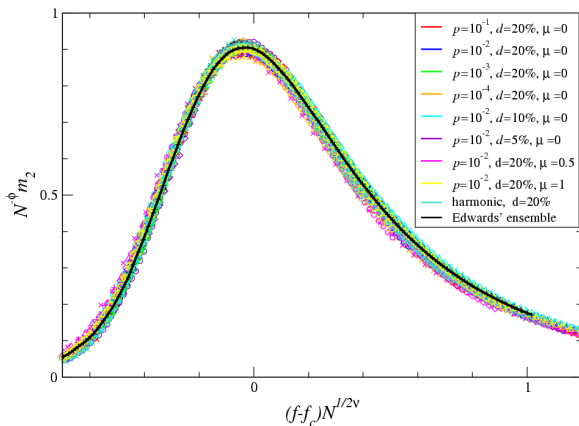
$$f = 1.5f_c$$

# Spatial structure of force networks

[Nature **439**, 828 (2006)]

- force network
- links stronger than threshold  $f$
- second moment of clusters (largest removed):

$$m_2(f, N) \approx A^{(\text{param.})} N^\phi M_2 \left( [f - f_c^{(\text{param.})}] N^{1/2\nu} \right)$$





# Spatial structure of force networks

[Nature **439**, 828 (2006)]

- force network
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## Universality class

Universal: scaling exponents:  $\phi$ ,  $\nu$   
scaling function:  $M_2(\cdot)$

Non-universal:  $f_c$ , prefactors...

## Granular models (isotropic)

$$\phi = 0.89(1), \quad \nu = 1.6(1)$$

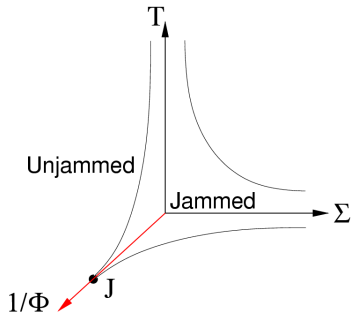
## q-model

$$\phi = 0.69(1), \quad \nu = 3.1(1)$$

## Percolation

$$\phi = 43/48 = 0.896\ldots, \quad \nu = 4/3 = 1.33\ldots$$

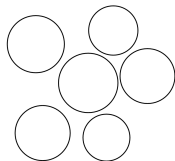
# Jamming transition



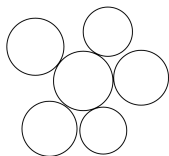
[Cates et.al, 1998; Liu, Nagel, 1998, 2001]

- unjammed state: floppy
- jammed state: support shear load
- examples: granular packings, foams, glassy systems, ...

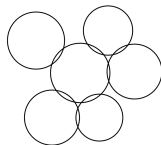
→ → → increase volume fraction  $\Phi$  → → →



loose particles  
 $\Phi < \Phi_c$

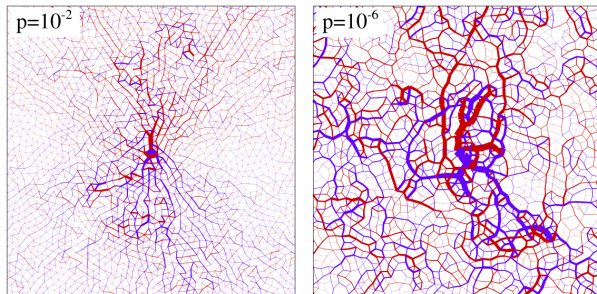


JAM: particles touch  
 $\Phi = \Phi_c$  random closed packed



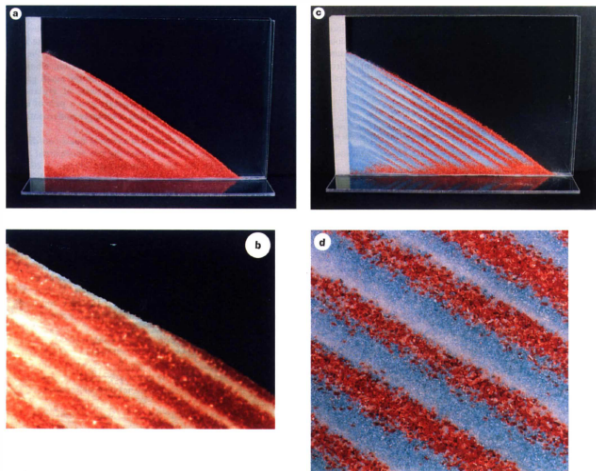
particles deform  
 $\Phi > \Phi_c$

# Fluctuations



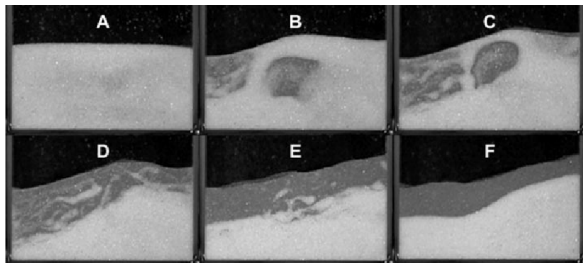
Deformation for point loading:  
characteristic length scale:  $l^* \sim 1/\Delta z$

# Segregation

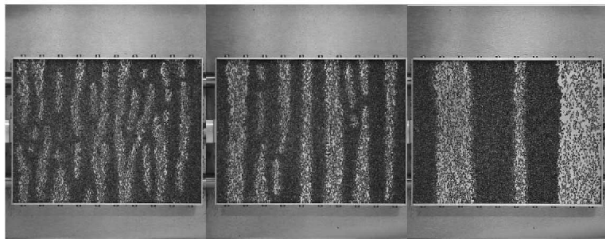


Makse, Havlin, King, Stanley, Nature (1997)

# Segregation



Burtally, King, Swift, *Science* **295**, 1877 (2002)



Mullin, *PRL* **84**, 4741 (2000)

