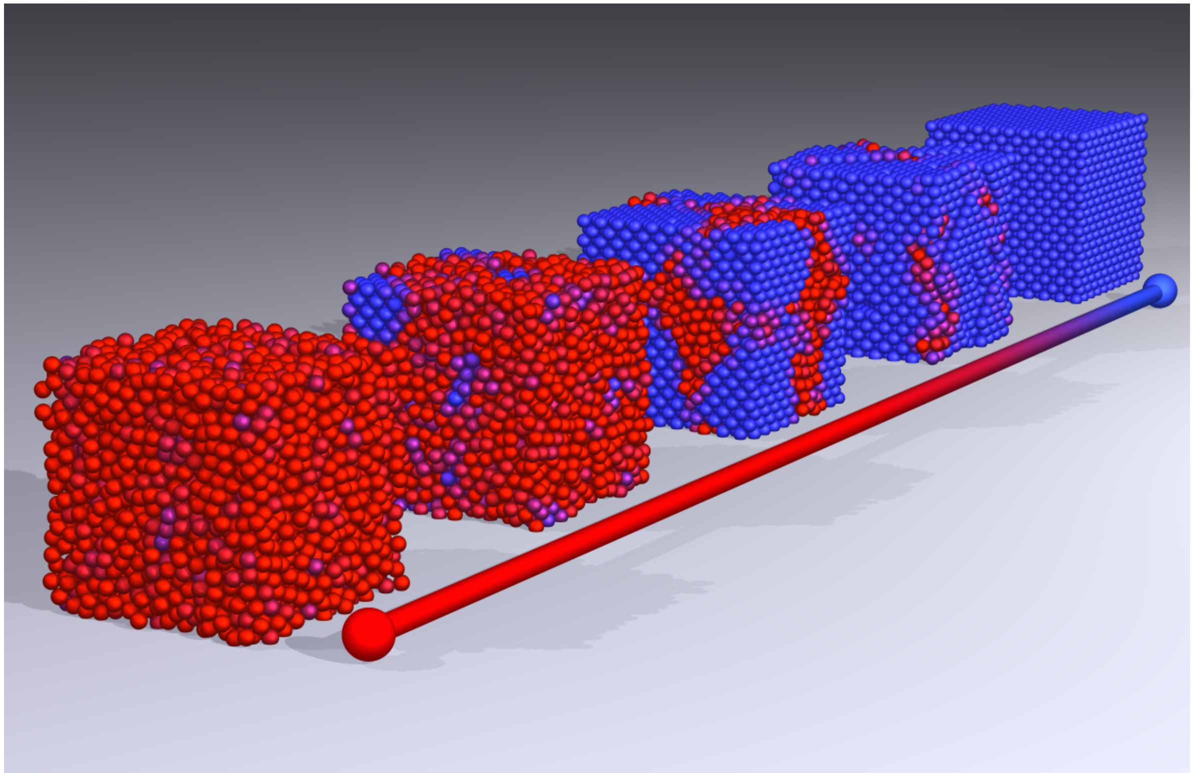
Poles of order and disorder

Edinburgh; June 24, 2014



What is role of (dis)order for mechanical behavior?

Echoes

Condensed matter ↔ Particle/astro-physics

Higgs ↔ symmetry breaking in superconductors

Dirac anti-particles ↔ Semiconductor bands, graphene

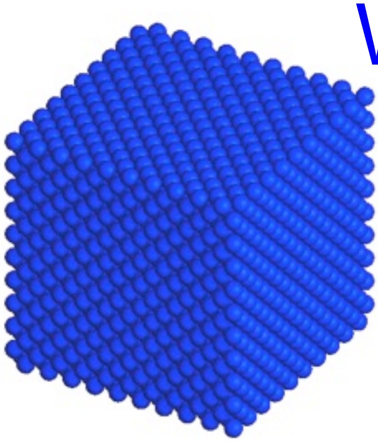
Techniques: field theory, renormalization, scattering…

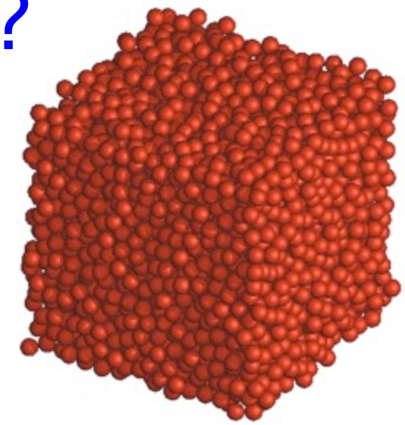
But we have something unique

Our toughest (and most common) problem is unimportant for those other fields.

Disorder and non-equilibrium (i.e, glassiness, free-energy landscapes…)

Crystals are essence of order
What is essence of disorder?





Why ask that?

Cannot perturb crystal (*i.e.*, add defects) to get physics of glasses

Need other limit - complete disorder

Prototype of an*other* way of making solids:

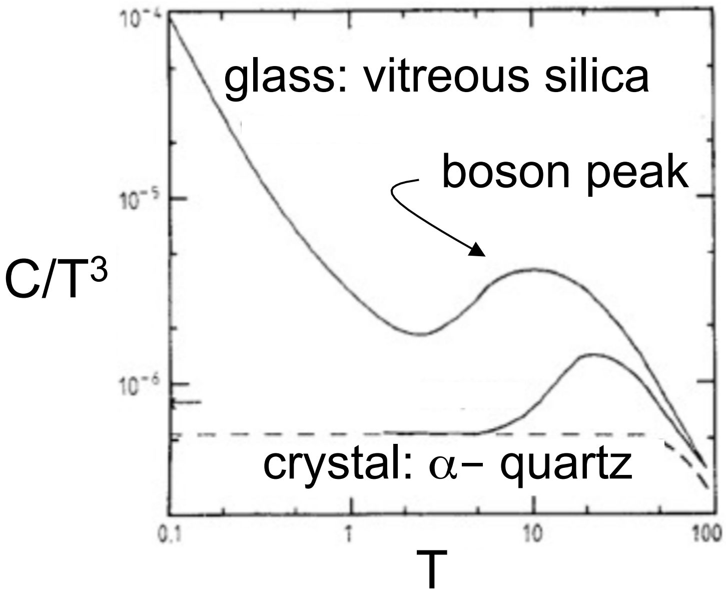
Crystallization: 1st-order nucleation transition

What (non-equilibrium) process creates complete disorder?

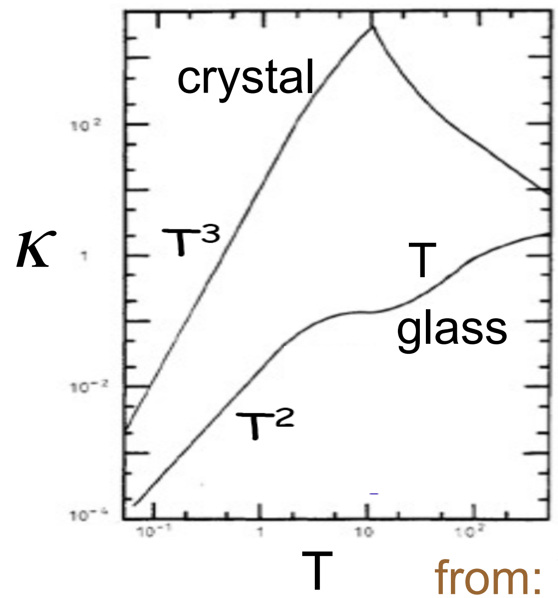
Example: phenomena created by disorder

Qualitatively different from crystals

specific heat: excess low-T excitations



thermal conductivity



from: W.A. Phillips

Quantum-mechanical two-level (tunneling) systems have been postulated to explain low-temperature properties of glasses

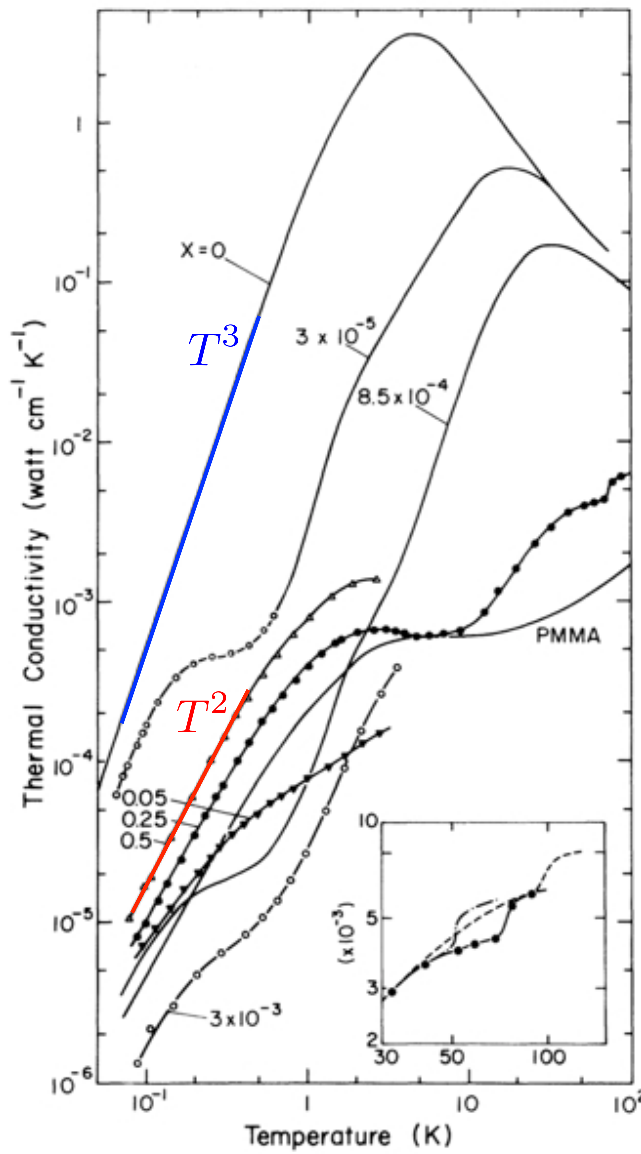
Orientational glass: $(KBr)_{1-x}\,(KCN)_x$

X = 0 → crystal

X ≈ 0.5 → orientational glass

Crossover from ordered to disordered behavior occurs at *very low* disorder

$X_{crossover} \approx 0.01$



De Yoreo *et al.* PRL (1983)

Initial questions

ITP-Santa Barbara workshop in 1997

Is granular matter related to classes, colloids?

- Can we learn about glasses from granular materials & vice versa?
- Are there similar relaxation phenomena?

What is transition between amorphous solid and liquid?

- Do length scales diverge at transition?

Why are low-temperature properties of glasses anomalous?

- Is it only due to quantum mechanics?

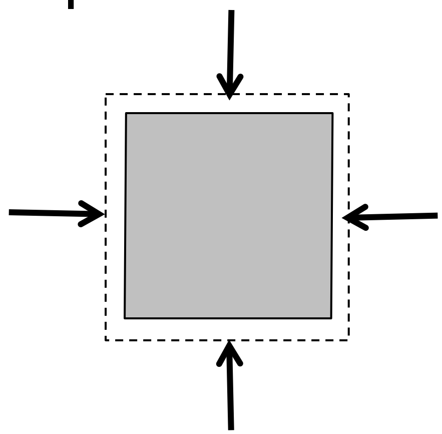
Do different ways of creating rigidity produce same behavior?

- What are properties of amorphous solid?

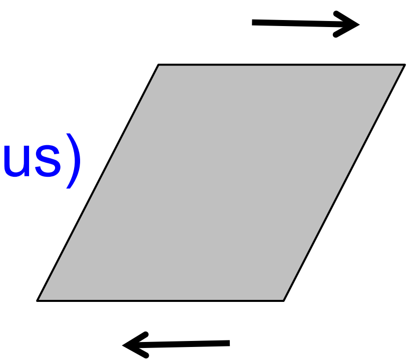
Nature of rigidity

Response to compression and to shear:

B
(bulk modulus)



G
(shear modulus)



In crystals, G always comparable to B

Excitations: Normal modes of vibration

density of states
spatial properties
heat transport
anharmonicity

Does disorder matter?

Jamming:

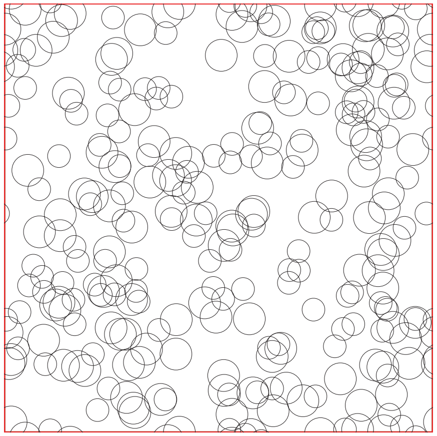
Compress random collection of spheres in a box

Does this protocol produce different physics from crystals?

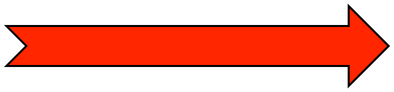
Simulate finite-range, repulsive potentials:

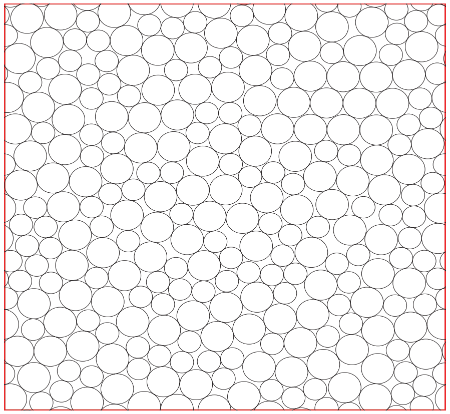
$$V(r) = V_0 (1 - r/\sigma)^{\alpha} \quad r < \sigma \qquad D = 2,\ D = 3$$
$$= 0 \qquad r > \sigma$$

ϕ_c -- onset of jamming at $T = 0$

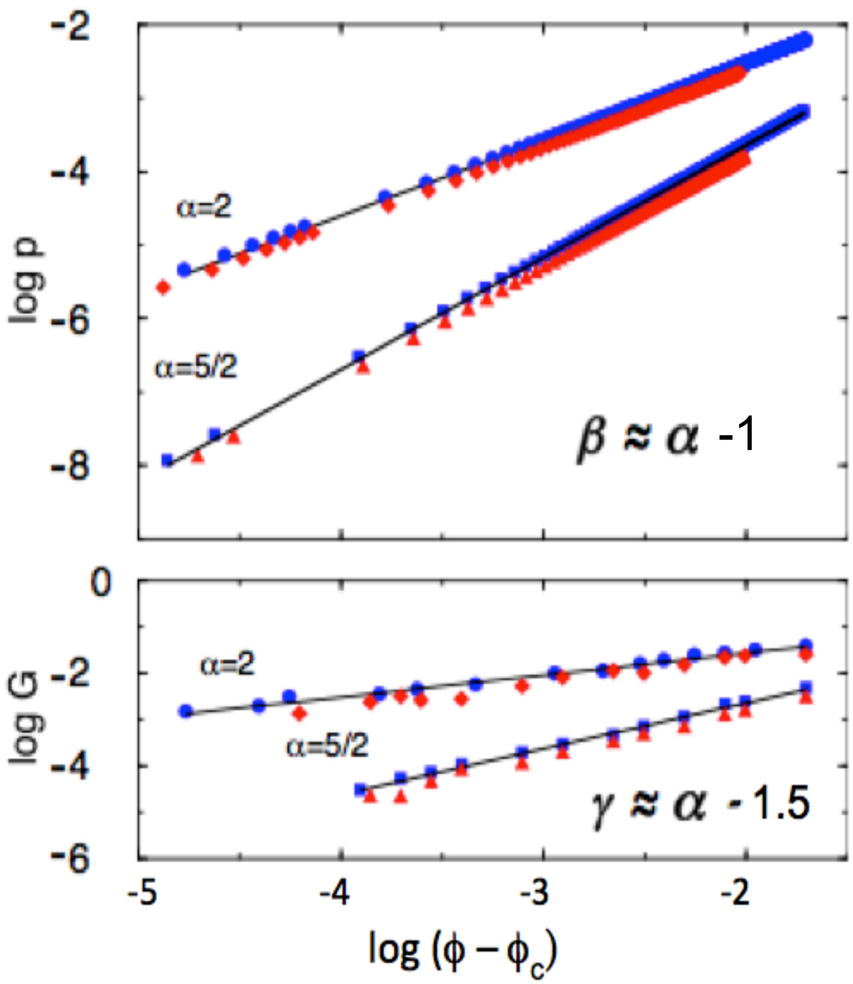


Quench to local energy minimum





Jammed solids different from crystals



Jamming

G/B → 0 at ϕ_c (like liquid)

Crystal

G/B ~ 1

Shear and compression become constrained at same ϕ_c

Shear infinitely weaker than bulk modulus at transition

Durian, O'Hern, Liu

Maxwell criterion for rigidity

Minimum number of overlaps needed for mechanical stability

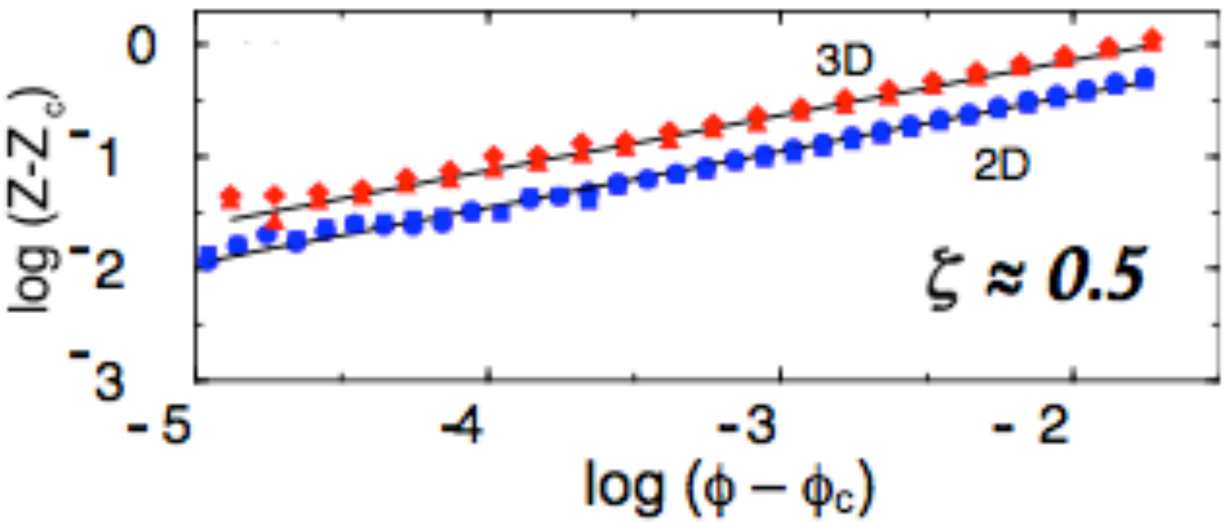
N frictionless spheres in D dimensions:

Match # equations (# non-trivial degrees of freedom) = ND
to # unknowns (# interparticle normal forces) = NZ/2

$$\Longrightarrow Z_c = 2D$$

Criterion for rigidity: *global* condition - not *local*

Physics governed by connectivity (Thorpe, Phillips, Alexander)



O'Hern, Liu

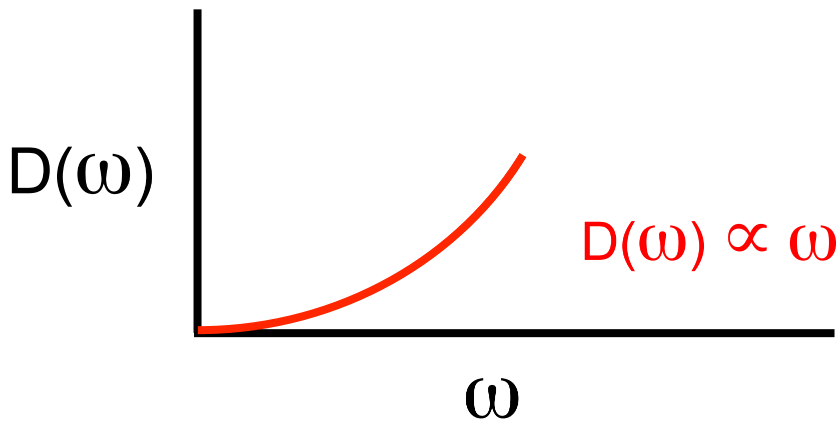
Normal modes in "normal" solid

Low-frequency normal modes

$\Longrightarrow$ long-wavelength plane waves.

Density of modes, $D(\omega)$, from counting waves:

$D(\omega) \propto \omega^{d-1}$ in d-dimensions.

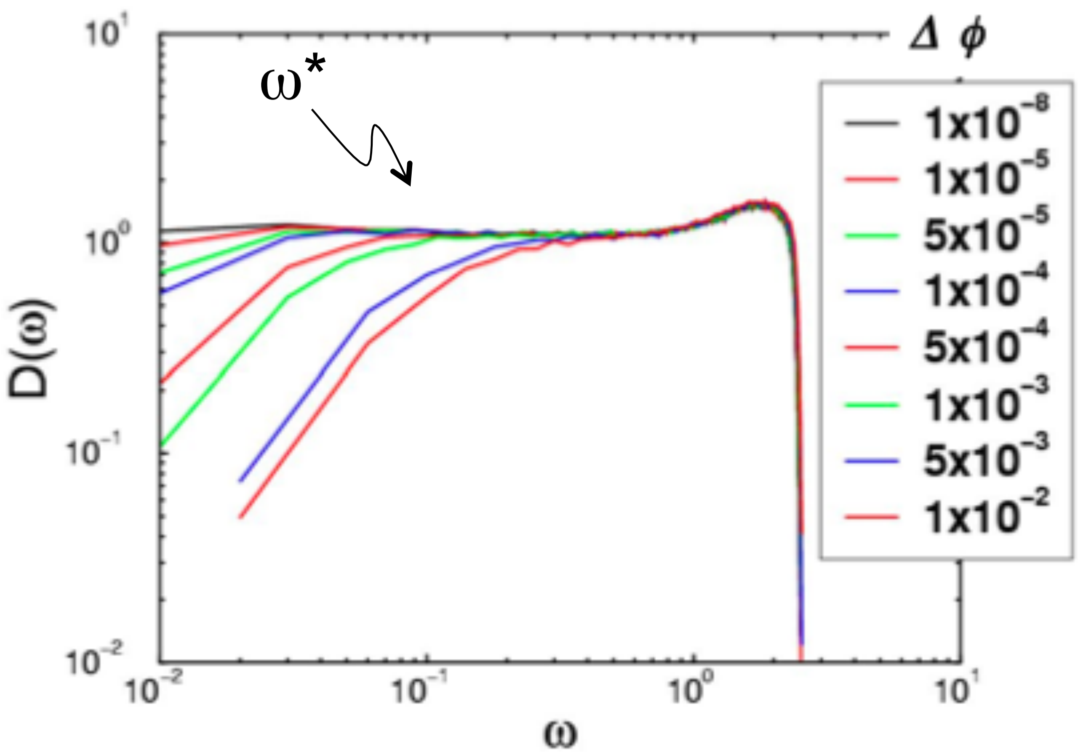


$D(\omega) \propto \omega^2$ in 3-D

Long wavelengths "average" over disorder.

All solids *should* behave this way.

Density of states near jamming:
no Debye behavior at ϕ_c



ω^* is characteristic onset-frequency of new excitations

$\omega^* \rightarrow 0$ as $\Delta\phi \rightarrow 0$

Jamming is epitome of disorder

(no length on which one can average to recover elasticity)

New class of excitations

Silbert, Liu

Concrete example of new class of excitations:

emerge from critical point

What are they?

Created from soft modes:

Cutting argument (Wyart)

Structure (not plane waves):

"Quasi-localized" at low frequencies

Heat transport at low T:

Poor conductors -- nearly-constant diffusivity

Highly anharmonic:

Dynamic heterogeneities?

Properties tuned by varying $\Delta\phi = (\phi - \phi_c)$

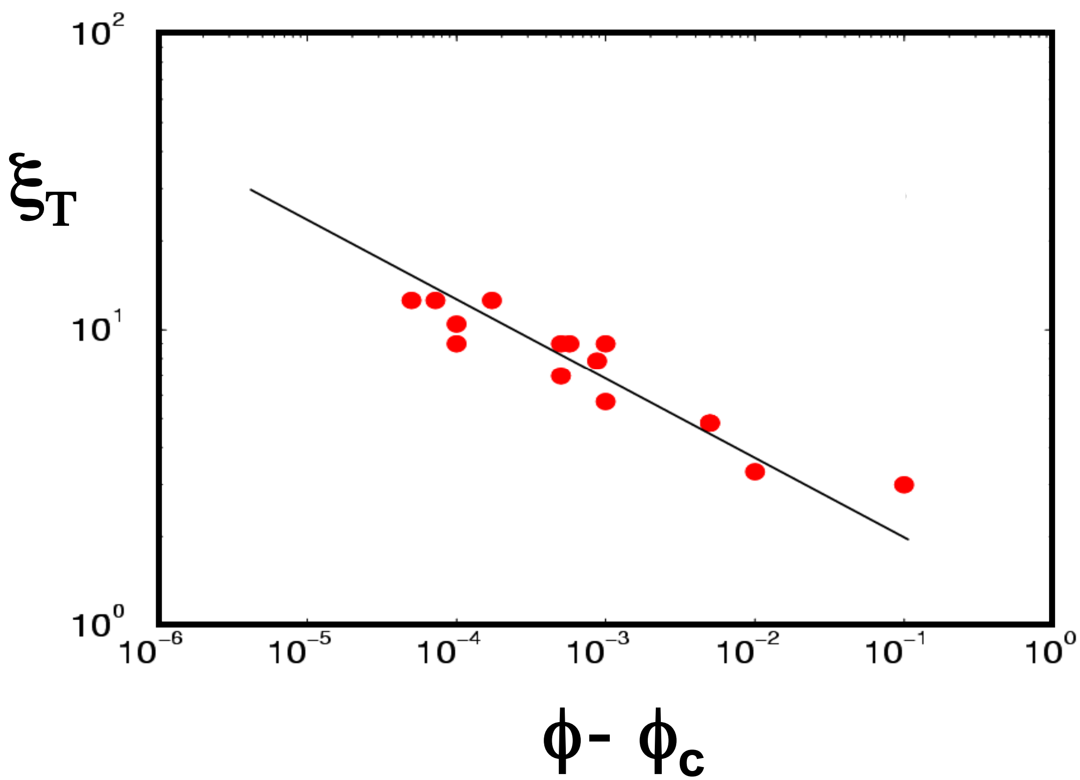
Nature of transition

2 lengths determined from ω^* and sound speeds

$\xi_L = 2\pi\, c_L / \omega^* \propto (Z - Z_c)^{-1}$ $\quad\quad$ $\xi_T = 2\pi\, c_T / \omega^* \propto (Z - Z_c)^{-1/2}$

$\xi_L = L^*$ (from cutting argument)

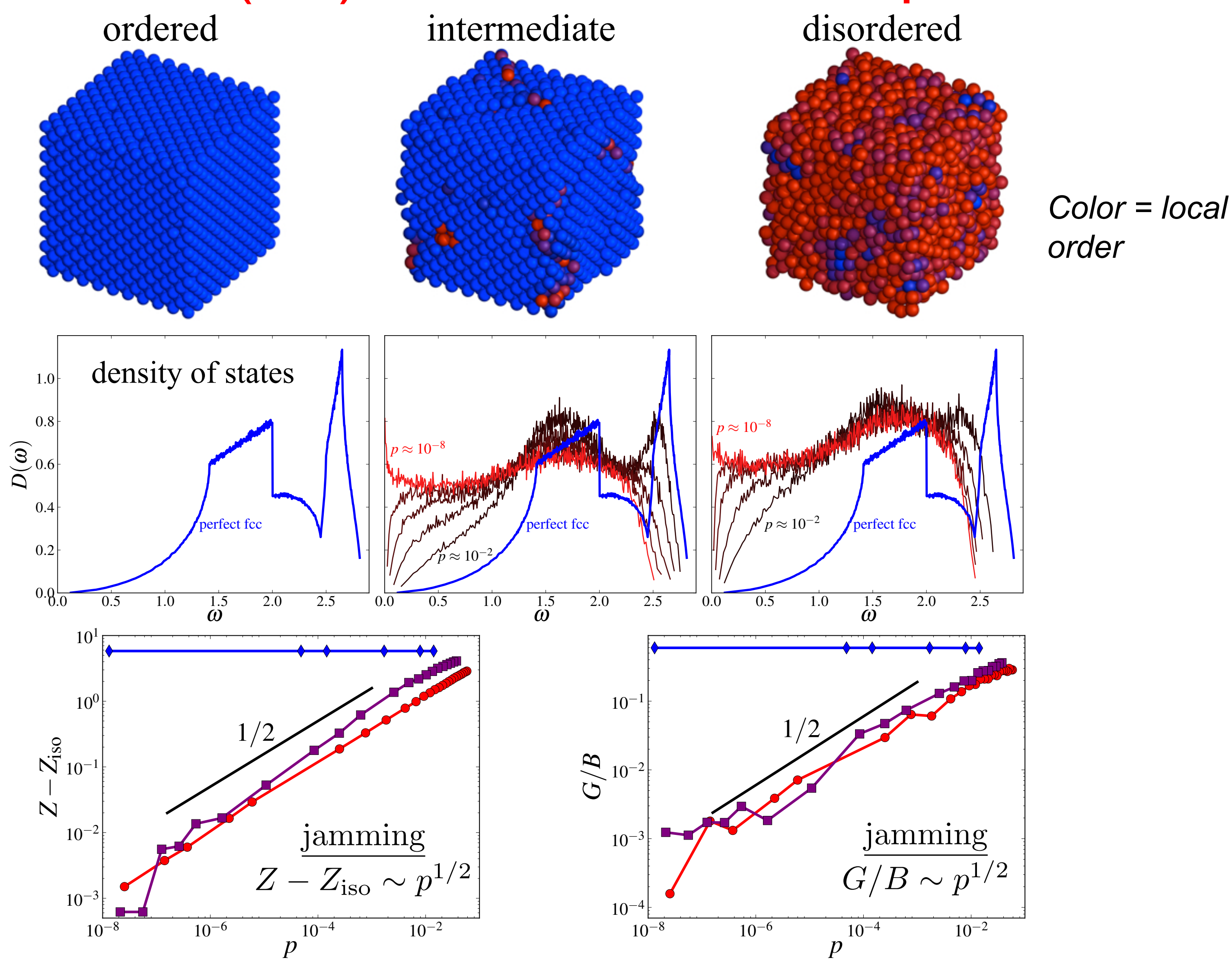
Both diverge at transition from solid to “fluid”



Silbert, Liu

From order to disorder:

When does (dis)order dominate response?



Little disorder makes it behave like jammed solid

"Experiment – *Where theory comes to die*"

Theory has been very powerful in giving a framework for understanding glasses.
It has been less successful in being useful for experiment.

Goal for next ten years: to find ways/systems/phenomena to make contact between experiment and theory.

How does theory relate to experiment?

What needs to be explained?

What are precise tests of theory?

What new phenomena are predicted?

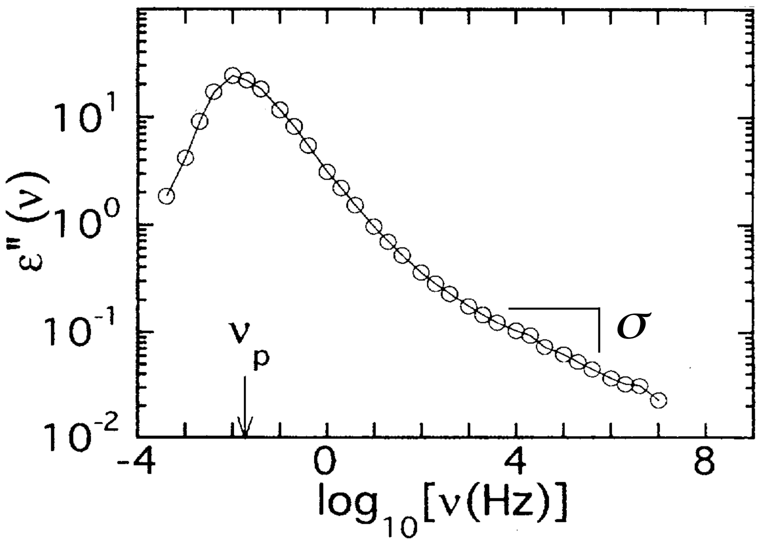
What needs to be explained in glasses?

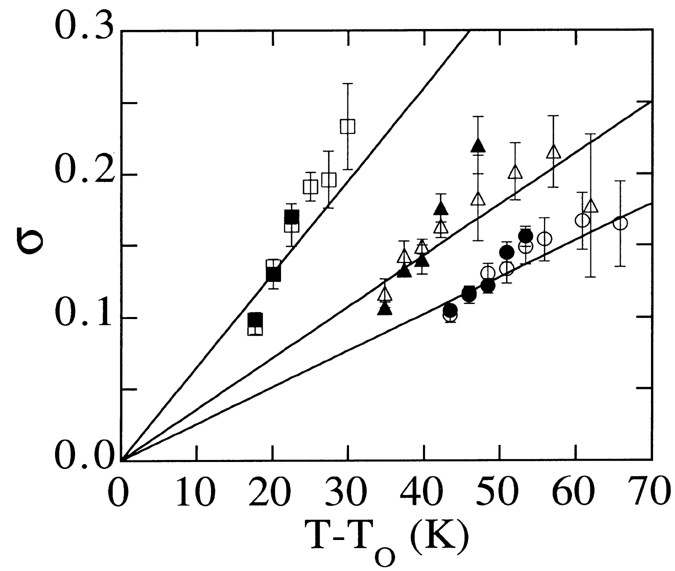
Glasses:

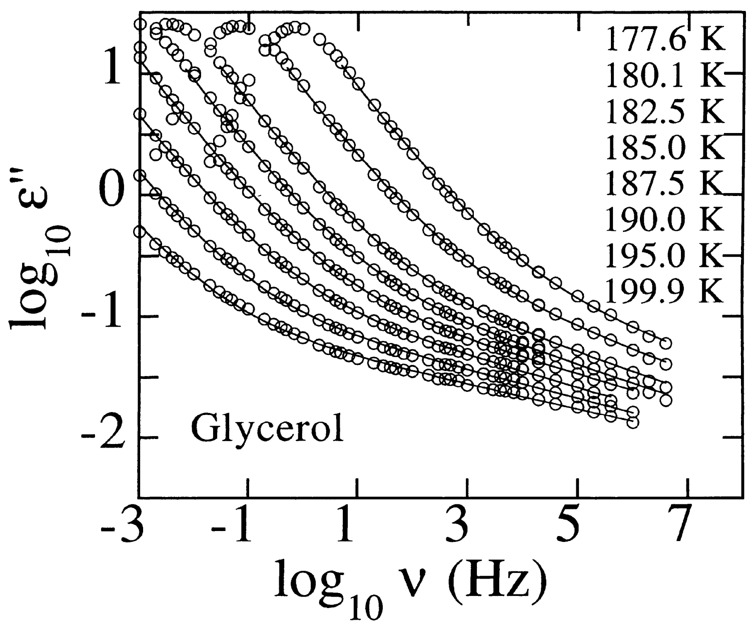
1) Activated relaxation; long relaxation times
2) Cause of super-Arrhenius relaxation
3) High-frequency response reflects dynamical slowing
   (glasses and spin-glasses)
4) Surface (confinement) effects

Where is diverging length scale?

High-frequency response reflects dynamical slowing







Slope, σ, $\rightarrow$ 0 near where relaxation time diverges

$\Rightarrow$ Divergent static linear susceptibility

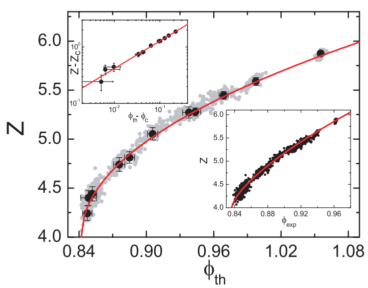
Jamming – a concrete example

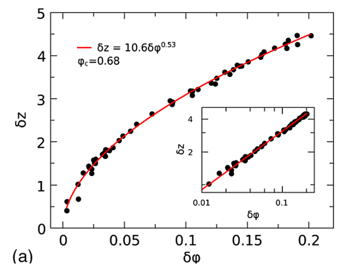
new physics associated with critical point

Many properties can be understood; experimentally relevant

Coordination number *vs*. packing fraction

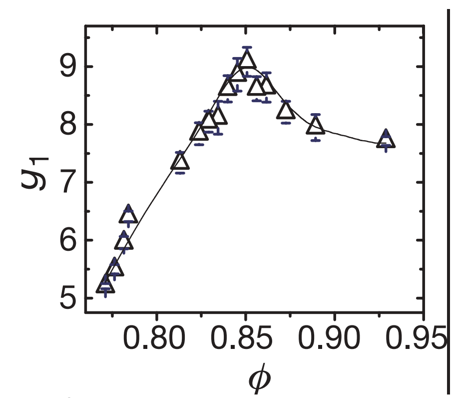
Experiments on foams and emulsions (Brujic *et al.;* van Hecke et al.)





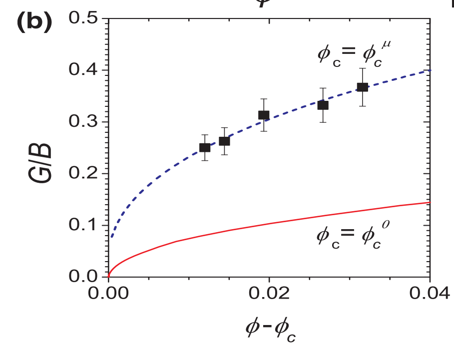
Shape of g(r) *vs*. T and p: $g(r_p)$ peak at ϕ_c

Experiments on colloids (Yodh *et al*.; Nagel *et al.*)



Ratio of G/B for frictional particles

Experiments on colloids (Yodh *et al.*)



Jamming – a concrete example

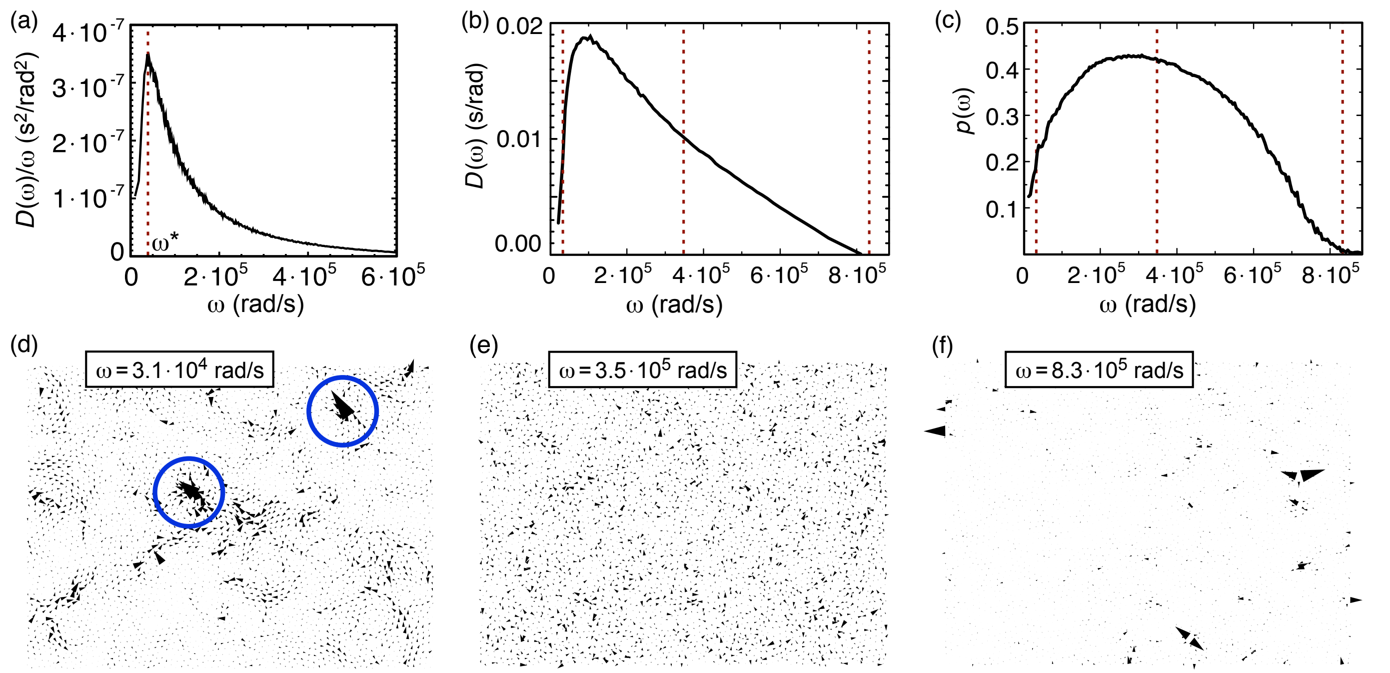
new physics associated with critical point

Many properties can be understood; experimentally relevant

Quasi-localized modes at low frequencies

– anharmonic with low energy barriers

Experiments on colloids *(Yodh et al.; Bonn et al.)*



Jamming –
disordered limit for rigidity

Low-T glasses $\Longleftrightarrow$ Jamming

Excess low-energy excitations $\Rightarrow$ Boson peak

Small constant diffusivity $\Rightarrow$ $\kappa(T) \propto T$ above plateau

Anharmonic modes $\Rightarrow$ phonon echoes

Basic results hold for:

Long-range interactions with attractions (*e.g.*, L-J potentials)

New class of excitations

$\Rightarrow$ new way to think about glasses

Current questions about jamming transition (point J)

Is J a glass transition (or is it a singular limit)?

Is J too ideal (or does potential, shape, T, etc. matter)?

Is J relevant to laboratory systems (or is it only in computer)?

Can jamming help understand low-T properties of glasses?

Can jamming be used to understand poly-crystalline matter?

How does one go between ground states?

Can one tune G/B in real materials?

Is there a lattice model for jamming?

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