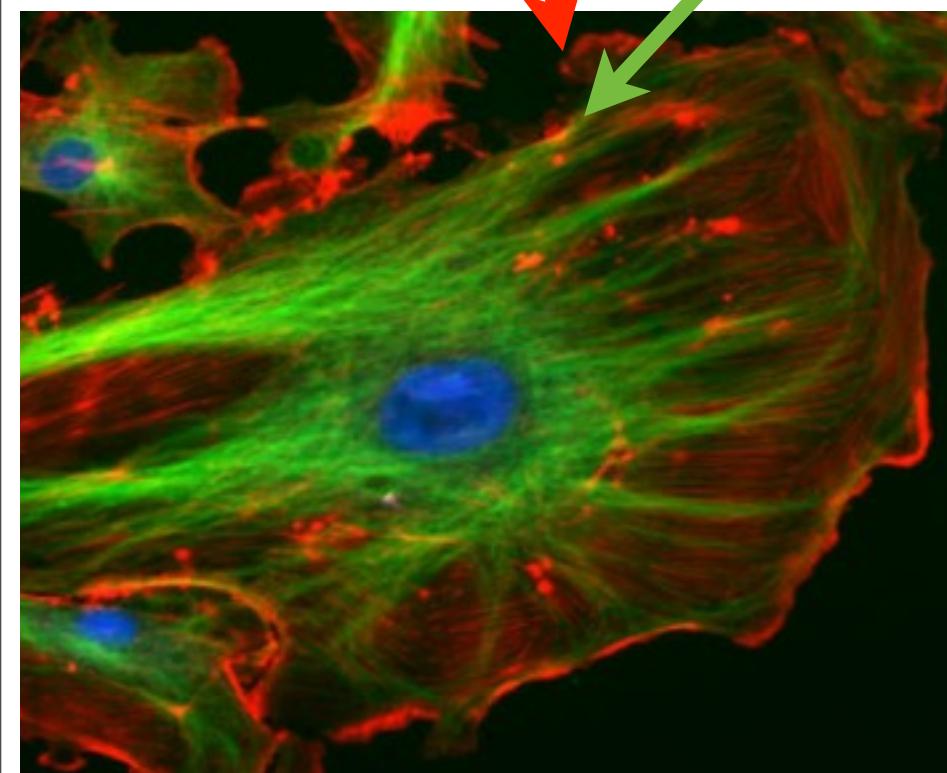
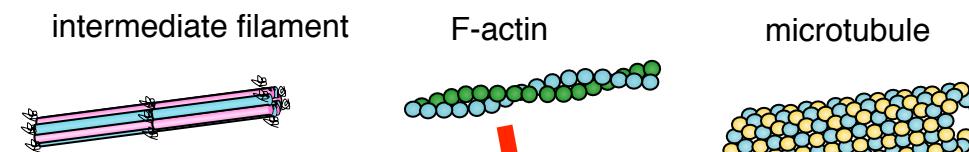


The cytoskeleton, an *ACTIVE* network

The Cell

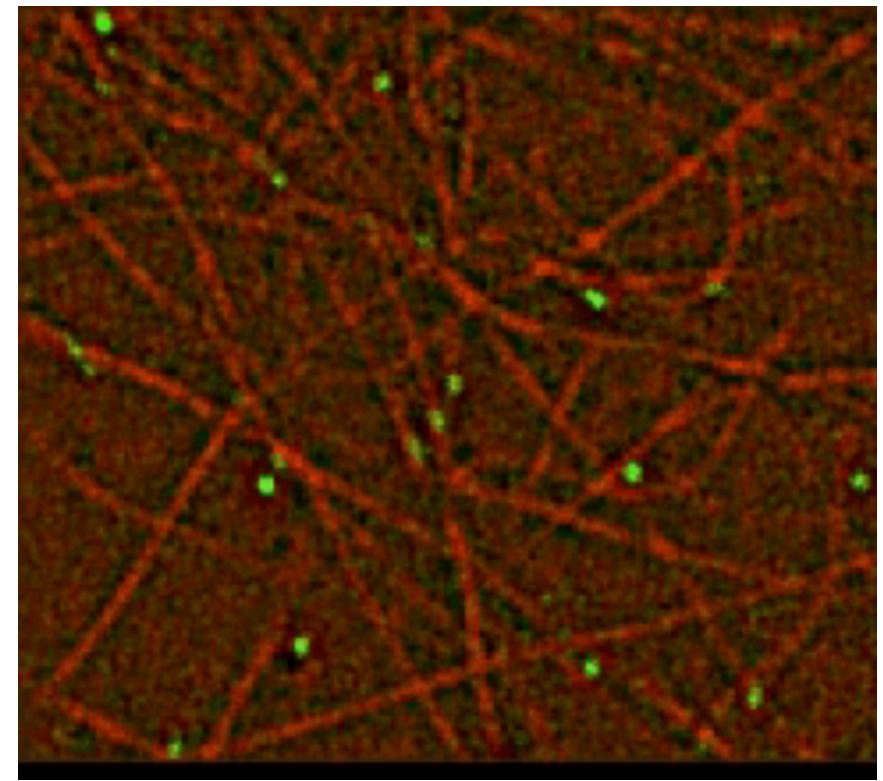
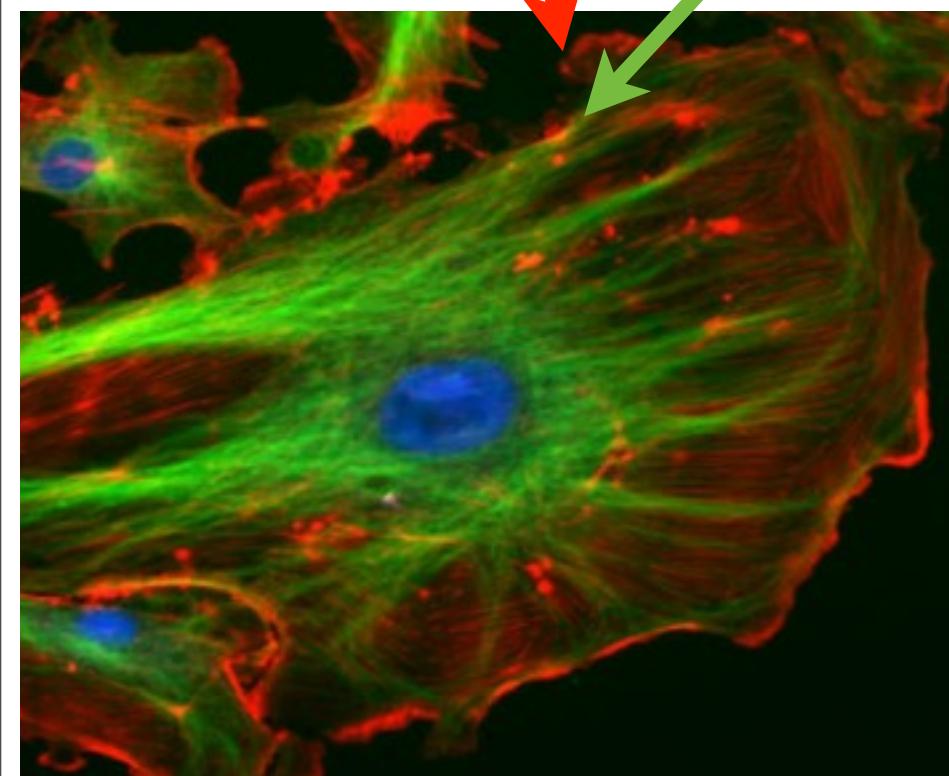
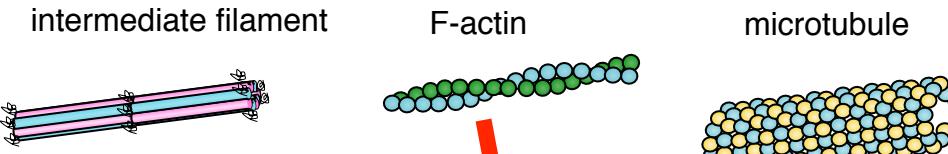


Vale lab, UCSF

five.com

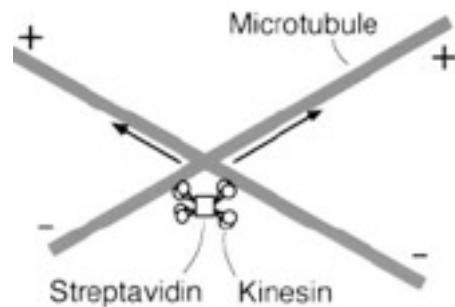
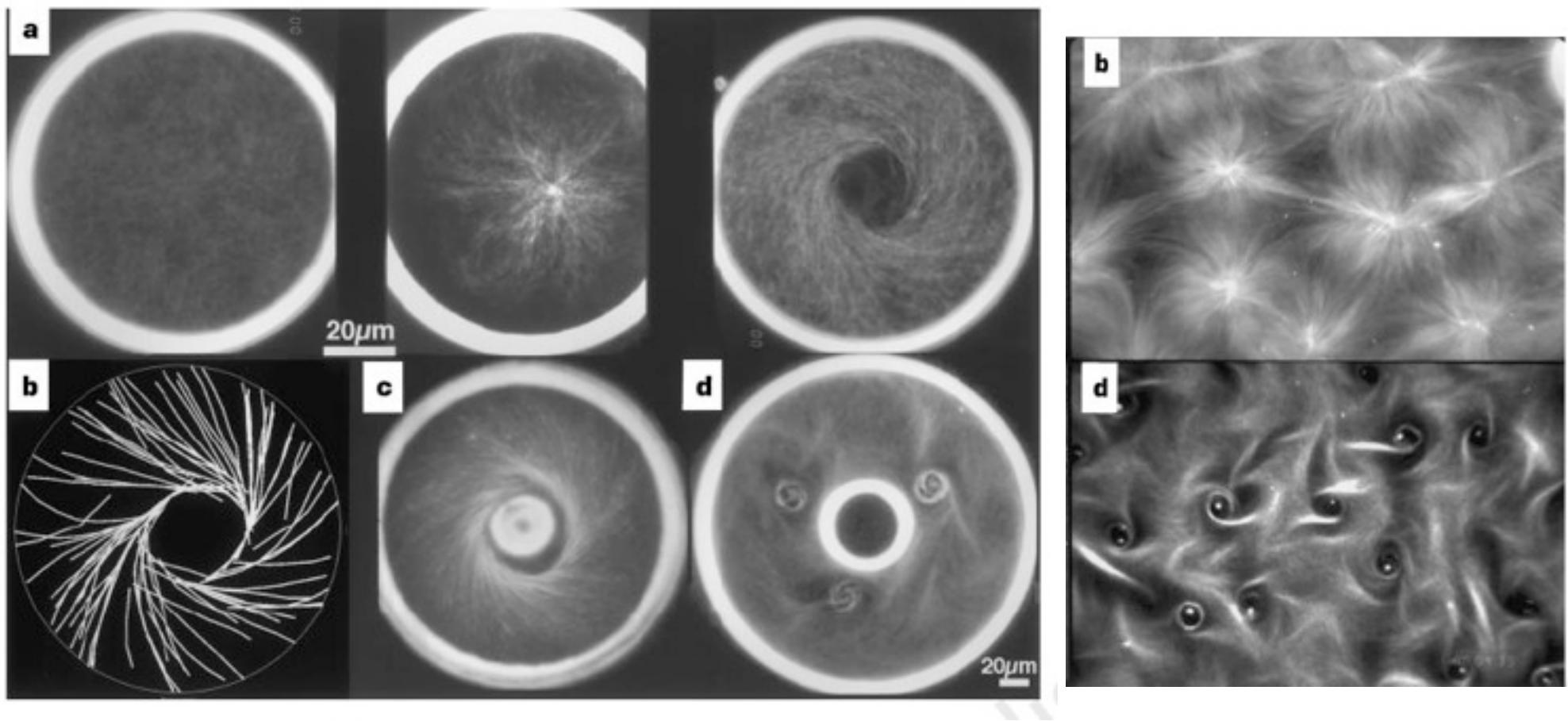
The cytoskeleton, an *ACTIVE* network

The Cell



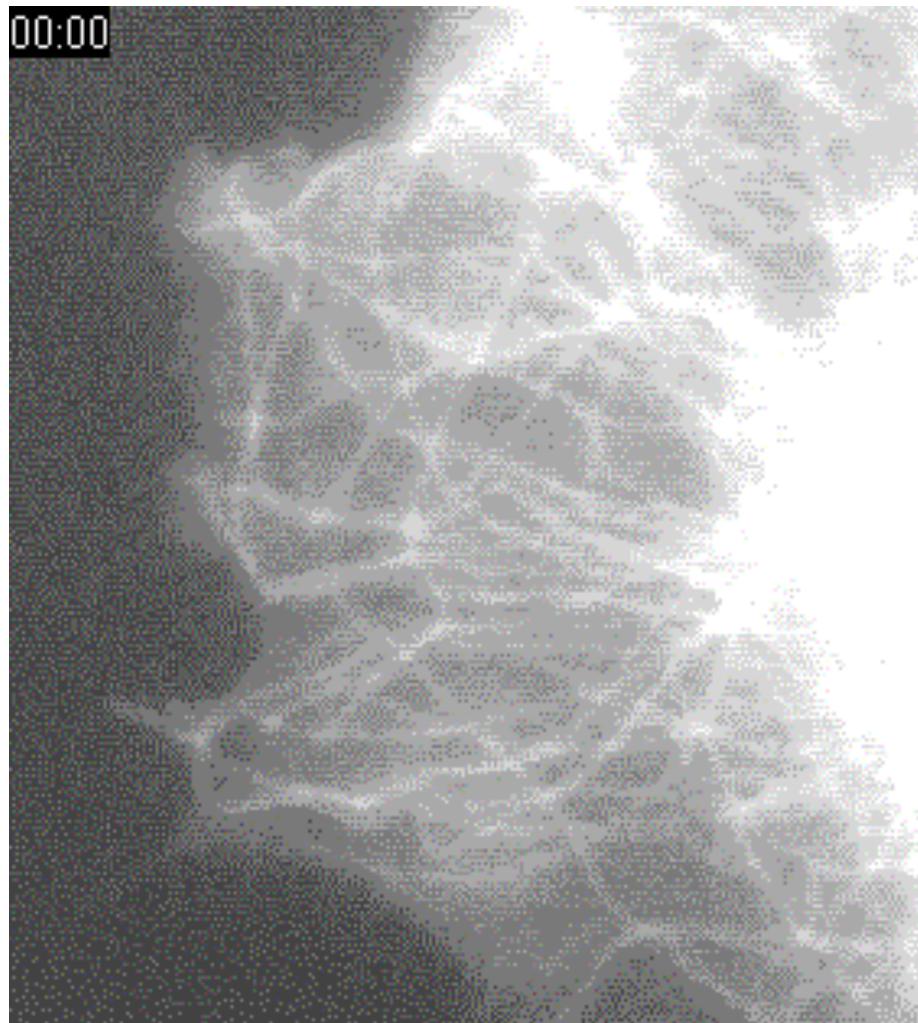
Kapitein et al., *Current Biol.*, (2010).

Microtubule-motor pattern formation



Nedelec, Surrey, Maggs and Leibler, *Nature* 1997

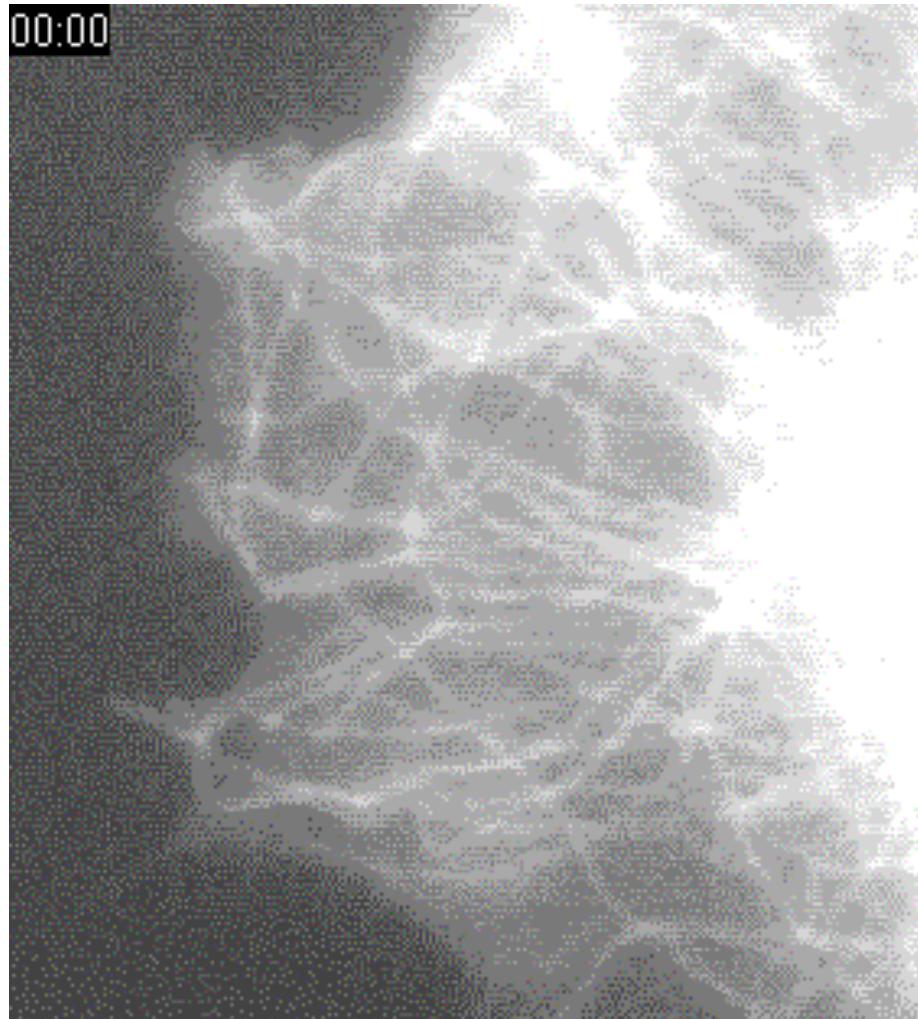
Motion in cells?



What governs motion in cell?
-Directed/active processes
-Random/thermal fluctuations

w/ Brangwynne et al., *PNAS* (2007); *J Cell Biol*, (2008).

Vital, non-thermal motion?



What governs motion in cell?
-Directed/active processes
-Random/thermal fluctuations
-Non-directed active motion



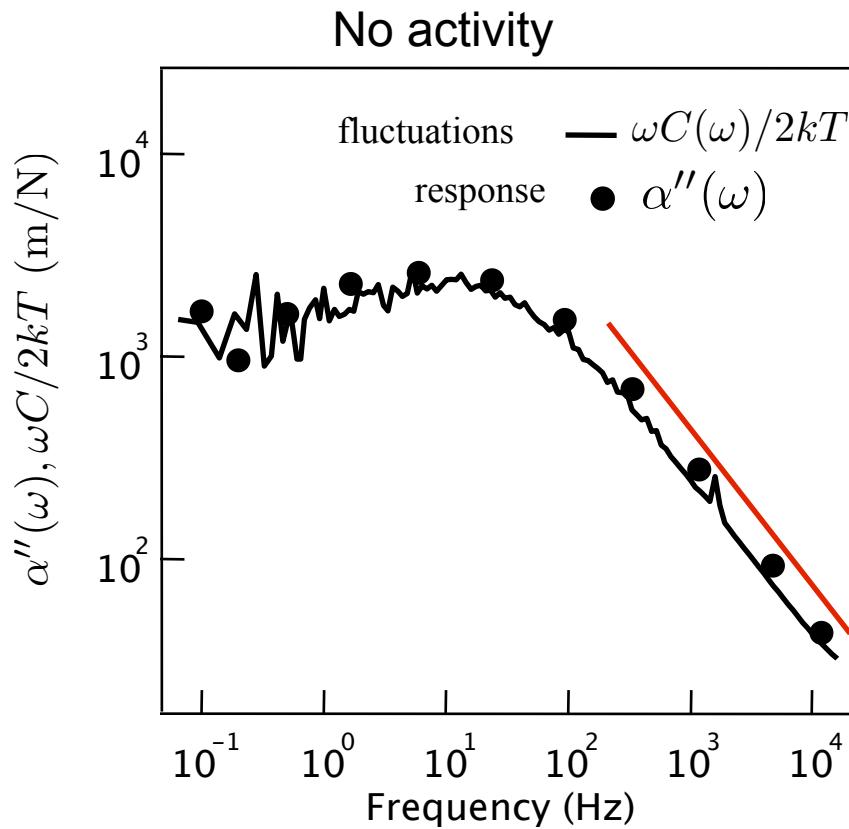
Brown:

Having found motion in the particles of the pollen of living plants which I had examined, I was led next to inquire whether this property continued after the death of the plant ...

w/ Brangwynne et al., *PNAS* (2007); *J Cell Biol*, (2008).

Effect of molecular motors: Active gels

Mizuno, et al., *Science*, (2007).

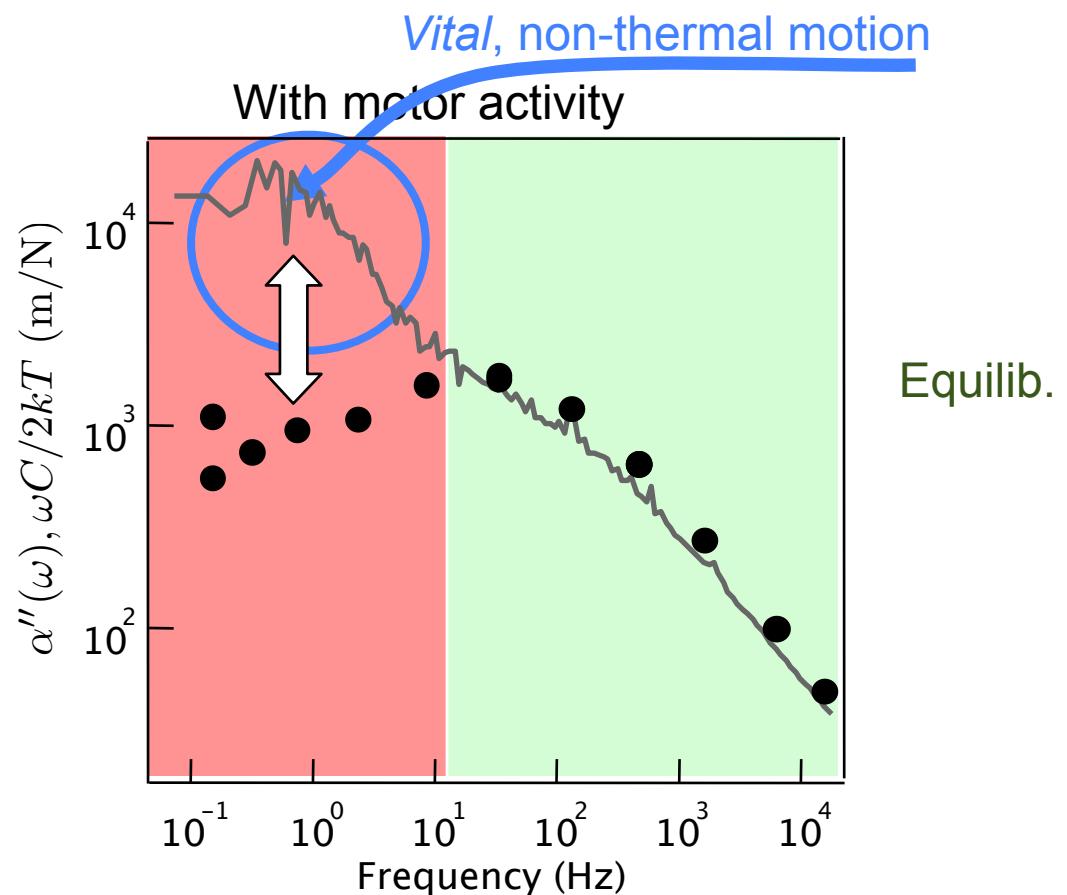
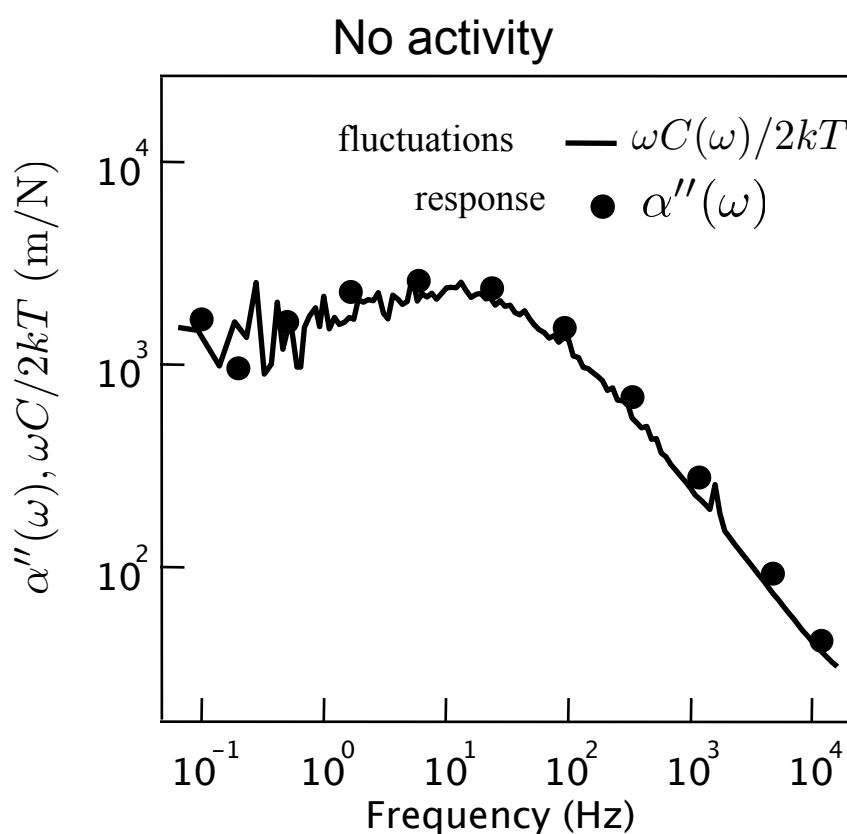


$$C(\omega) = \int \langle x(t)x(0) \rangle e^{i\omega t} dt = \frac{2kT}{\omega} \alpha''(\omega)$$

$$x_\omega = \alpha(\omega) f_\omega$$

Effect of molecular motors: Active gels

Mizuno, et al., *Science*, (2007).

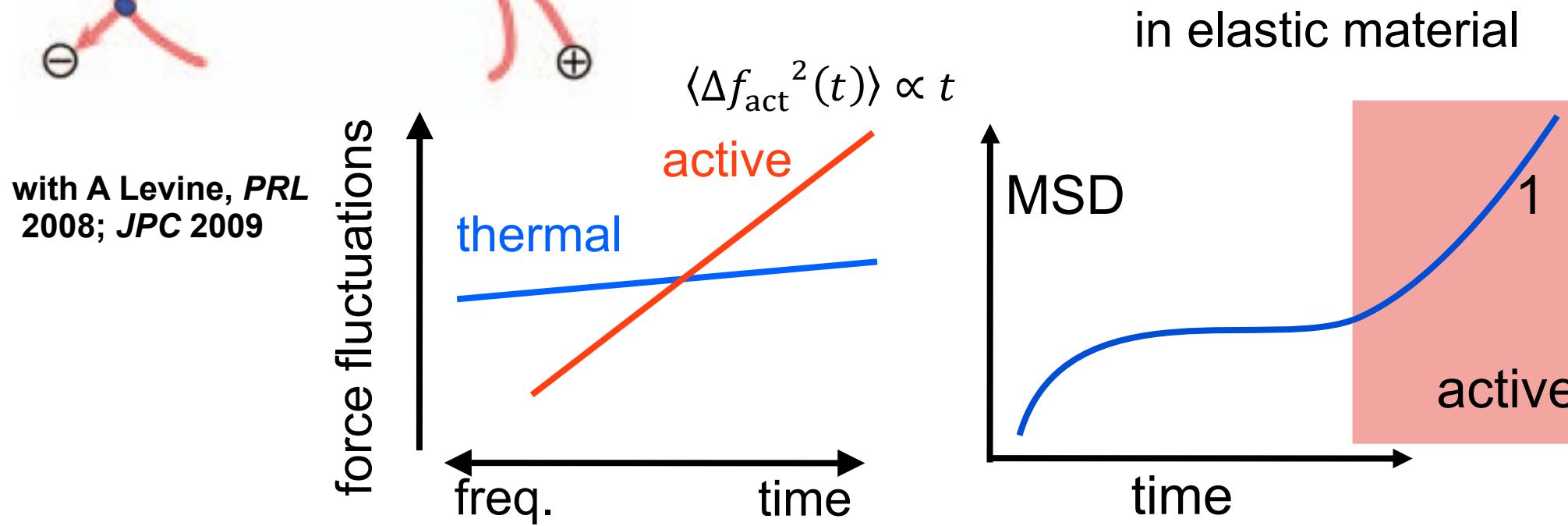
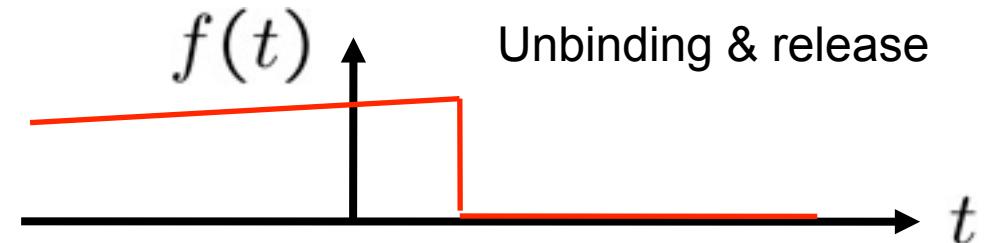
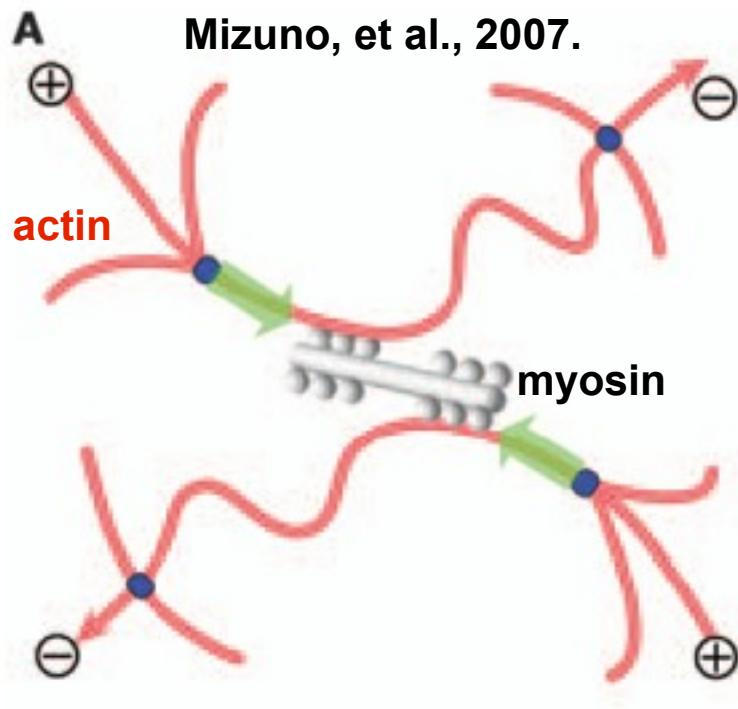


$$C(\omega) = \int \langle x(t)x(0) \rangle e^{i\omega t} dt \neq \frac{2kT}{\omega} \alpha''(\omega)$$

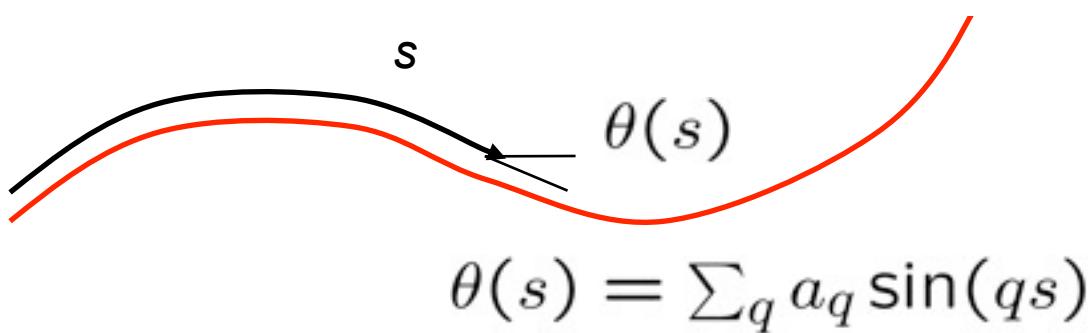
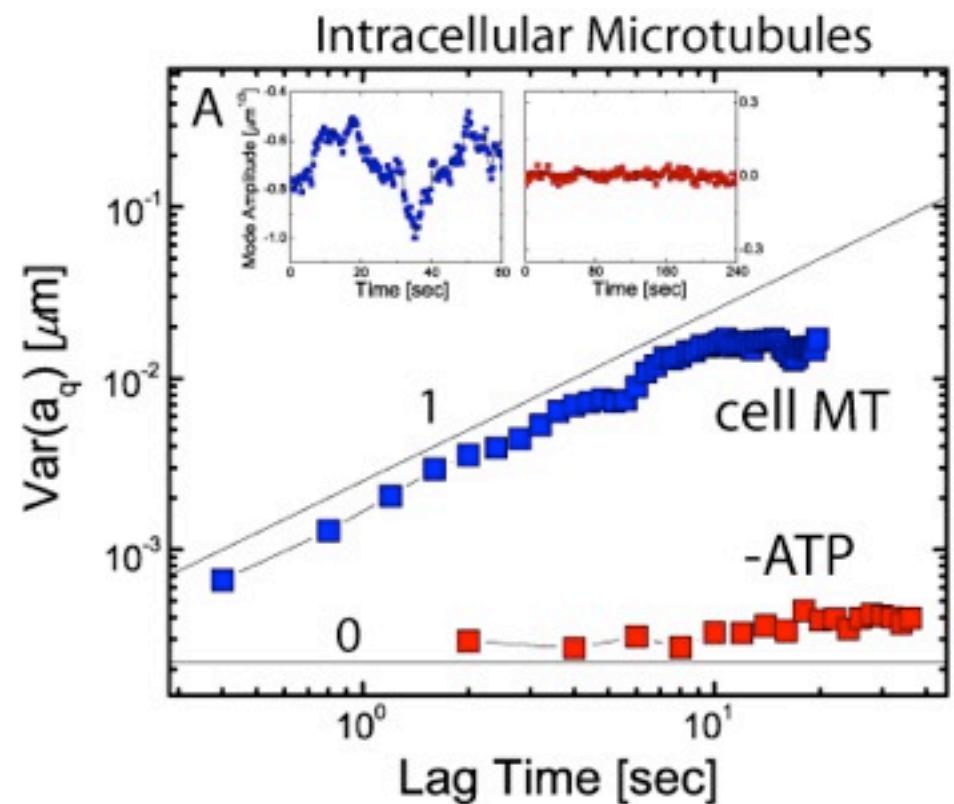
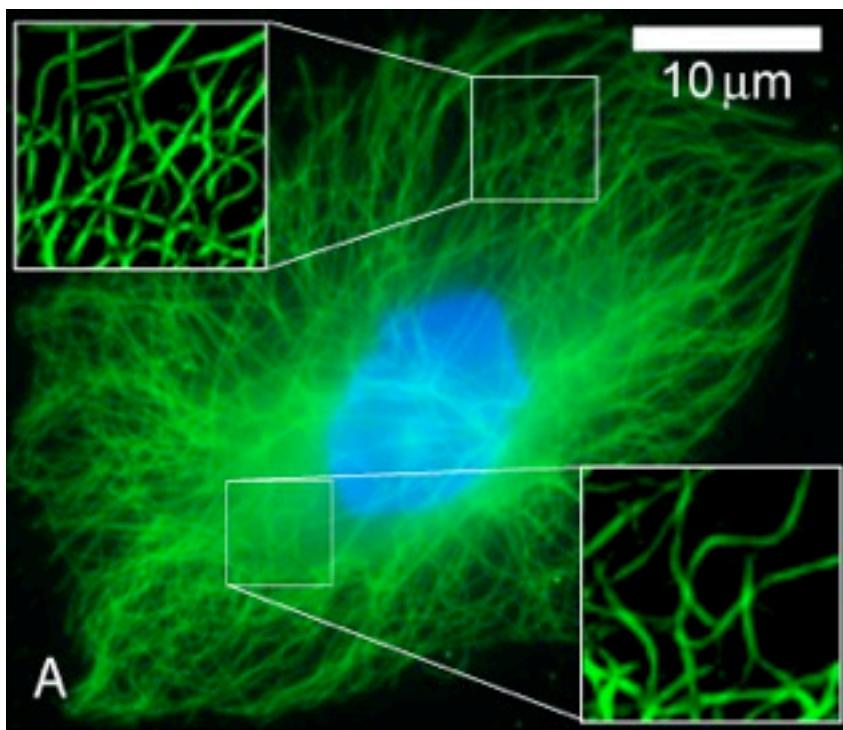
$$x_\omega = \alpha(\omega) f_\omega$$

Along with these contractile fluctuations, there is a nearly 100-fold ATP-dependent stiffening of the network, which is consistent with tensions \sim few pN

Effect of molecular motors: Active fluctuations



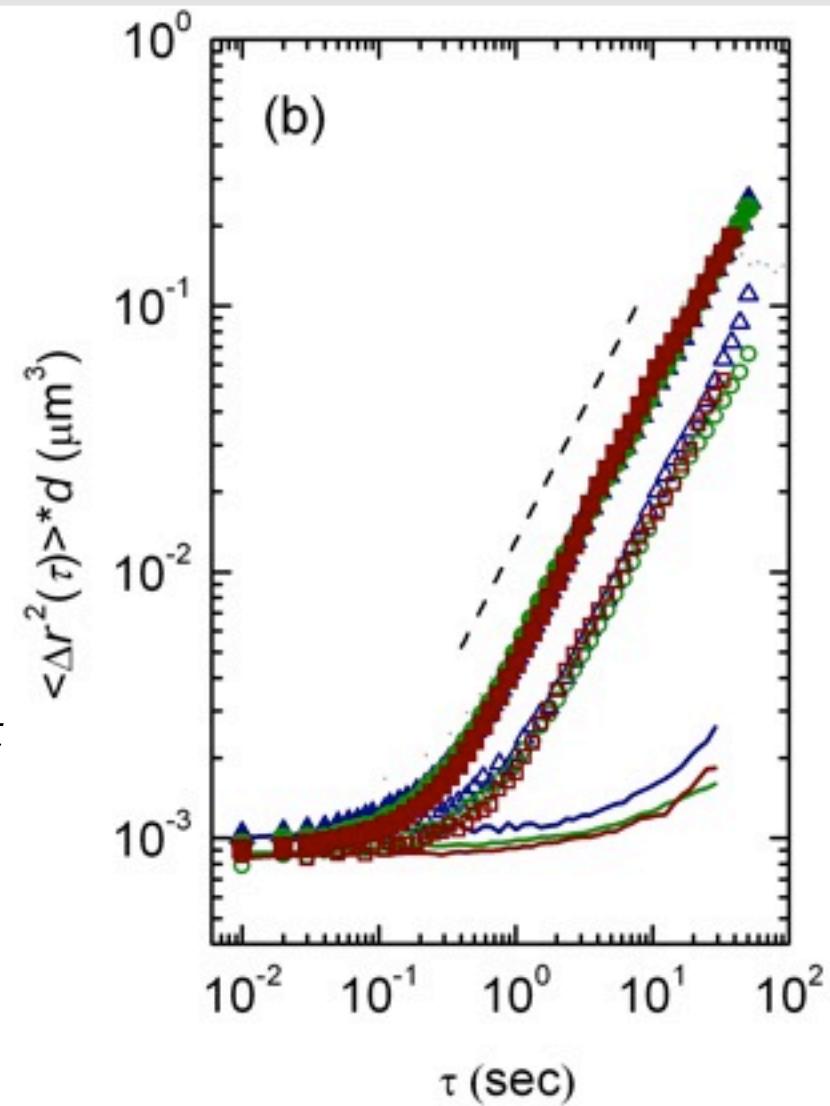
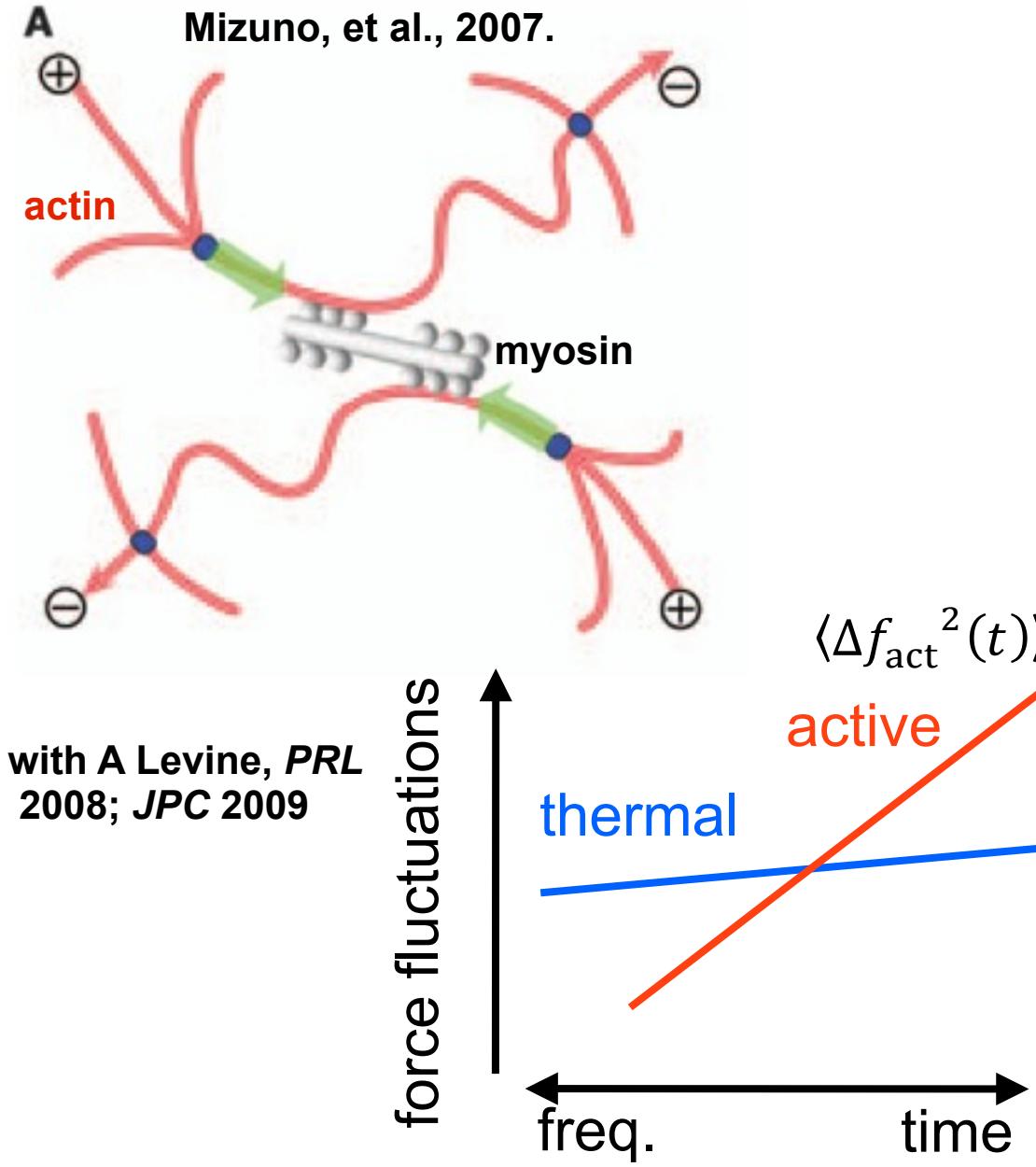
Athermal Fluctuations of MTs



$$\langle |a_q(t) - a_q(0)|^2 \rangle \sim t$$

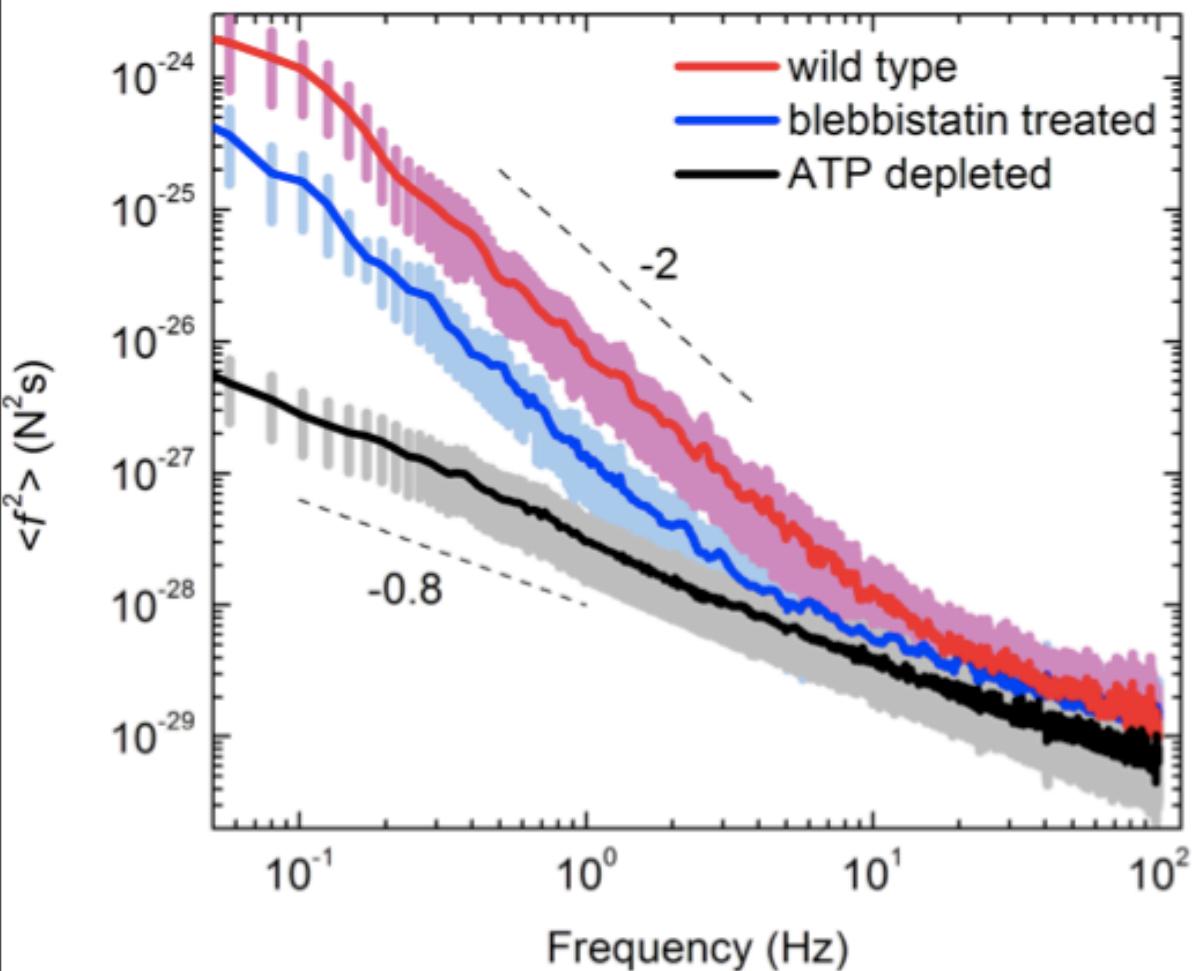
with Brangwynne, Koenderink,
Weitz, *PNAS* 2007, *PRL* 2008,
JCB 2008.

Effect of molecular motors: Active fluctuations



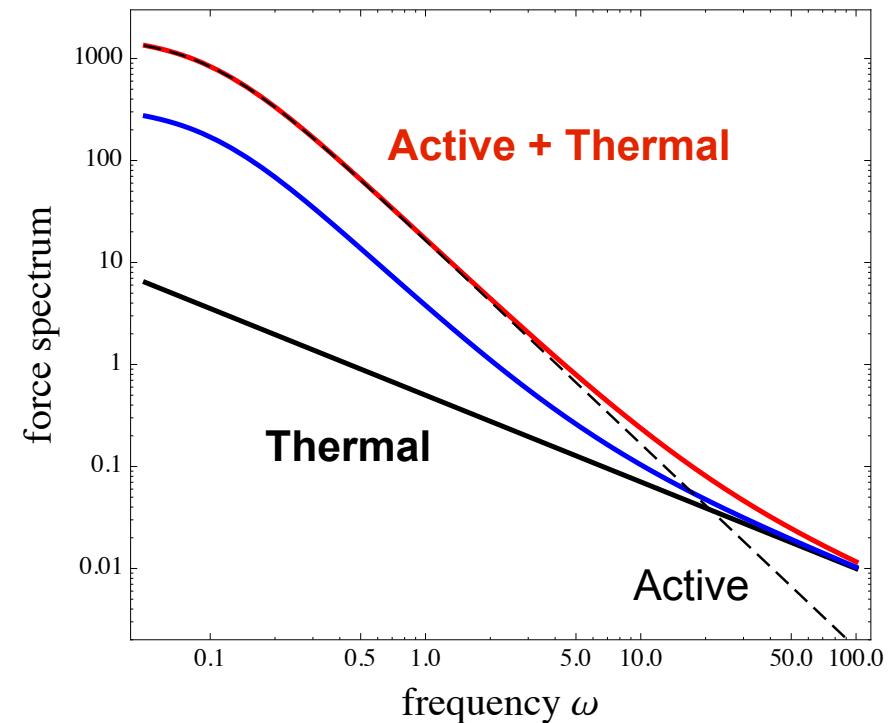
with Guo and Weitz,
unpublished

Cell activity & mechanics probed by injected beads



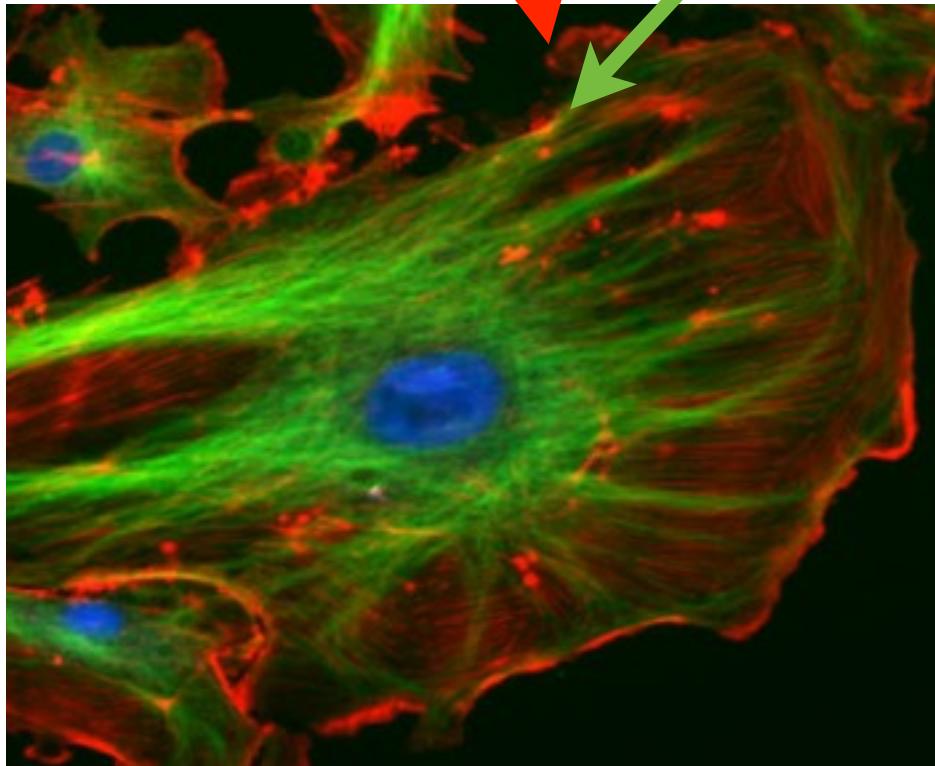
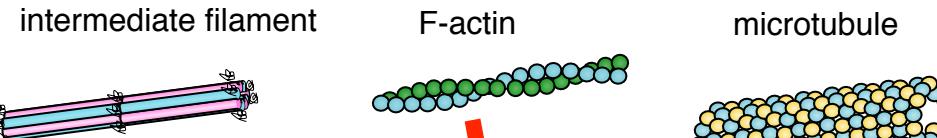
with Guo and Weitz, unpublished

see also Lau et al., *PRL* 2003 and Mizuno et al., *PRL* 2009.

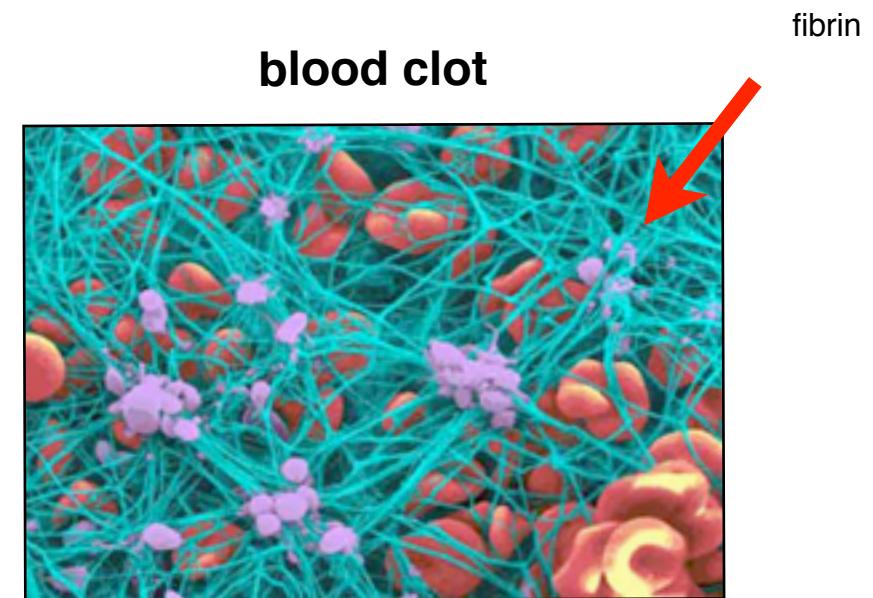


The cytoskeleton, a *fibrous composite*

The Cell



Extracellular matrix

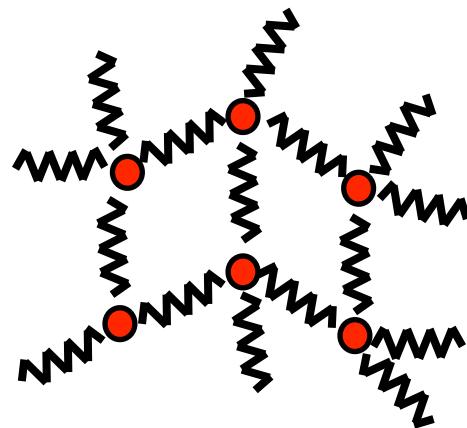


Yuri Veklich and John Weisel

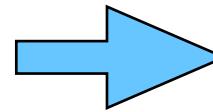
Challenges:

- nature & origins of elasticity
- non-equilibrium aspects
- contrast with polymers

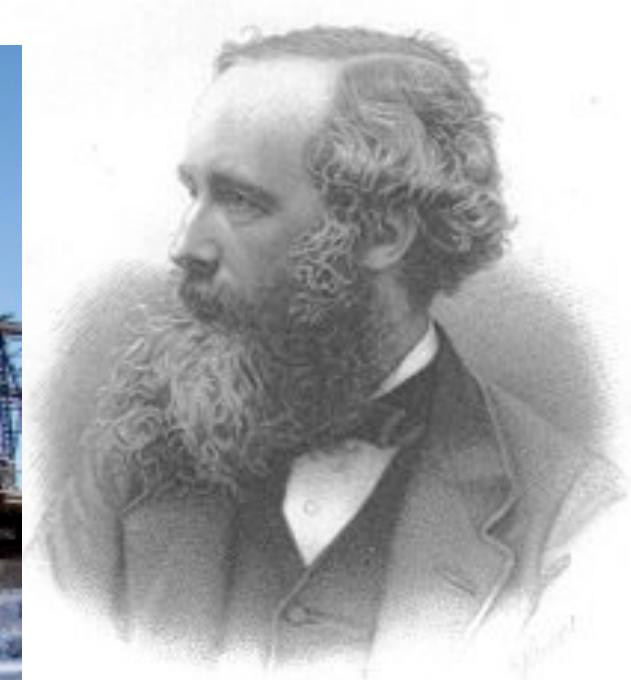
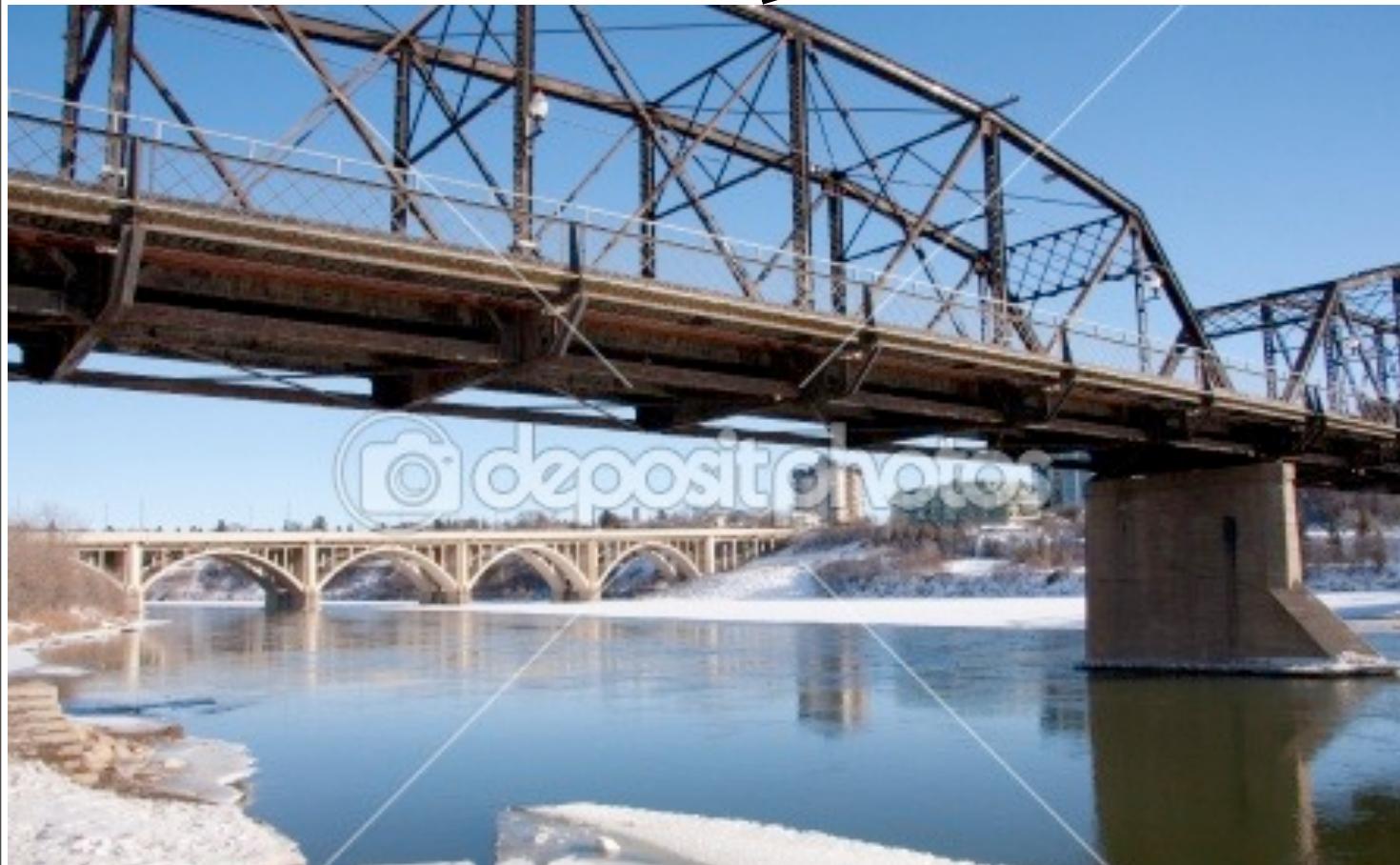
Network Connectivity, Stability and Marginality



isostatic coordination number

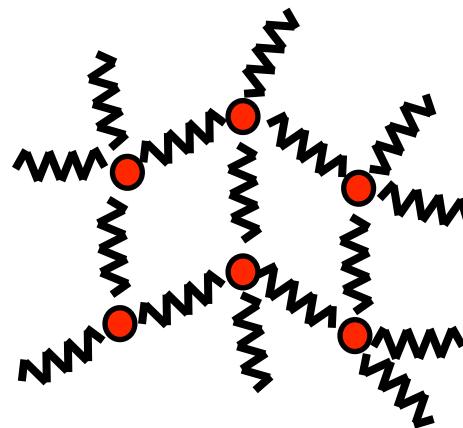


$$z_c = 2d$$

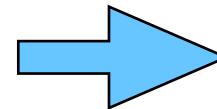


J. C. Maxwell, Philos. Mag. **27**, 294 (1864).

Network Connectivity, Stability and Marginality



isostatic coordination number



$$z_c = 2d$$

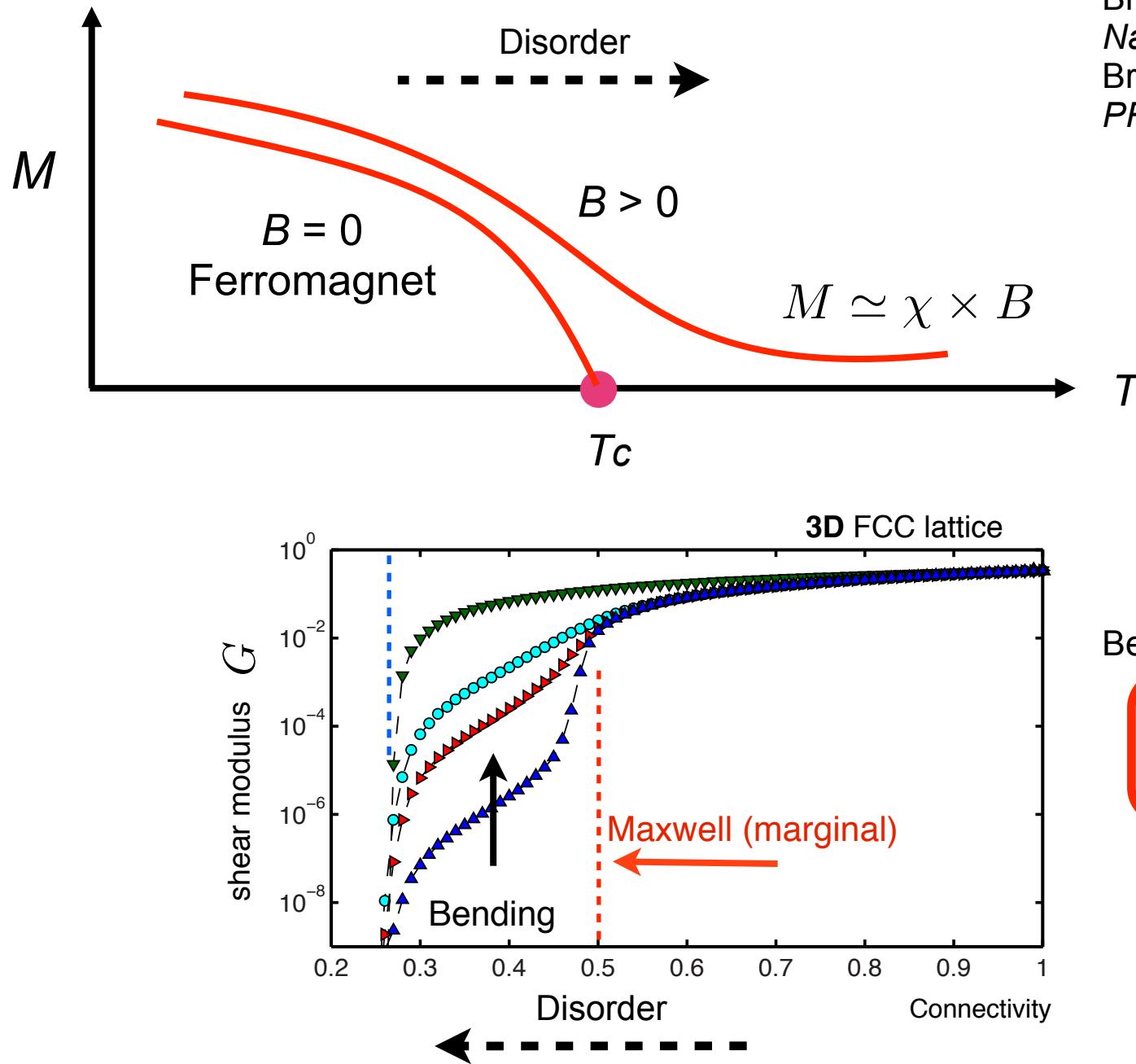
QUESTION:

Stability below isostatic point?

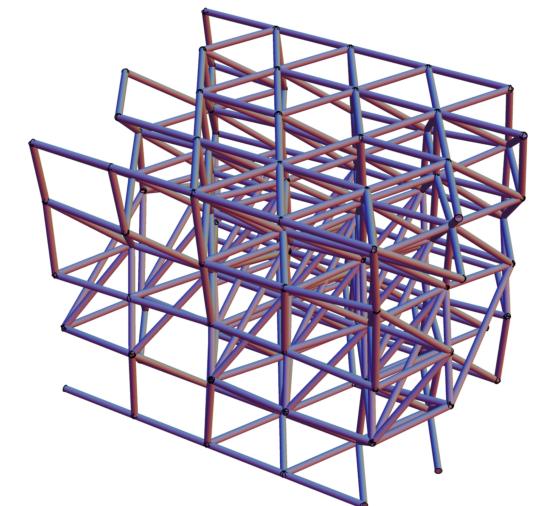
- fiber bending rigidity
- motor stress
- thermal fluctuations
- normal stresses in collagen
- remodeling of marginal networks



Magnetic analogy for marginal networks



Broedersz, Mao, Lubensky, FCM,
Nature Phys (2011);
Broedersz, Sheinman, FCM,
PRL (2012).

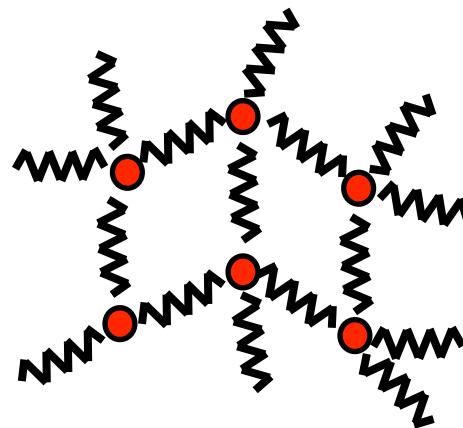


Below marginal point

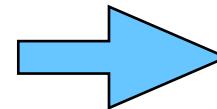
$$G \simeq \chi \times h$$

h is a *stabilizing field*,
e.g., κ

Network Connectivity, Stability and Marginality



isostatic coordination number



$$z_c = 2d$$

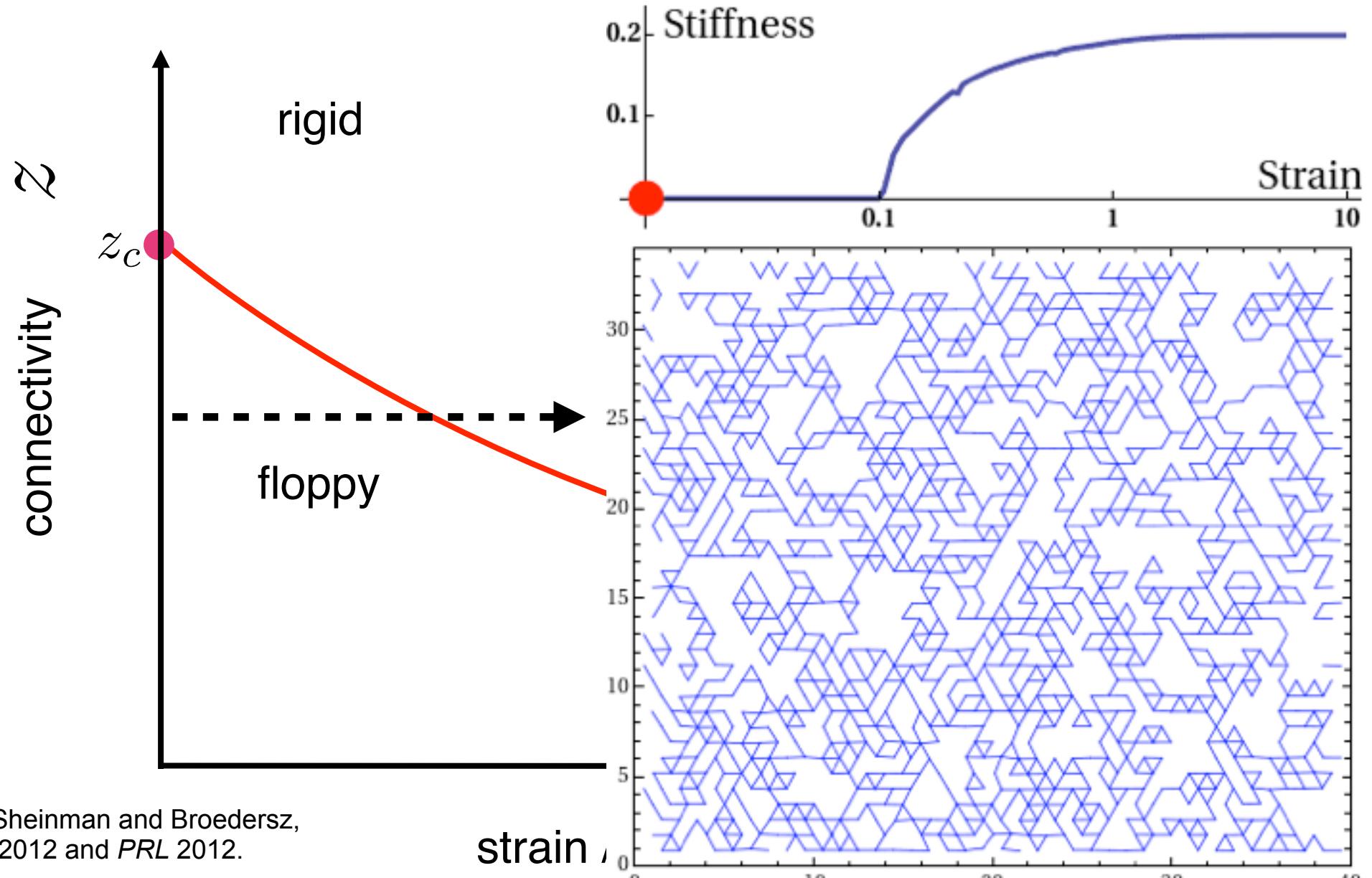
QUESTION:

Stability below isostatic point?

- fiber bending rigidity
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- thermal fluctuations
- normal stresses in collagen
- remodeling of marginal networks



Stress/strain can stabilize (sub-isostatic) floppy networks

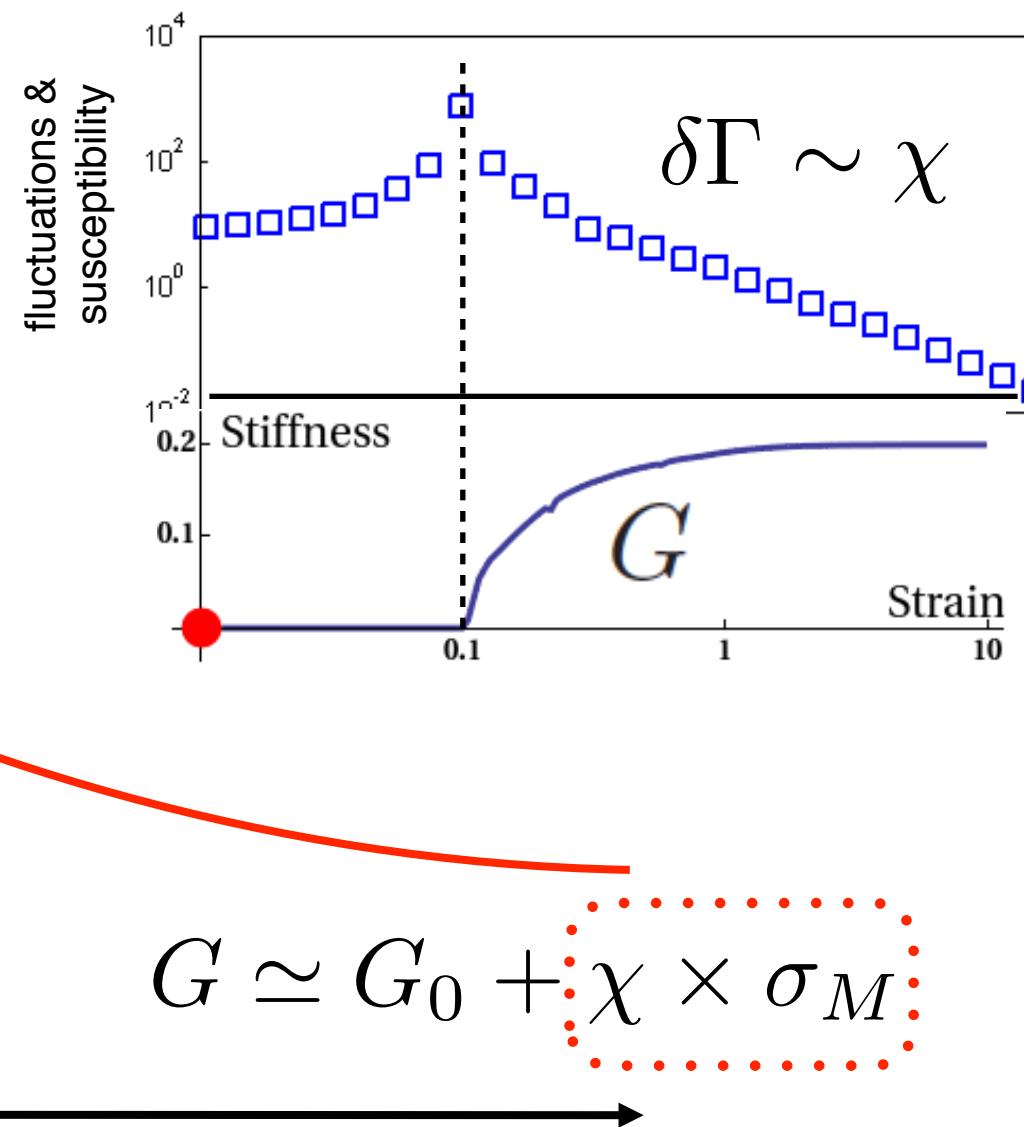
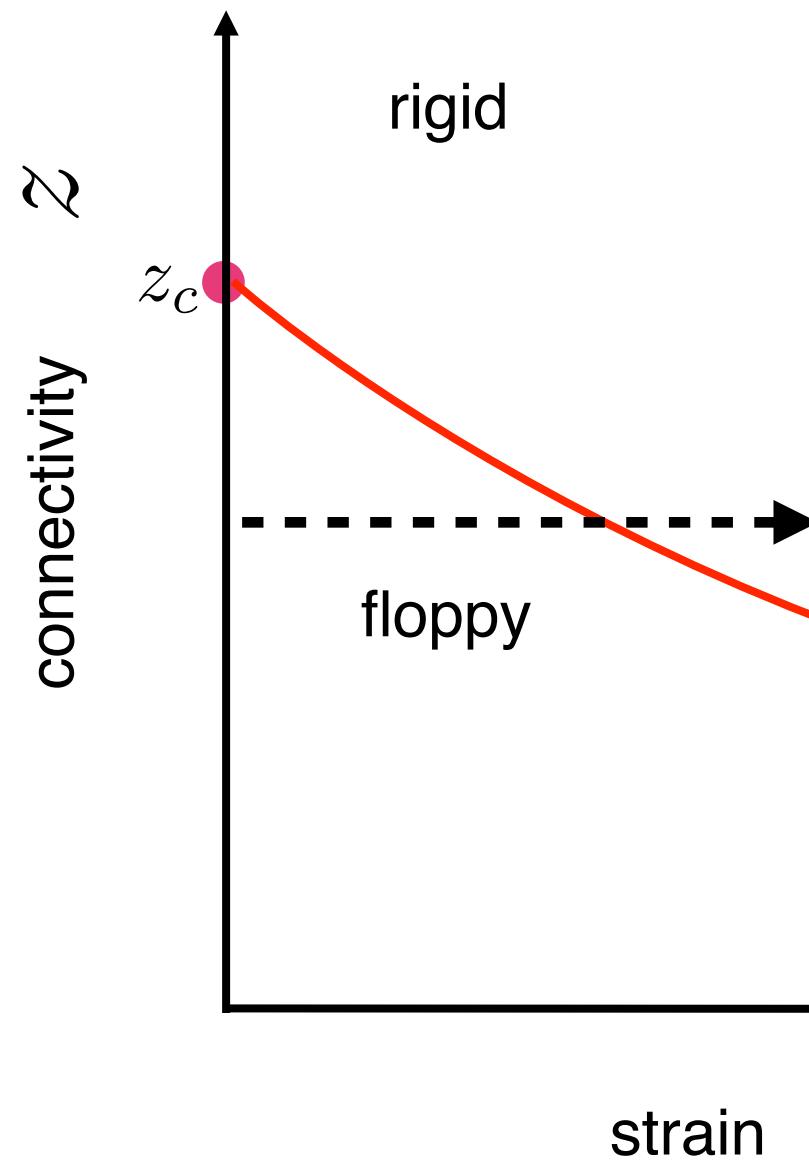


with Sheinman and Broedersz,
PRE 2012 and *PRL* 2012.

strain

<http://www.youtube.com/watch?v=ANSQePygfYU>

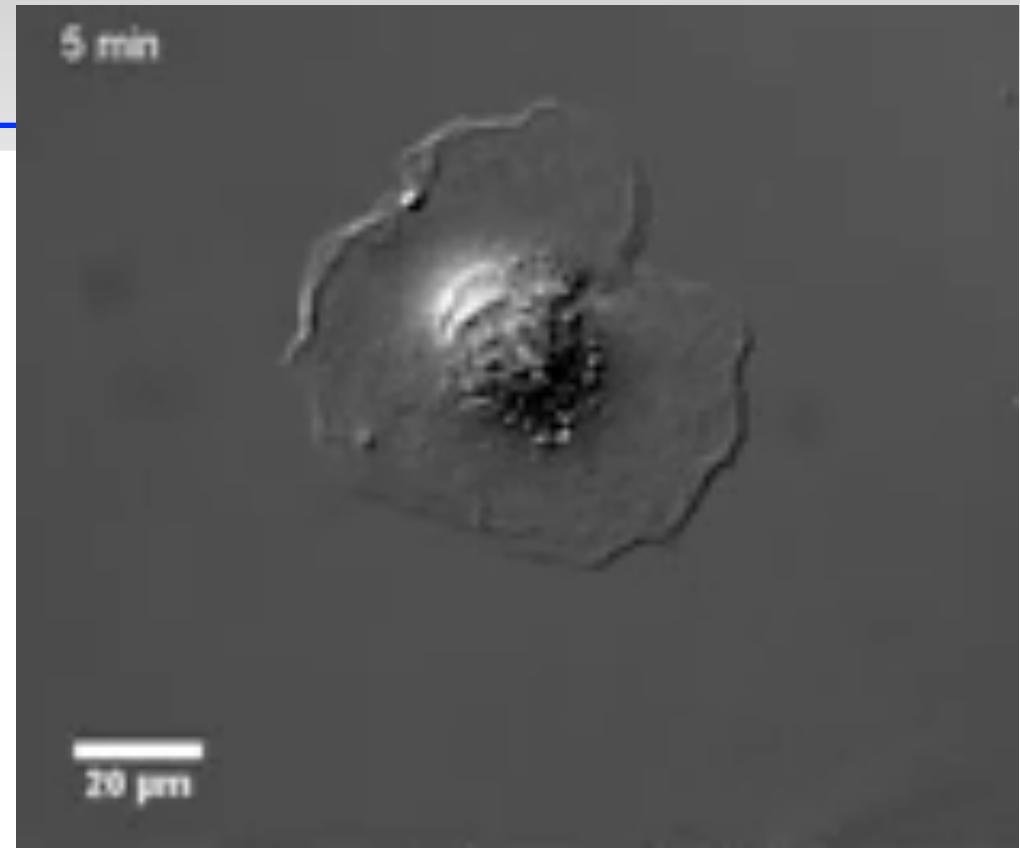
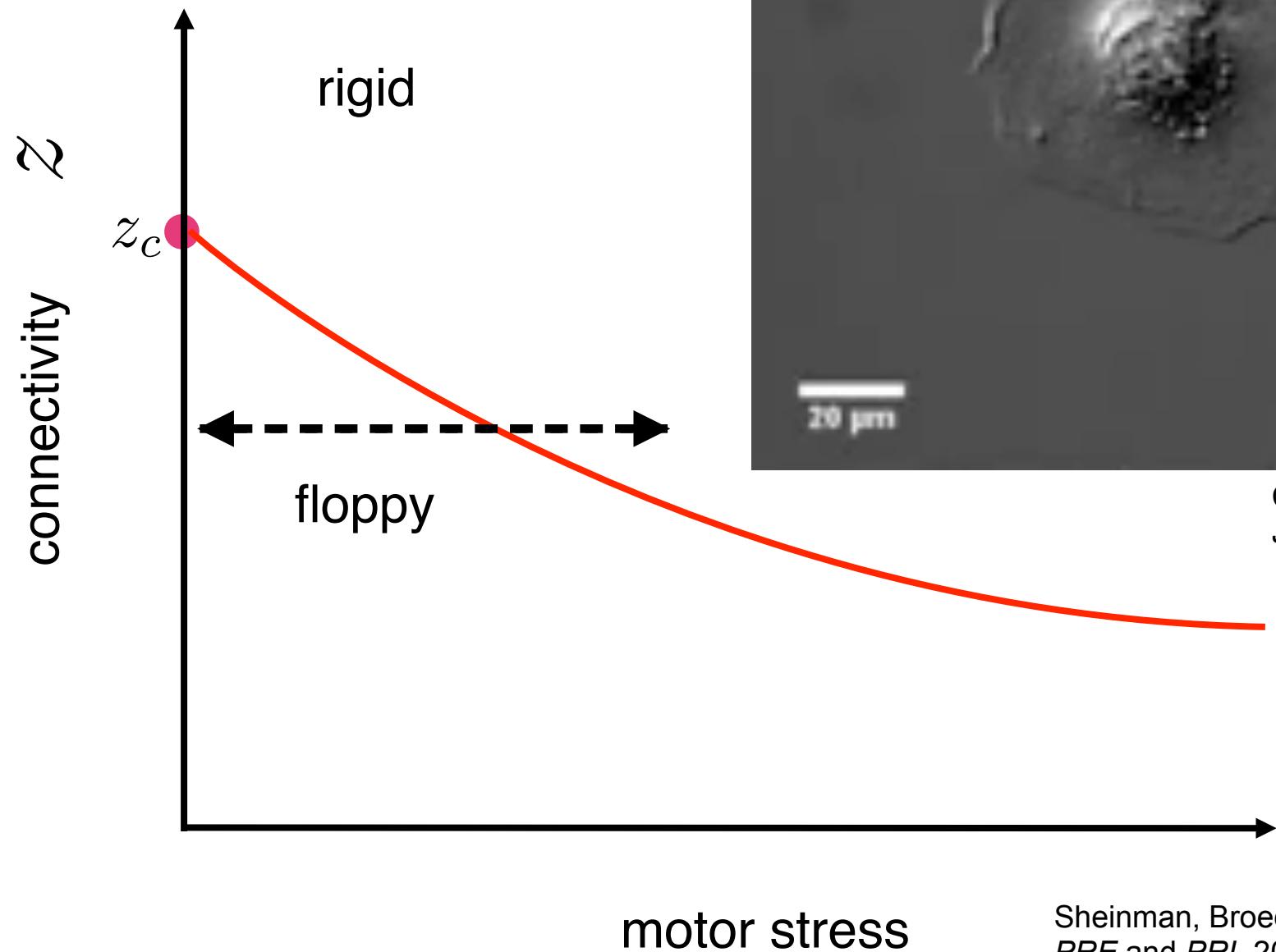
Strong fluctuations and response near marginal state



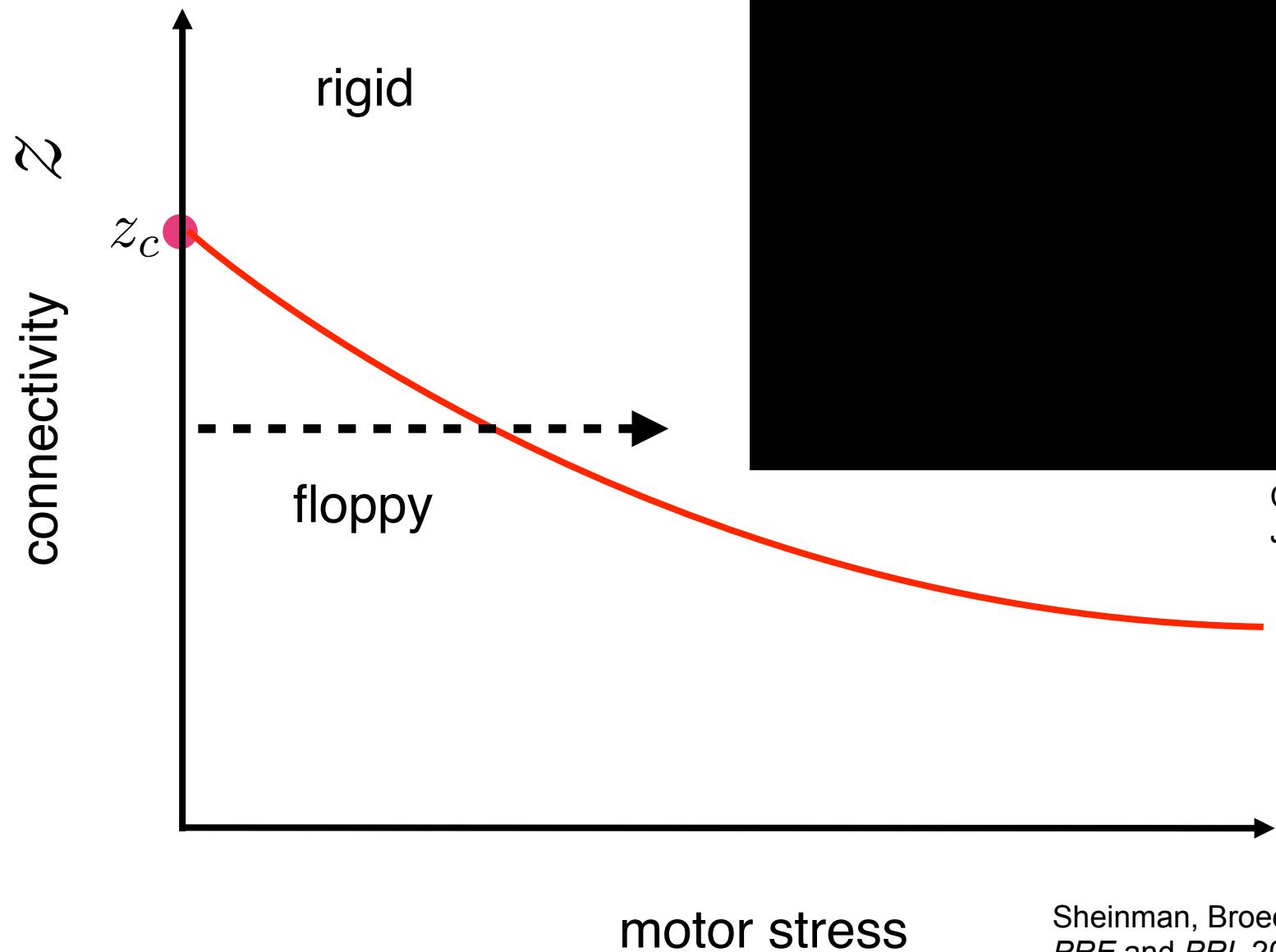
Sheinman, Broedersz, FCM
PRE and PRL 2012.

Motor stress needed for stability

19



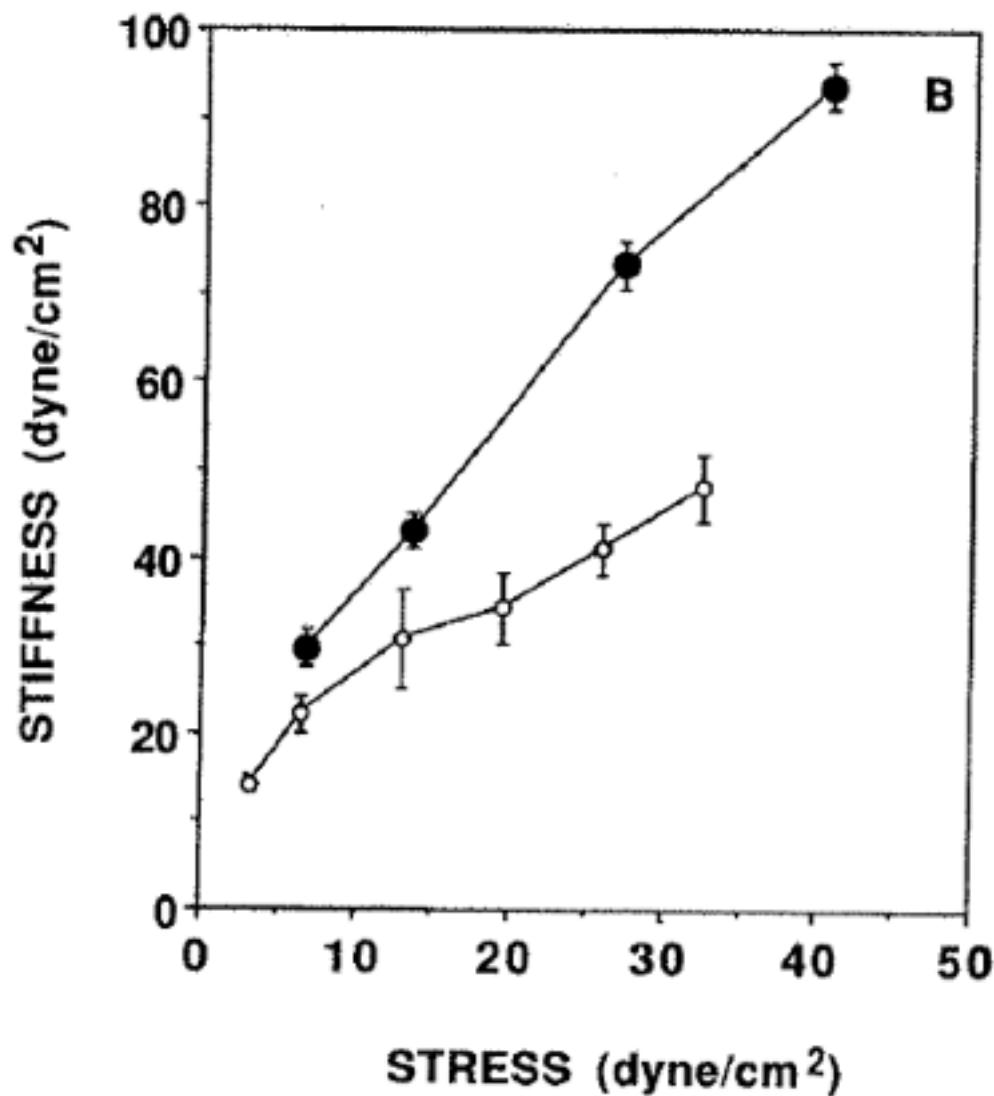
Motor stress needed for stability



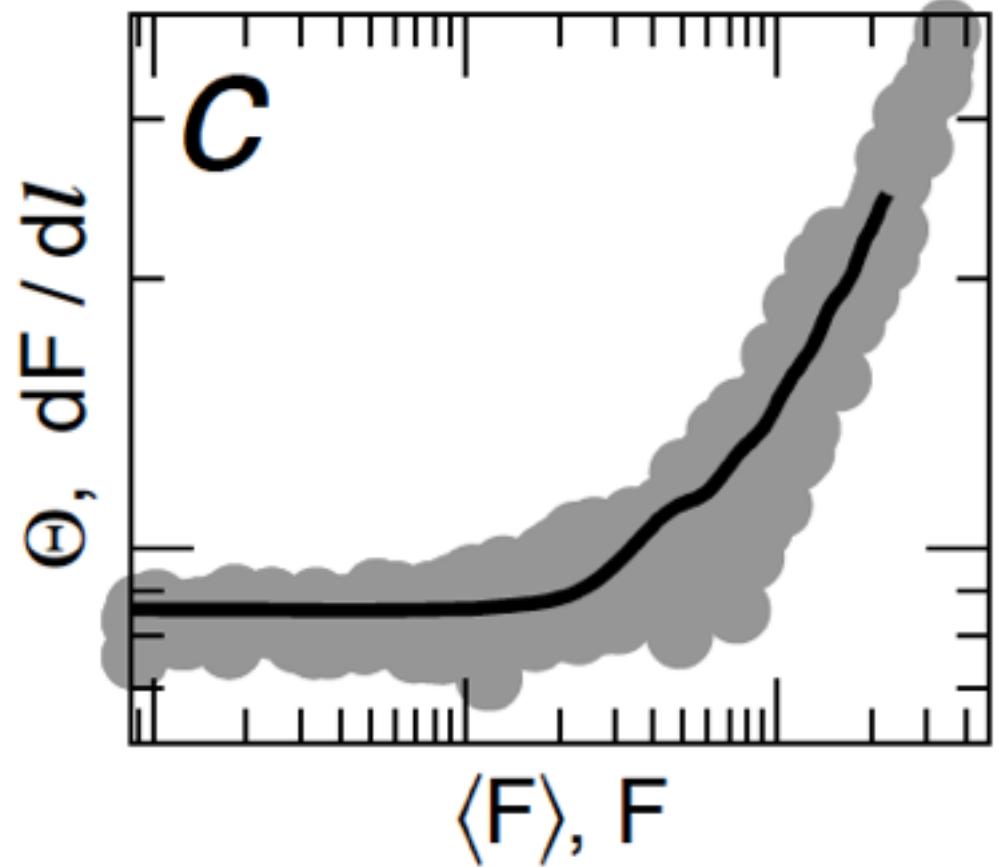
Cai et al.,
J Cell Sci (2010).

Sheinman, Broedersz, FCM
PRE and *PRL* 2012.

Stress controls stiffness of cells

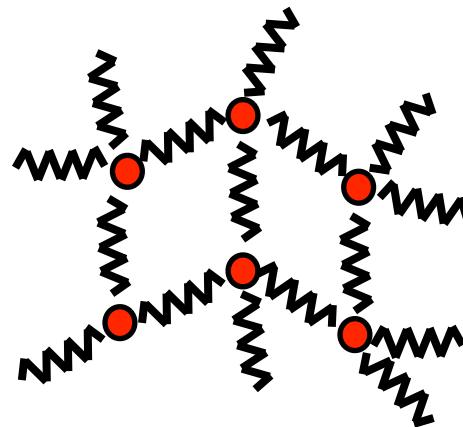


Wang & Ingber, 1994

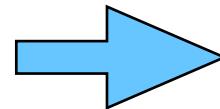


Fernandez & Ott, 2008

Network Connectivity, Stability and Marginality



isostatic coordination number



$$z_c = 2d$$

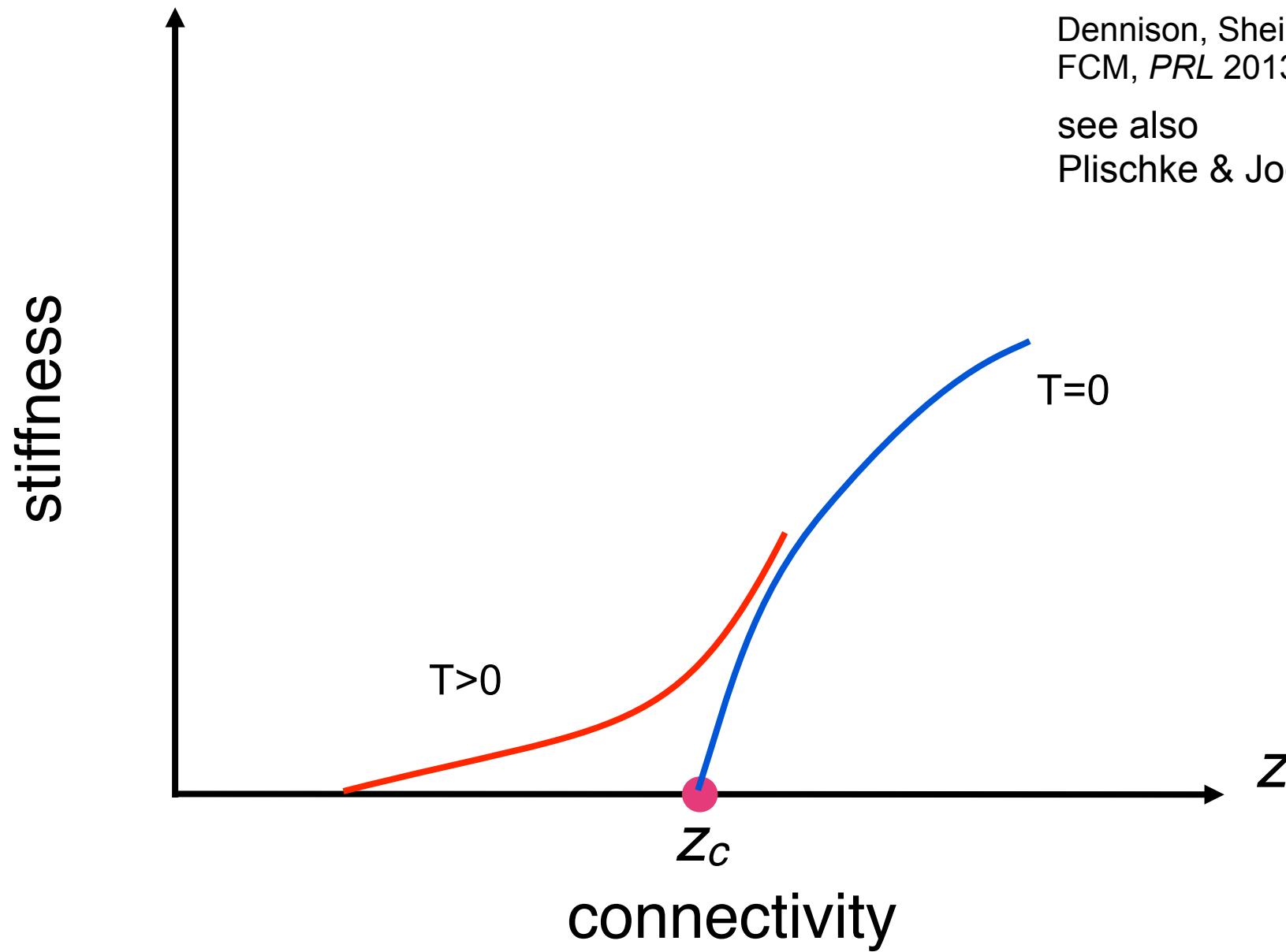
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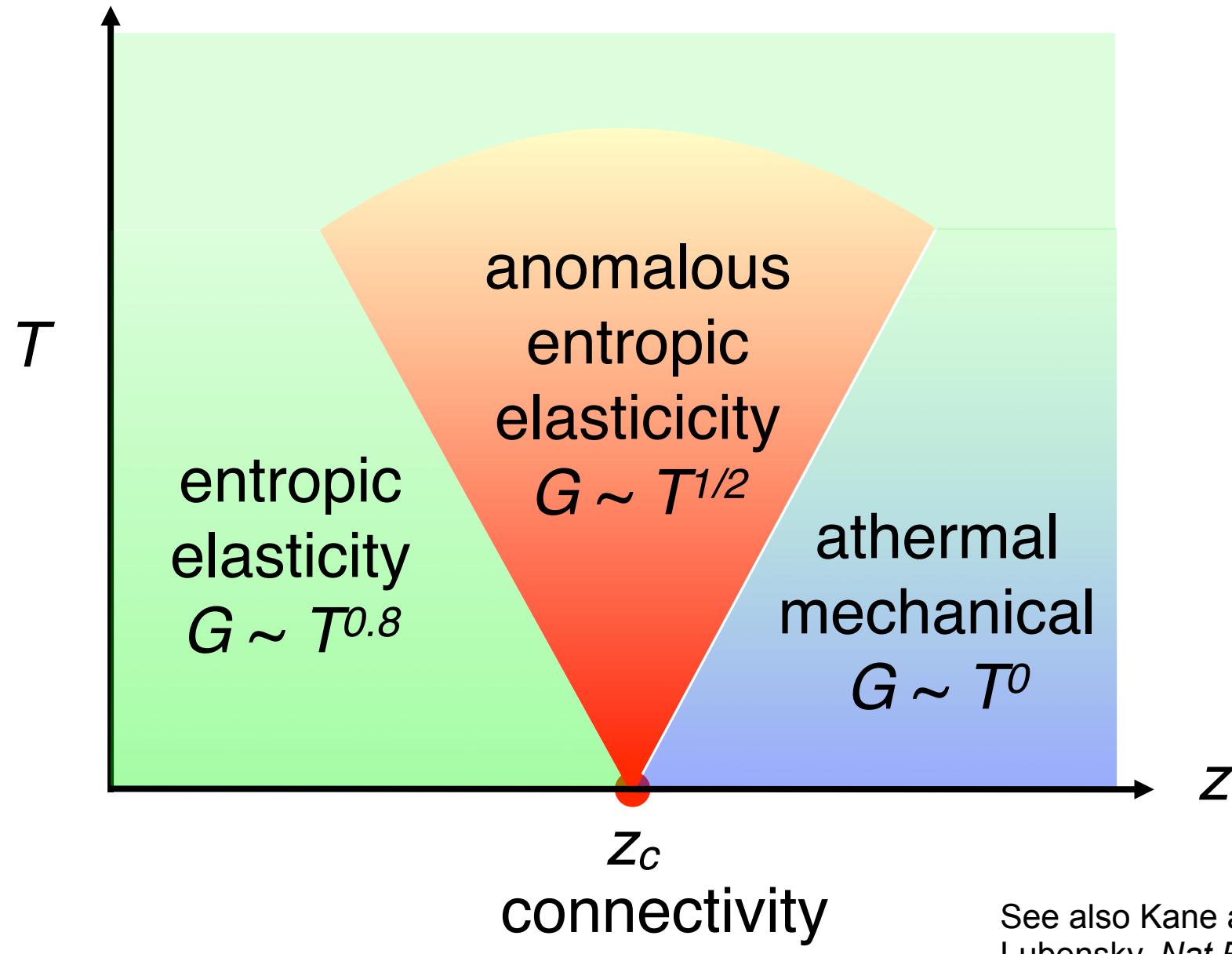
Thermal fluctuations and stability ?



Dennison, Sheinman, Storm,
FCM, *PRL* 2013.

see also
Plischke & Joos, *PRL* 1998.

Phase diagram & analogies with *quantum critical* phenomena



See also Kane and Lubensky, *Nat Phys* 2014.