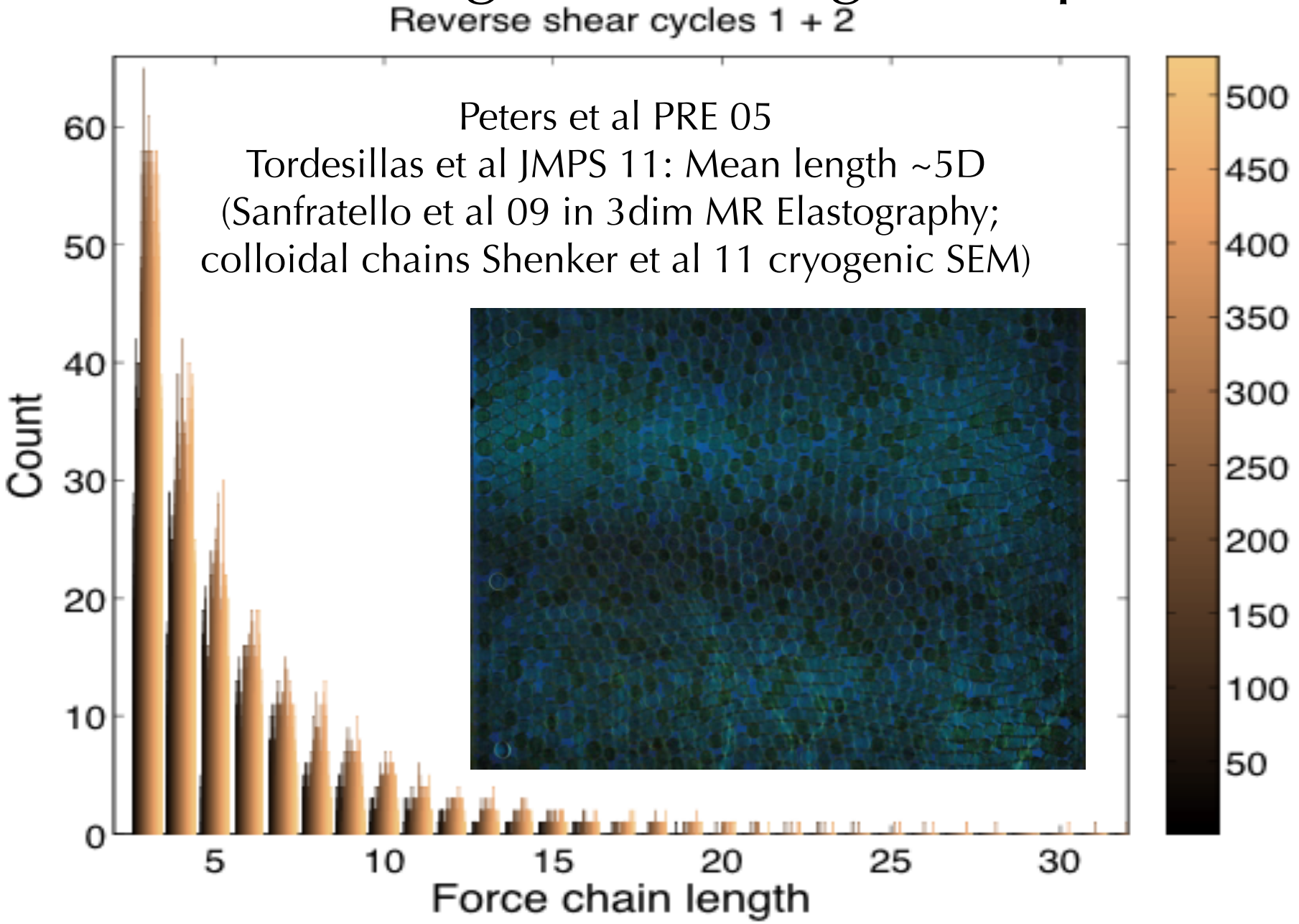
Plan of the rest of this talk ..

- **What data from DEM/EXP tell us about length scales of observed patterns from contact forces & topology in granular materials**
- Pattern recognition from Complex Systems Theory and what patterns teach us about the nature of complex systems

---

- Extraction of length scales from Grenoble data on Hostun sand
- Results from extraction
- Inception of Hostun sand and the null hypothesis to test length scales are robust, meaningful and **real**
- Results from inception
- Lessons learned and where to next …

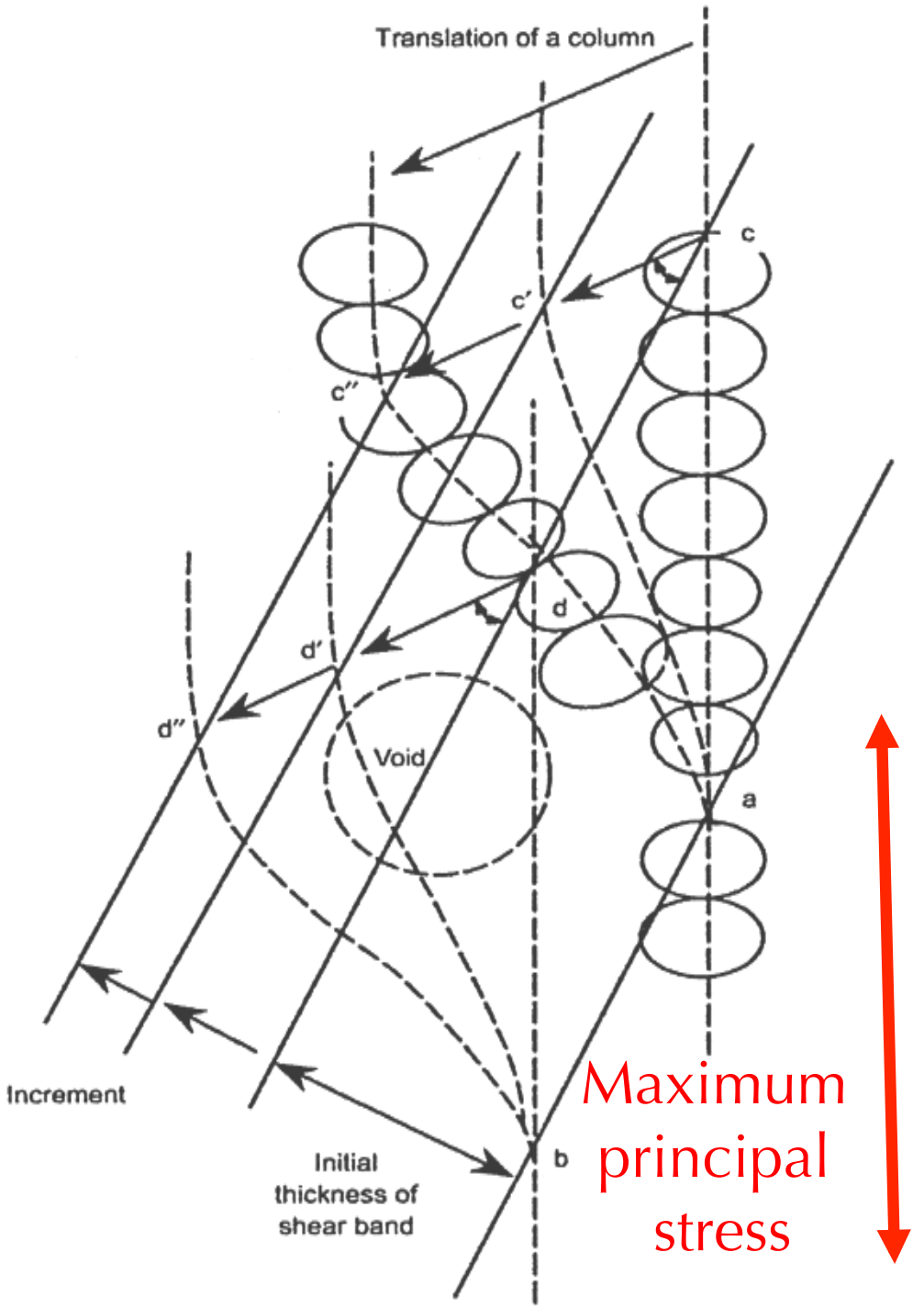
Force chain lengths (Behringer's experiment)



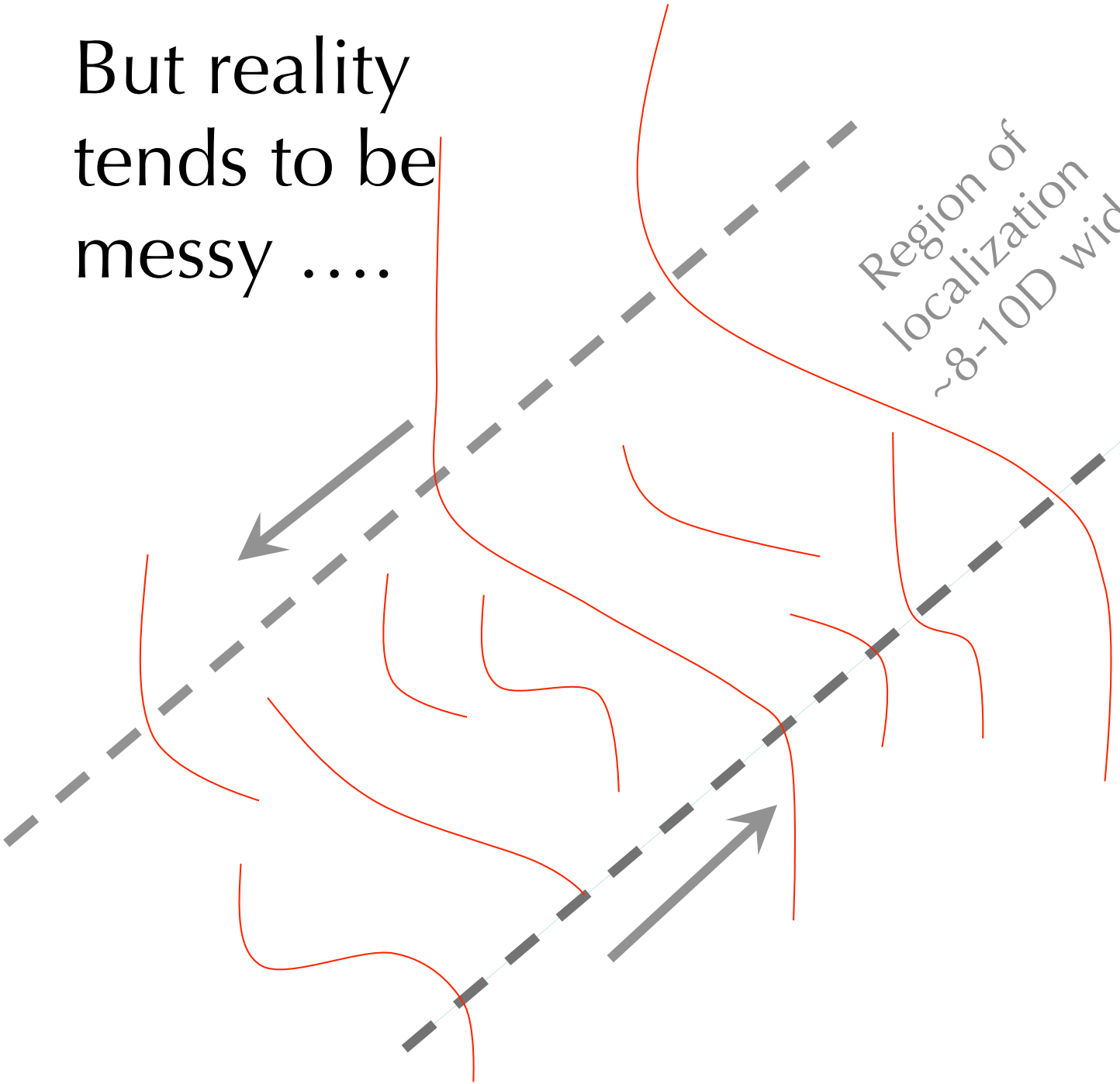
Oda's view of route to shear banding:

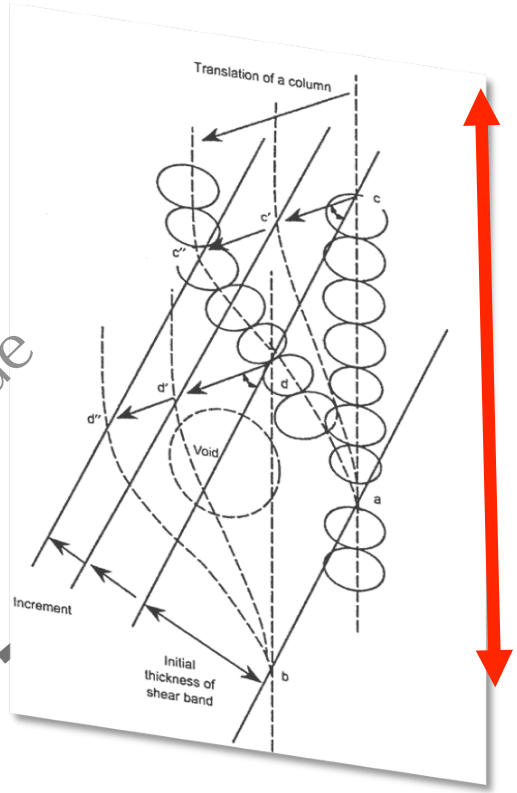
Oda & Kazama 98, Geotechnique, **48** (fig 15)

Oda's hypothesis: "… columns extending parallel to the major principal stress direction. The columns start buckling at the peak stress, and the buckling columns tend to concentrate in shear bands during the strain softening process …."



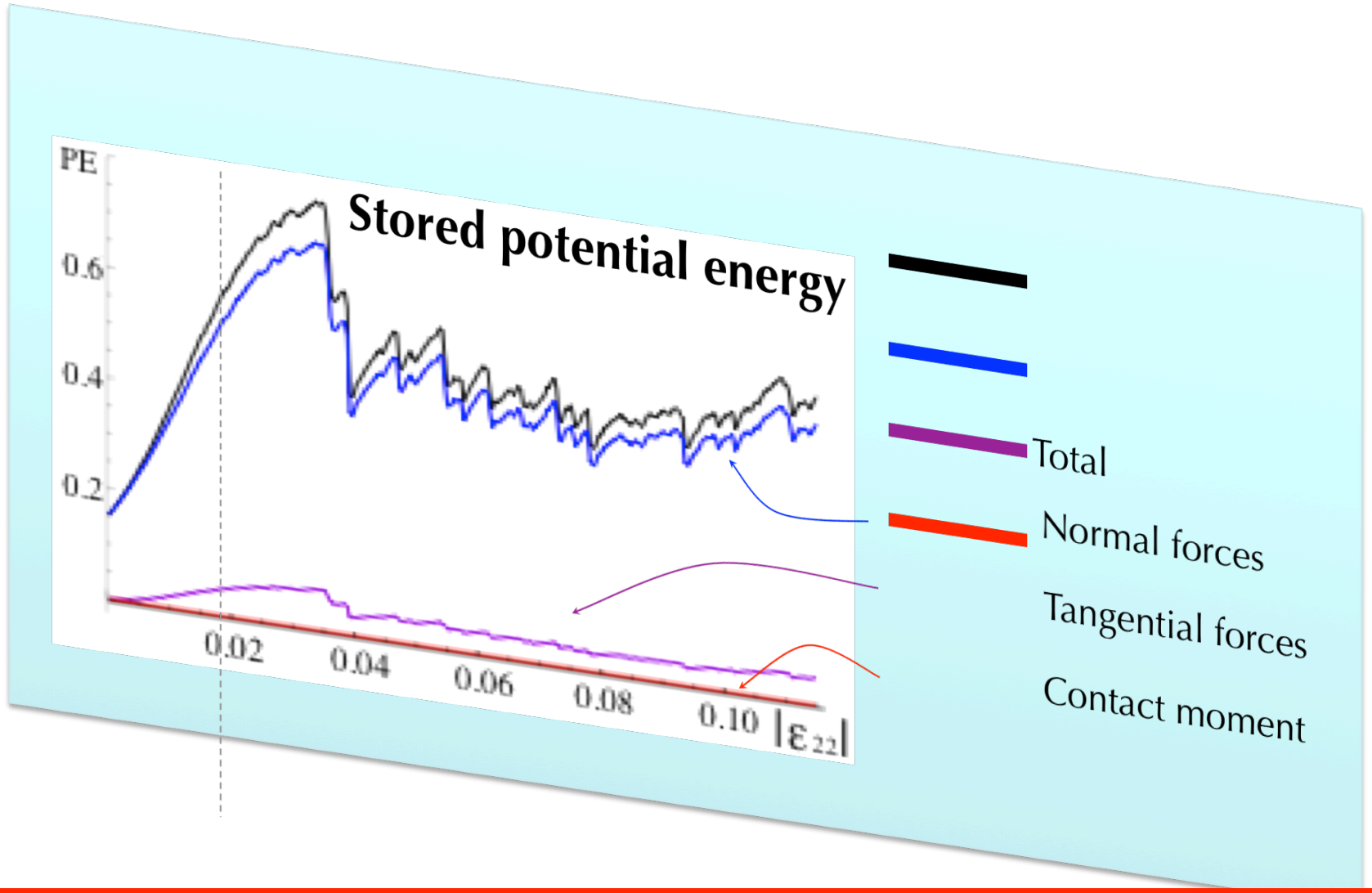
But reality tends to be messy ….





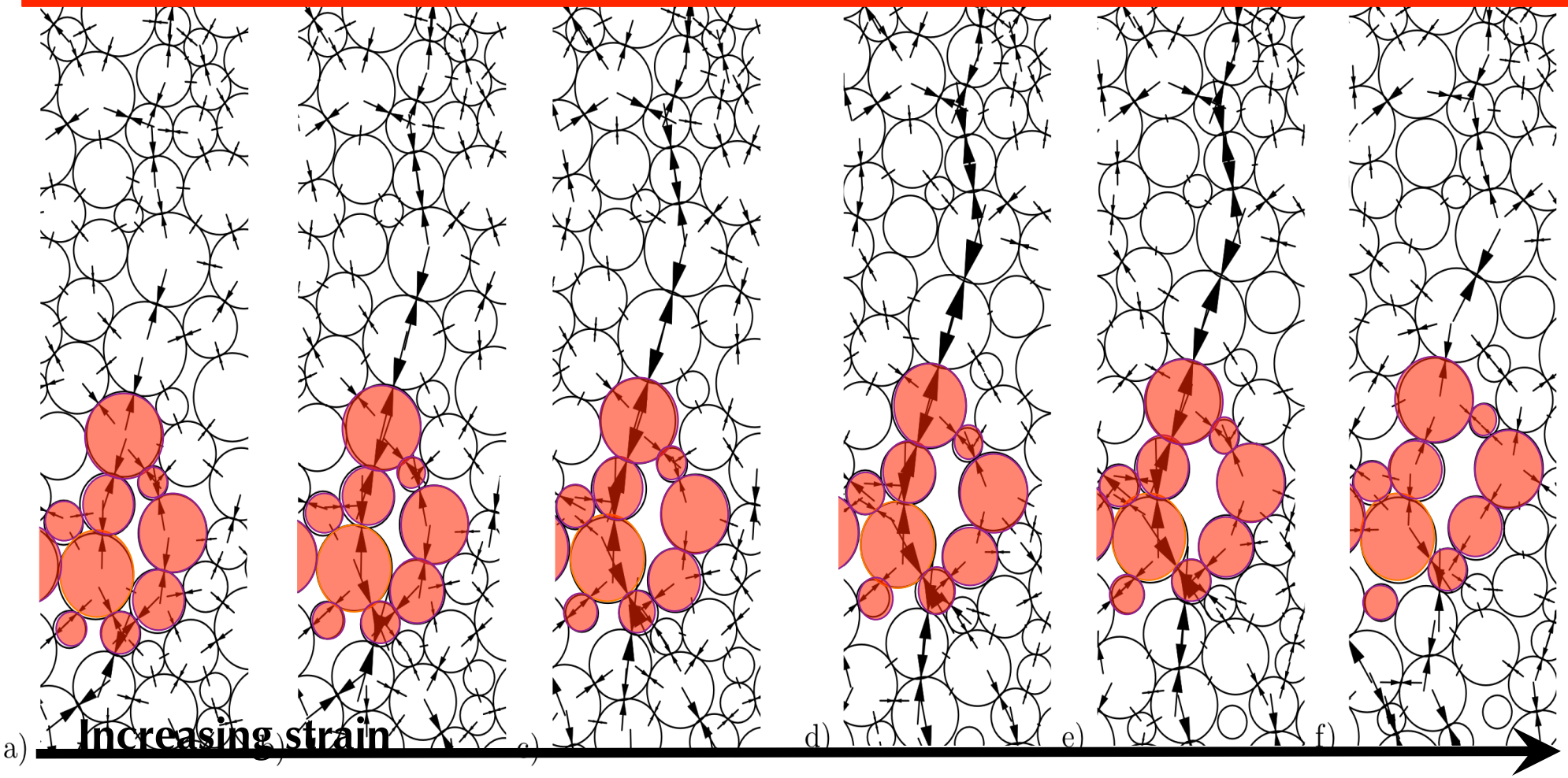
Maximum principal stress

Follow the energy ..



Baseline system: 2D DEM, Biaxial test with constant confining pressure, 5098 particles

Baseline system: 2D DEM, Biaxial test with constant confining pressure, 5098 particles



Key mechanism for release of energy stored in force chains?

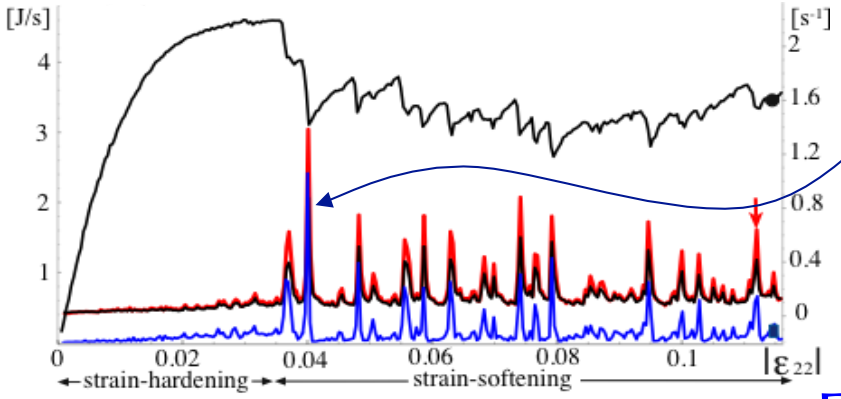
Slip or sliding limits the growth of tangential forces.

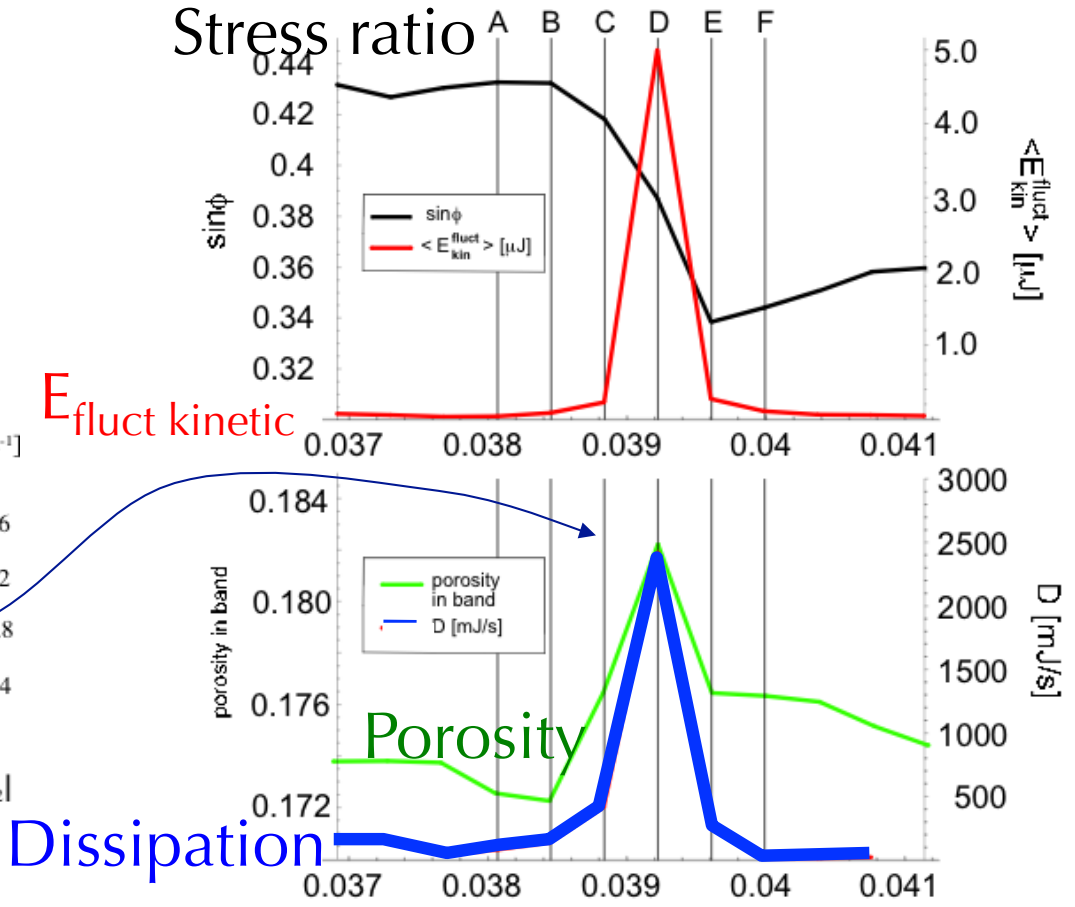
Rolling limits the growth of contact moments.

What limits the growth of normal forces?

Granular Matter 07

Dissipation in a single unjamming event - 2nd drop in stress ratio





- Follow the energy trail ……..

Where is the energy stored ?

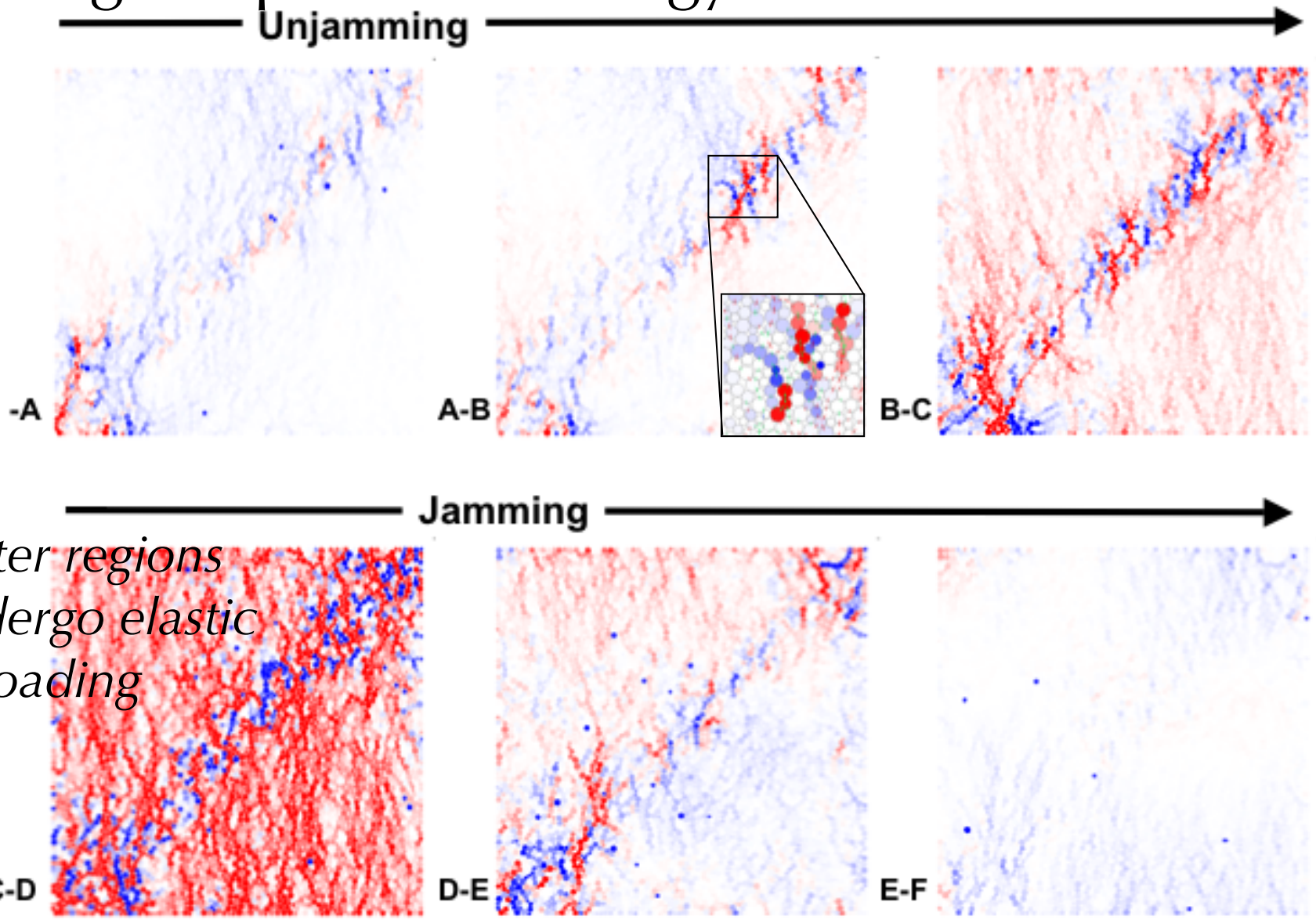
What triggers energy release?

Tordesillas Phil Mag 07

Baseline system: 2D DEM, Biaxial test with constant confining pressure, 5098 particles

Change in potential energy

Phil Mag 07

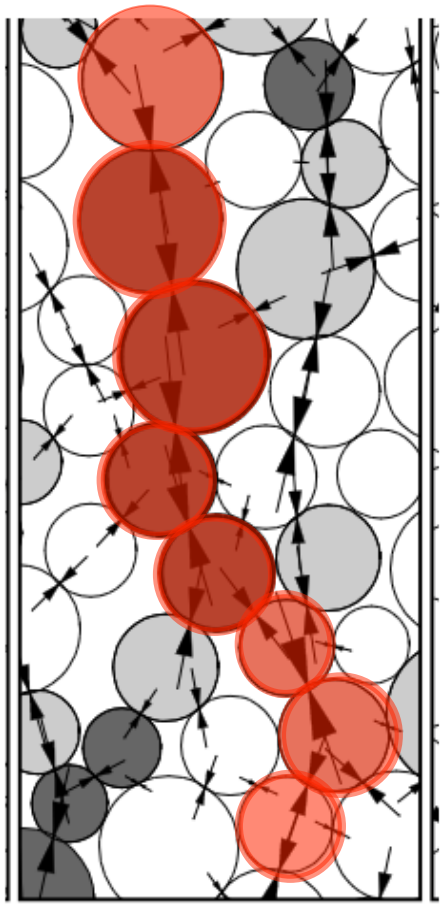


Outer regions undergo elastic unloading

Baseline system: 2D DEM, Biaxial test with constant confining pressure, 5098 particles

Key mechanism for energy release?

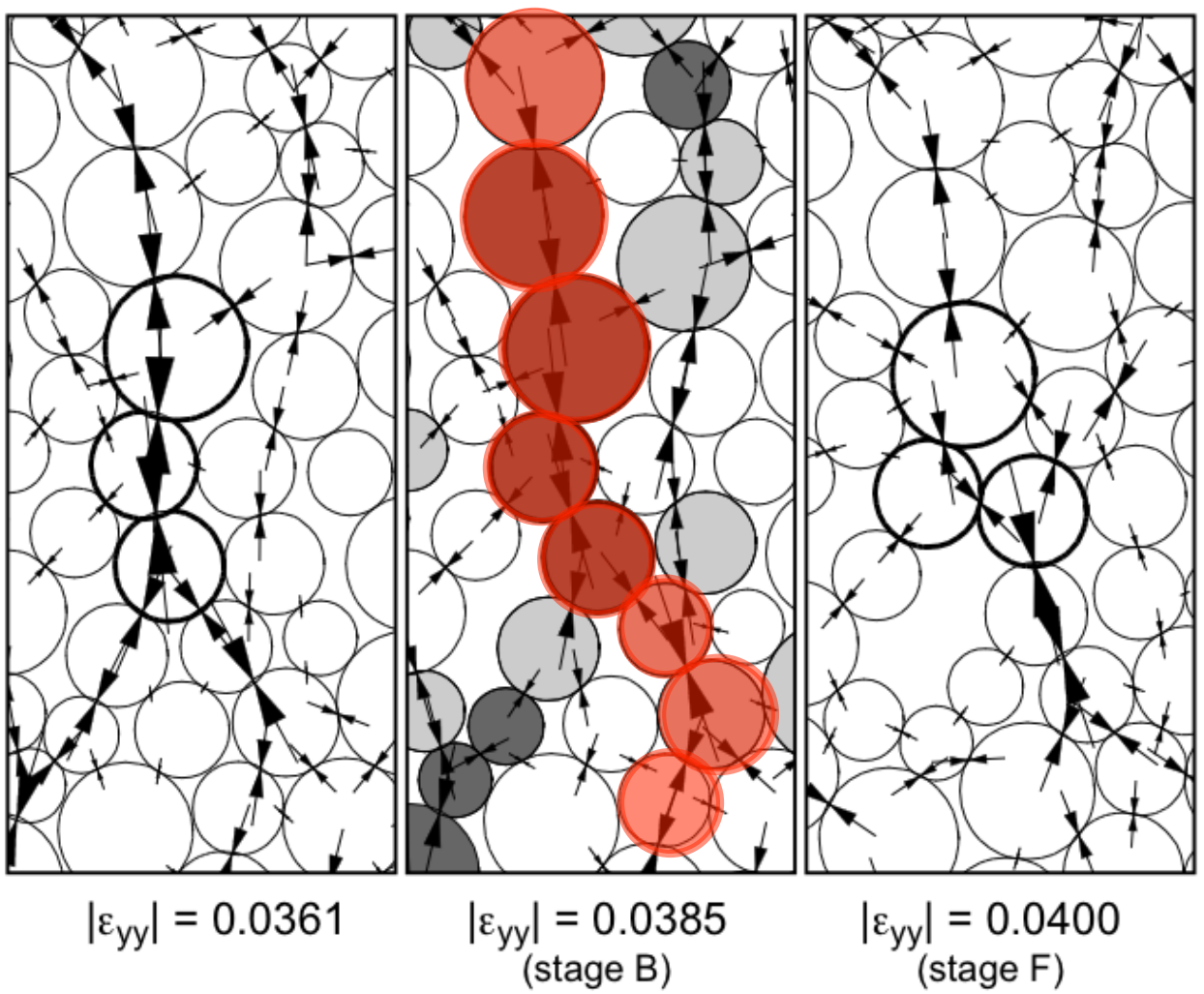
- Since force chains are where energy is mainly stored, the prime suspect is the mechanism for force chain failure.



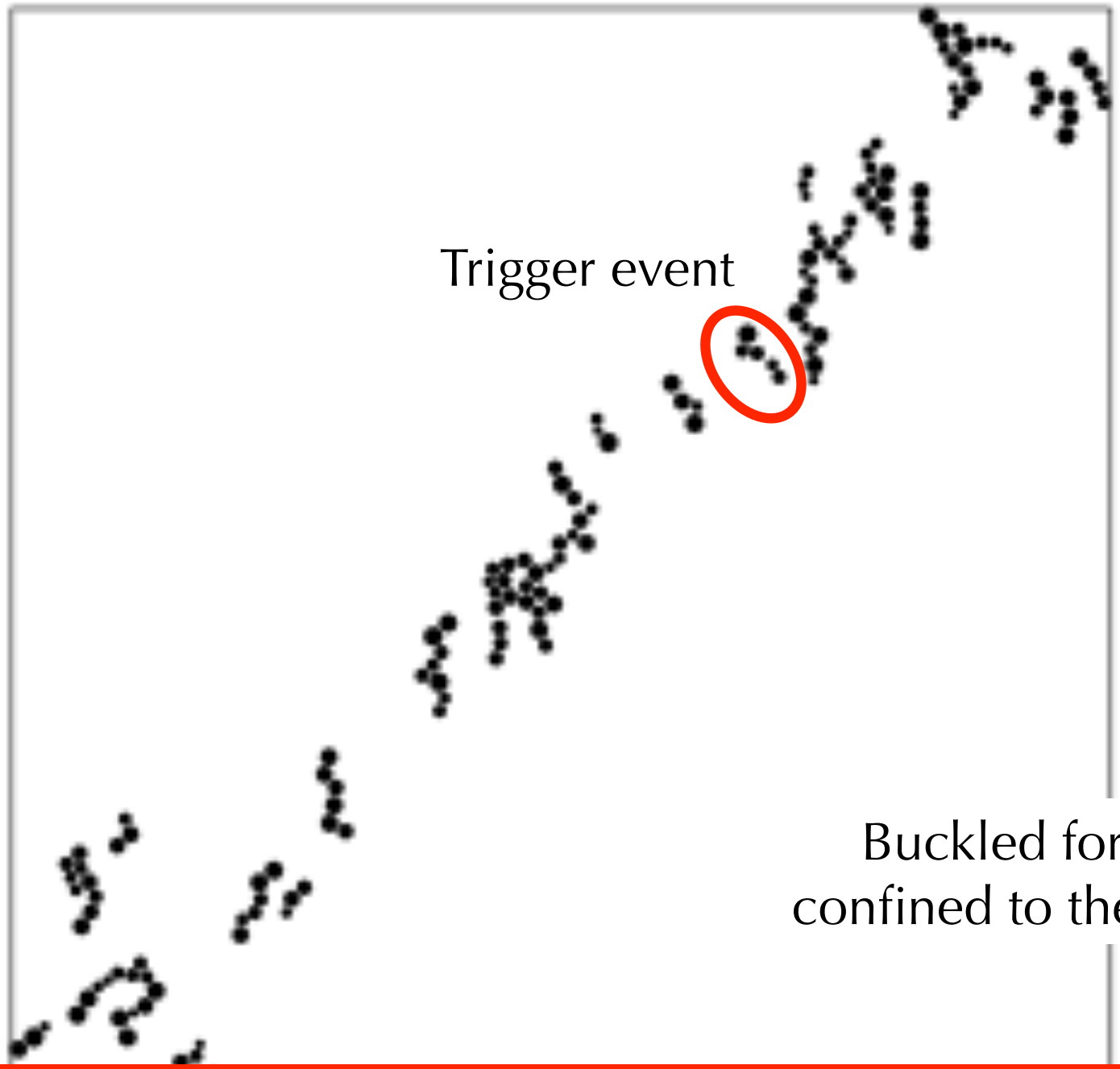
$|\varepsilon_{yy}| = 0.0385$
(stage B)

Maximum principal stress

Baseline system: 2D DEM, Biaxial test with constant confining pressure, 5098 particles



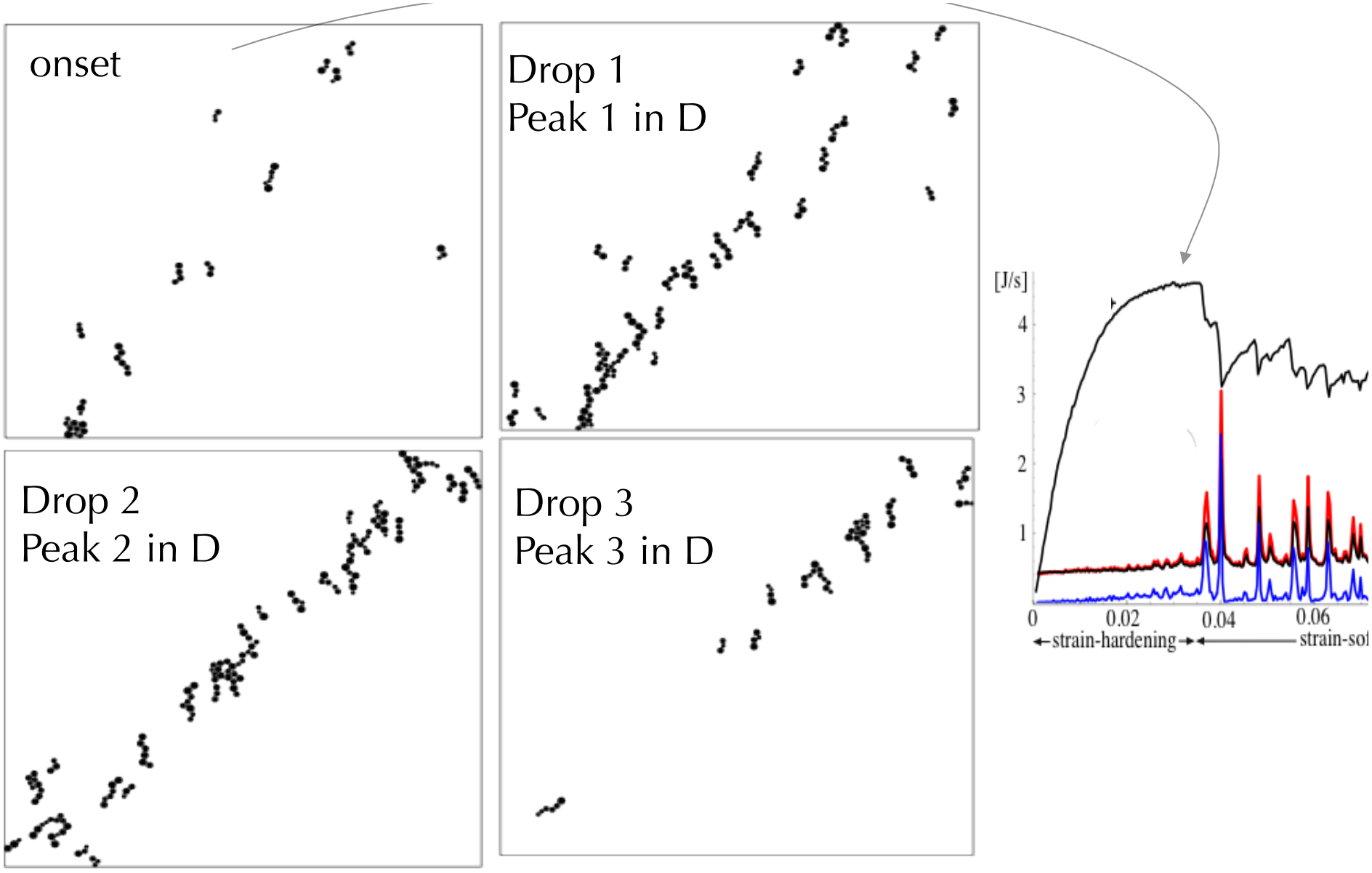
Oda's hypothesis: "…columns extending parallel to the major principal stress direction. The columns start buckling at the peak stress, and the buckling columns tend to concentrate in shear bands during the strain softening process …."



Buckled force chains
confined to the shear band!

Baseline system: 2D DEM, Biaxial test with constant confining pressure, 5098 particles

Spatial distribution of buckled force chains



Baseline system: 2D DEM, Biaxial test with constant confining pressure, 5098 particles

Plan of the rest of this talk ..

- **What Structural Mechanics tell us about length scales of observed patterns in granular materials**
- Pattern recognition from Complex Systems Theory and what patterns teach us about the nature of complex systems

---

- Extraction of length scales from Grenoble data on Hostun sand
- Results from extraction
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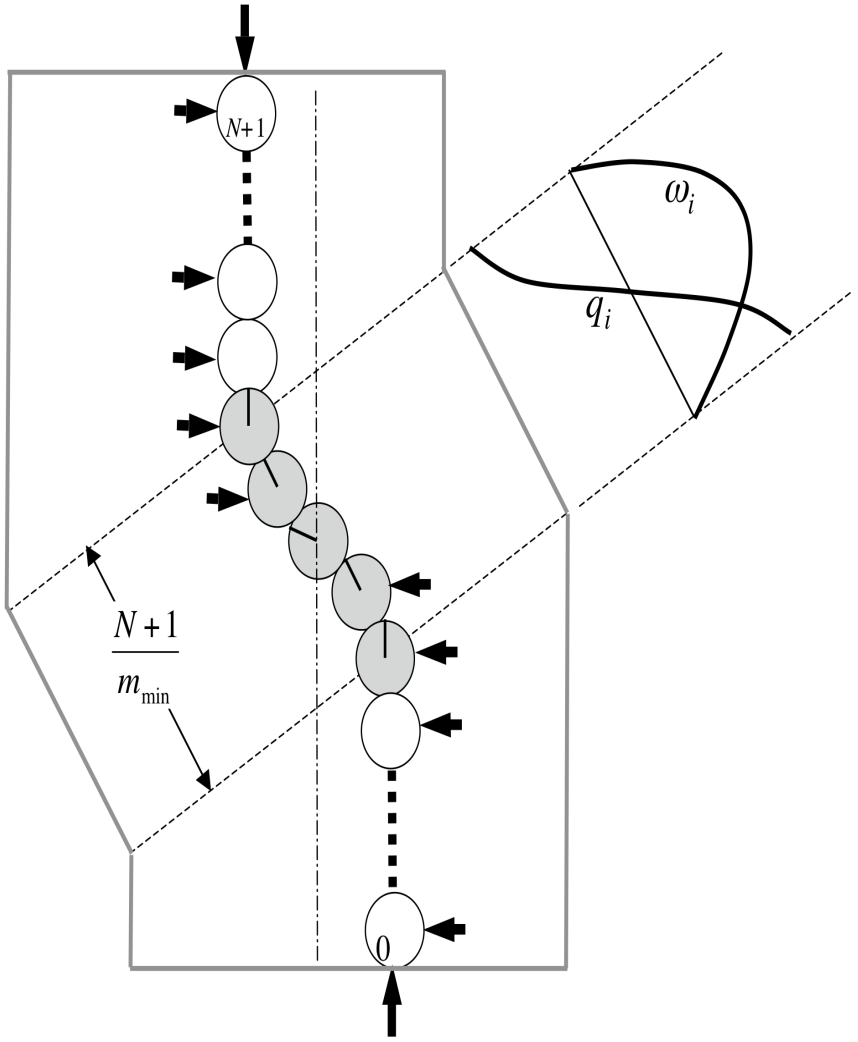
Linking force chain buckling to shear band width

- Confined elastic-plastic buckling of 3-force chain (Tordesillas & Muthuswamy, JMPS 09)

- Confined elastic buckling of N-force chain (Hunt, Tordesillas, Green & Shi, Phil Trans Roy Soc 10)

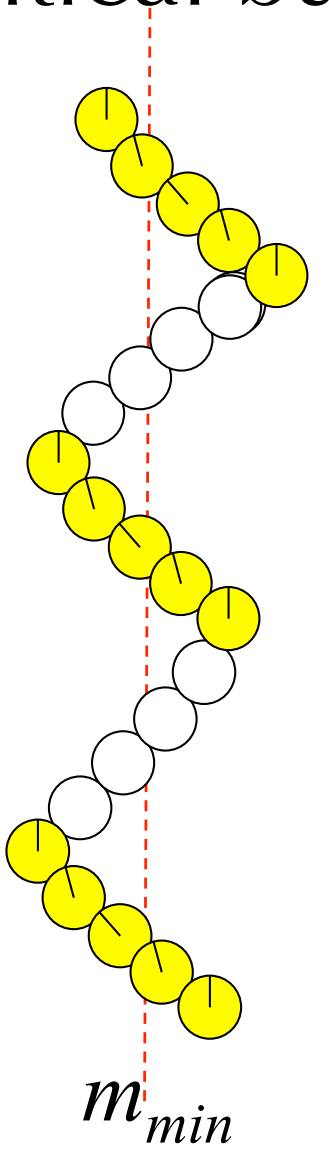
- **Localization to ~8D from confined elastic buckling of N-force chain (Tordesillas, Hunt & Shi, Gran Mat 11)**

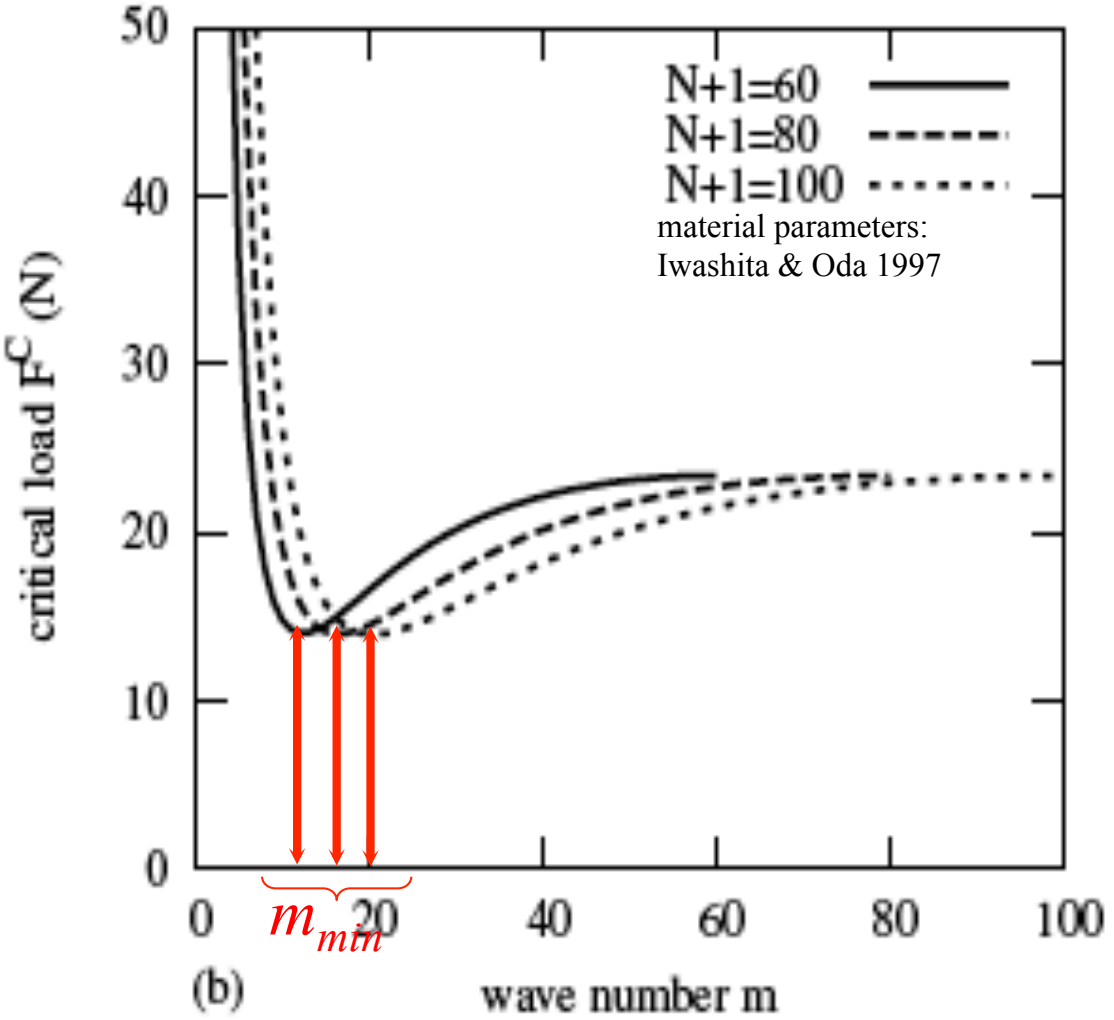
- Collective localized buckling of a lattice of force chains (Tordesillas, Shi & Tshaikiwsky, IJNAMG 11)



Force chain: N+2 particles

Critical buckling load F^c_{min}





Hunt, Tordesillas, Green & Shi, Philosophical Transactions R Soc A 10′

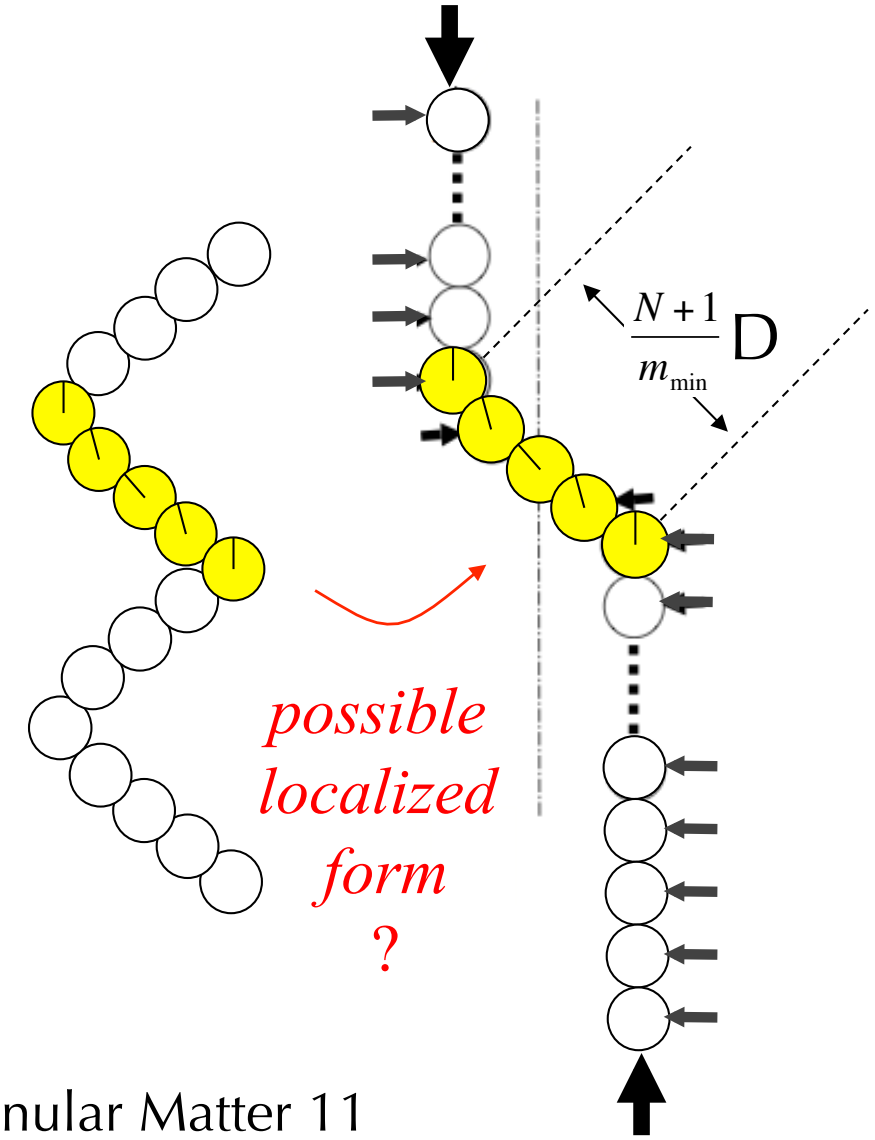
How critical is critical buckling mode m_{min}?

- Normally ….

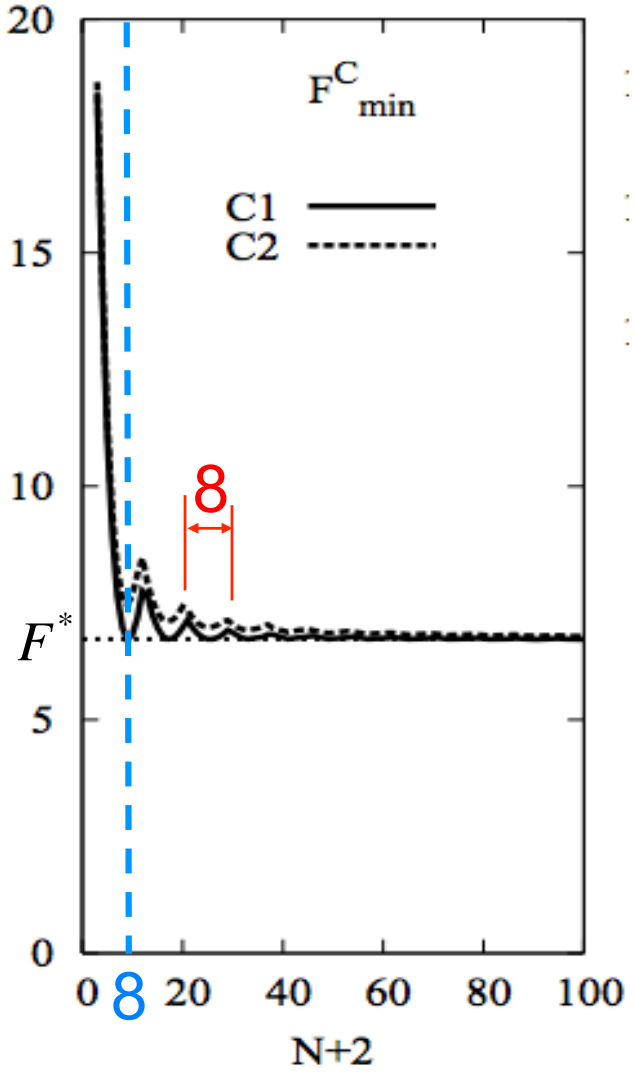
this critical mode is not 'critical' in postbuckling regime!

- Segments exhibit shear band kinematics, **each of length (N +1)/m_{min}** x D

D=particle diameter



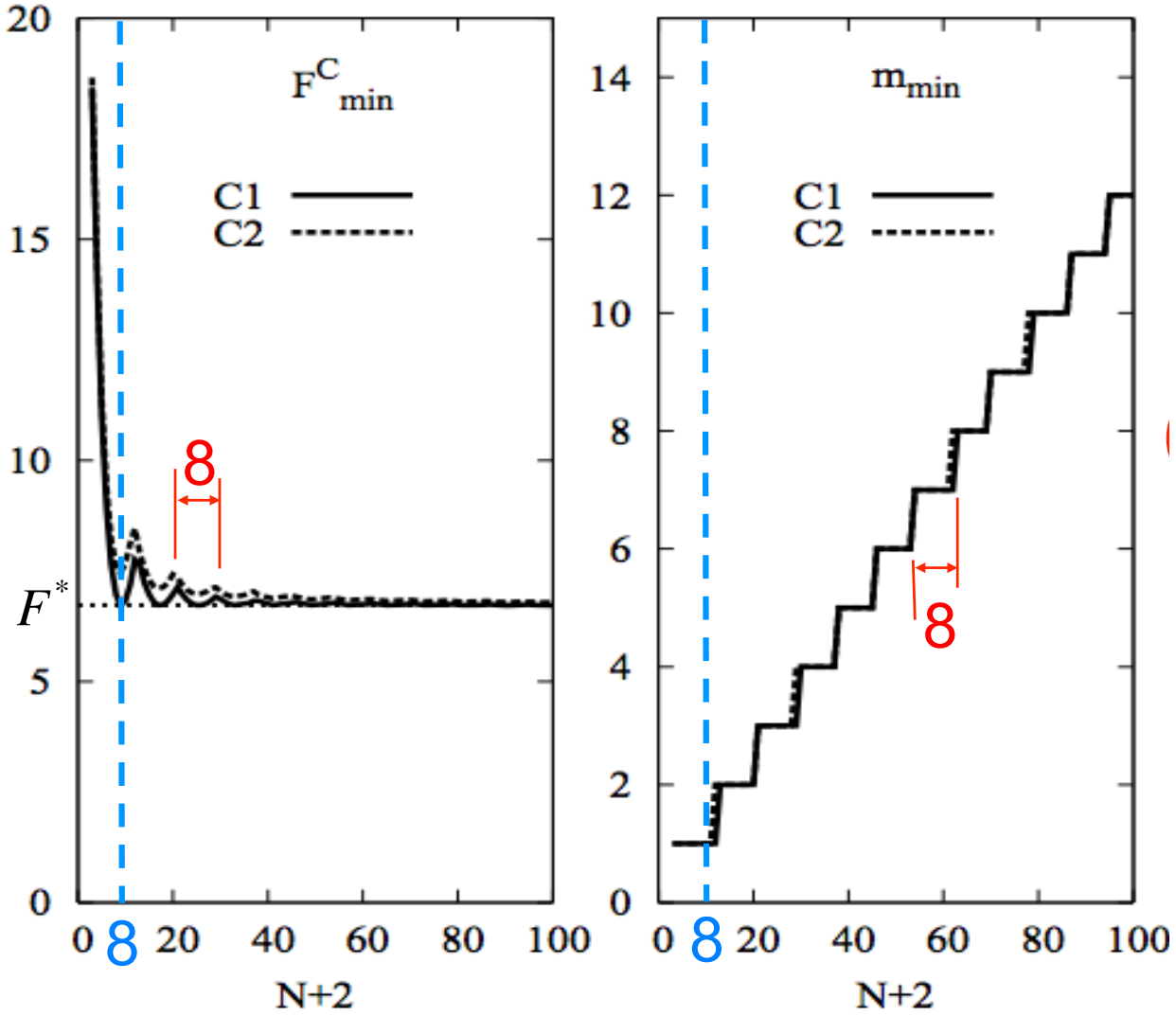
Characteristic load-carrying capacity



For this set of material parameters, longer force chains will buckle at essentially the same axial load needed to buckle a force chain of length 8D.

Shear band width ~ 7-10 x mean diameter Iwashita & Oda 1997

Characteristic load-carrying capacity & thickness

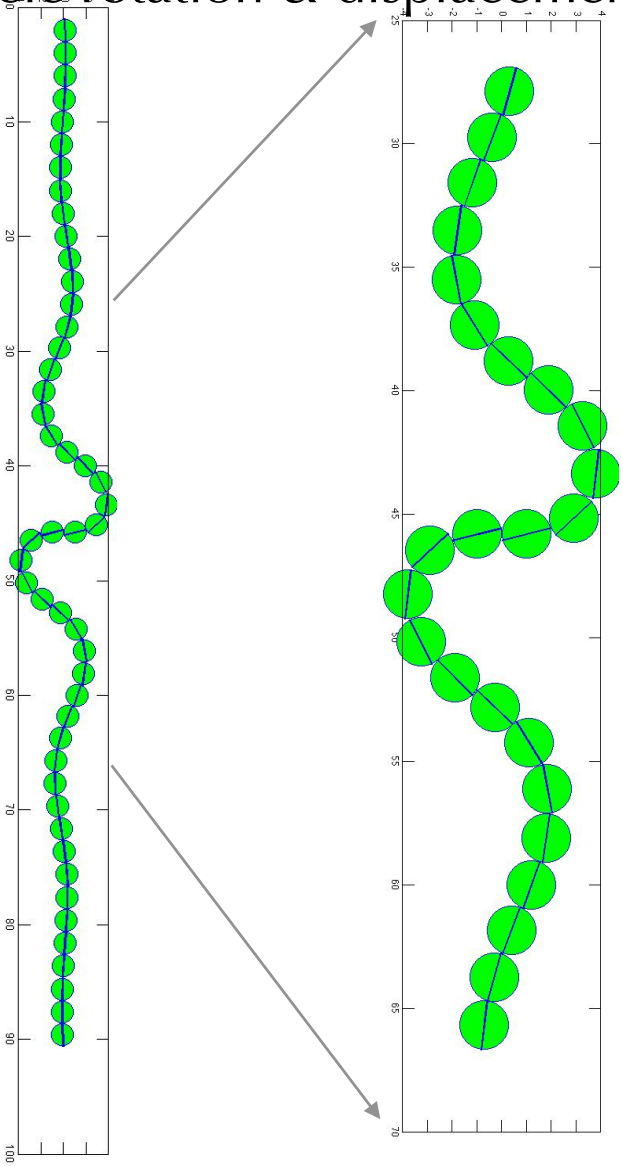


$$\left(\frac{N+1}{m_{\min}}\right)^{*} = ?$$

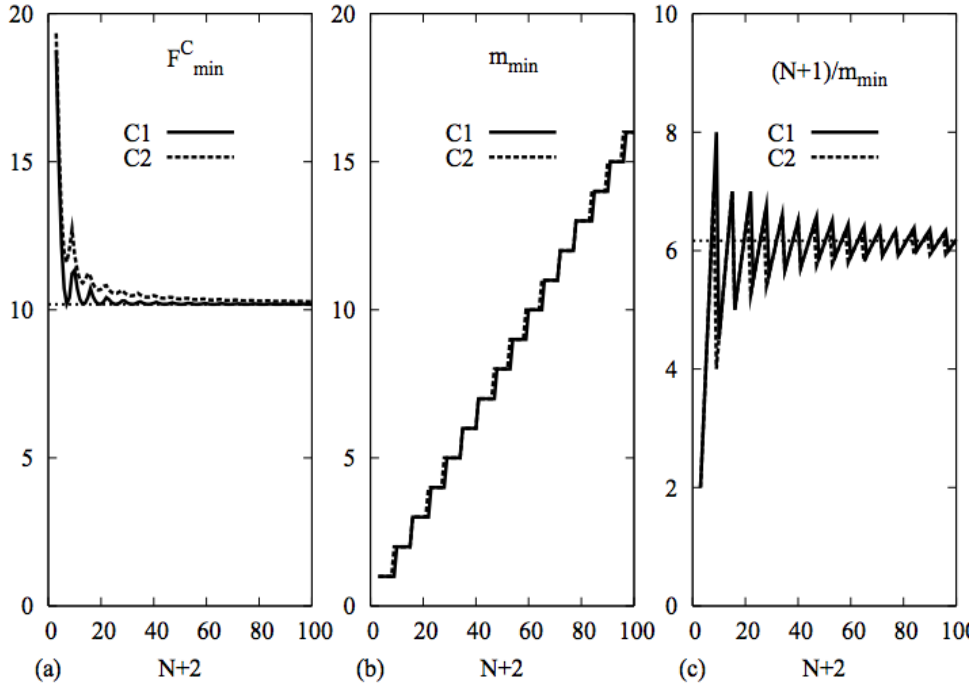
Shear band width ~ 7-10 x mean diameter Iwashita & Oda 1997

Do force chains show a ‘genetic predisposition’ to undergo localized buckling across several particles?

Particle rotation & displacement



Buckling of force chain with 50 particles, beginning to localize internally; ultimate $(N+1)/m_{min}$= 6 particles



Tordesillas, Hunt & Shi Granular Matter 11

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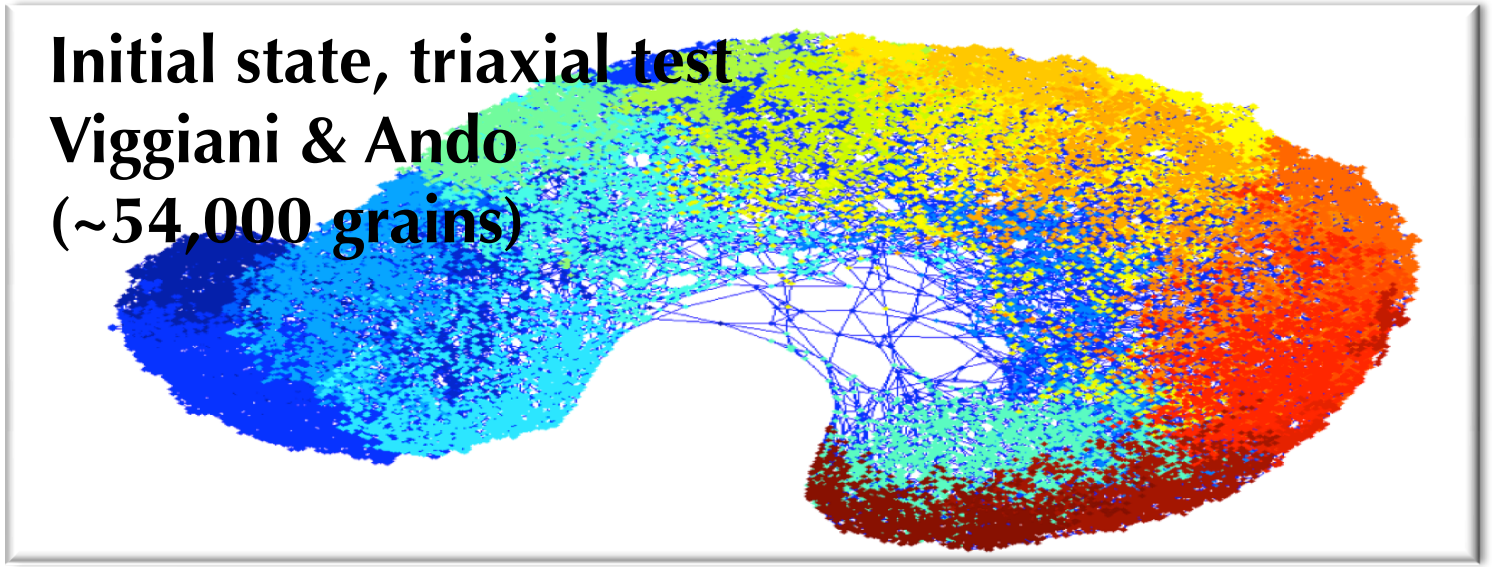
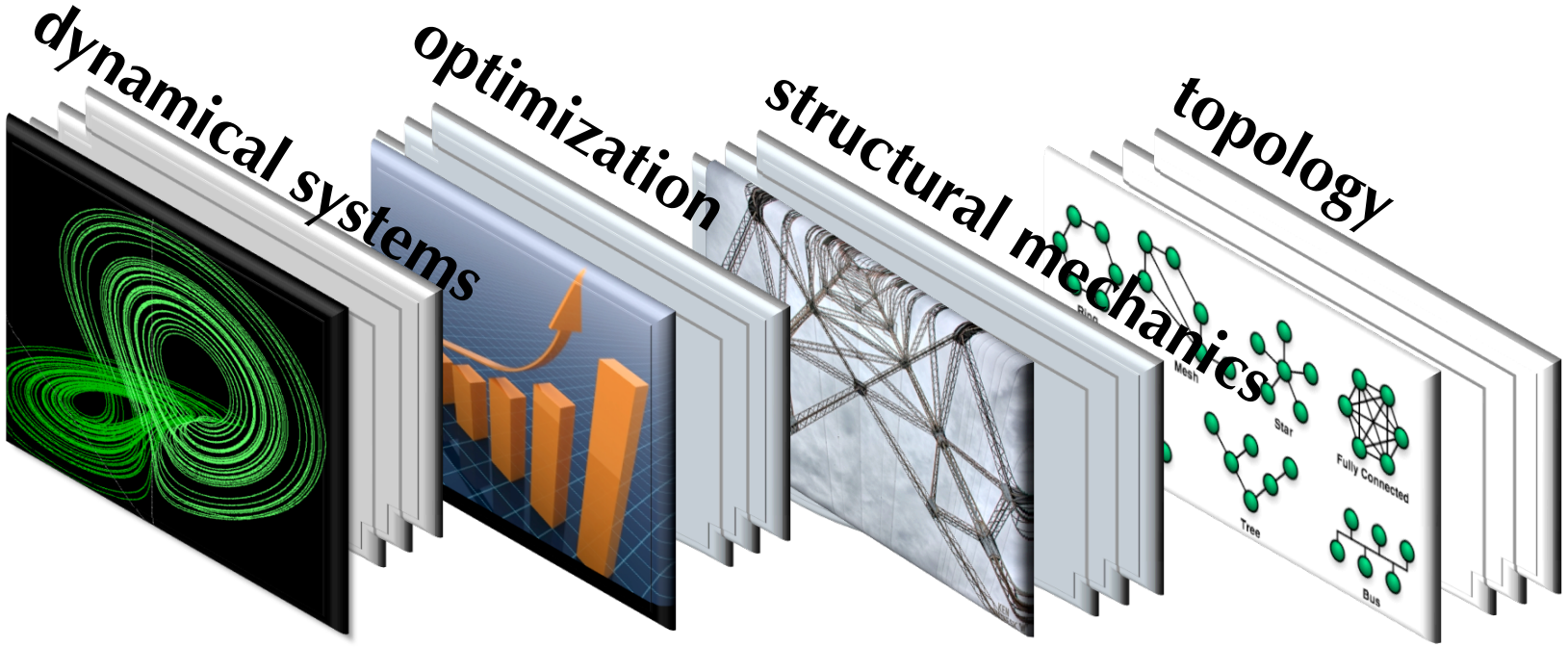
Complex Systems: Our Approach

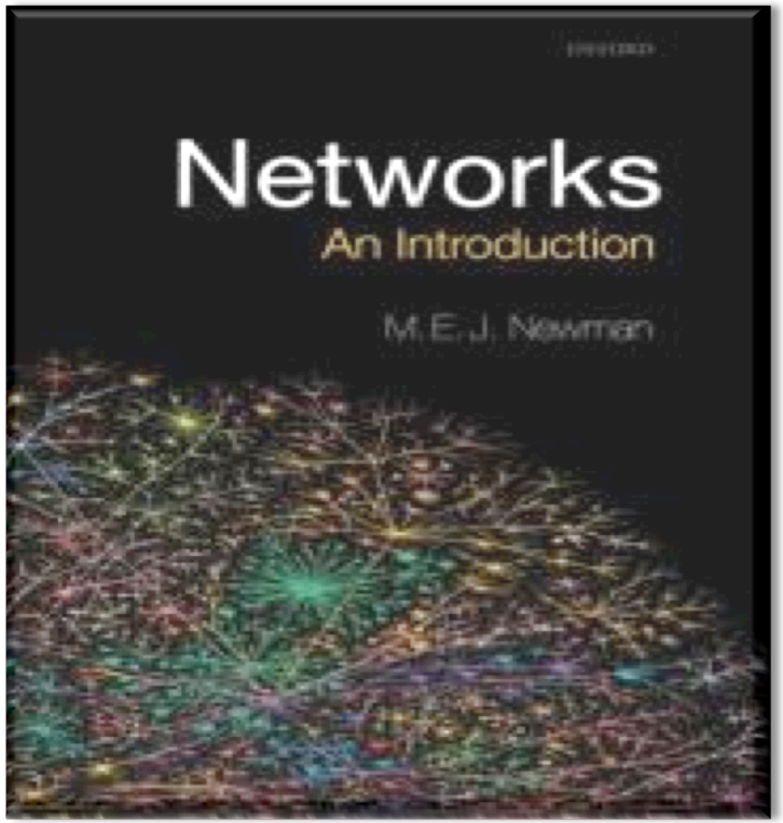
Stage 1

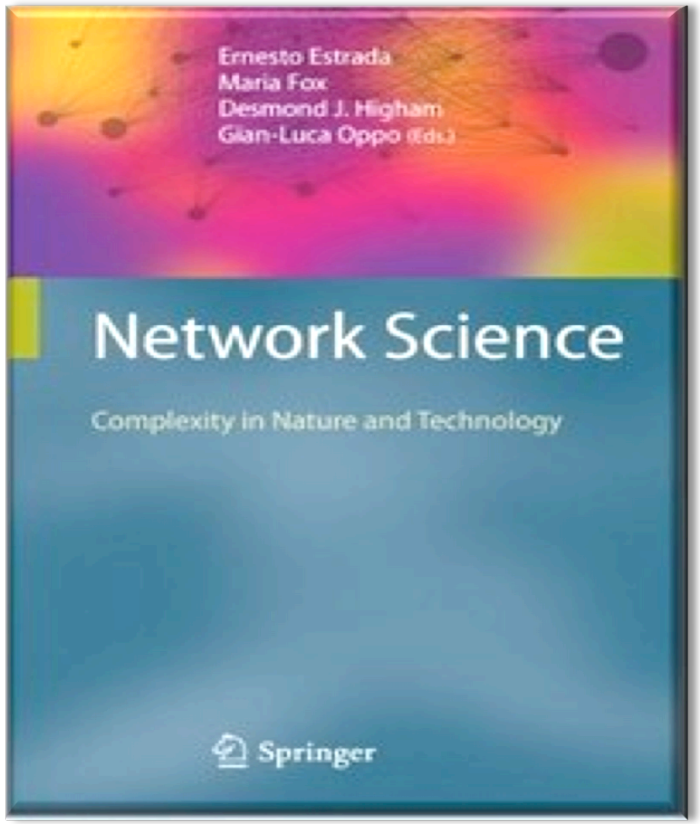


Stage 2



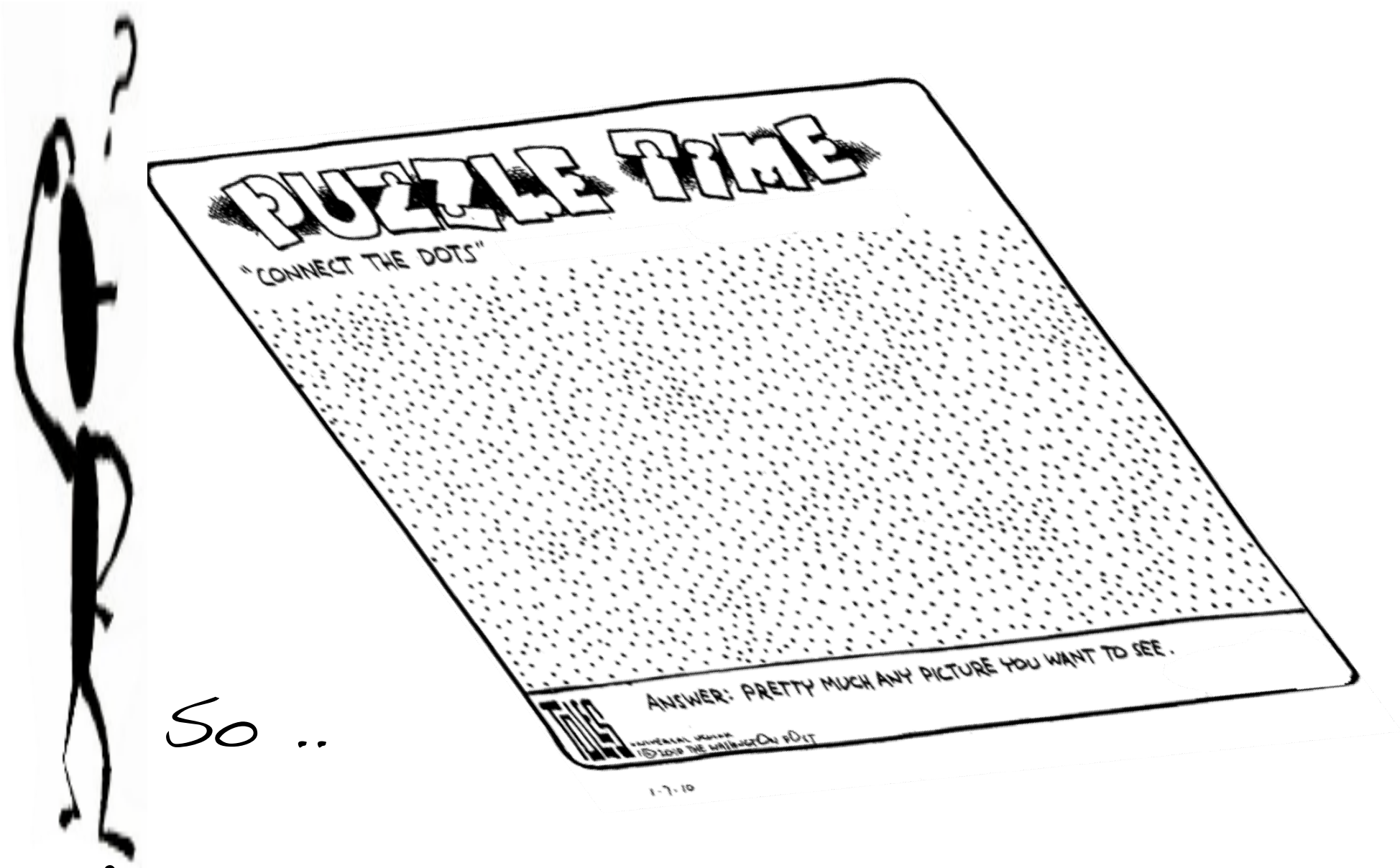
Complex Networks: graphs of complex systems





❑ ***The Structure of Complex Networks: Theory & Applications by E. Estrada*** *Coming Soon! (Oxford Univ Press)*

Connecting dots is too easy – *or is it?*



So ..

What do you want to see?

Initial state of Hostun: 54,000 dots

Internet

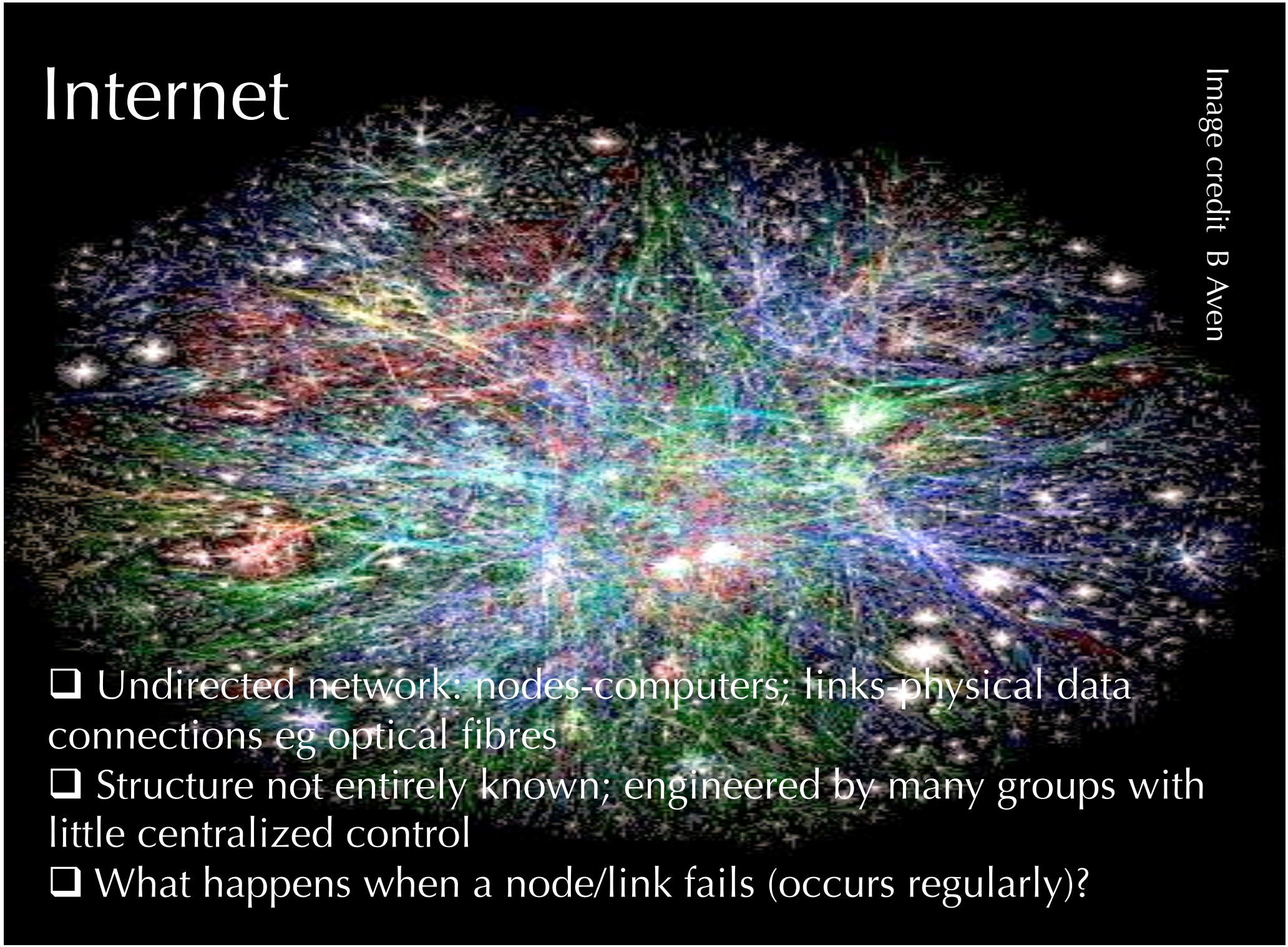
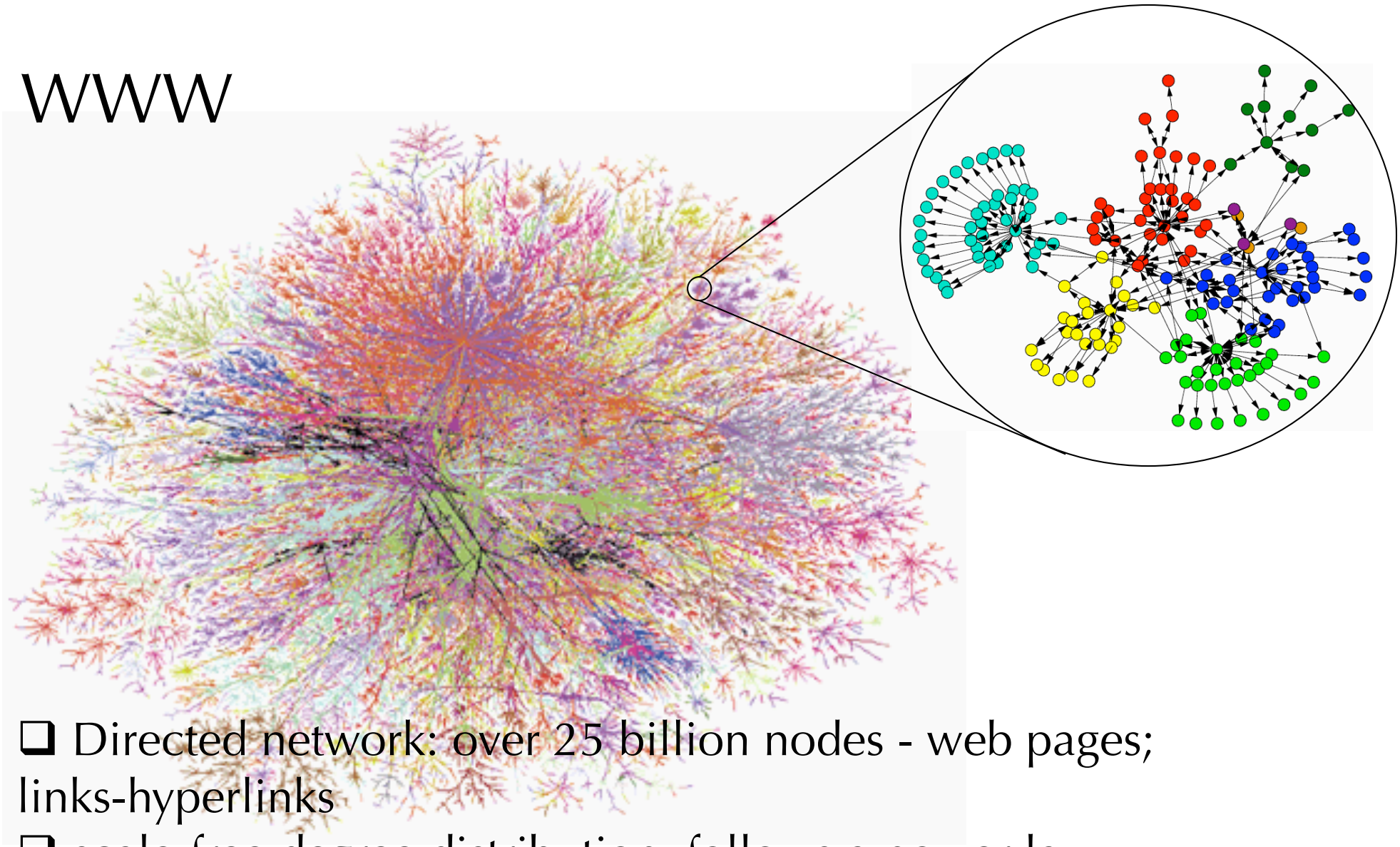


Image credit B Aven

- Undirected network: nodes-computers; links-physical data connections eg optical fibres
- Structure not entirely known; engineered by many groups with little centralized control
- What happens when a node/link fails (occurs regularly)?

WWW



- Directed network: over 25 billion nodes - web pages; links-hyperlinks
- scale-free degree distribution: follows a power law (degree of a node=number of links)
- small-world

Newman & Girvan Physical Review E 04

It's a small world ..

- high clustering (i.e. groups of nodes share many nearest neighbors in common) AND short path lengths between distant nodes (e.g. brain networks)

- **small-world topology: optimized network for information flow,** supporting both segregated and distributed information processing

- extent to which our brain is small-world (tied to high IQ) depends mainly on our genes! Fornito et al *J Neuroscience* 11 (in press)*

- "Six degrees of separation"

The Melbourne Model

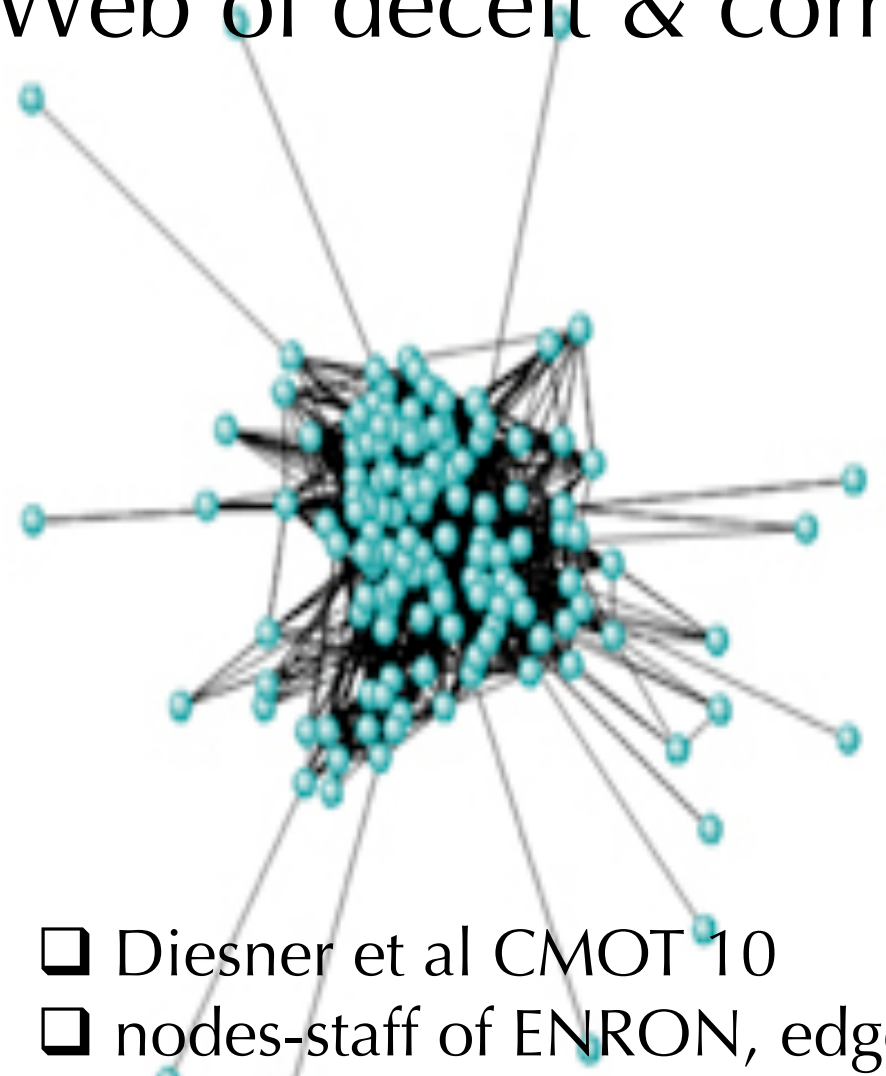
THE UNIVERSITY OF MELBOURNE

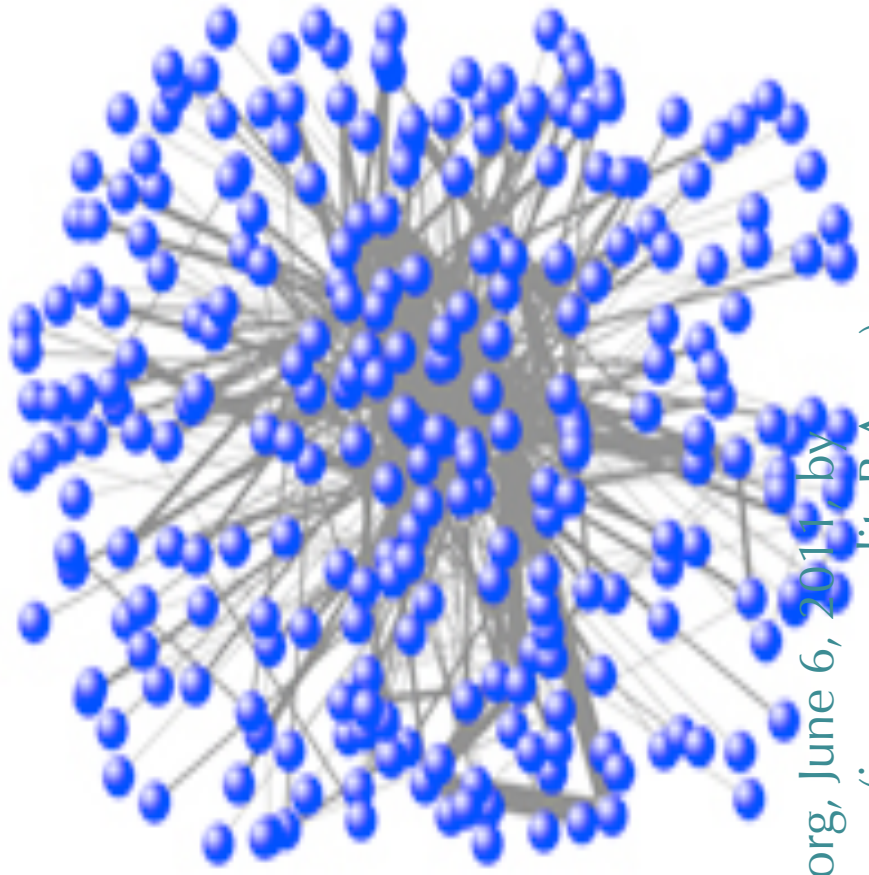
- "In a radical break with its 150-year-old traditions, the University of Melbourne is to be the first in Australia to adopt the model set out in the Bologna Declaration." The Times Higher Education

- US President Barack Obama, Mexico's President Felipe Calderon, British Prime Minister Gordon Brown, Canadian Prime Minister Stephen Harper, South Korea's President Lee Myung-bak, Italian Prime Minister Silvio Berlusconi, French President Nicolas Sarkozy; US Foreign Secretary Hilary Clinton; Pope Benedict XVI; Actress Cate Blanchett.

..within 4 degrees of separation

Web of deceit & corruption

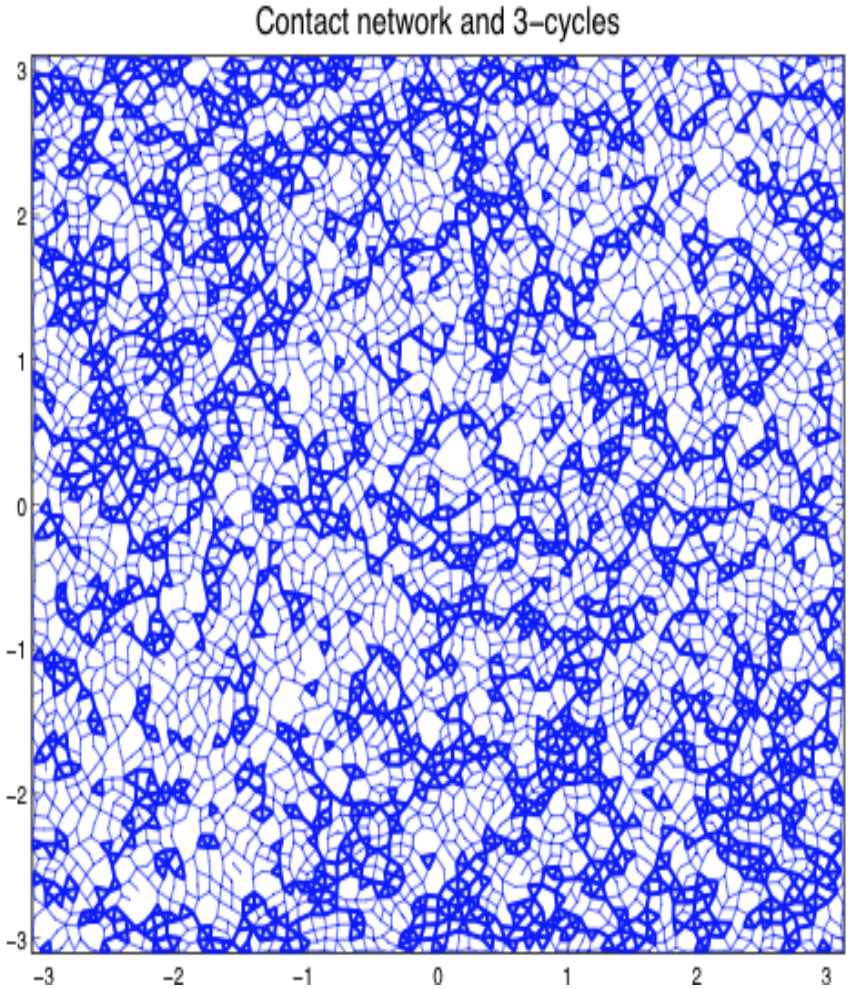




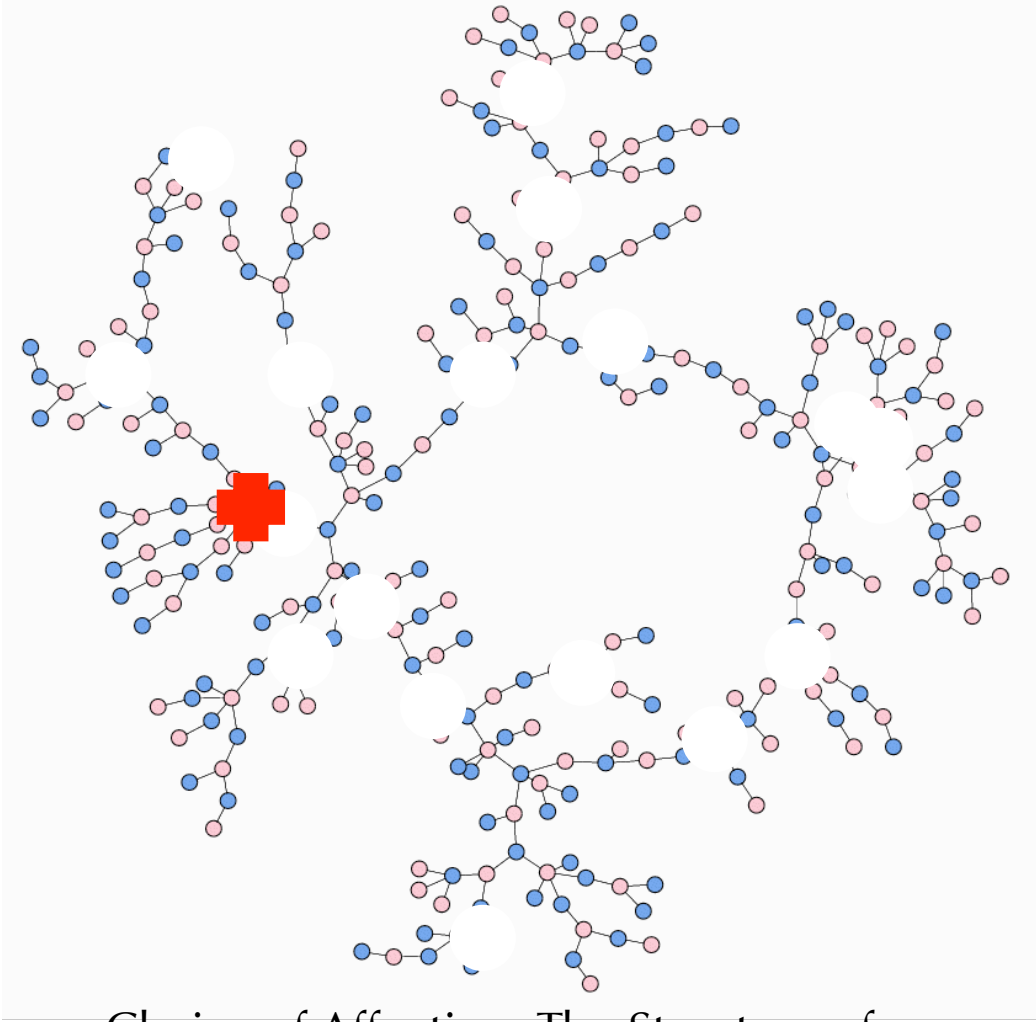
- Diesner et al CMOT 10
- nodes-staff of ENRON, edges-email communication
- legitimate: reciprocal, widely shared information
- illicit: hubs with spokes in isolation, thus less likely to whistle-blow and can be played off each other.

ScienceNews.org, June 6, 2011 by Rachel Ehrenberg (image credit B Aven)

Connections in granular vs sexual networks



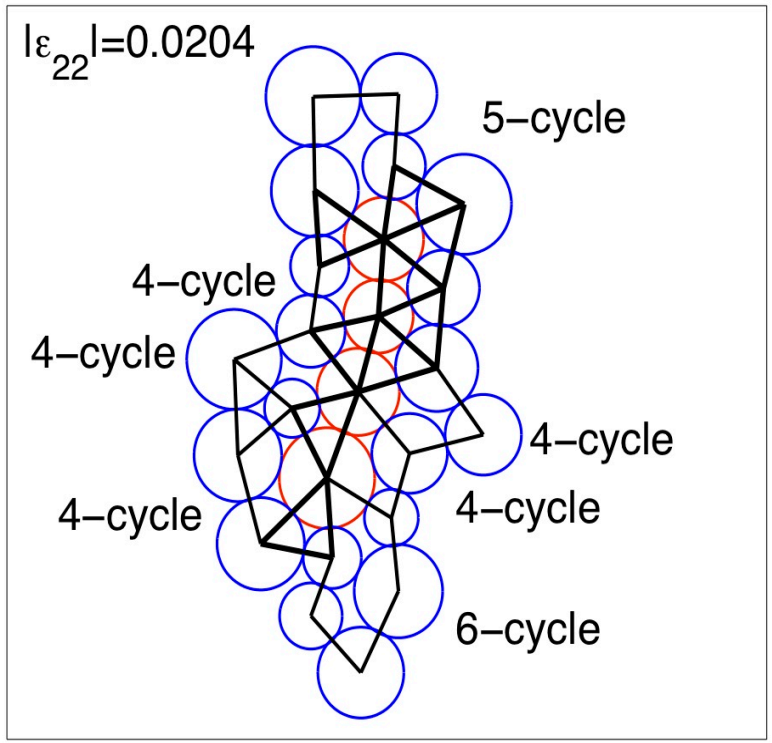
Force cycles and force chains, Tordesillas et al (10)



Chains of Affection: The Structure of Adolescent Romantic and Sexual Networks, Bearman et al (04); M Newman (U Michigan)

Baseline system: 2D DEM, Biaxial test with constant confining pressure, 5098 particles

Dirty grains: tales of selectivity & promiscuity



Force cycles and force chains,
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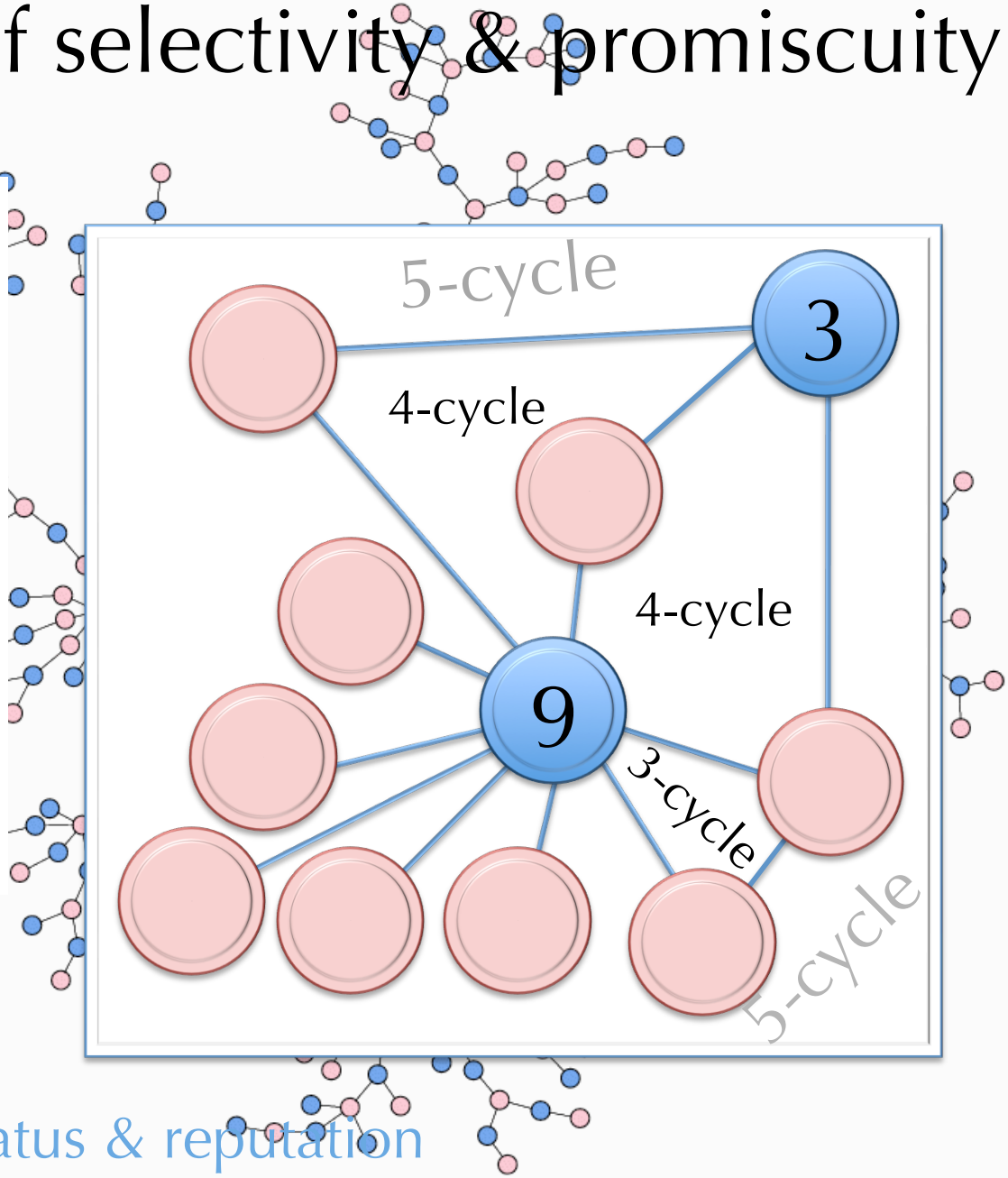

- Stability & survival vs Status & reputation

Baseline system: 2D DEM, Biaxial test with constant confining pressure, 5098 particles

So how do we use Complex Networks to identify the relevant length scales for Hostun sand?