Stick-slip failure in sheared granular materials

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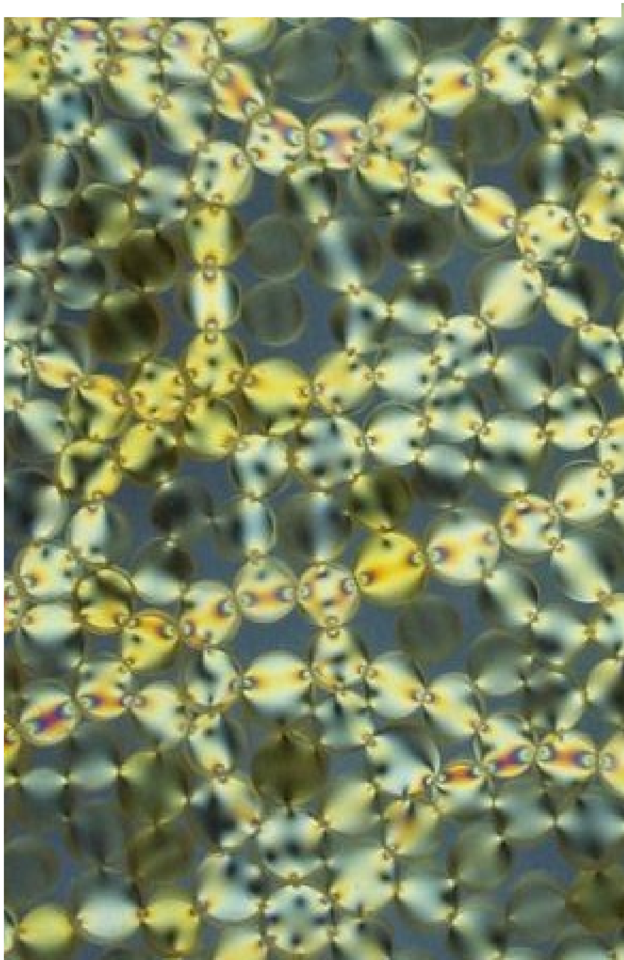
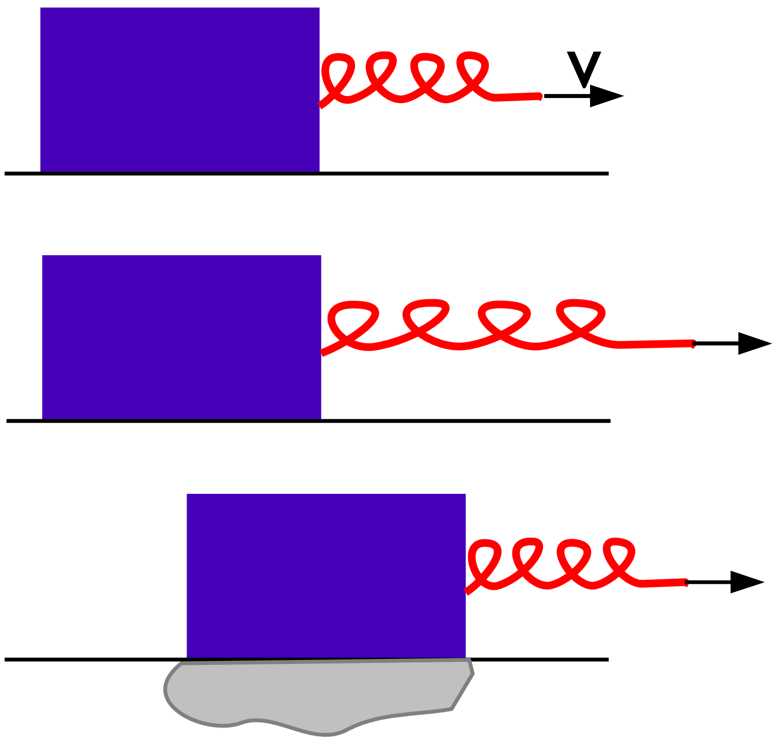
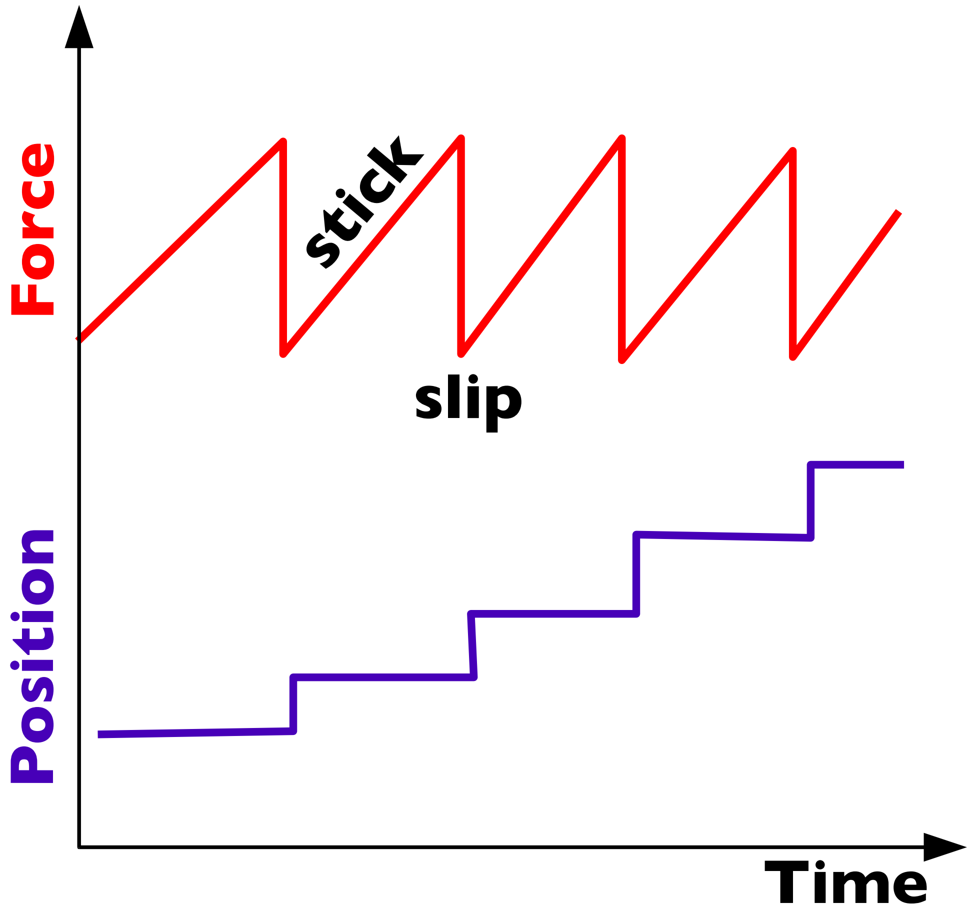


Stick-slip dynamics

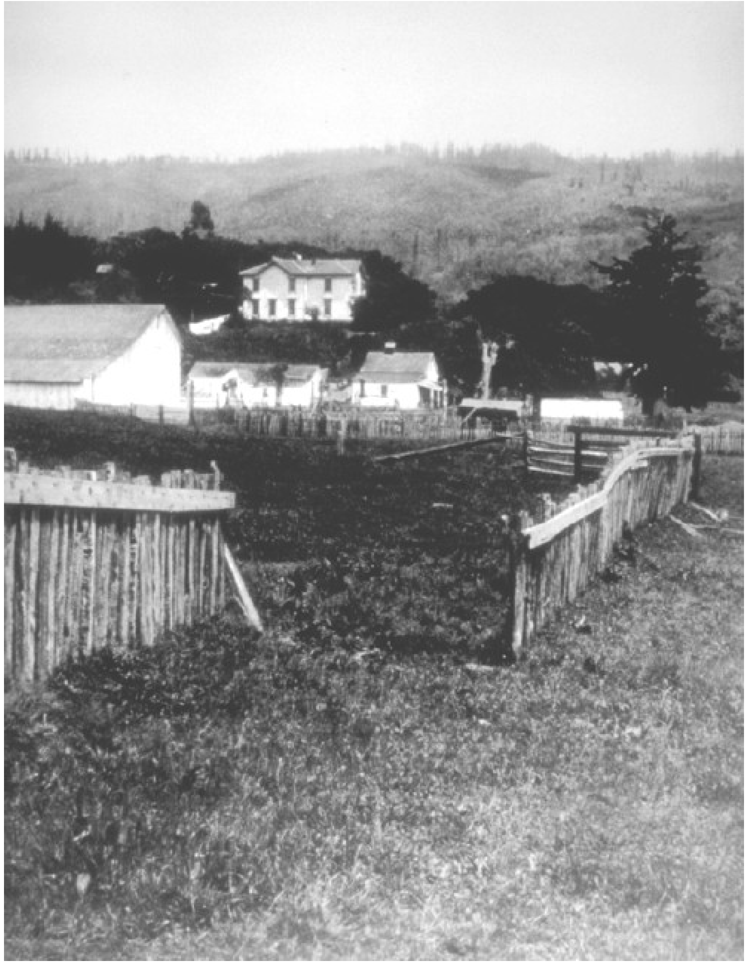




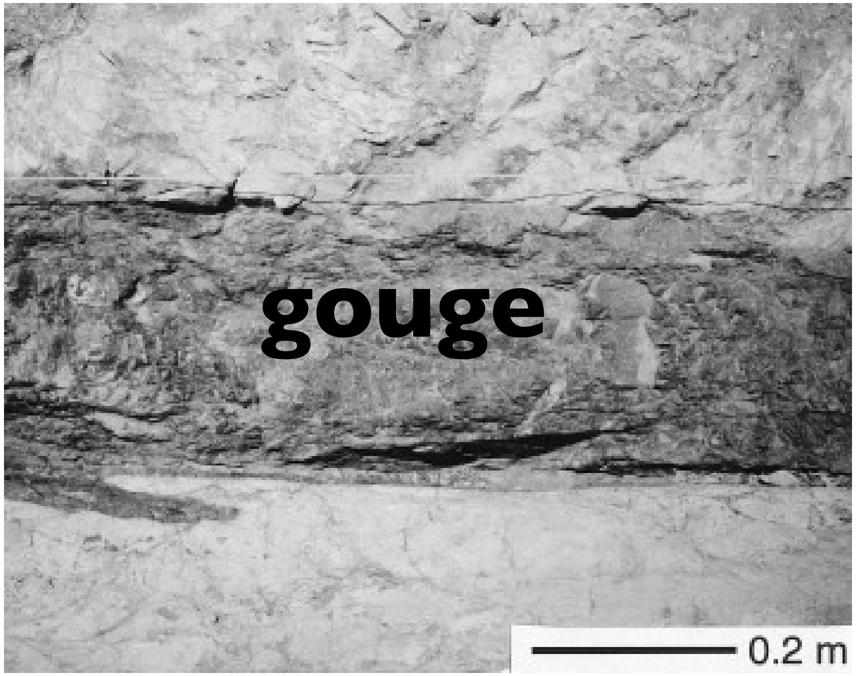
- Stick: slowly evolving state between events
- Slip: block moves then halts during events

Heslot, Baumberger, Caroli et al 1994; Nasuno, Kudrolli, Gollub et al 1998

Stick-slip motion in geological faults



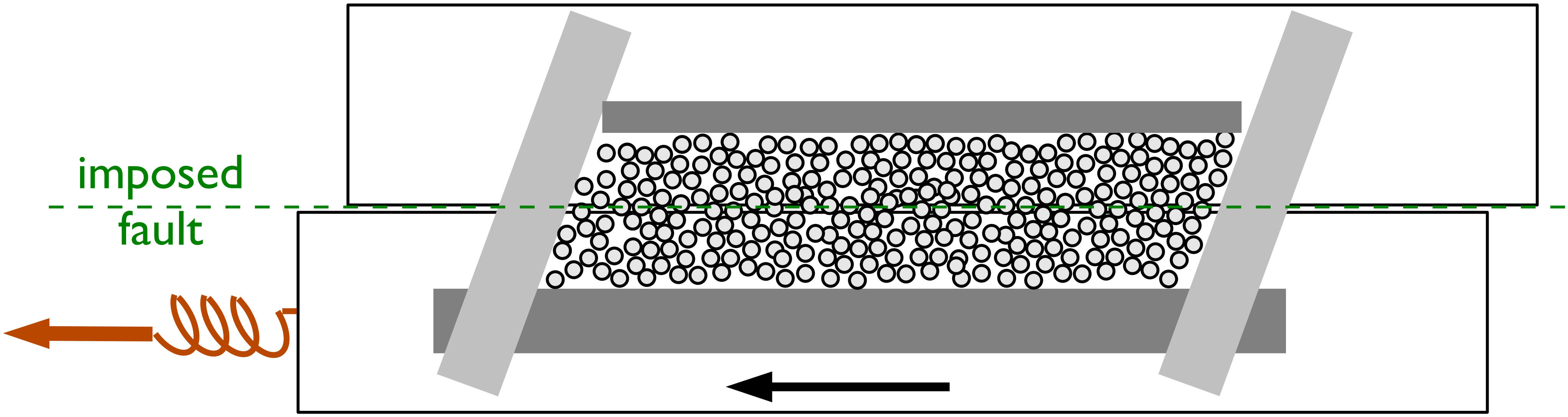
1906 San Francisco earthquake



exhumed Punchbowl Fault
Chester & Chester (1998)

what is the origin of different spatiotemporal patterns of failure?

Granular-on-granular shear



(top view)

"Stick" vs. "Slip"

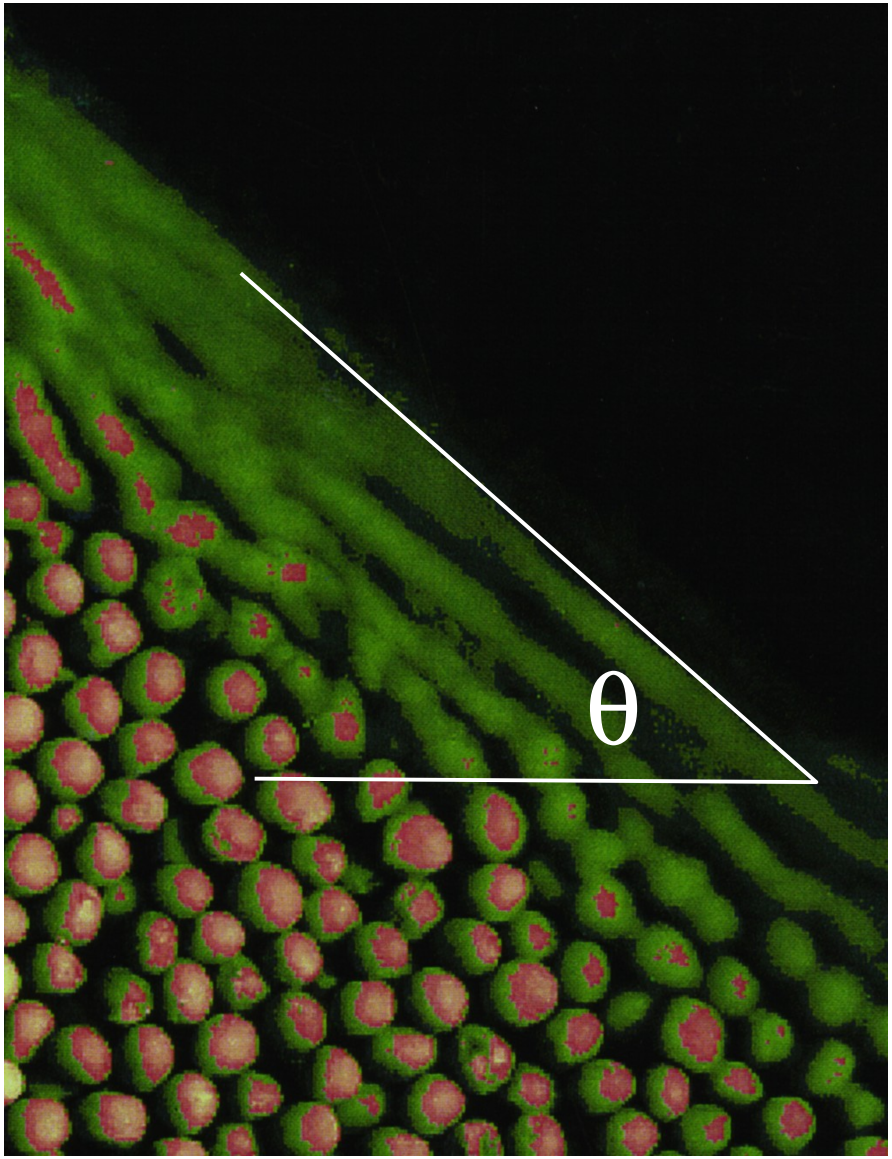
- stress builds up
- slip/failure doesn't occur
  - particle strength
  - interparticle friction
  - geometrical barriers to rearrangement

- stress released
- particles rearrange/~~break~~
- energy dissipated through friction, sound
- dissipation eventually arrests process

Granular friction

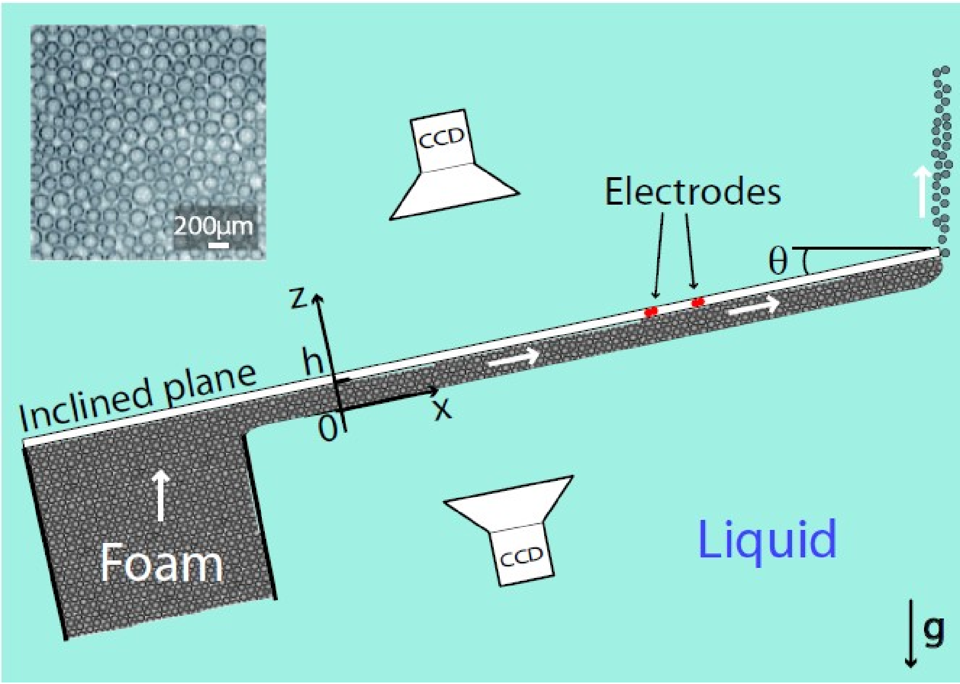
angle of repose

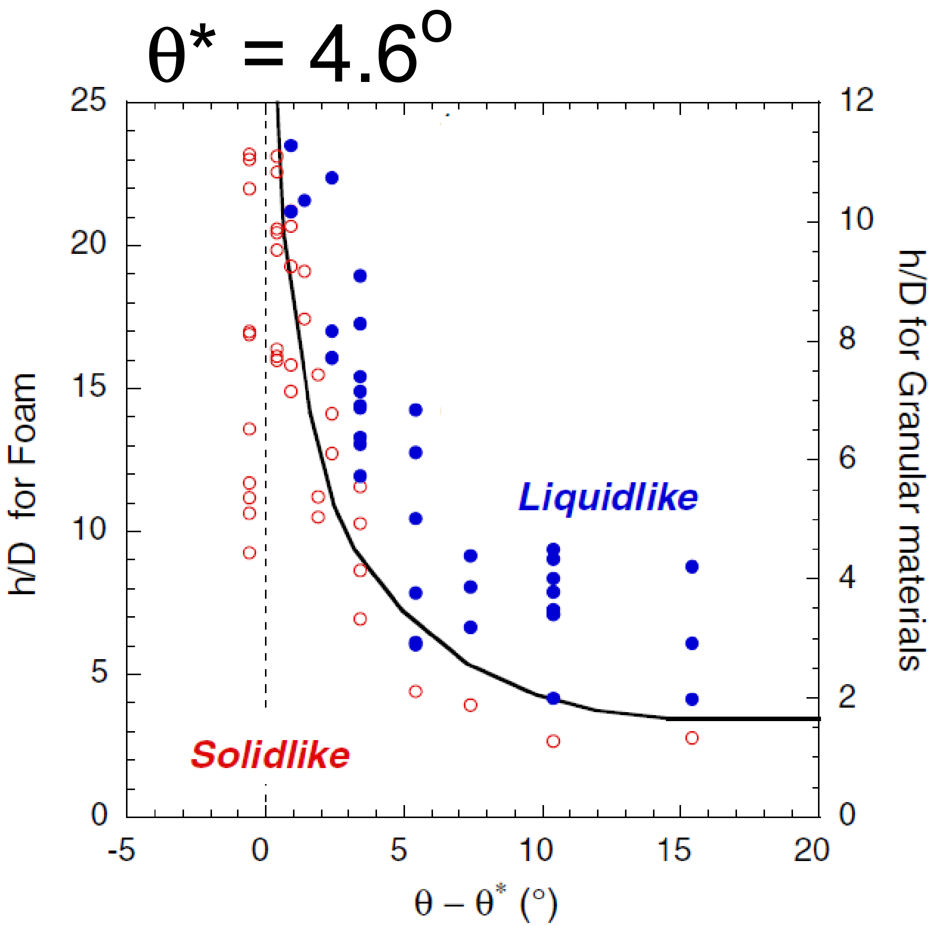
$$\mu = \tan \theta$$



Physics Today cover (1996)

Friction without Friction

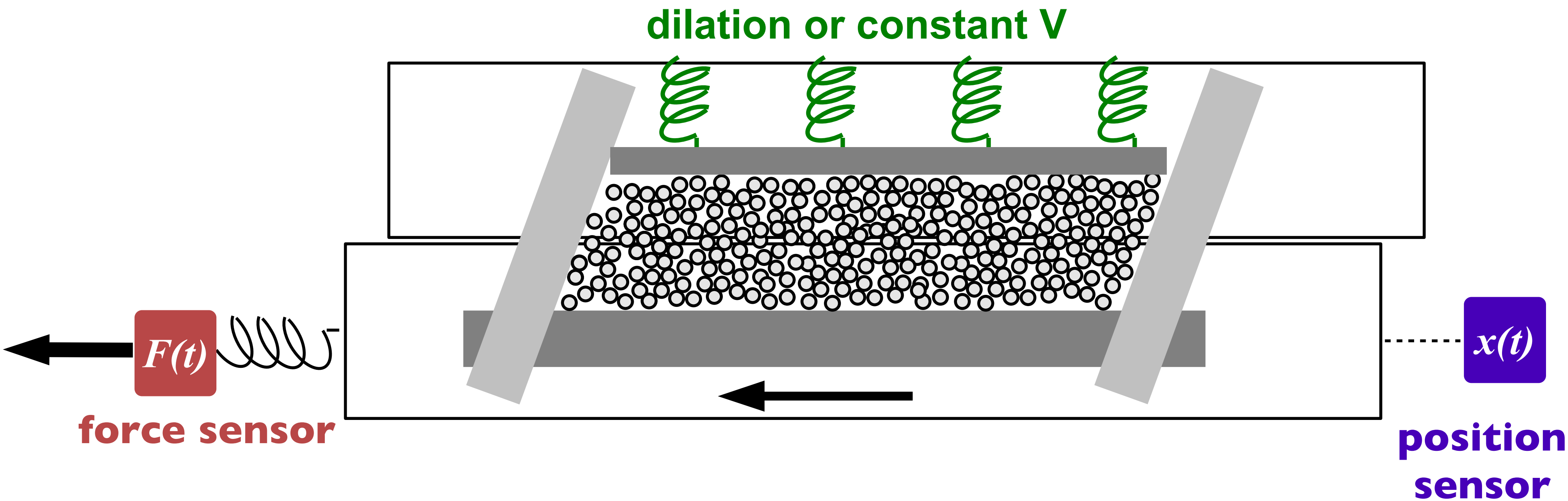




<u>frictionless</u> angle of repose

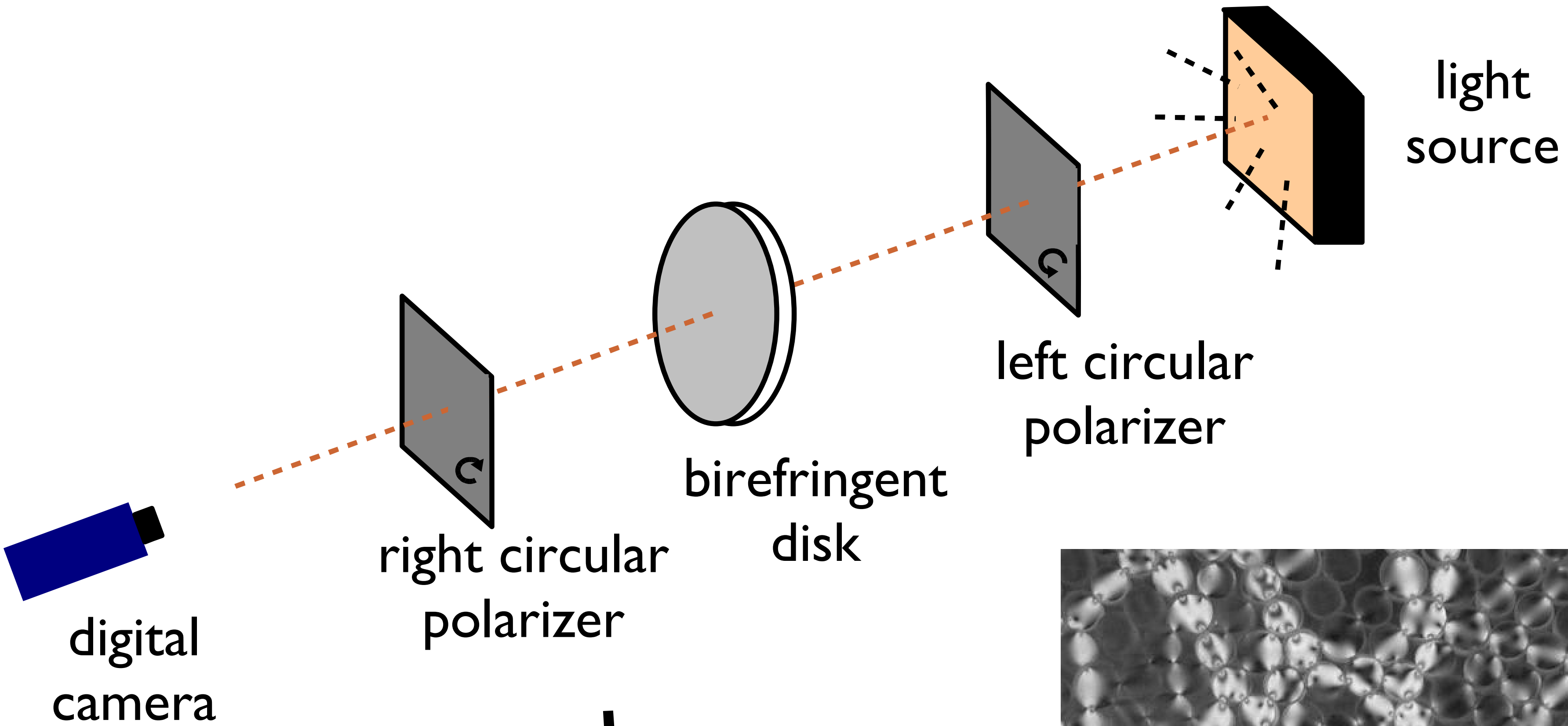
Lespiat, Cohen-Addad, and Höhler. PRL (2011)

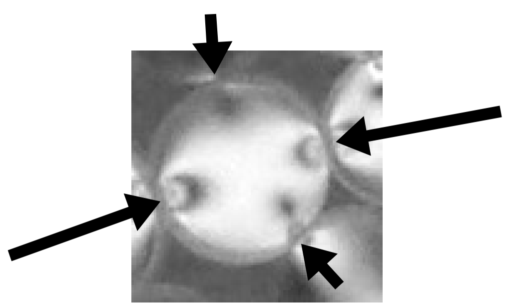
Granular-on-granular shear

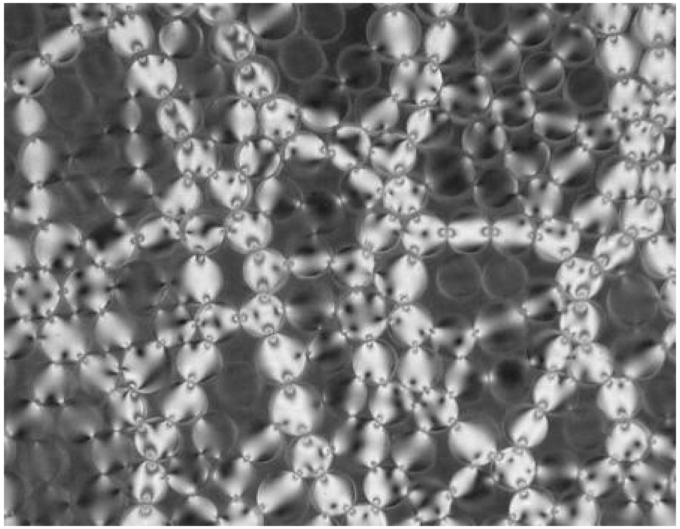


- ~10^4 photoelastic particles fill shearing region
- imposed fault at boundary between front/back halves
- front half driven at constant velocity (spring-coupled)
- vary packing density: $0.80 < \phi < 0.84$ (loose to dense packed)

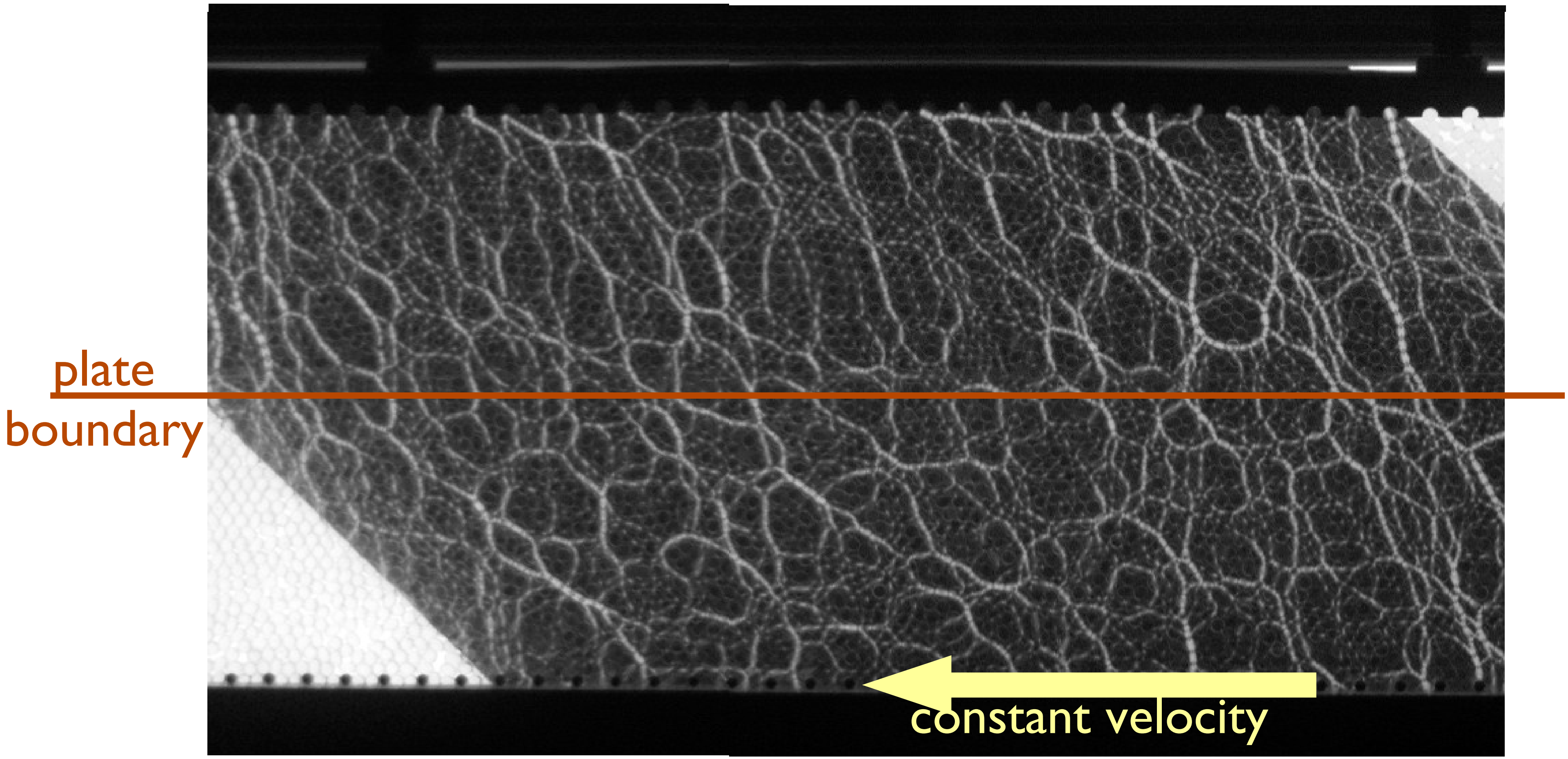
Photoelastic Force Measurements





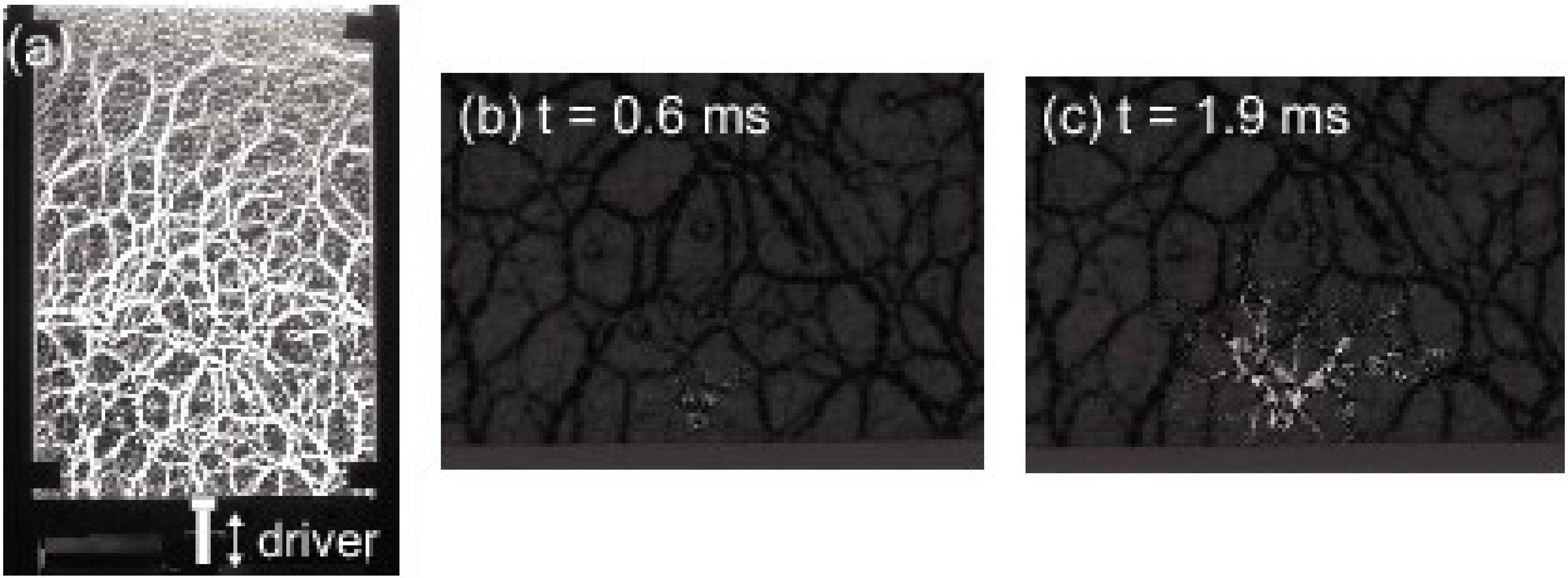


Force chains under shear



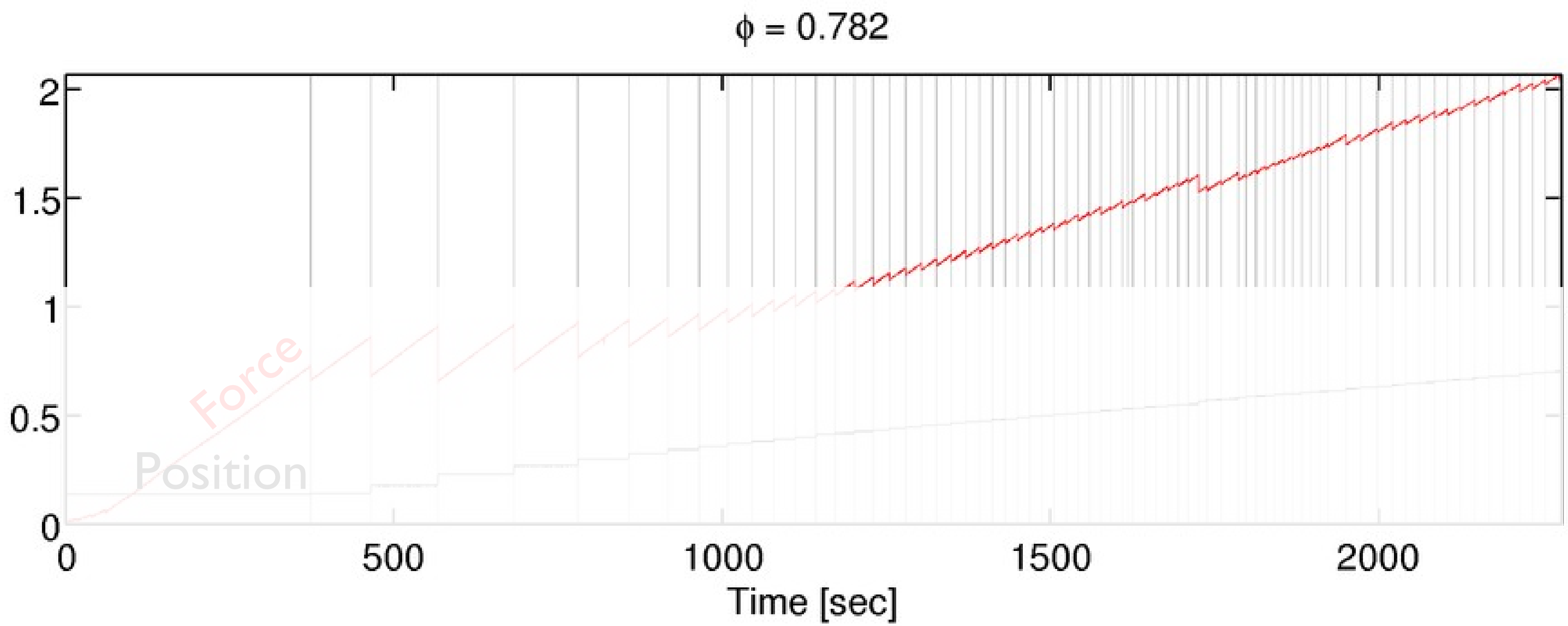
- force chains oppose shear
- ~ exponential force distribution
- longer length scale from force chains

Force chains propagate disturbances



Owens & Daniels, *EPL* (in press)

Stick-slip events

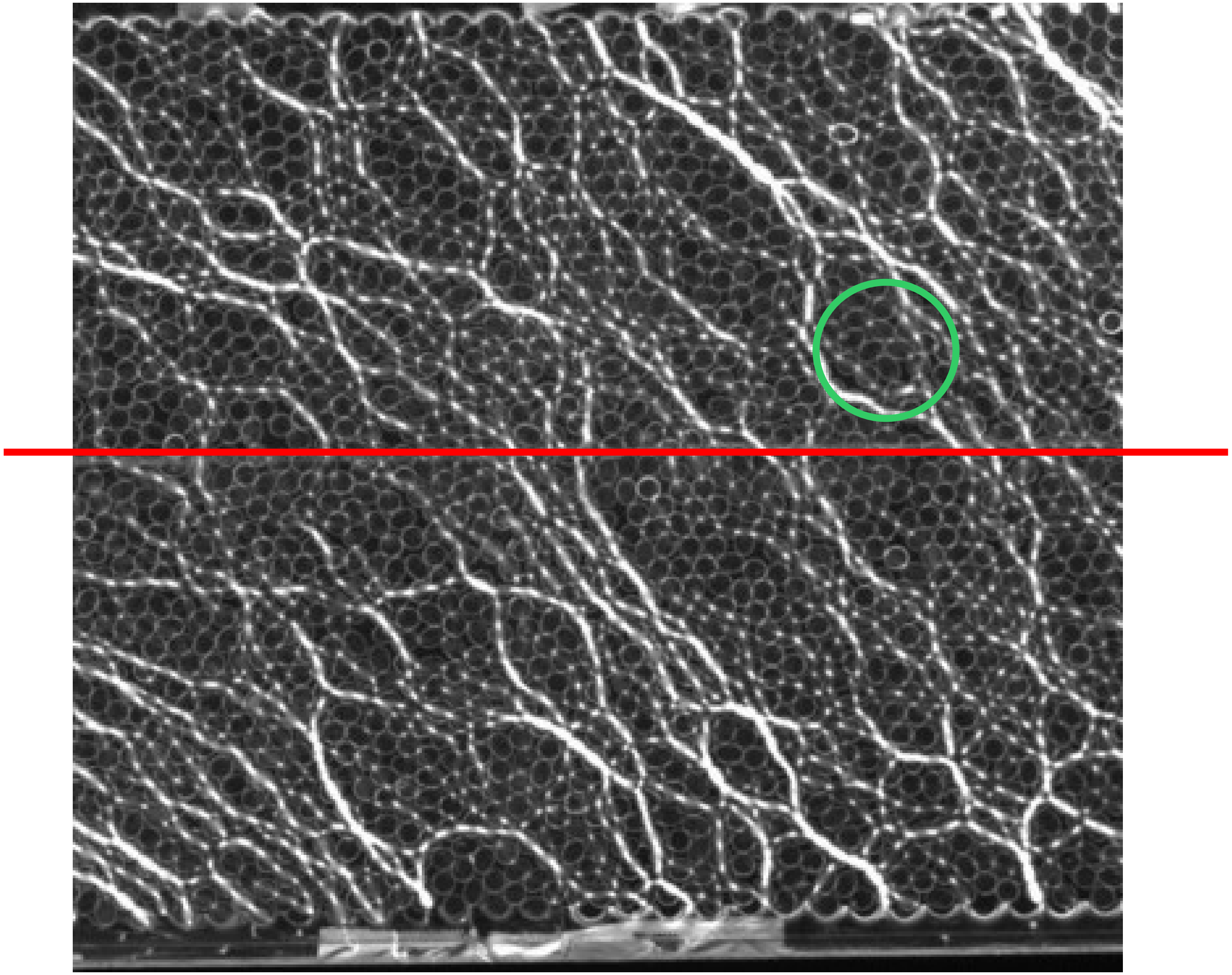


- measure position *x(t)* and pulling force *F(t)* during deformation
- events: rupture full fault → bulk slip + force drop
- use Wiener deconvolution to filter noise

Papanikolaou et al. *Nature Physics*, 2011

$$\tilde{X}(\omega)=\frac{\tilde{x}(\omega)}{h(\omega)}\frac{|\tilde{x}(\omega)|^2}{|\tilde{x}(\omega)|^2+|\tilde{n}(\omega)|^2}$$

Local failures, global effect



Spatial characterization

Track particles

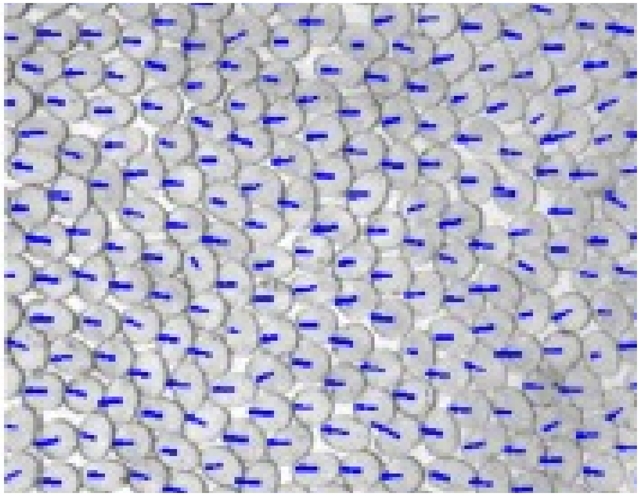
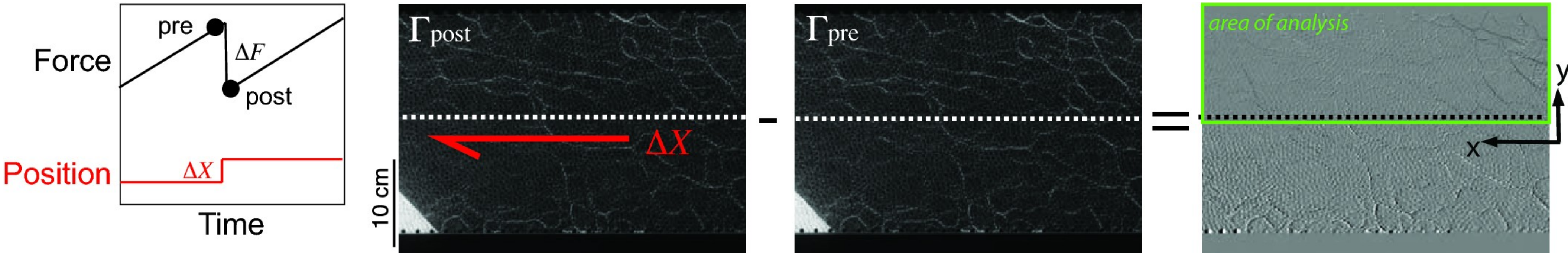
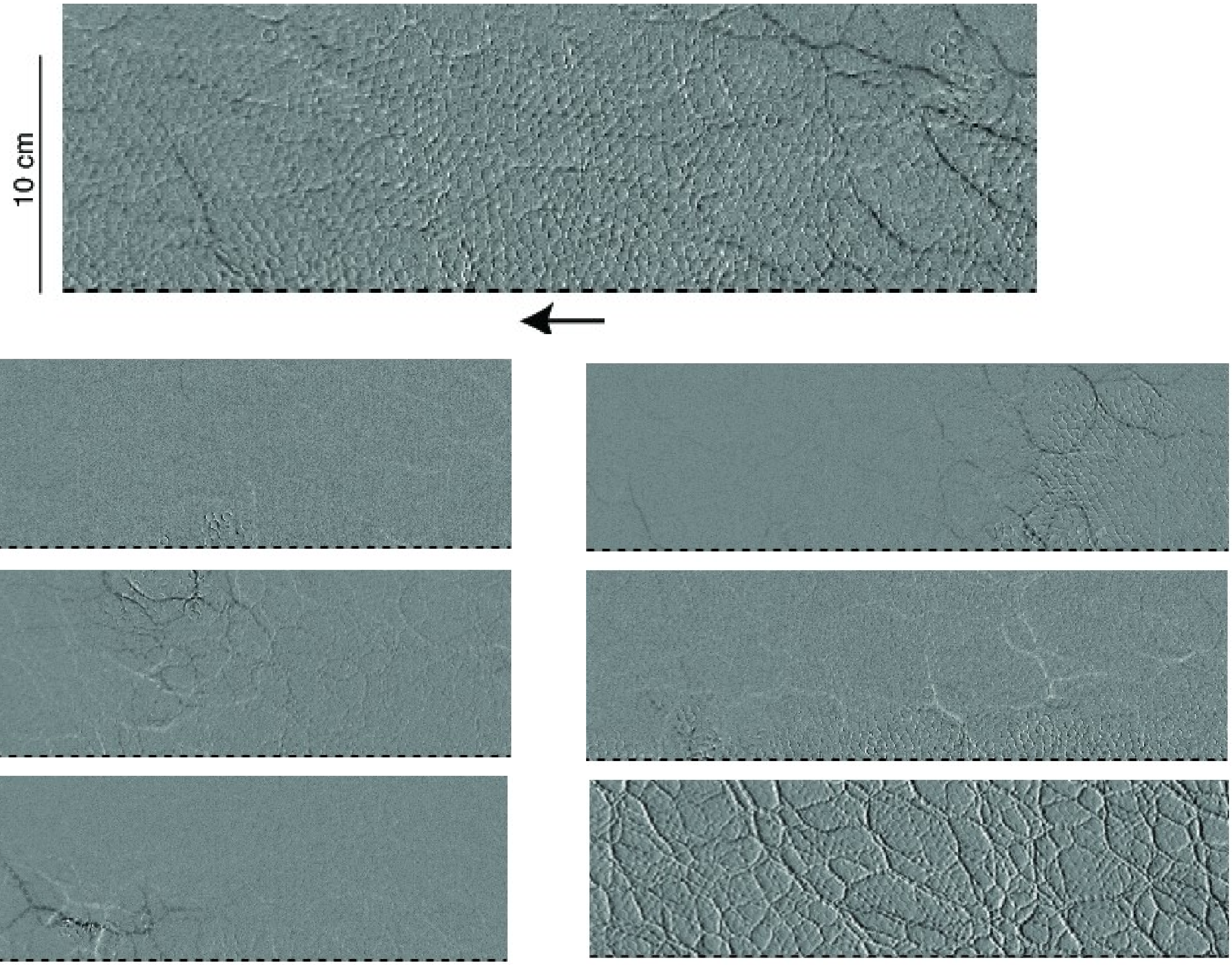


Image-differencing

β = fraction of participating particles



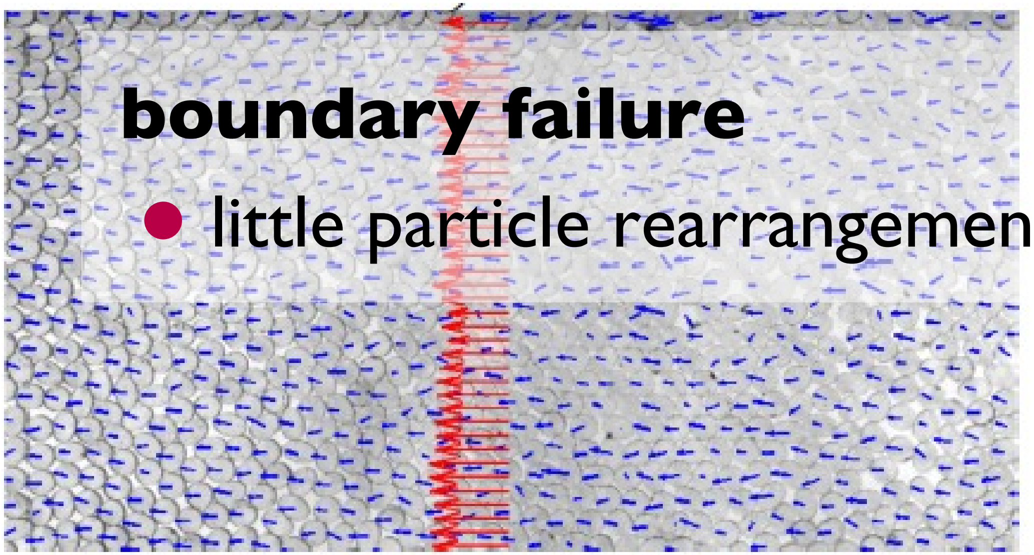


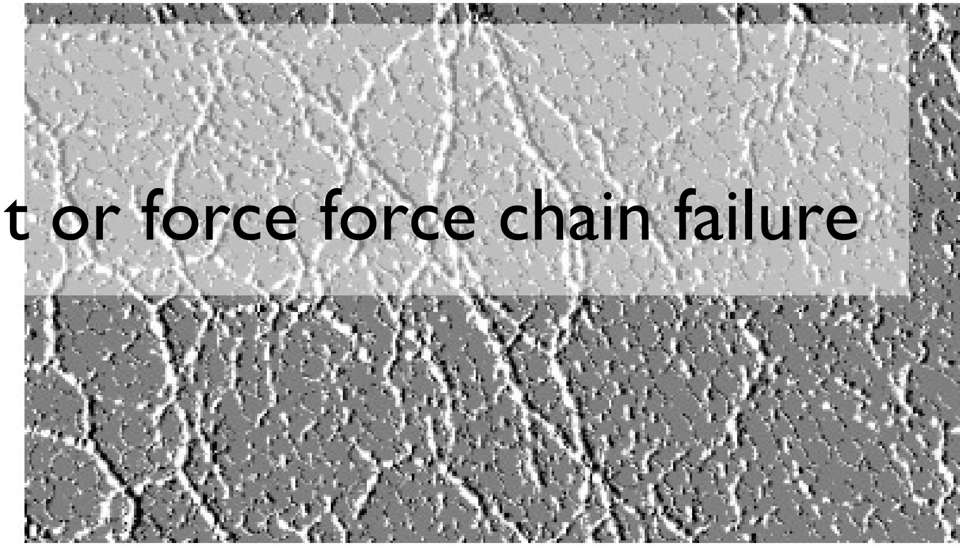
Daniels & Hayman *J. Geophys. Research* (2008)

Particle & force chain dynamics

boundary failure

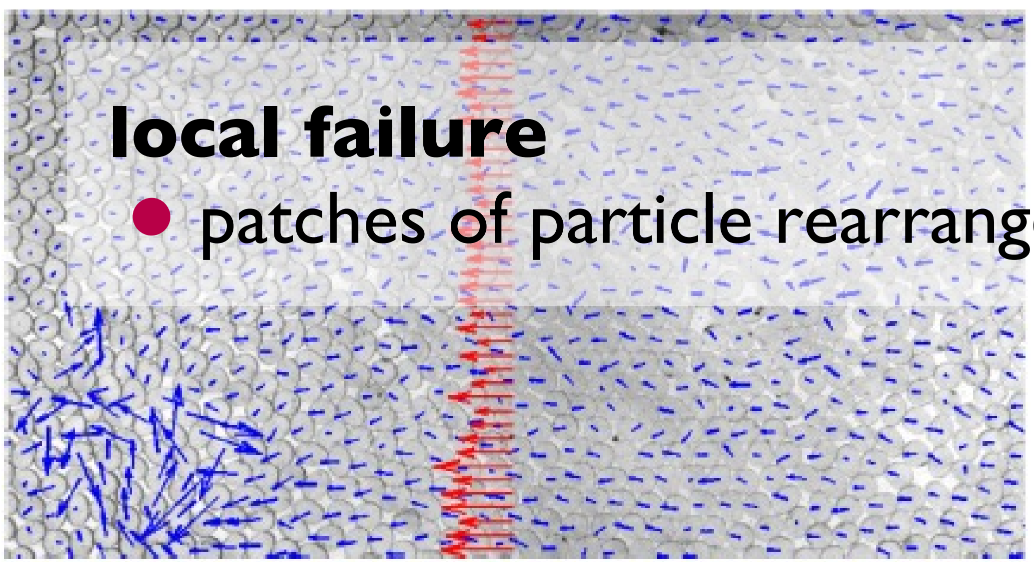
- little particle rearrangement or force force chain failure

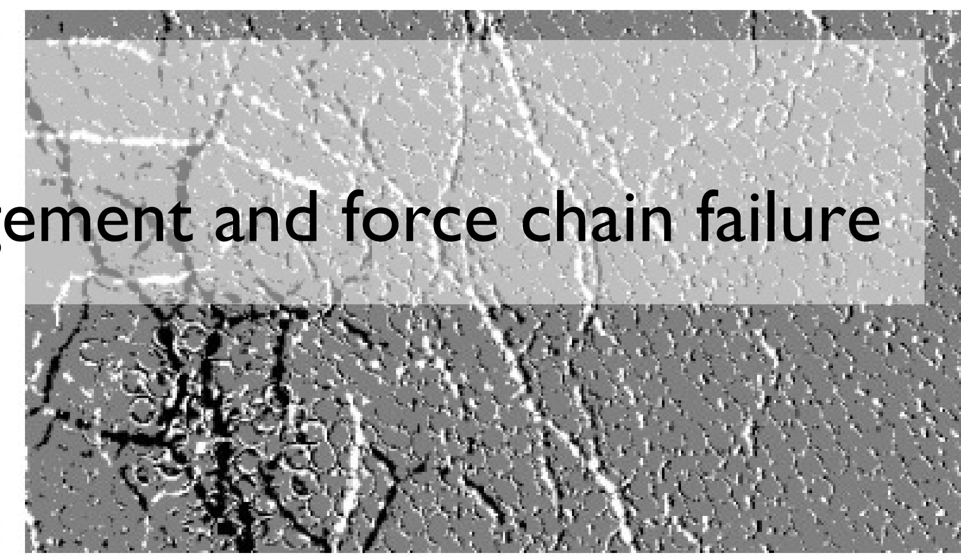




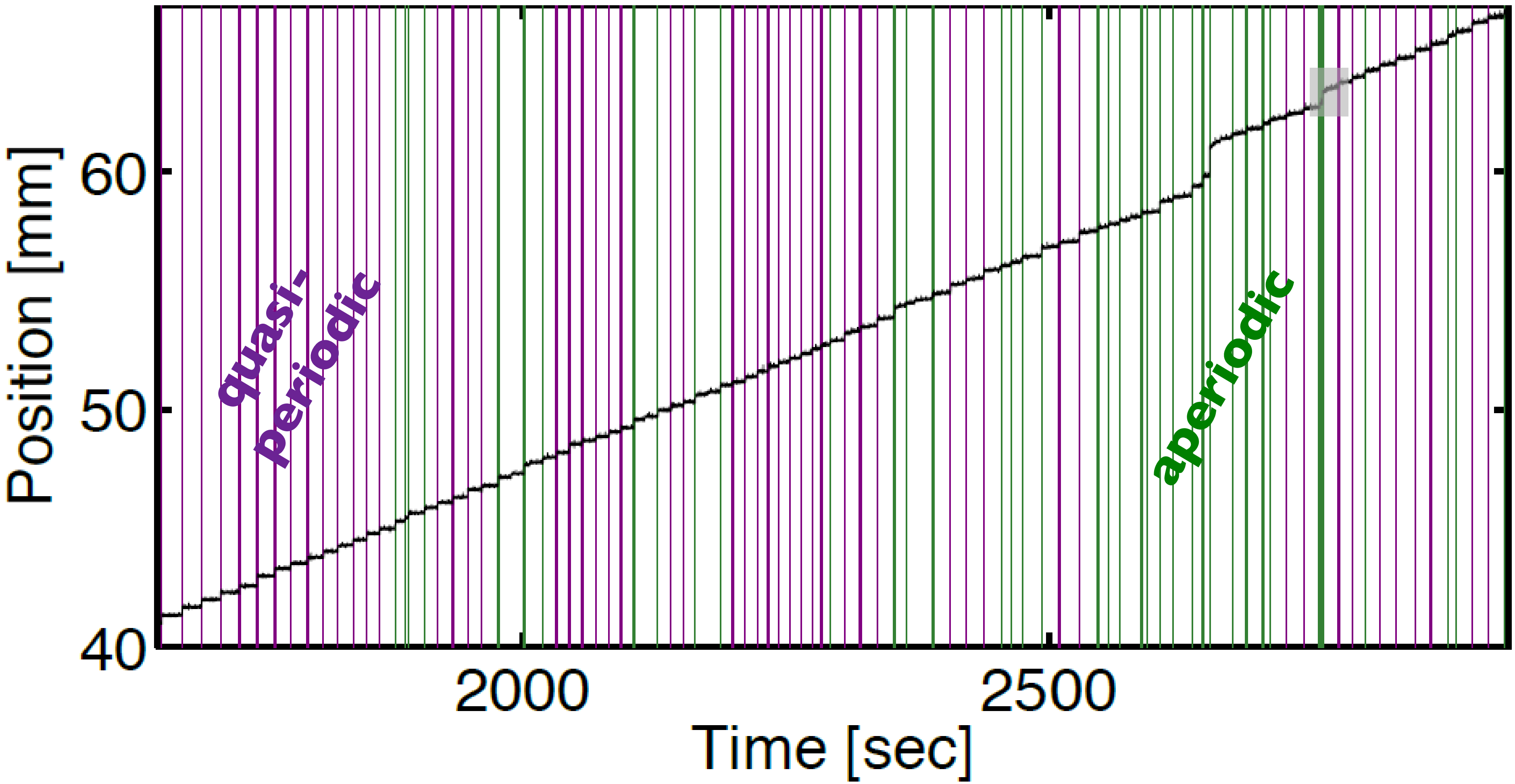
local failure

- patches of particle rearrangement and force chain failure





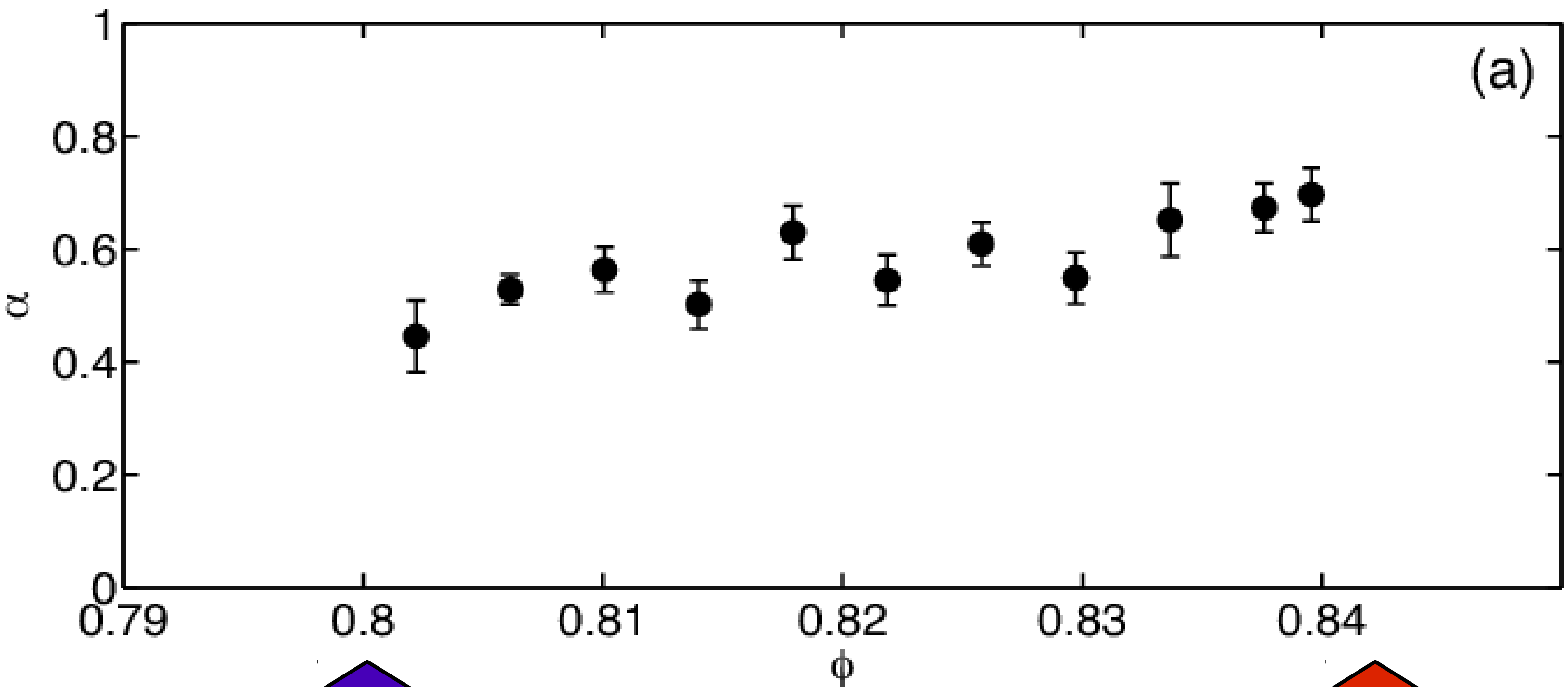
Periodic vs. aperiodic events



Hayman, Ducloue, Foco, Daniels. *Pure and Applied Geophysics* (2011)

Periodicity and packing fraction

fraction of events which are periodic



random loose packing
no mechanically stable random states with $\phi < \phi_{RLP}$
(Onoda & Liniger, 1990)

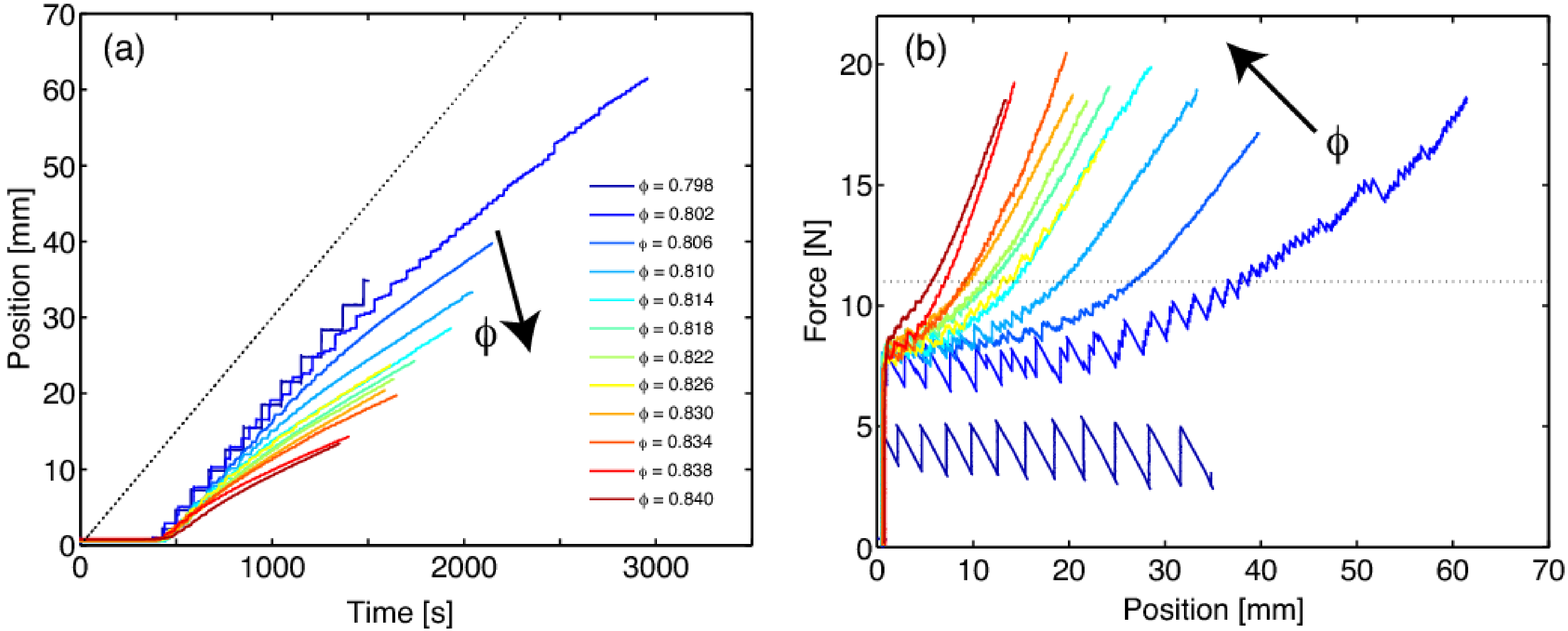
random close packing
can't have $\phi > \phi_{RCP}$ without crystallization
(Bernal, 1960)

Hayman, Ducloue, Foco, Daniels. *Pure and Applied Geophysics* (2011)

What is the effect of changing ϕ?

What are the origins of mode-switching?

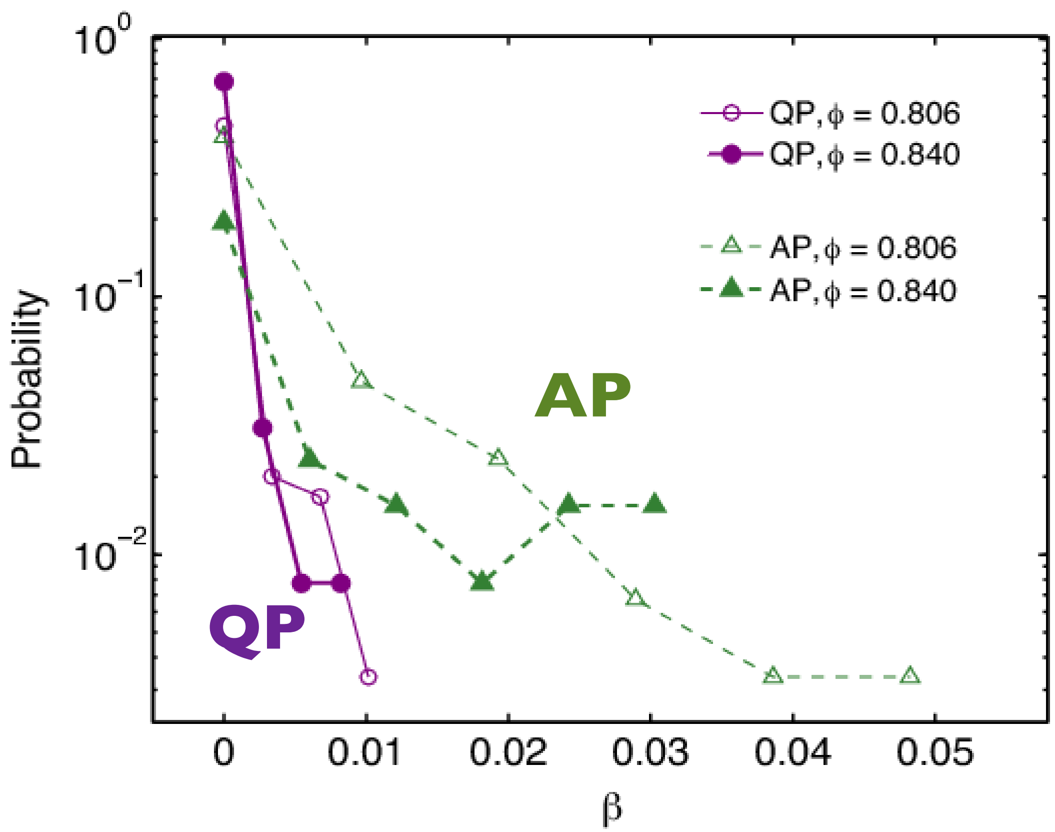
ϕ–dependent rheology



- close-packed aggregates (high ϕ) stiffen more quickly than loose-packed (low ϕ)
- stiffness $K = dF/dX$ increases with ϕ

Hayman, Ducloue, Foco, Daniels. *Pure and Applied Geophysics* (2011)

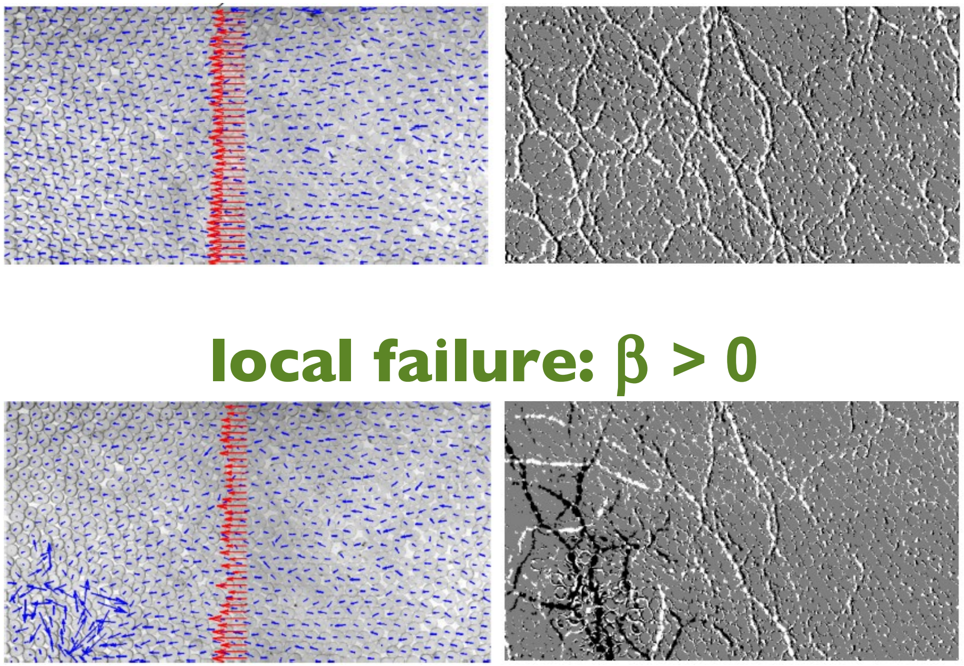
Quasi-periodic vs. aperiodic events



fraction of particles participating in rearrangements

boundary failure: β ~ 0

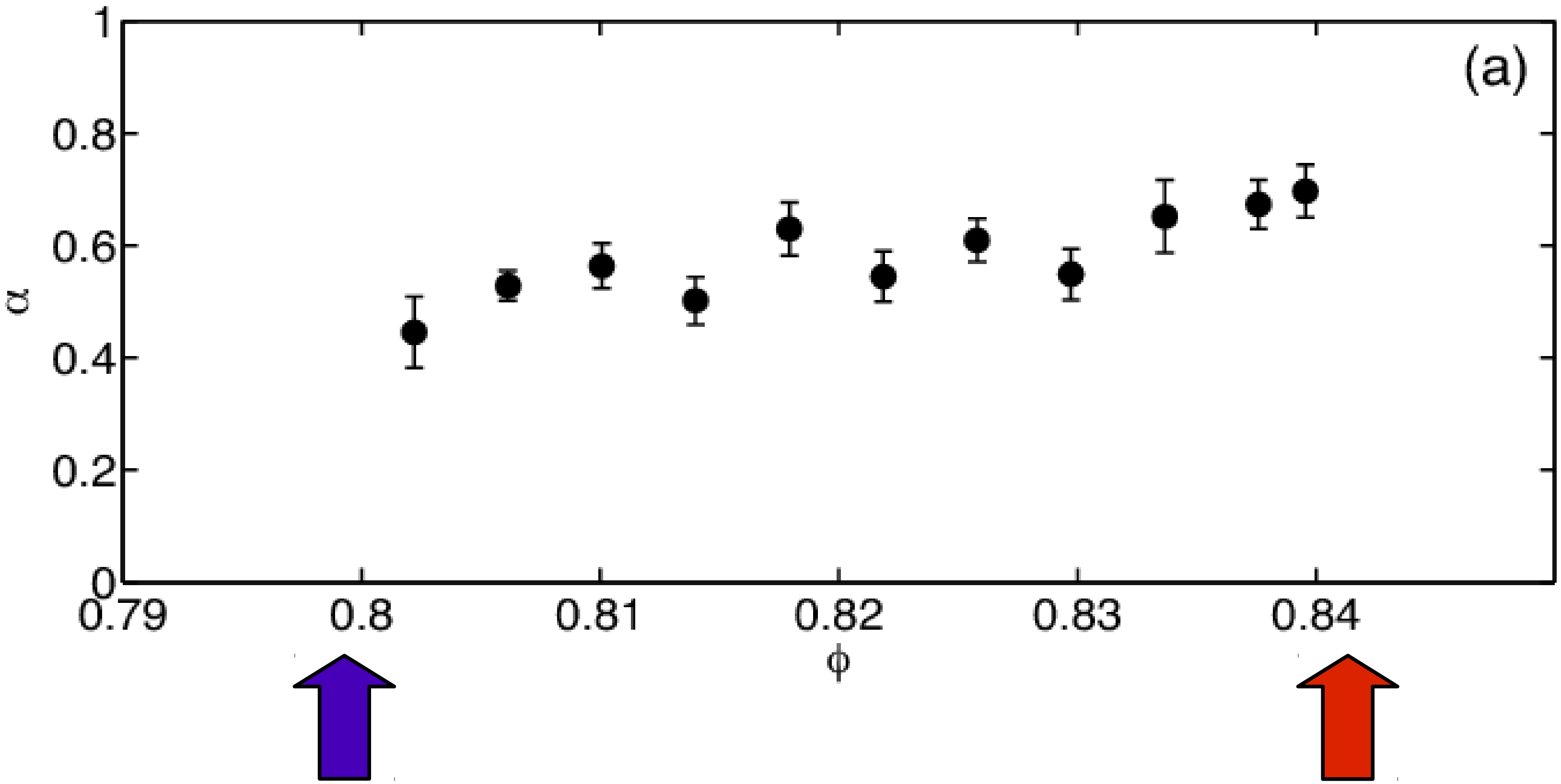
local failure: β > 0



Hayman, Ducloue, Foco, Daniels. *Pure and Applied Geophysics* (2011)

Periodicity and packing fraction

fraction of events which are periodic (boundary failure)

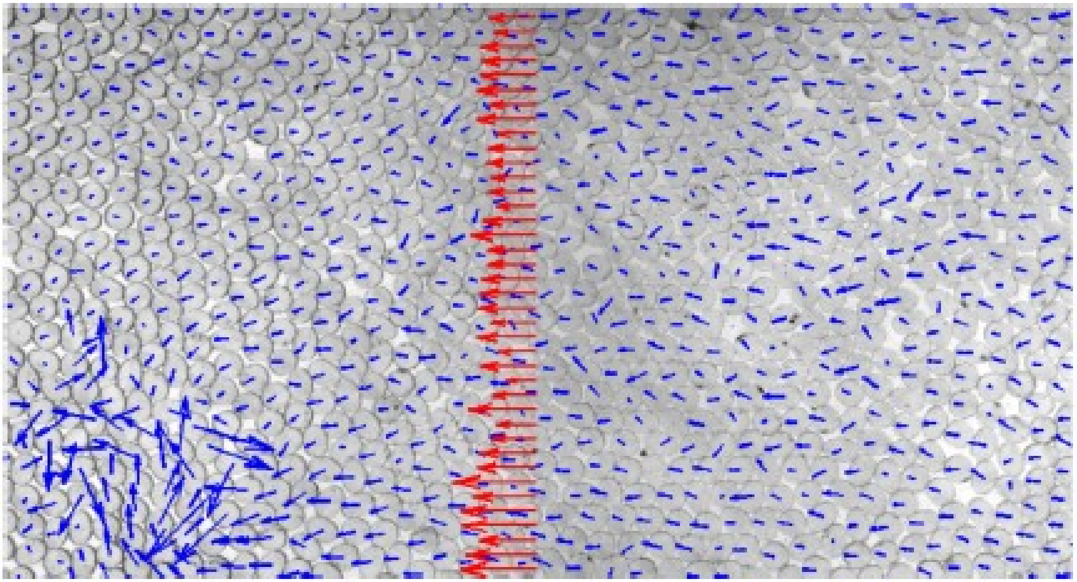


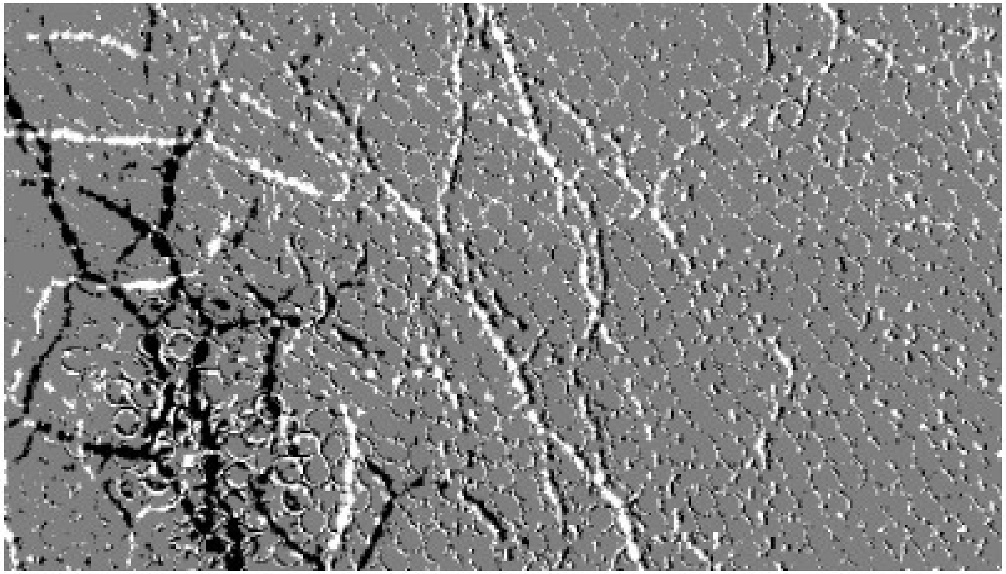
random loose packing

random close packing

why does system exhibit fewer local failures as $\phi \to \phi_{RCP}$?

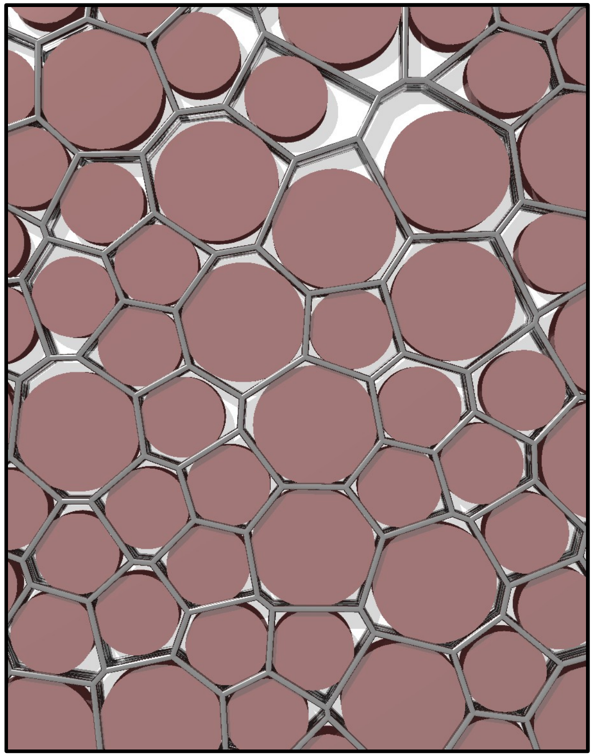
ϕ and localized failure

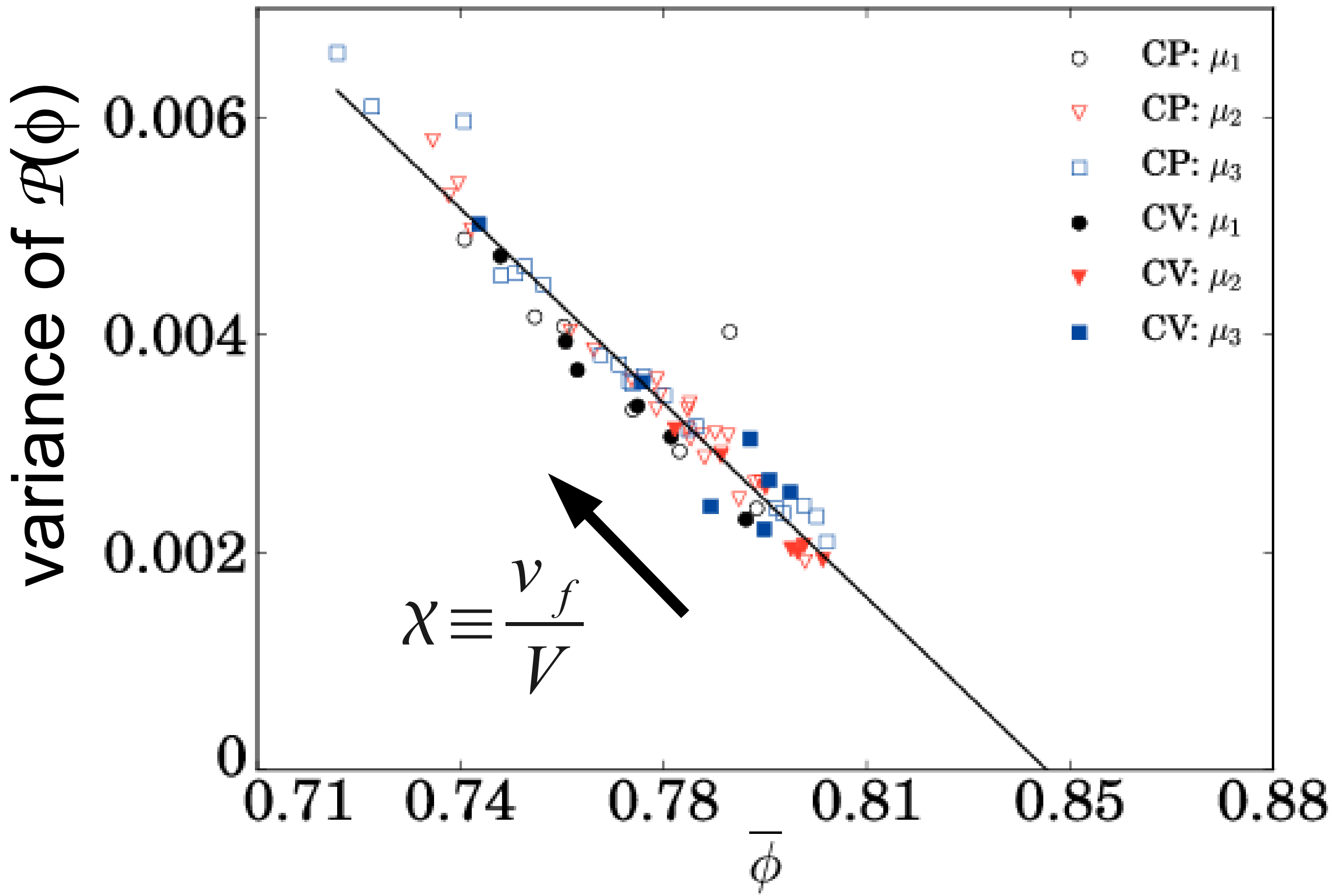




- failures involving force chain buckling & local rearrangements become more likely as ϕ decreases towards random-loose-packing
- accessibility of local rearrangement modes ↔ higher variance in $\mathcal{P}(\phi)$

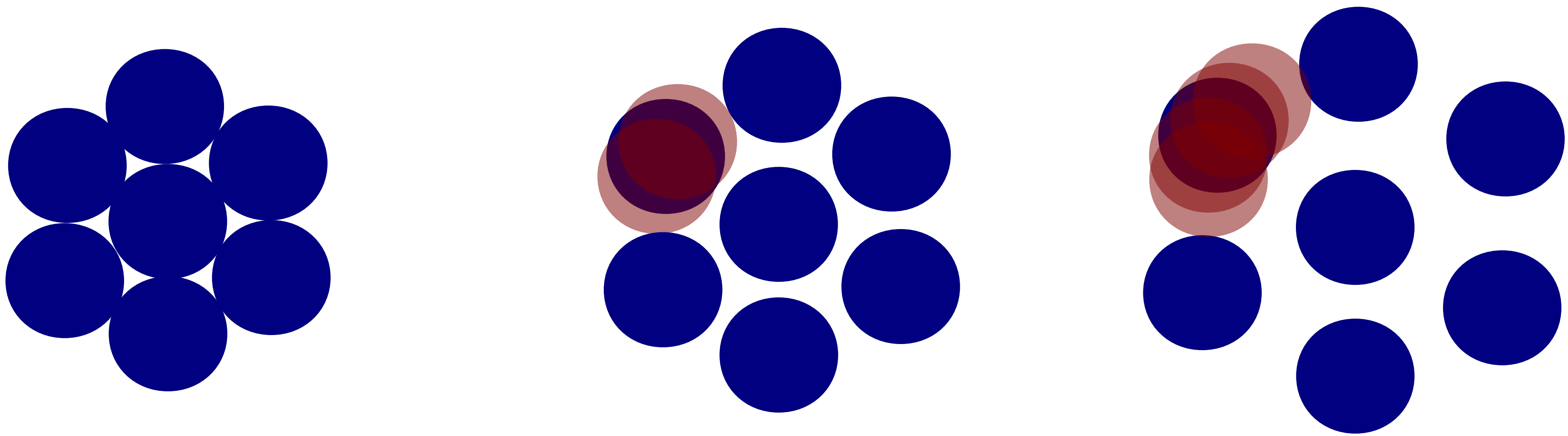
$\mathcal{P}(\phi)$ narrows as ϕ increases





Puckett, Lechenault & Daniels, *PRE* (2011)

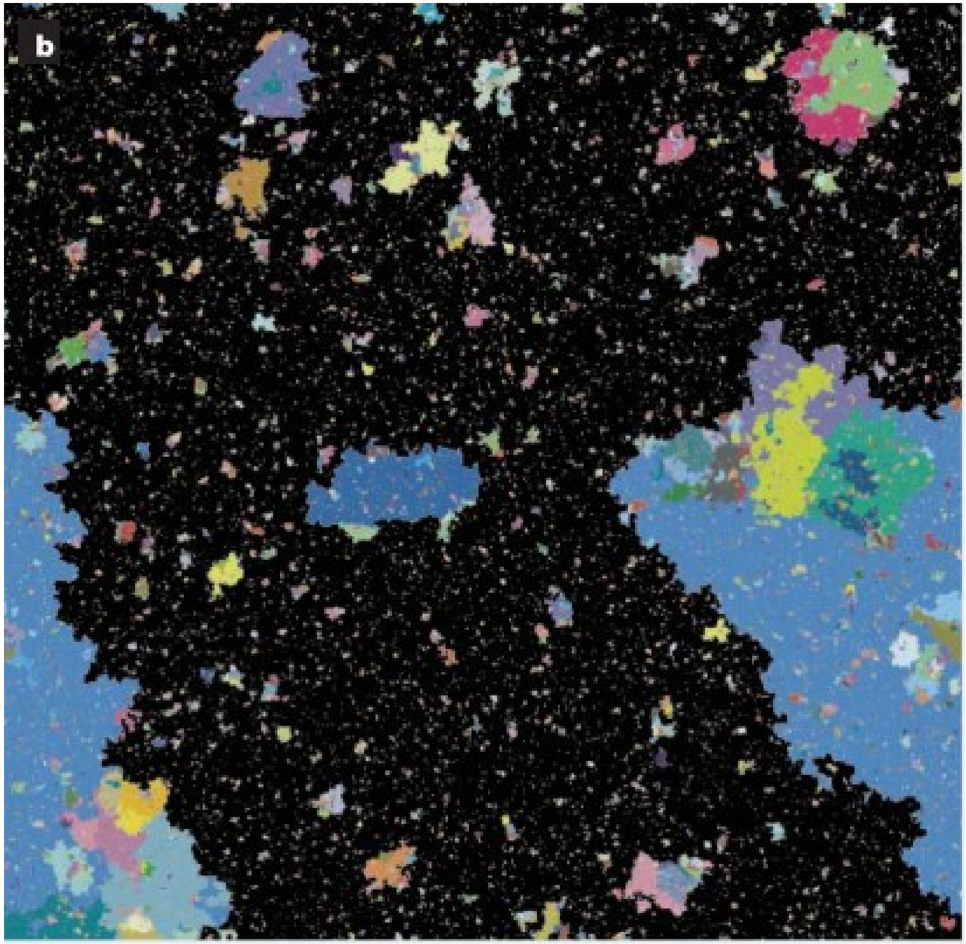
Ensembles of valid packings



high ϕ	low ϕ
zero variance	more variance
one valid configuration	many valid configurations

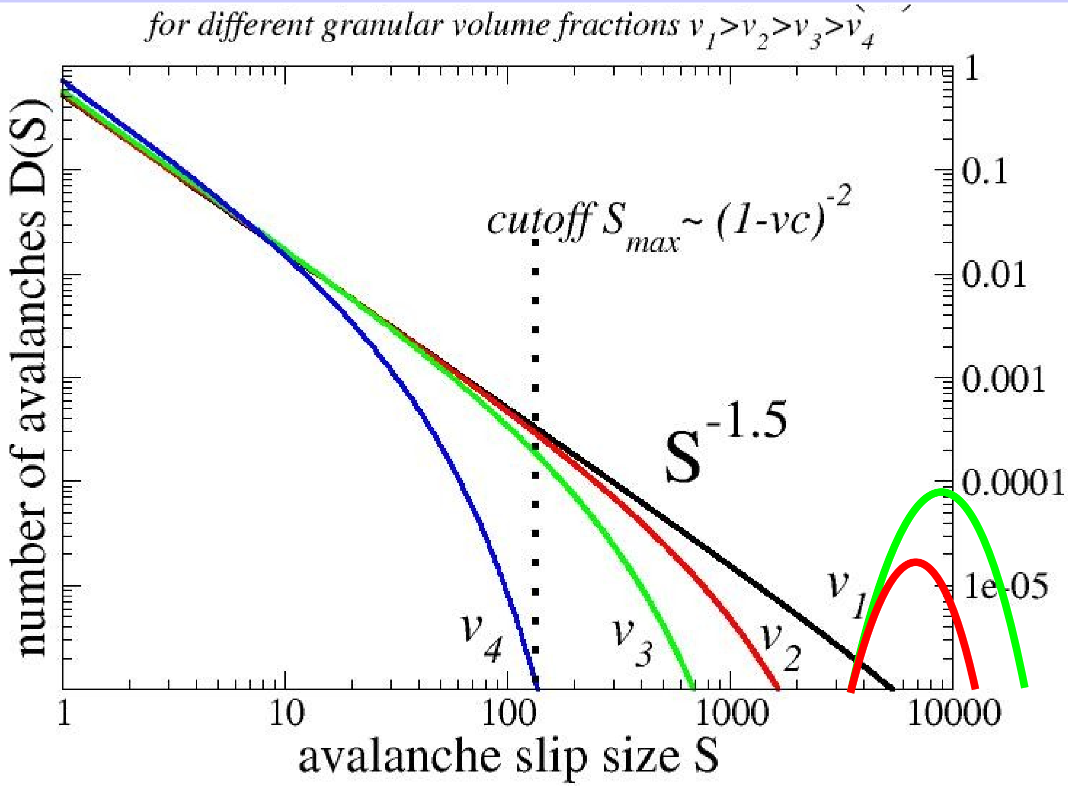
Crackling noise

- arises in a disordered system with many degrees of freedom subjected to slow forcing
- system produces discrete failure events with a wide variety of sizes
- events have scaling shapes and exponents predicted by renormalization group



Sethna, Myers, Dahmen (2001)

Mean field theory of slip 'avalanches'

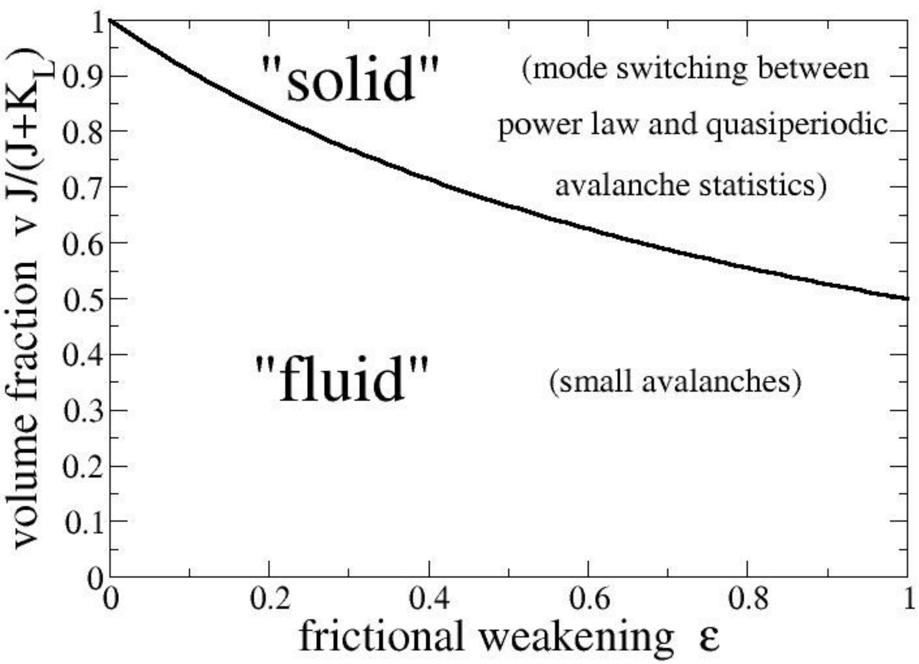


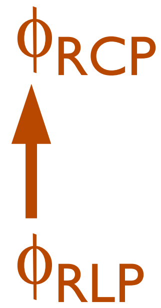
Dahmen, Ertas, Ben-Zion. *PRE* (1998)

Dahmen, Ben-Zion, Uhl. *PRL* (2009) & *Nature Physics* 2011

- slowly sheared material; well-separated avalanches
- key parameters:
  - volume fraction (ϕ, written as ν above)
  - weakening (ε)
  - random thresholds for slipping

Mode-switching





Dahmen, Ertas, Ben-Zion. *PRE* (1998)

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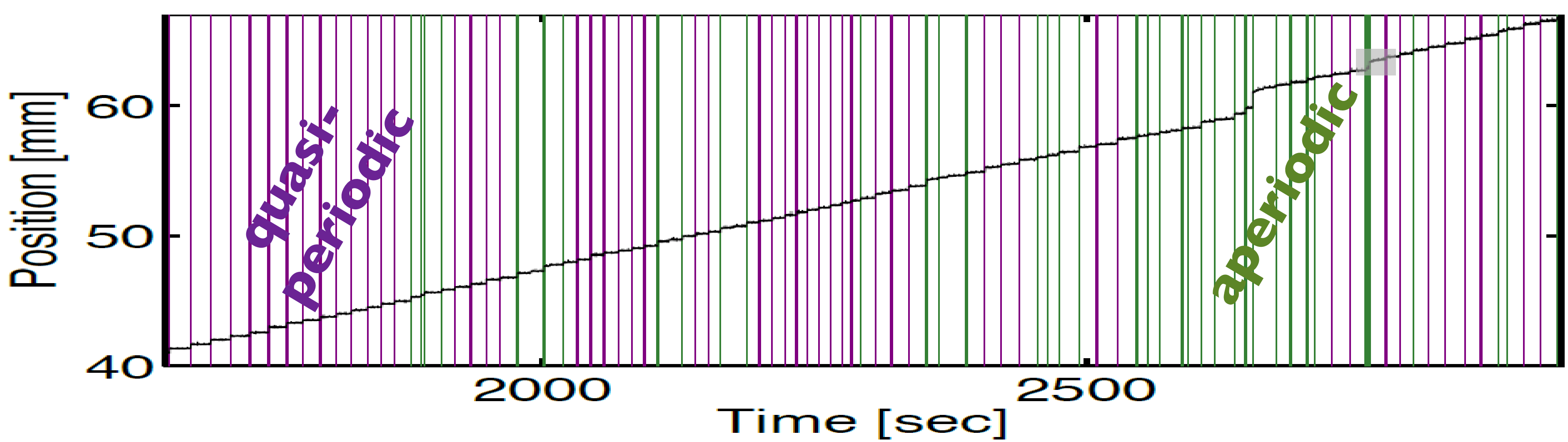
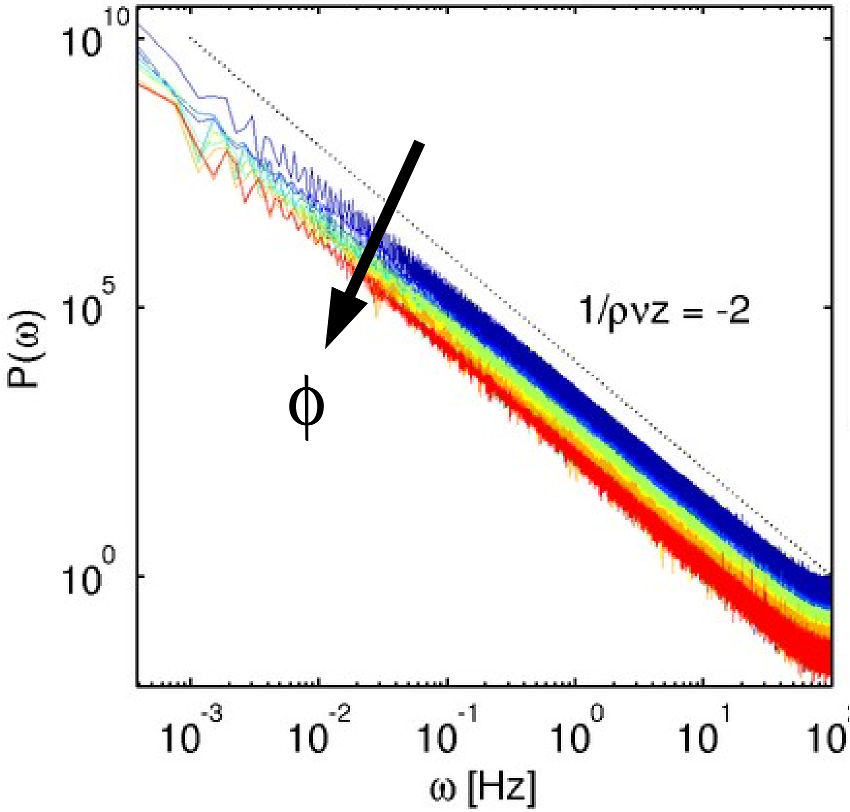
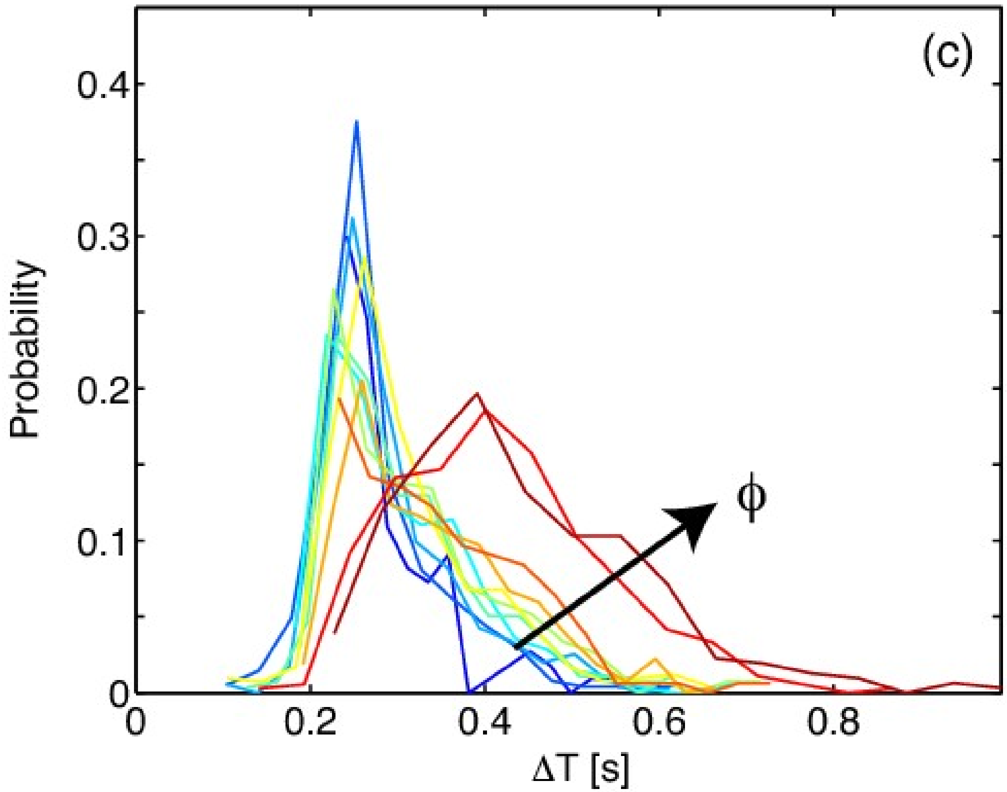


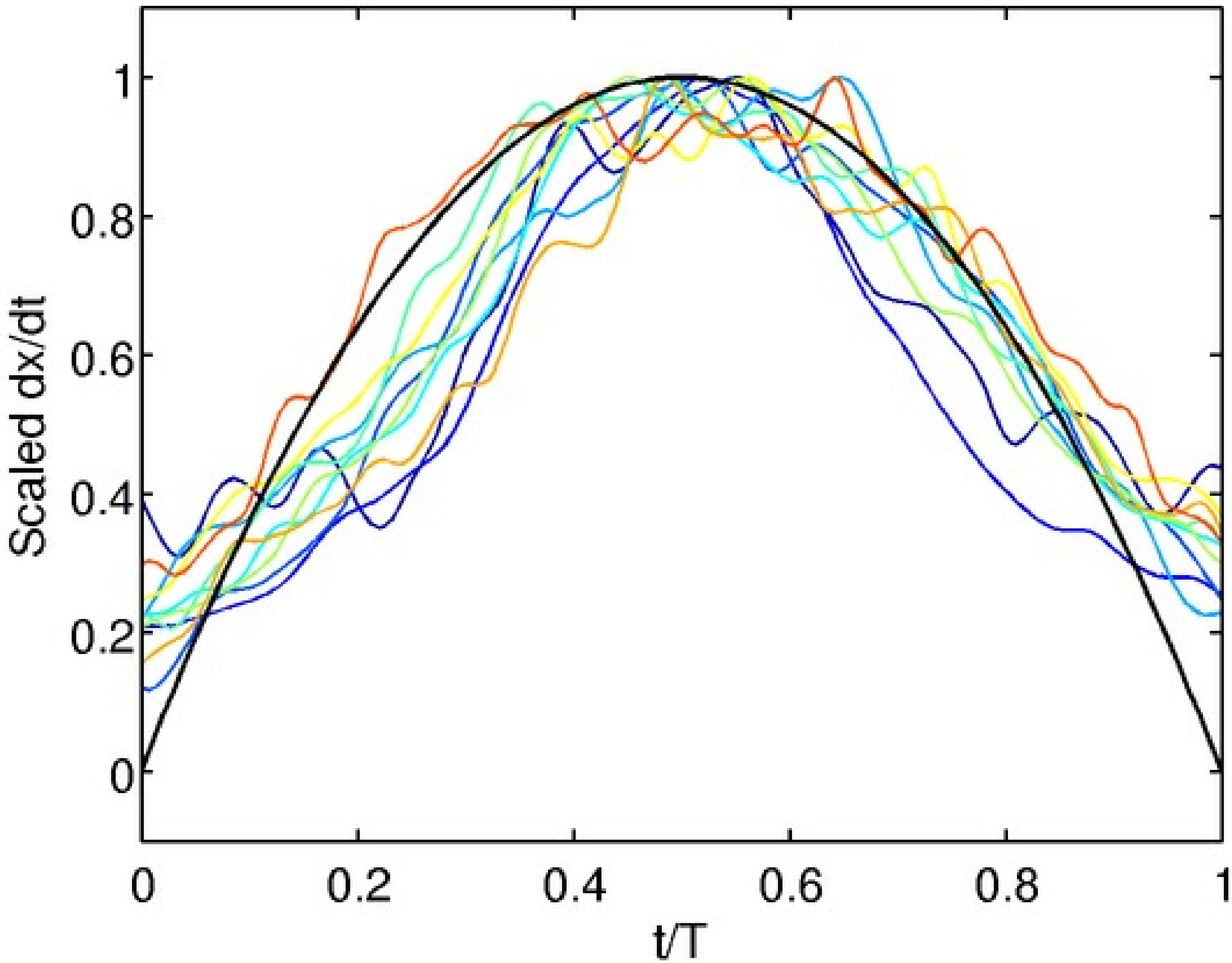
Comparison to MFT





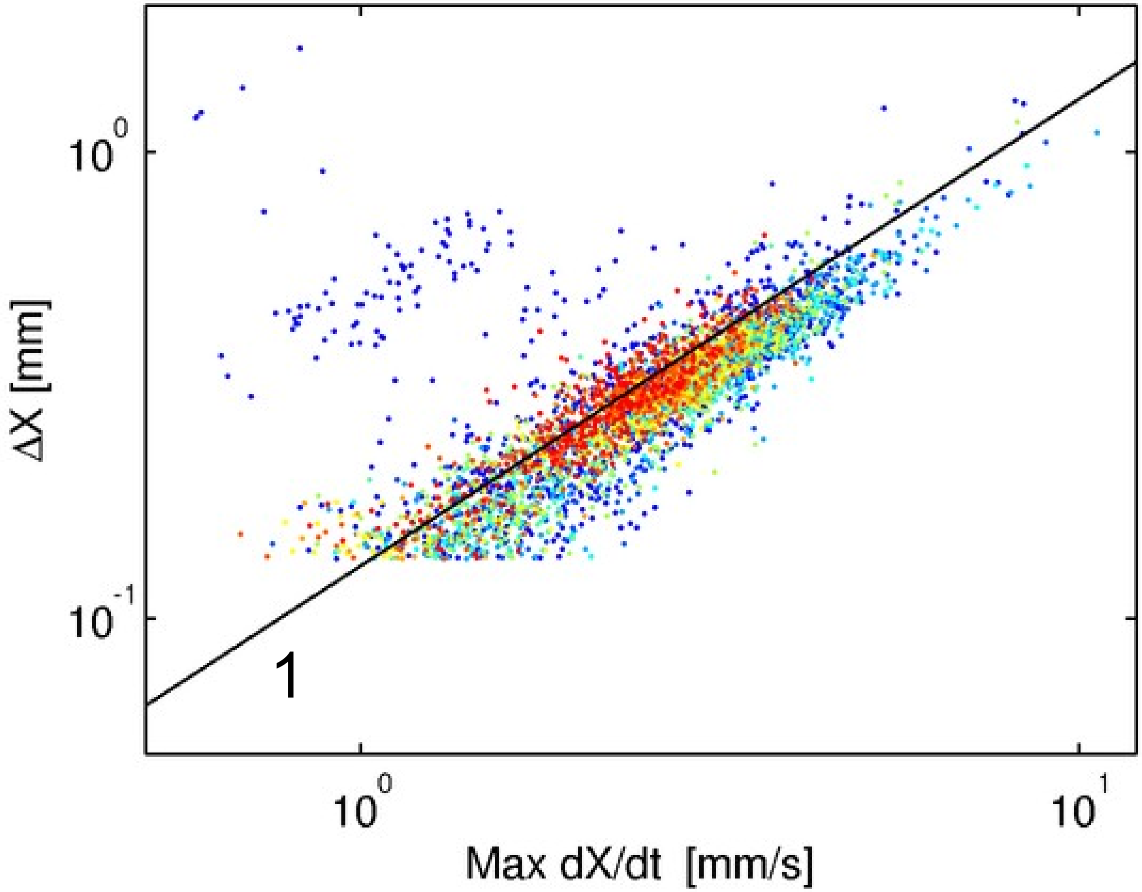
- all spectra have exponent -2, consistent with MFT
- … but event durations ΔT have a characteristic timescale (high ϕ has longer ΔT → less dissipation)

Event shapes



- Event shapes are universal, symmetric …
  and perhaps parabolic (MFT prediction)

Event size scaling



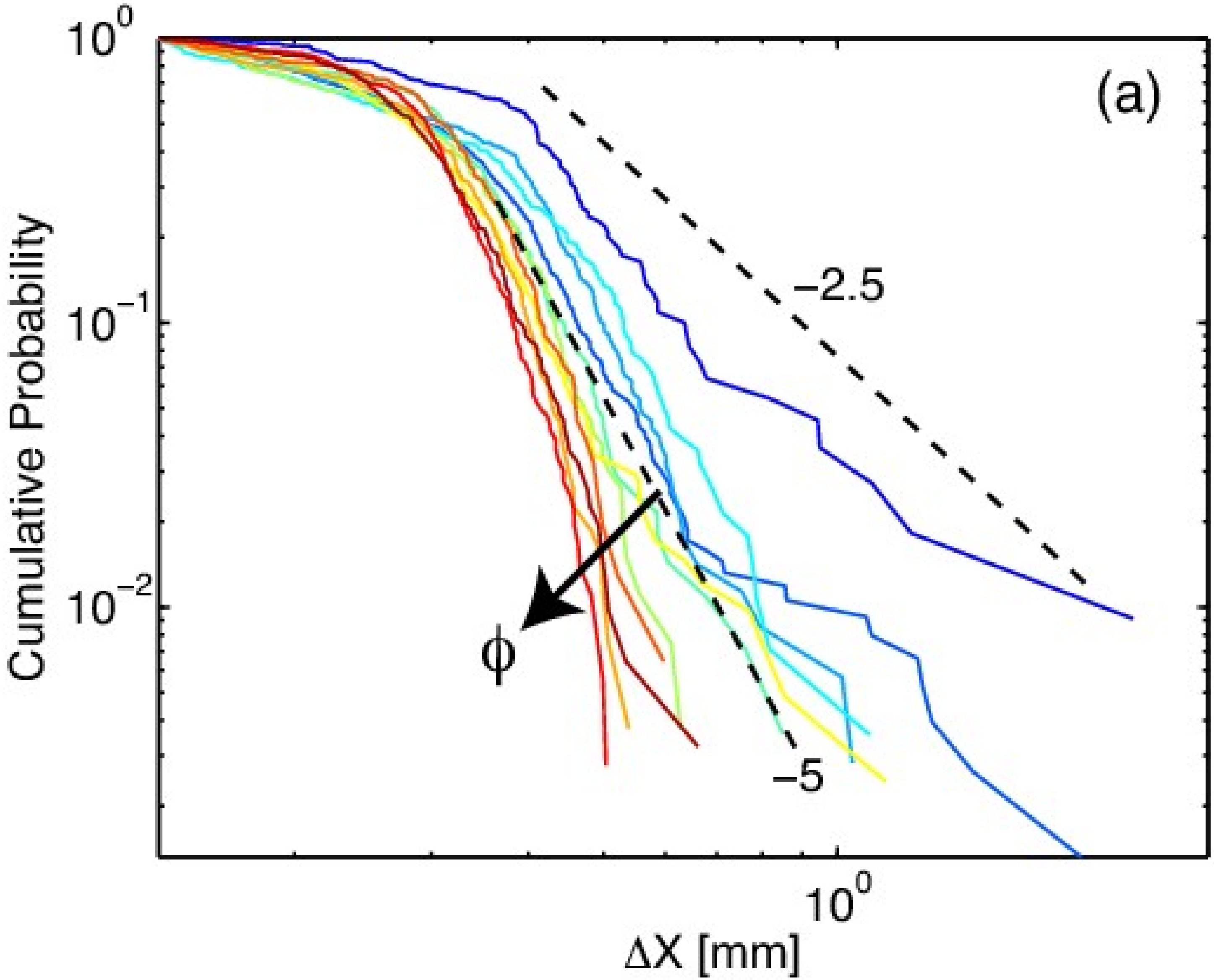
- observe size scaling exponent consistent with MFT prediction:

$$\frac{1}{\rho\, \nu\, z} - 1 = 2 - 1 = 1$$

What sets the size distribution?

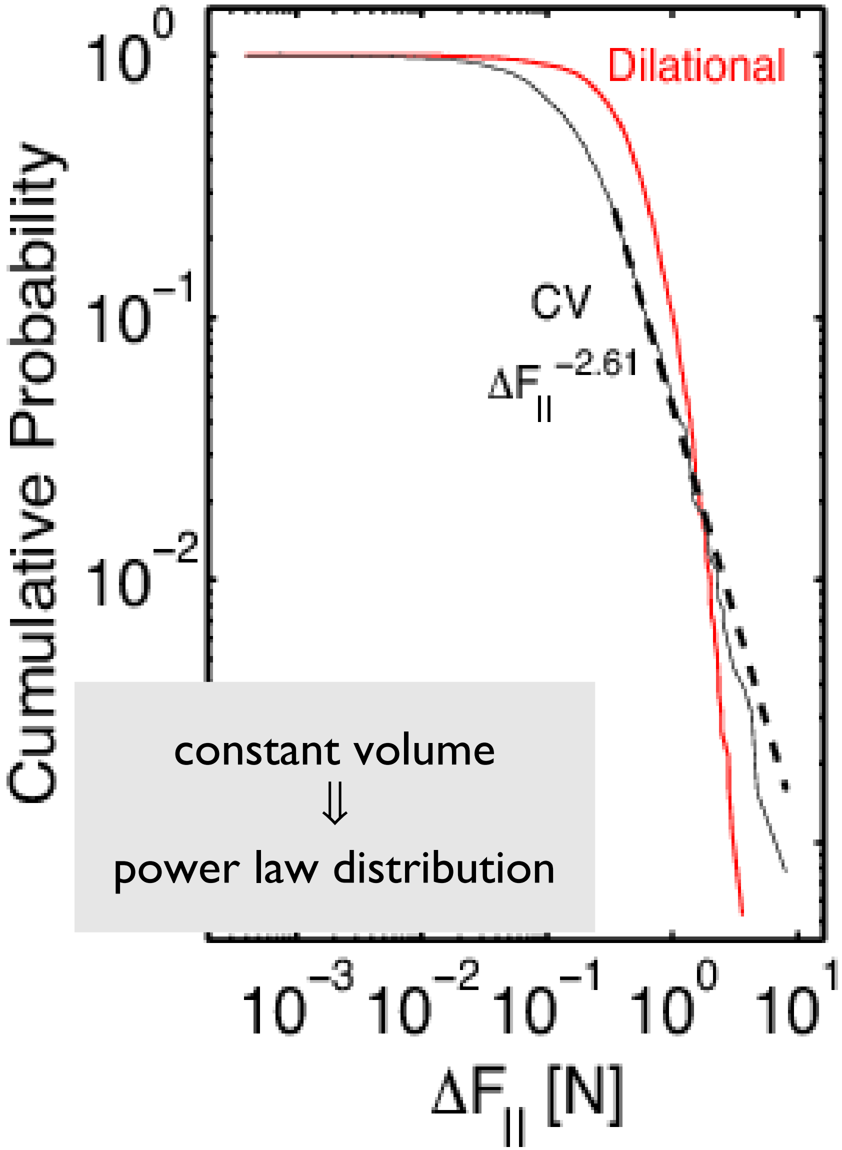
(remember: we detect only events that rupture the full fault)

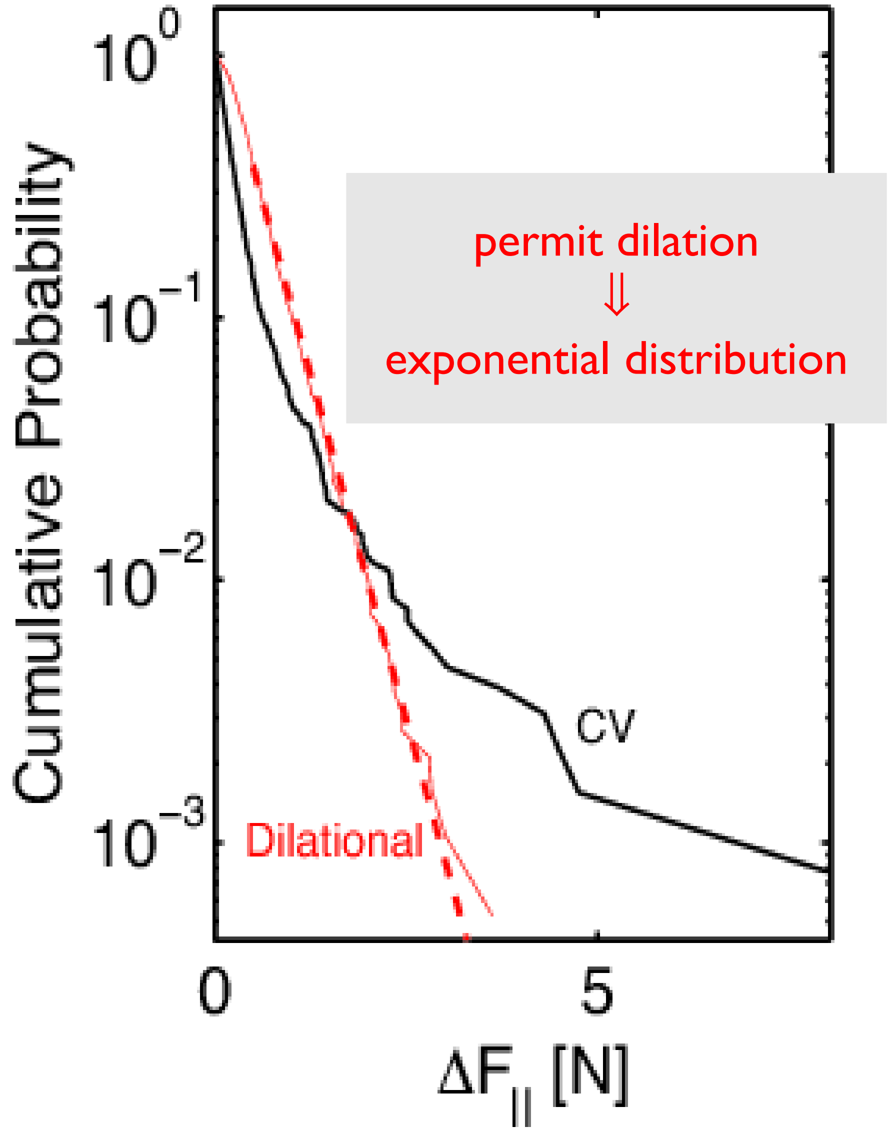
Size distribution: size dependence



Hayman, Ducloue, Foco, Daniels. *Pure and Applied Geophysics* (2011)

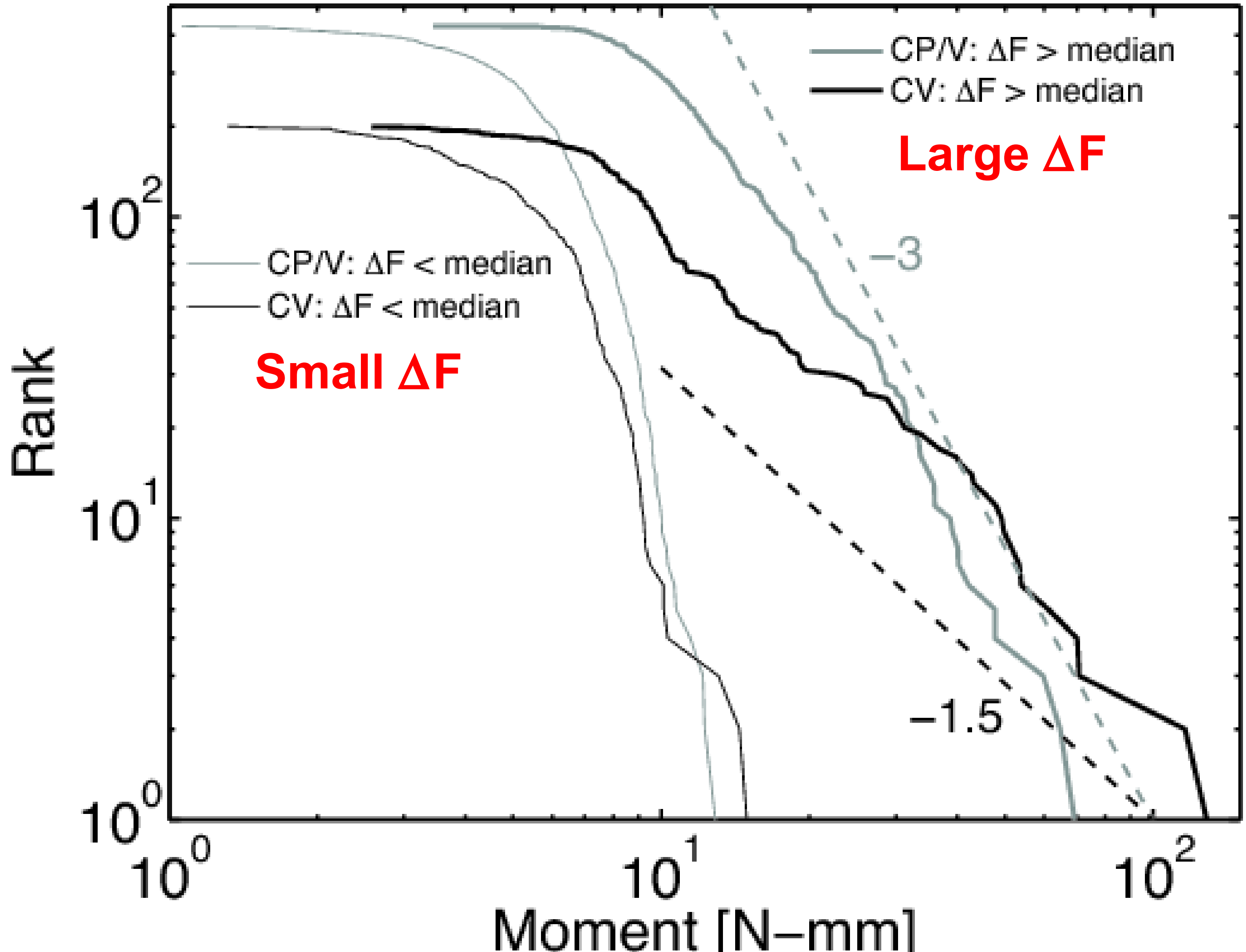
Boundary conditions matter





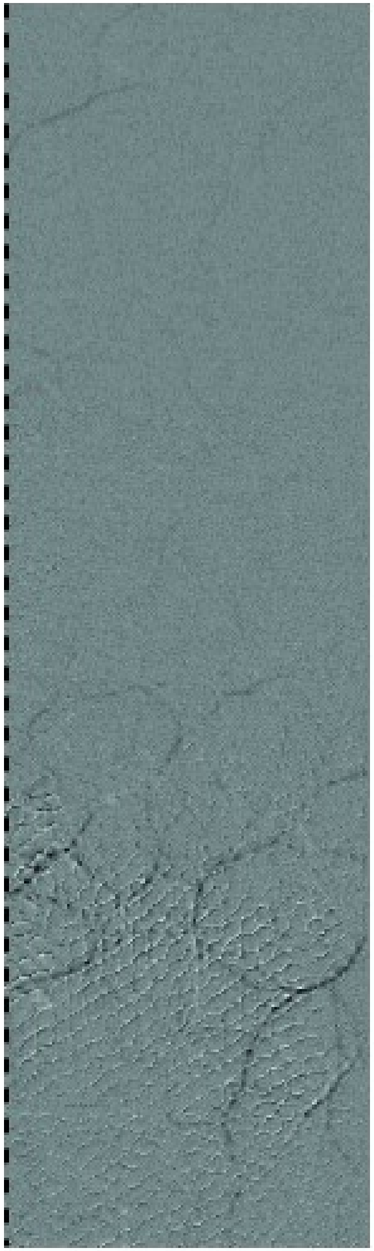
Daniels & Hayman *J. Geophys. Research* (2008)

Large events see the boundary



Daniels & Hayman *J. Geophys. Research* (2008)

Conclusions



- ← granular stick-slip failure can be quite heterogeneous
- observe changes in periodicity and size distributions as a function of the granular packing density and boundary condition
- observe Earth-like mode-switching between periodic and aperiodic stick-slip events
- scaling of events has a number of features in common with MFT