The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
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International Atomic
Energy Agency

SMR 1746 - 9

WORKSHOP ON DRIVEN STATES IN SOFT AND BIOLOGICAL MATTER
18 - 28 April 2006

Using Confocal Microscopy to Investigate Complex Matter Systems

(for Talk on "Using Confocal Microscopy to Investigate Yielding in Colloidal Crystals)

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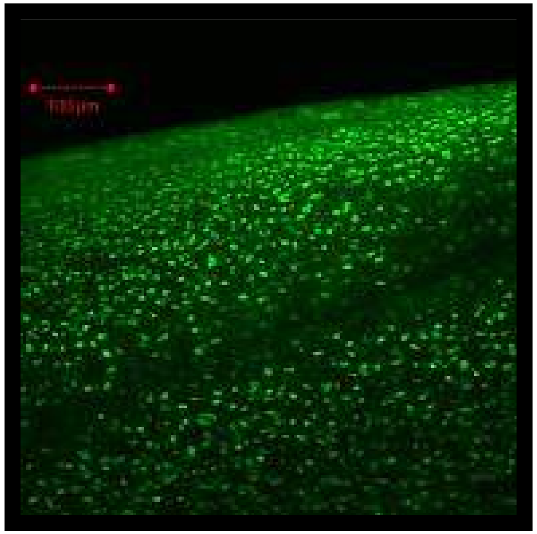
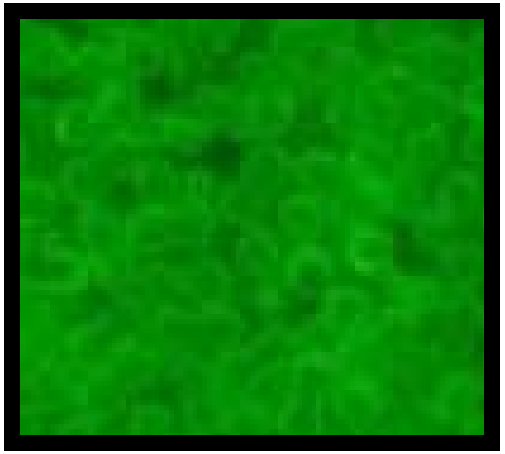
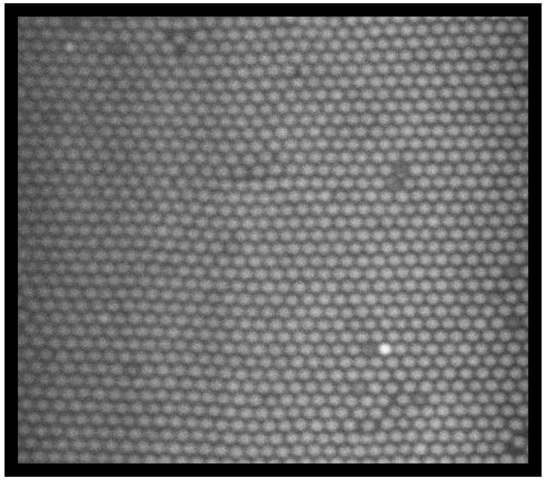
Using Confocal Microscopy to Investigate Complex Matter Systems

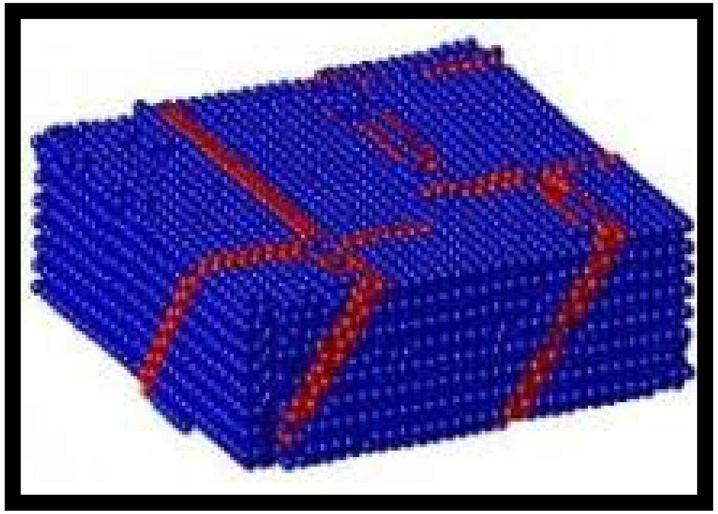


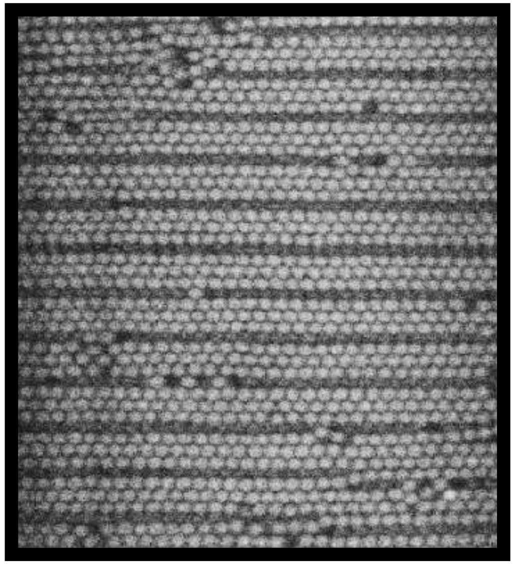
Role of material micro-structure in determining macroscopic flows



Itai Cohen







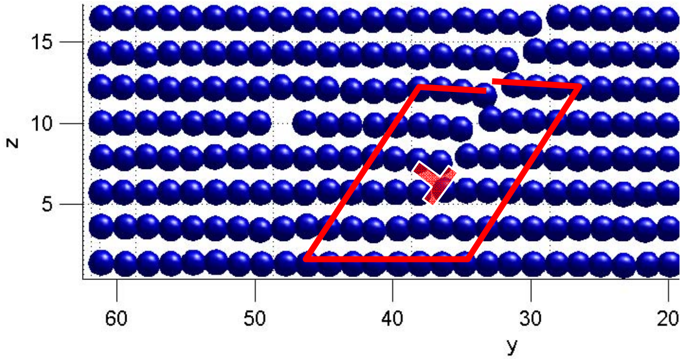
Why Colloids?

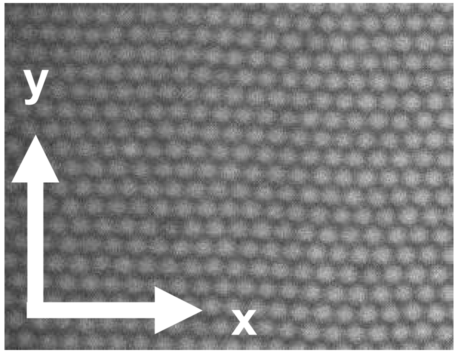
- **Industrially important**
  - Paints, coatings, lubrication, bio-rheology, electro-optical devices
- **Index and density matched to solvent**
- **Ising model of soft condensed matter:**
- **Rheology:**
  - **Shear thickening**
  - **Shear thinning**
  - **Shear banding**
  - **Etc.**
- **Models for atomic systems**

(E. R. Weeks, U. Gasser, D. A. Weitz, P. N. Pusey, and others)

Yielding Changes With Time Scales

Slow **Shear Rate** **Fast**



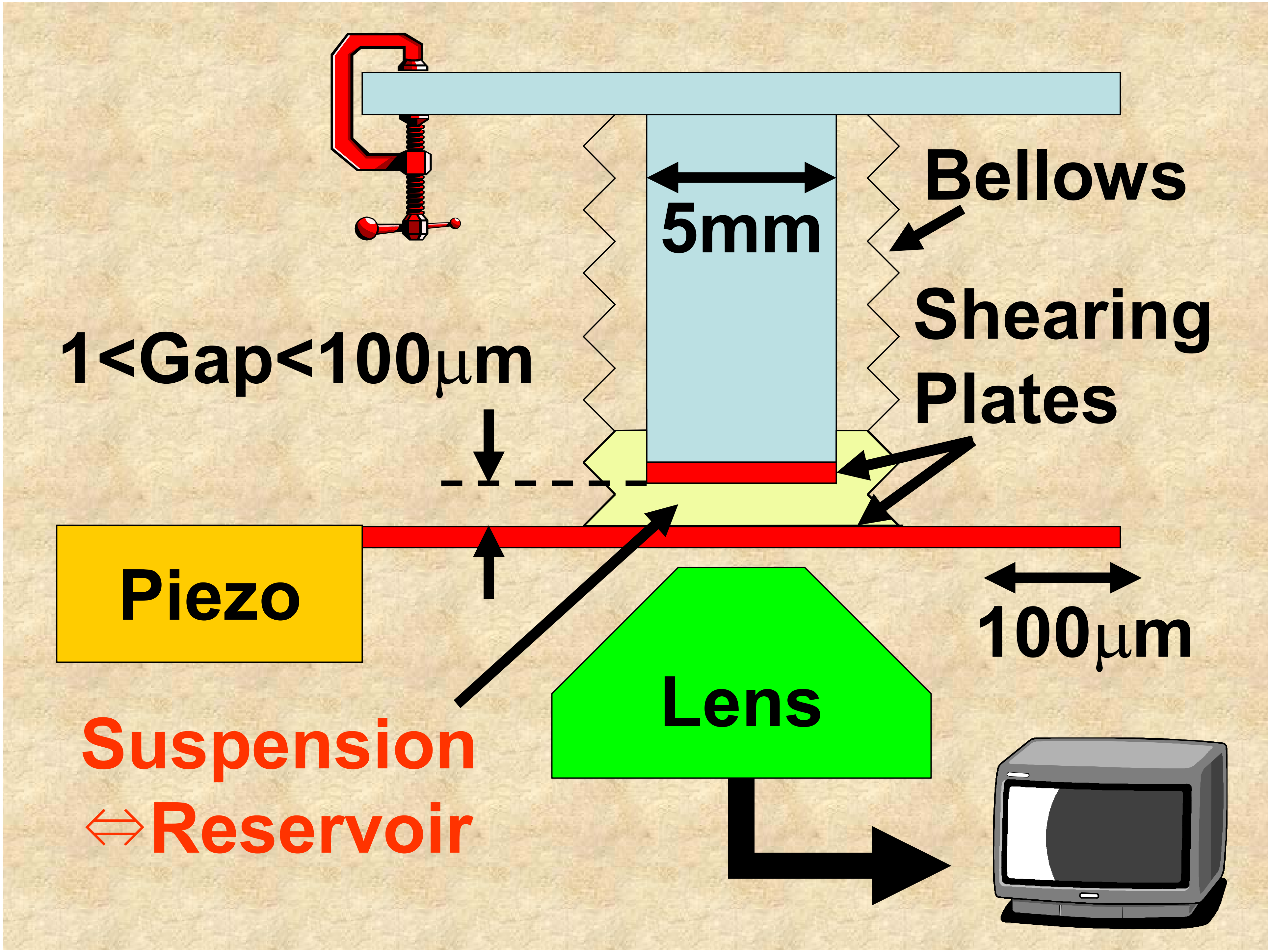


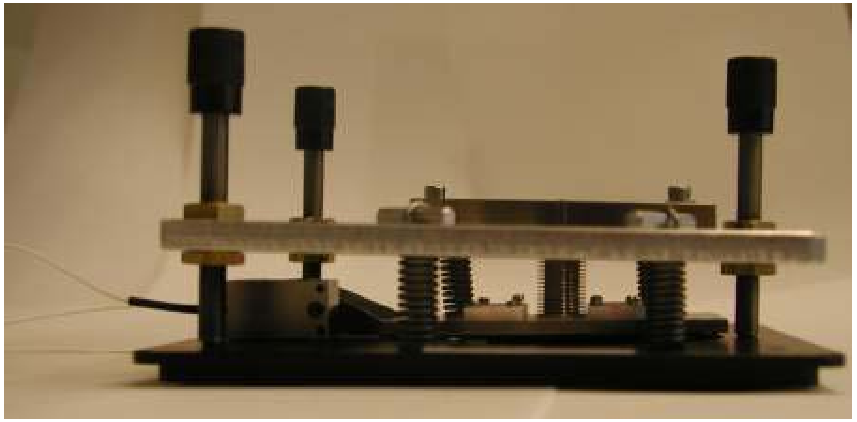
- Slow / Equilibrium: Brownian – Dislocations
- Fast / Non_equilibrium: Fluidization hcp layers
- <u>Study Equilibrium → Non-equilibrium</u>

Other Important Parameters

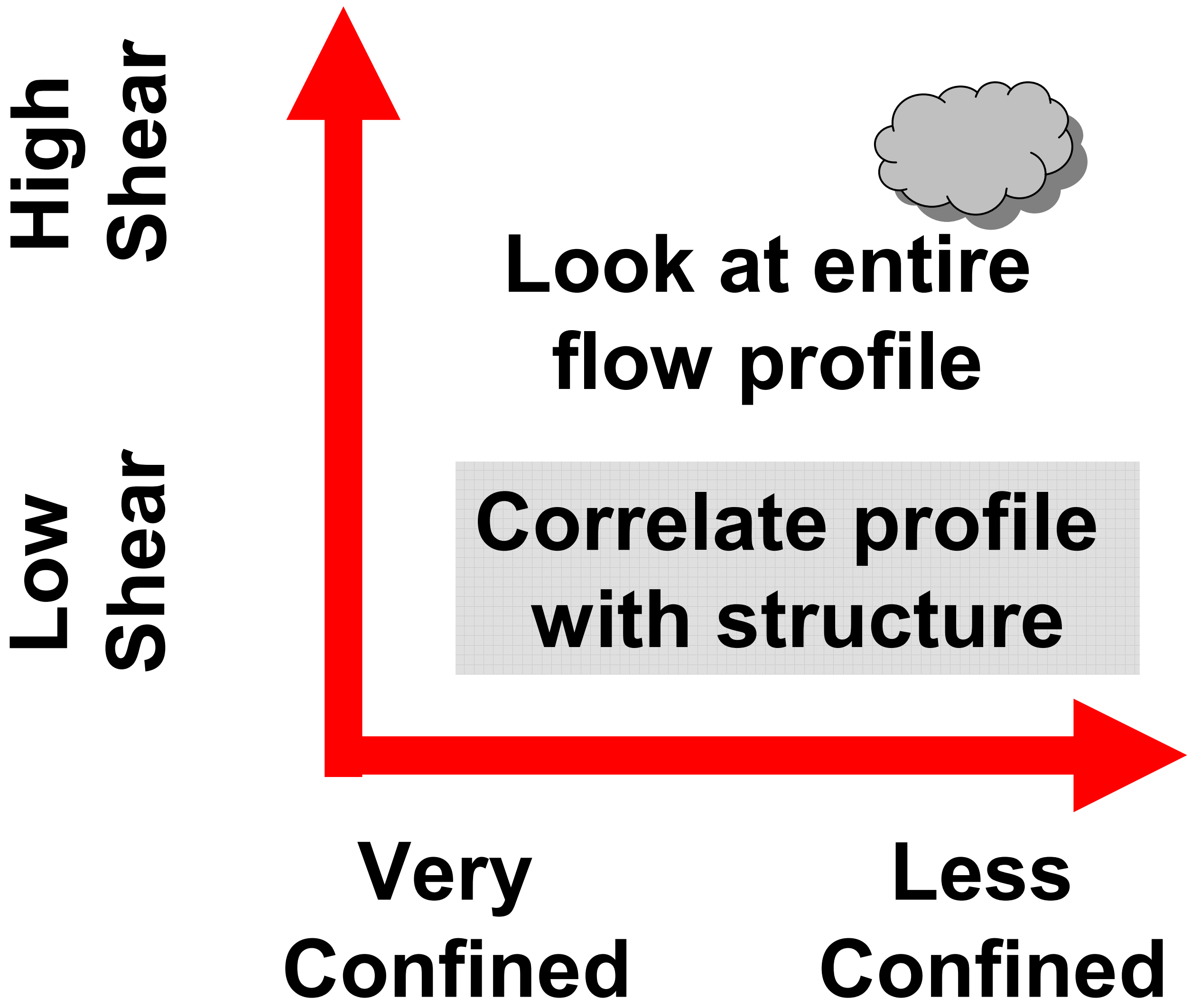
- Particle Shape: Spheres, diameter = 1.4 μm
- Particle interaction: Slightly charged
- Volume fraction: Φ = 61%
- Boundary conditions: Smooth plates

- Confinement
  - affects rheology of atomically thin films (Israelachvili, and others)
  - What about colloids?


Bellows
5mm
Shearing
Plates
1<Gap<100μm
Piezo
100μm
Lens
Suspension
⇔Reservoir



High Shear & Less Confined



$5\text{Hz} < f < 30\text{Hz}$

Amp. $\cong 30\mu m$

Gap $\cong 70\ \mu m$

<u>Diffusion:</u>

$D_0 = kT/6\pi\eta a$

$t_{a0} = \pi\eta a^3/kT$

For $a = 0.71\ \mu m$

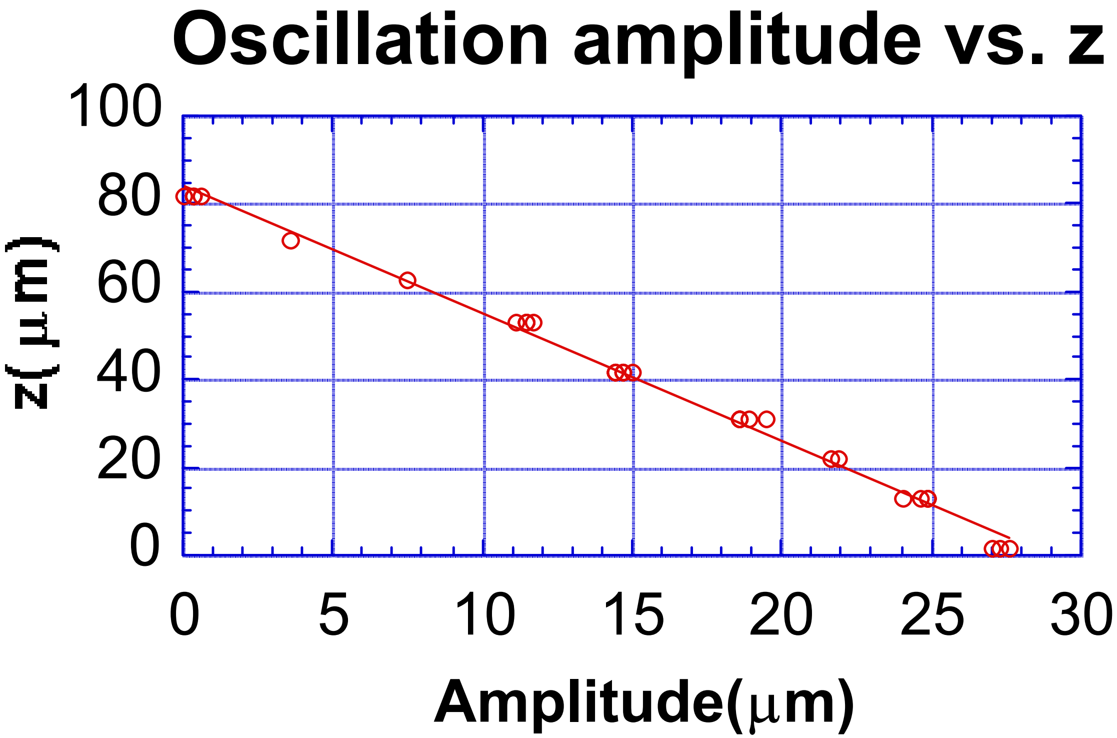
$t_{a0} \cong 0.7$ sec

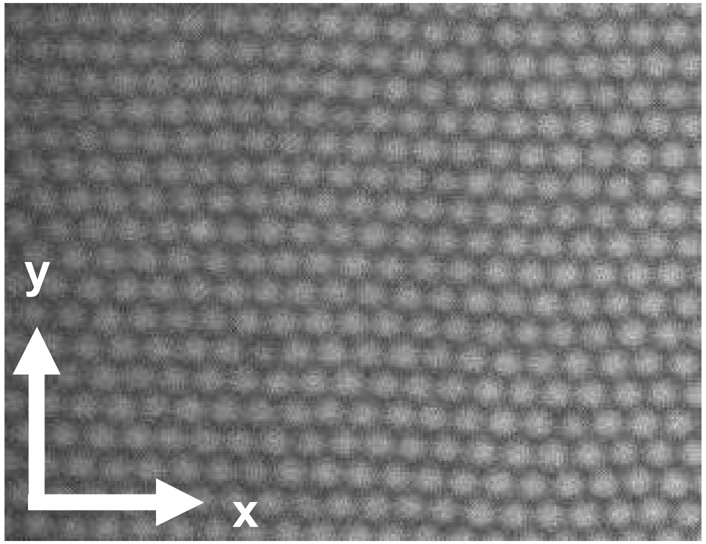
$Pe = \gamma f t_{a0} \cong 10$

Disordered Suspension → HCP Layers

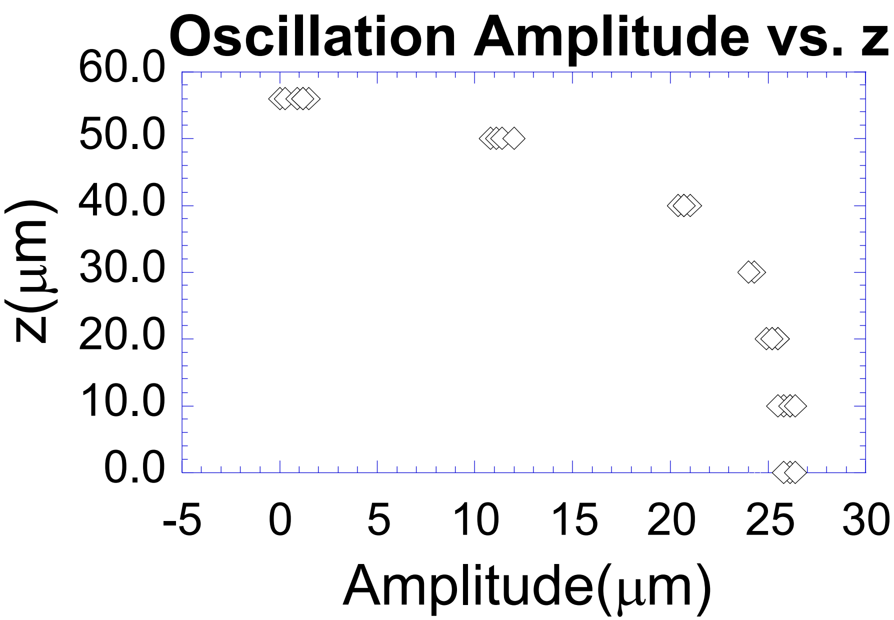
(Ackerson, Versmold and others)

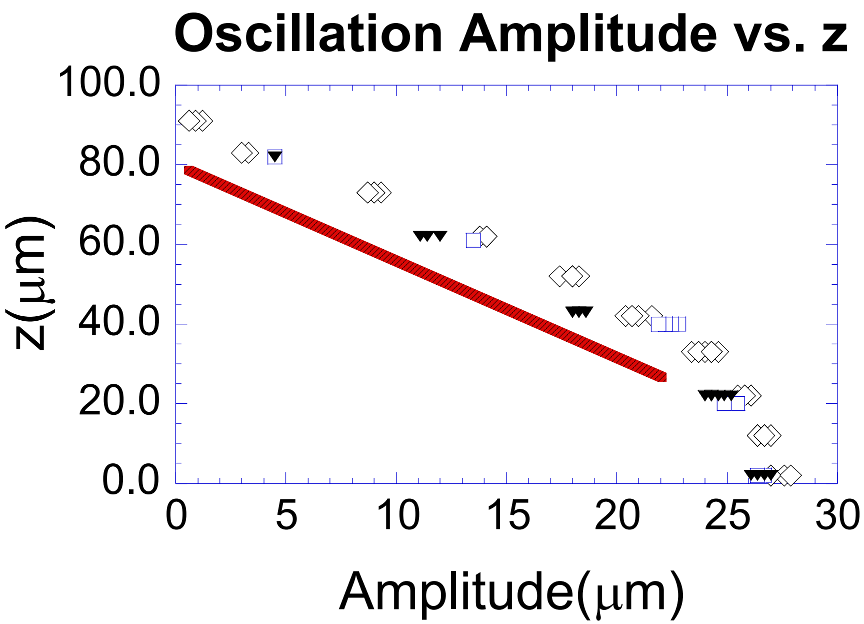
Track particle motion at different heights, z
Observe linear shear gradient

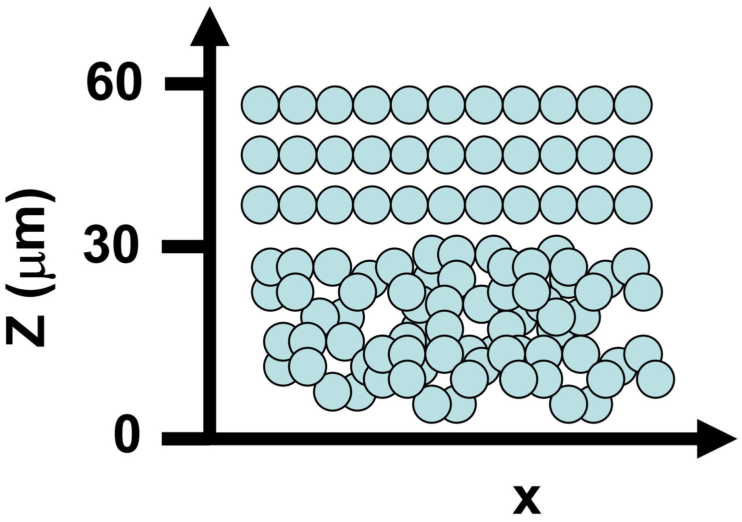


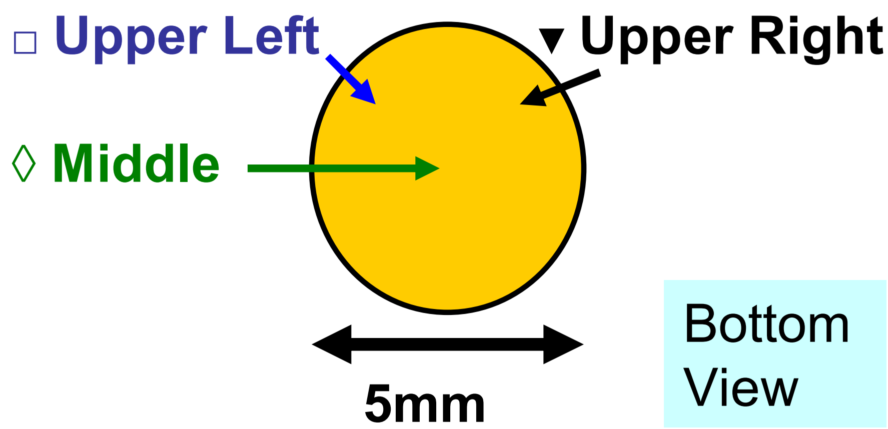


Local Disorder → Global Coupling



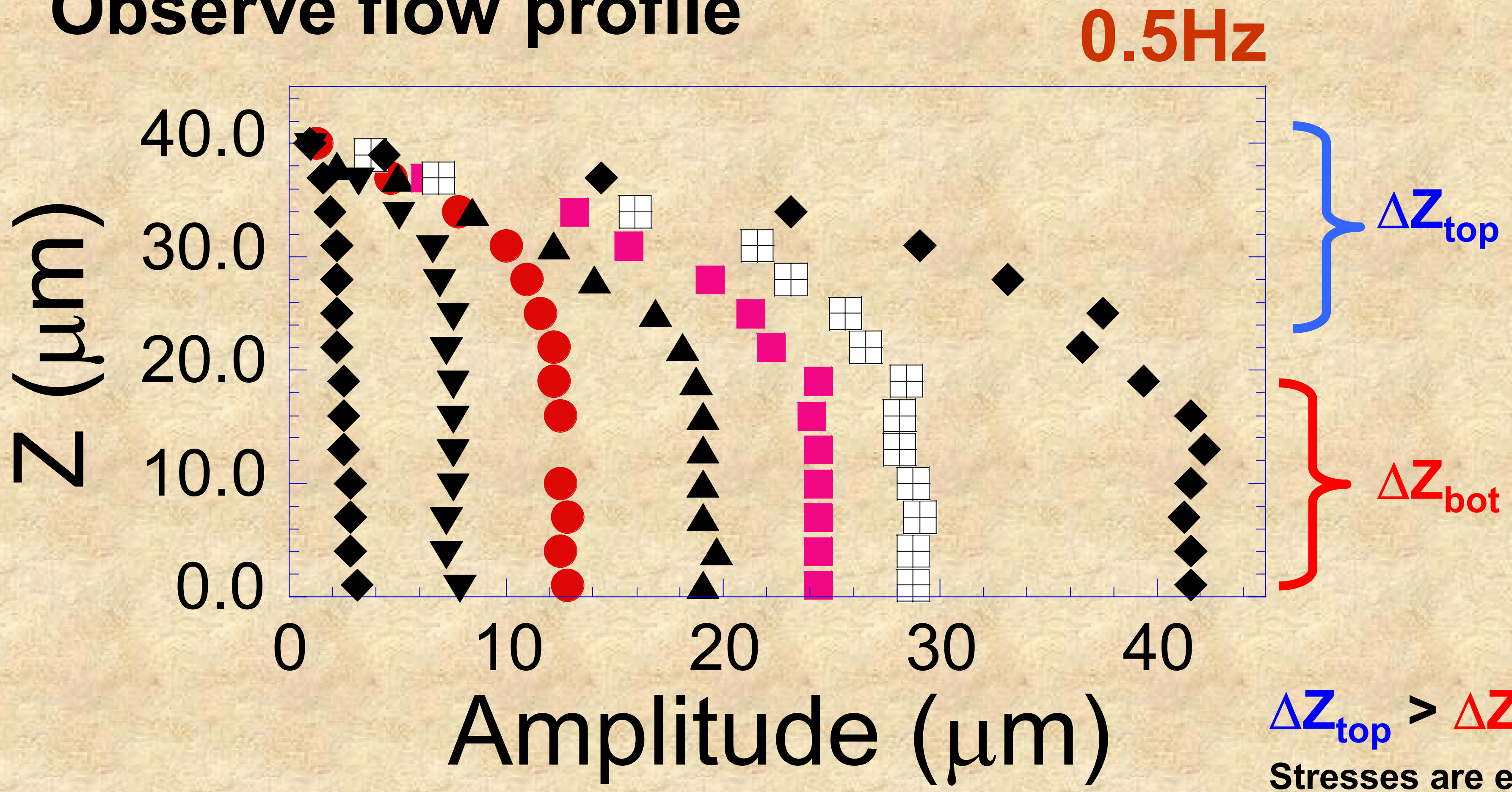






Shear Banding

Fix frequency, increase strain
Observe flow profile

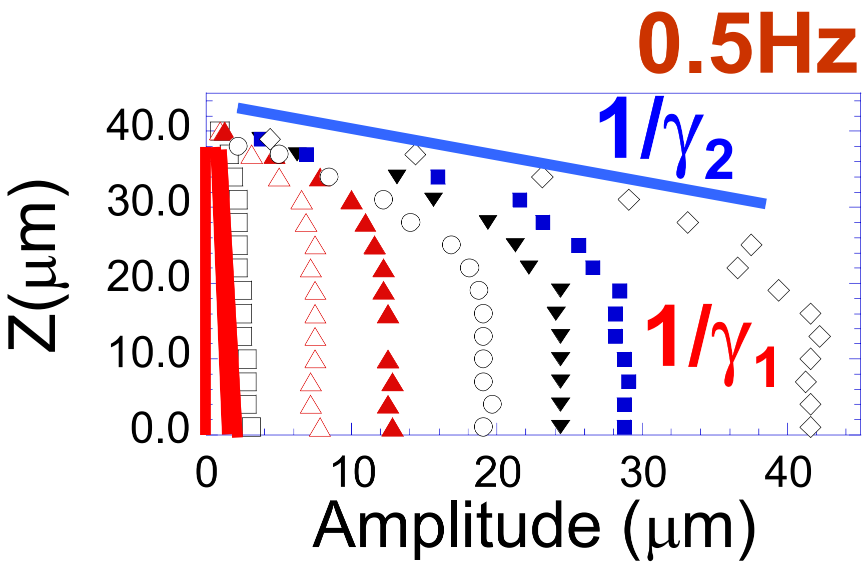


$\Delta Z_{top} > \Delta Z_{bot}$

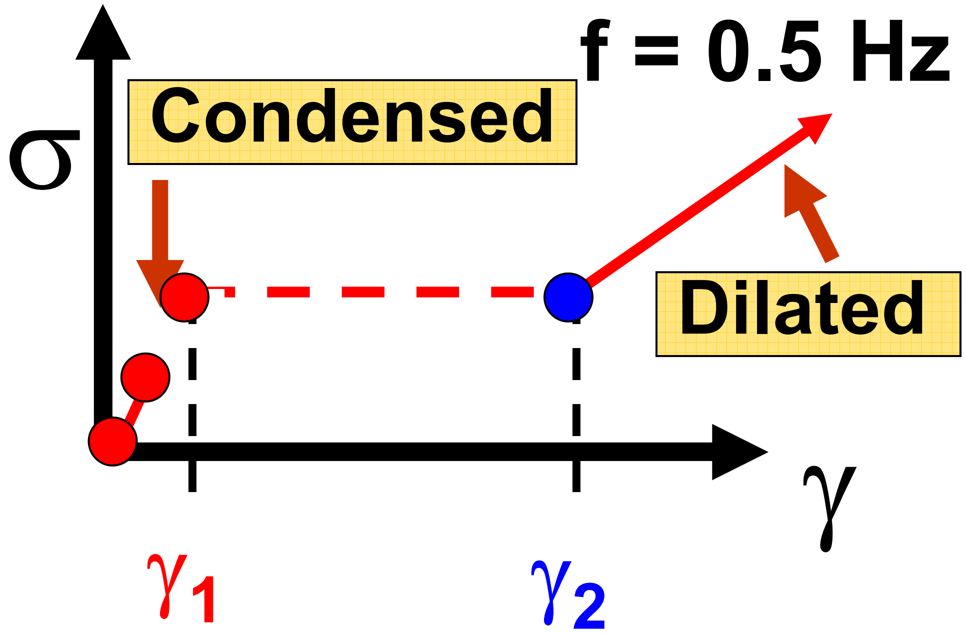
Stresses are equal

Shear Thinning Rheology?

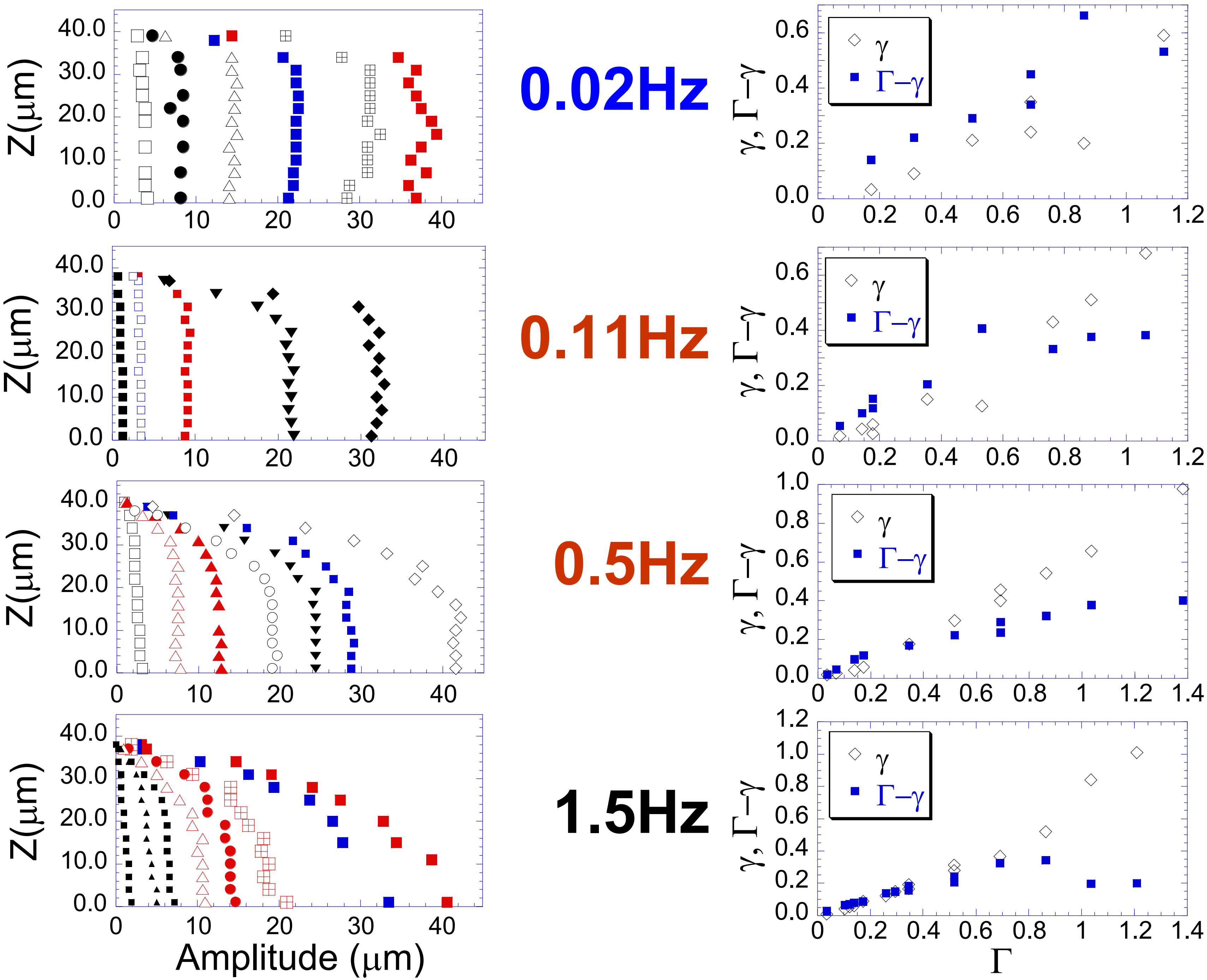
Data



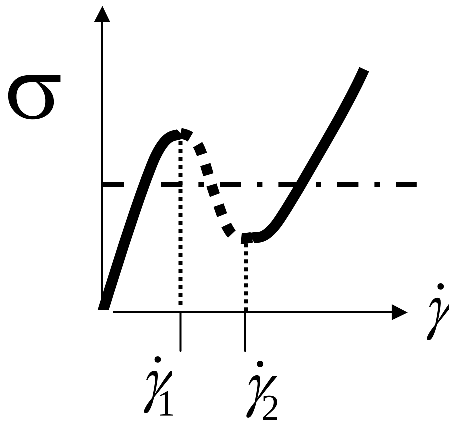
Schematic: stress vs. strain



Shear bands tell us about material rheology

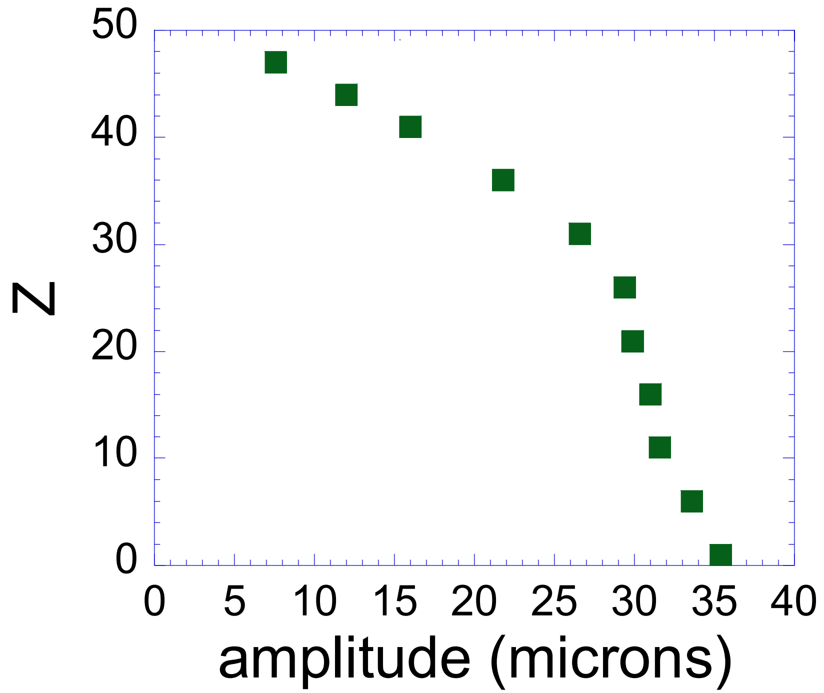


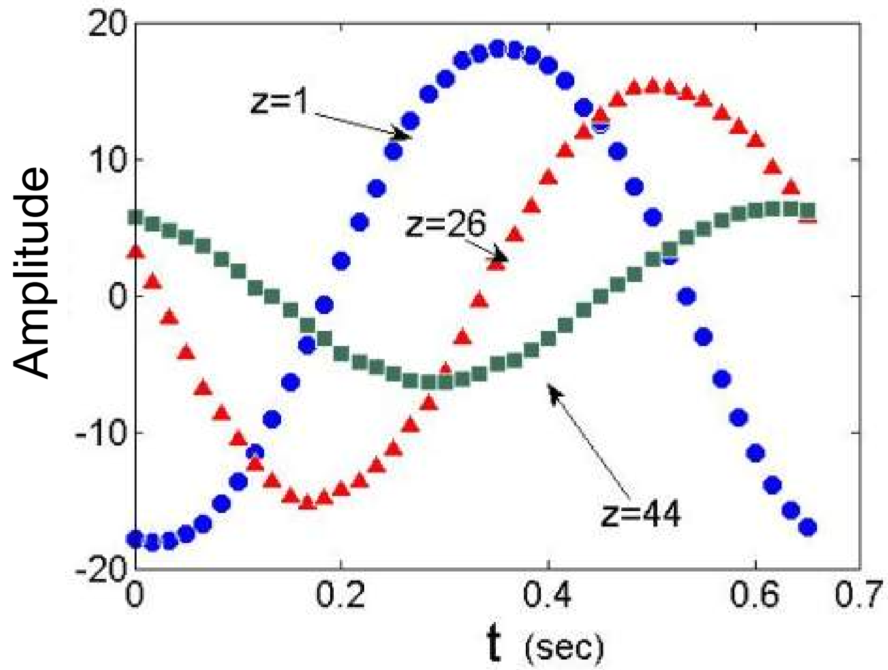
Z(μm)
Amplitude (μm)
0.02Hz
0.11Hz
0.5Hz
1.5Hz
γ, Γ−γ
Γ
γ
Γ−γ



Beny Davidovich:

- Nonlinearities → higher harmonics
- Discontinuous flows for oscillatory shear





Stresses

For shear flow viscous and viscoelastic (Kelvin):

$$\sigma_s = G\underbrace{\partial u_s / \partial z}_{\gamma} + \eta_s \underbrace{\partial(\partial u_s / \partial t)/\partial z}_{\dot{\gamma}}$$

$$\sigma_f = \eta_f \underbrace{\partial(\partial u_f / \partial t)/\partial z}_{\dot{\gamma}}$$

Linear Model

Solutions to $\nabla \sigma = 0$ are of the form:

$$u_s = r_s(z) e^{i[\phi_s(z) + wt]}$$

$$u_f = r_f(z) e^{i[\phi_f(z) + wt]}$$

Displacement

$r_{s,f}(z)$ are at most linear in z (the usual)
Generally, ϕ is also a function of z

Five Unknowns:

$r_s(z)$, ϕ_s (z), r_f (z), $\phi_f(z)$, z*

Continuity at z=z*

$$u_s(z = z^*) = u_f(z = z^*)$$

Eq. (1,2)

How well do we do?

If we float η_s, η_f, δ → too well

Stress Balance

$$G\partial u_s / \partial z + \eta_s \partial(\partial u_s / \partial t)/\partial z =$$

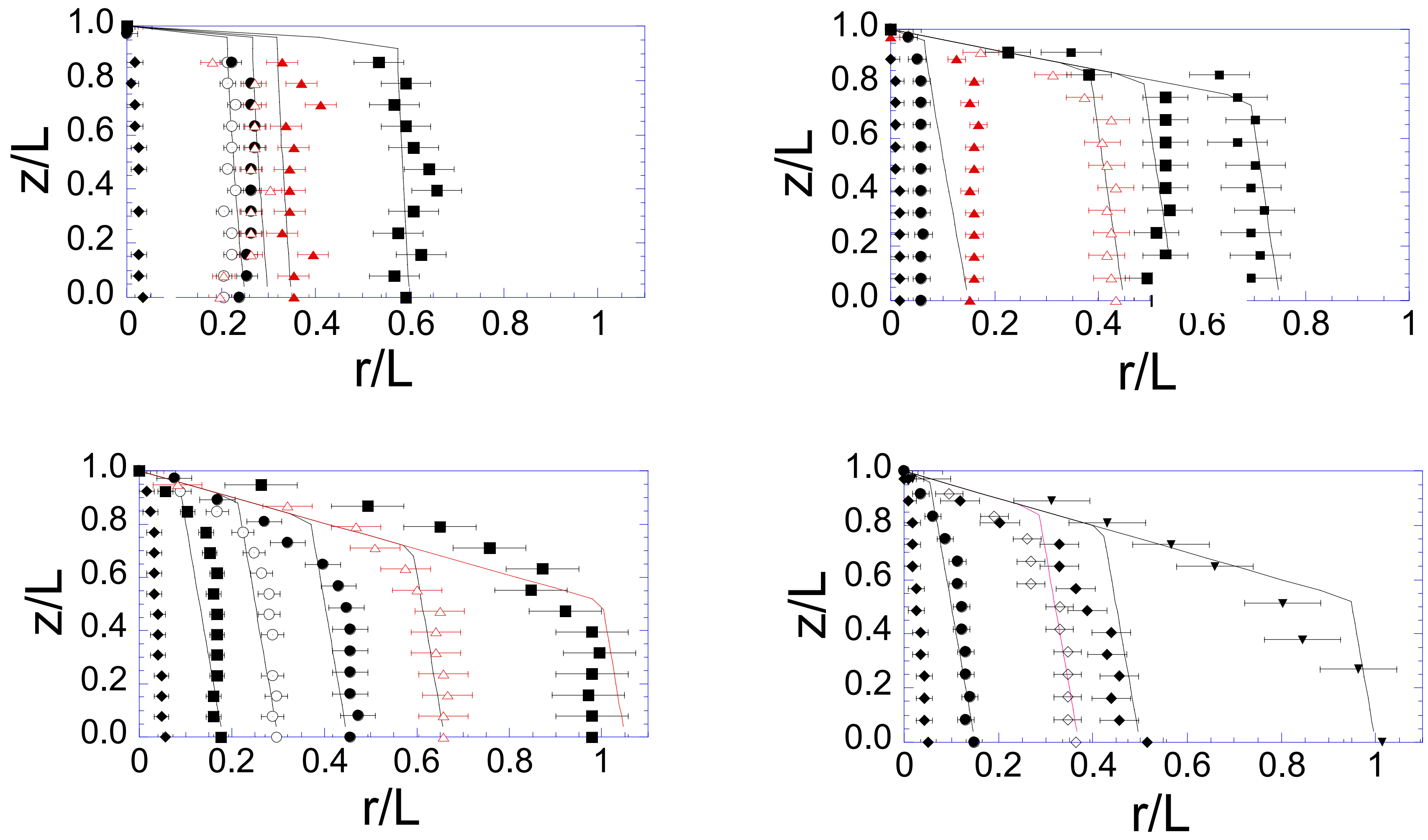
$$\eta_f \partial(\partial u_f / \partial t)/\partial z$$

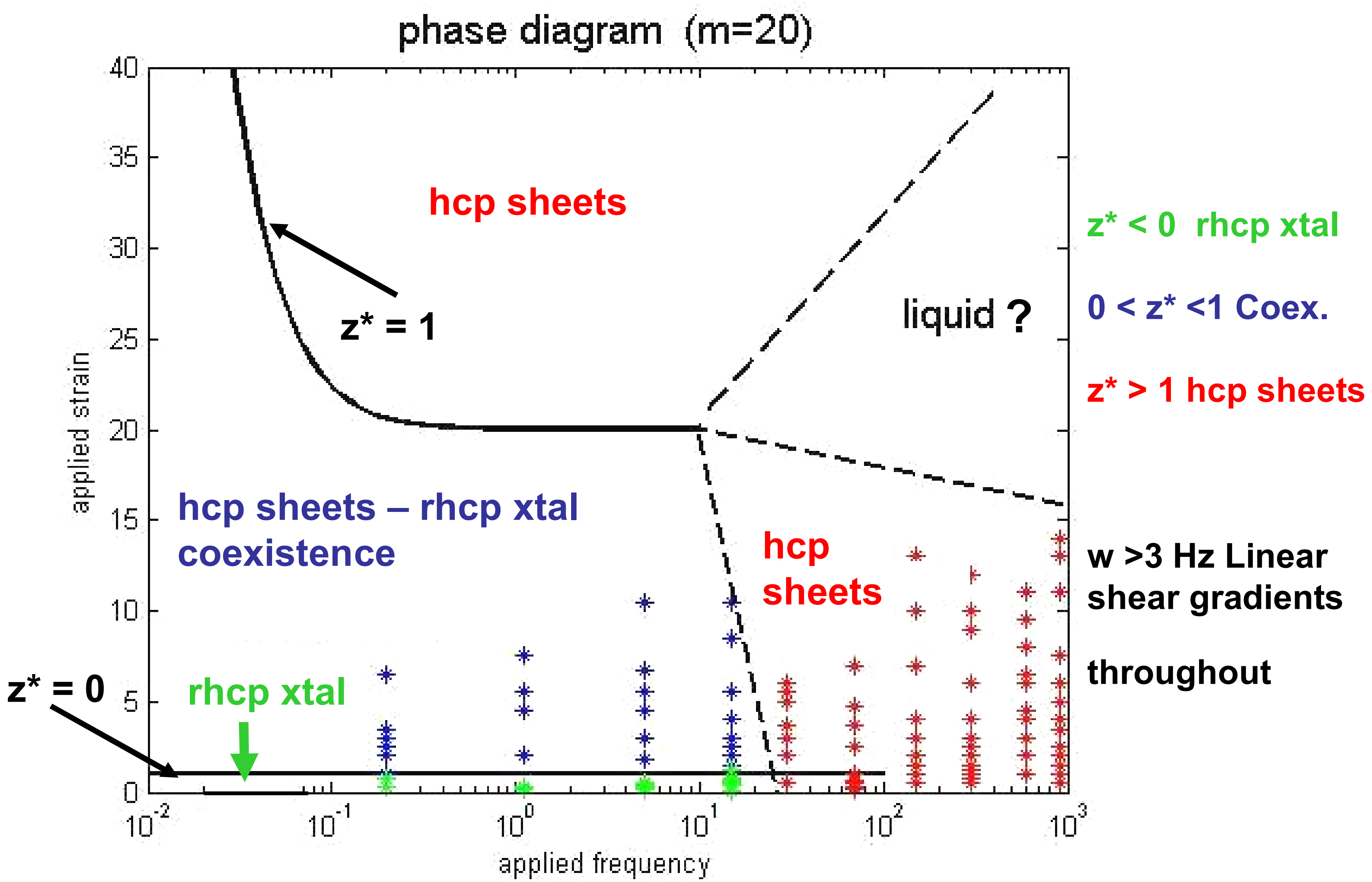
Eq. (3,4)

If we fix η_s, η_f, δ to be constant throughout

Selection problem
Transition stress = yield stress (δ) **Eq. (5) ?**

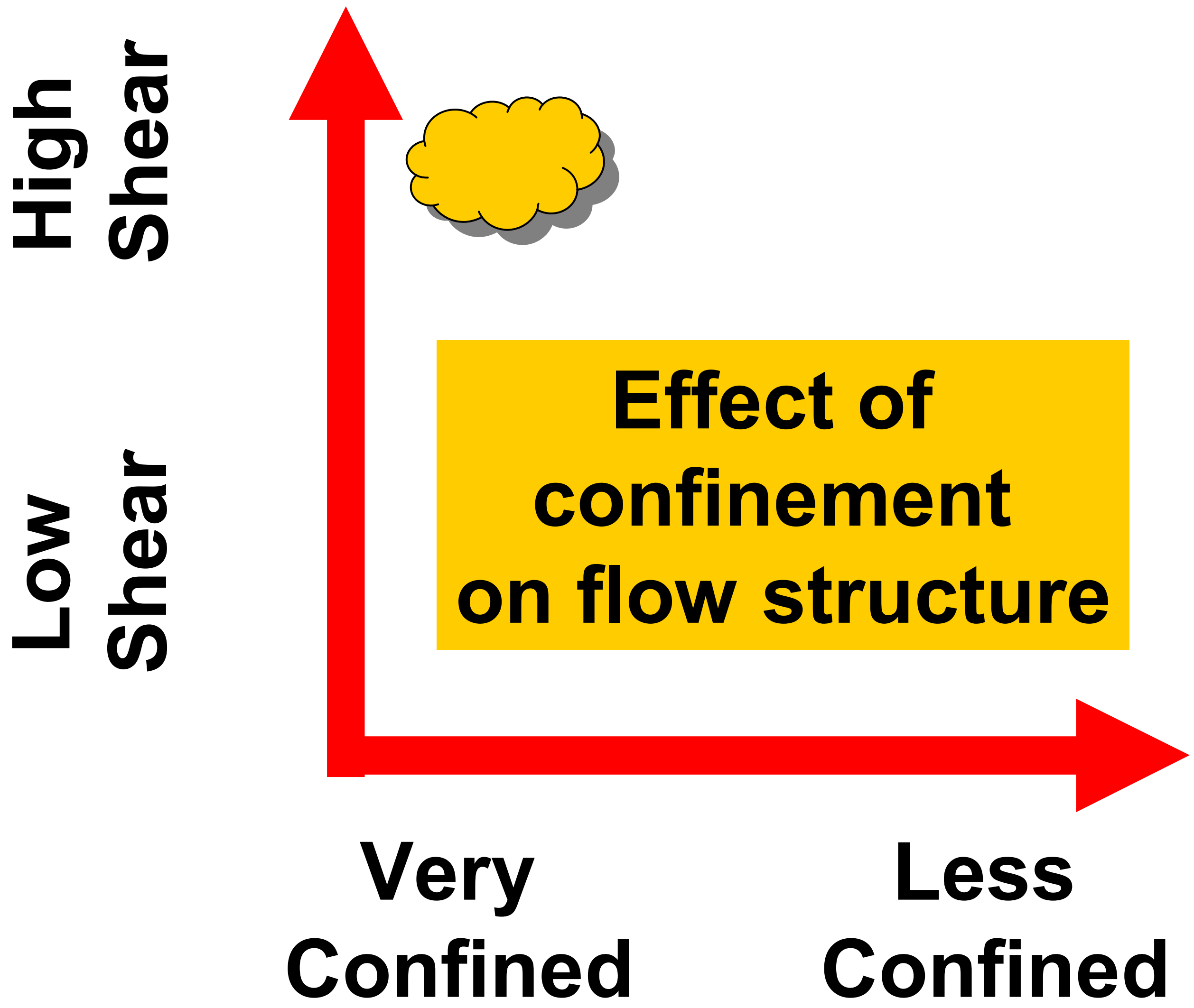
Linear model fixed η_s, η_f, δ





phase diagram (m=20)
applied strain
applied frequency
40
35
30
25
20
15
10
5
0
10-2
10-1
100
101
102
103
hcp sheets
z* = 1
liquid ?
hcp sheets – rhcp xtal
coexistence
hcp
sheets
z* = 0
rhcp xtal
z* < 0 rhcp xtal
0 < z* <1 Coex.
z* > 1 hcp sheets
w >3 Hz Linear
shear gradients
throughout

High Shear + Confinement

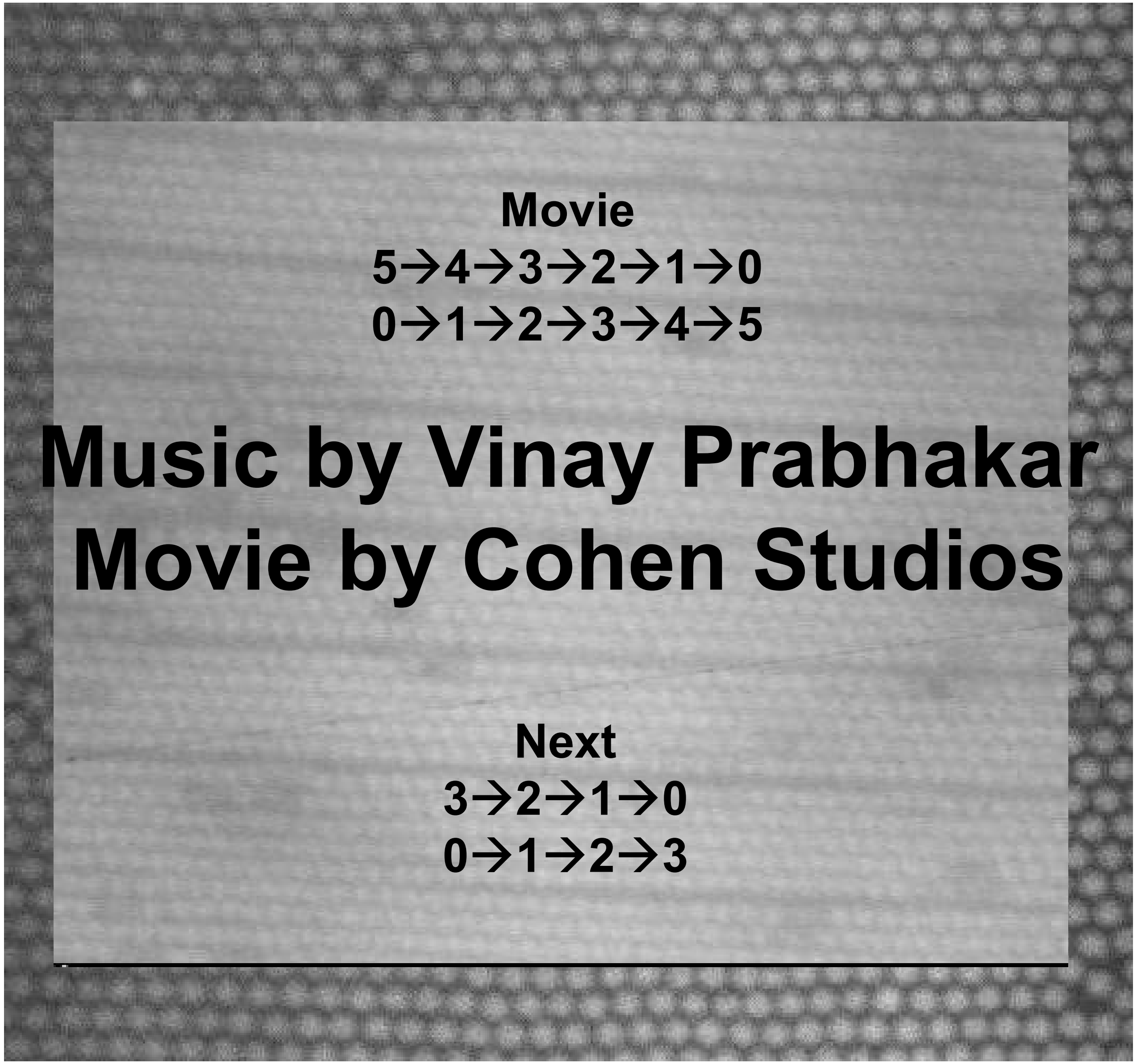


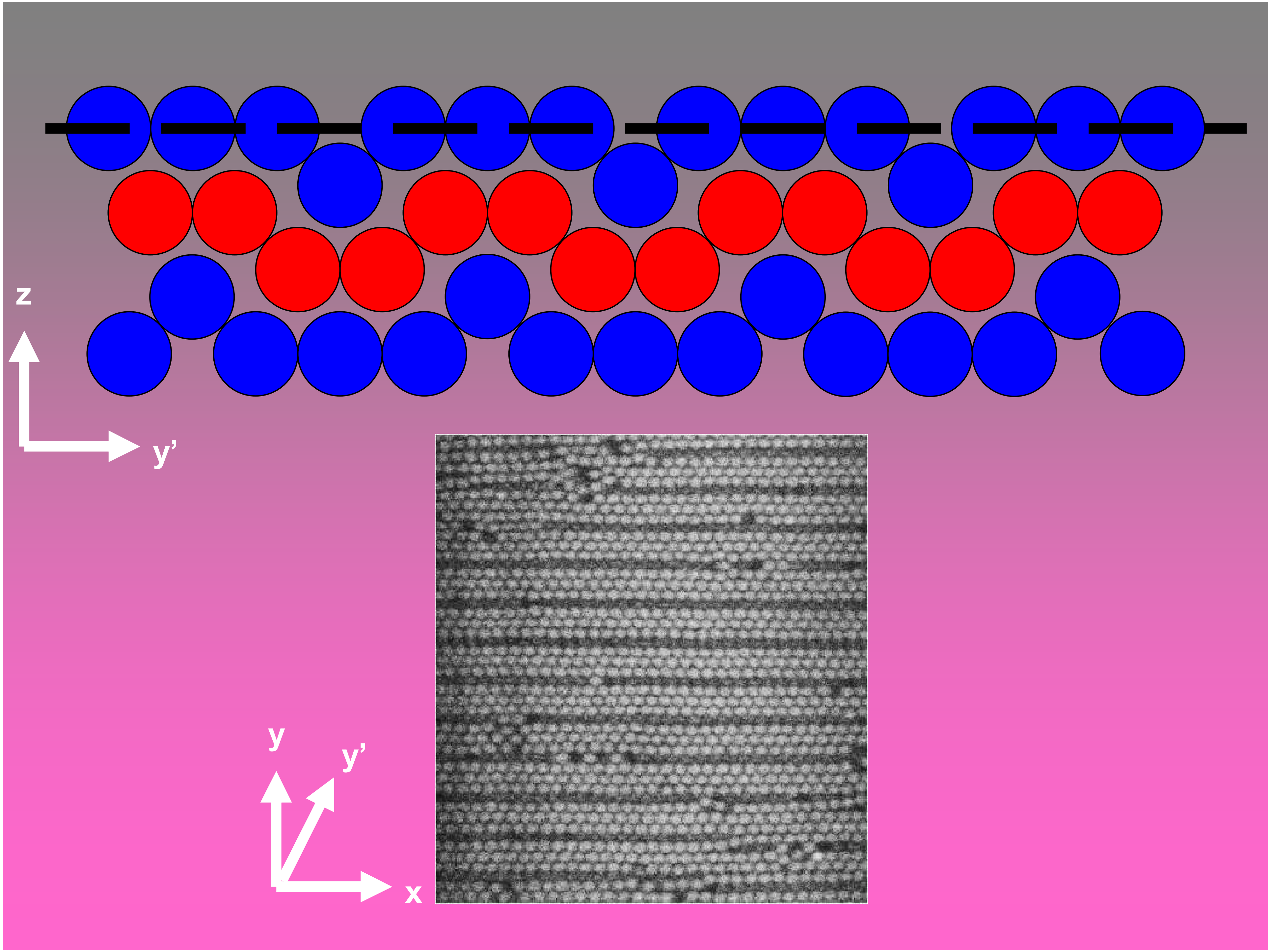
$\gamma > 0.3$

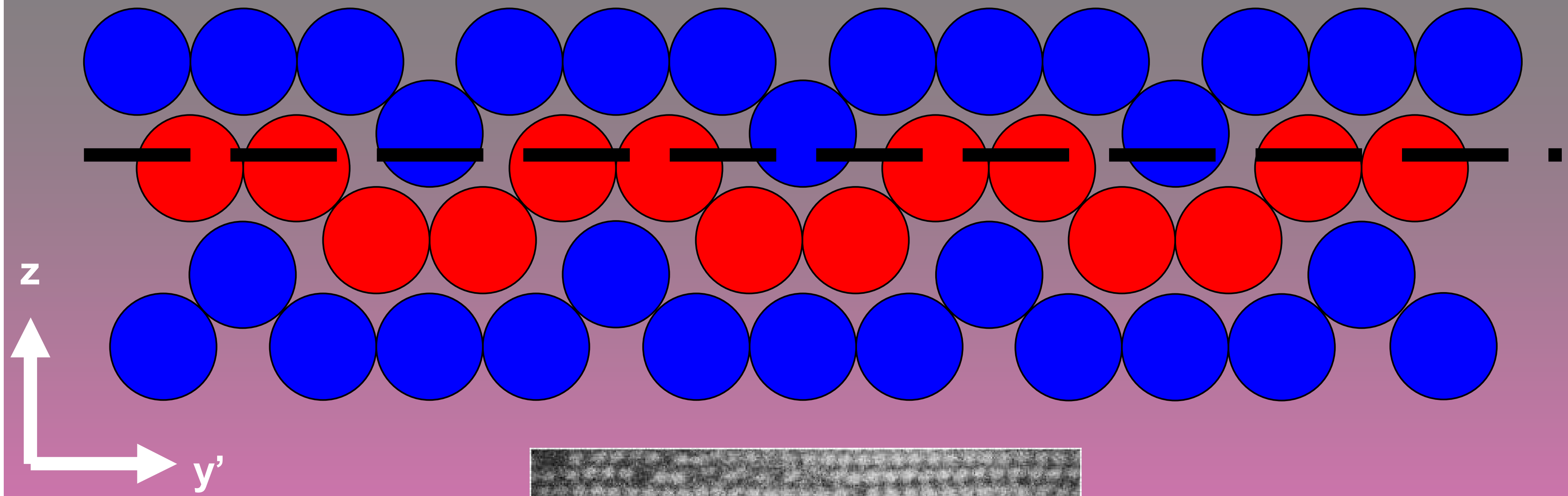
$f > 10$ Hz

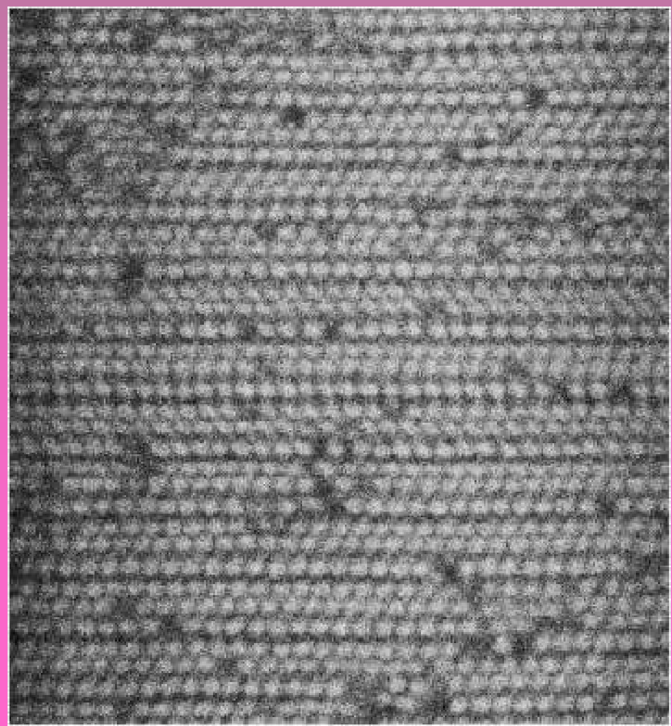
Gap $< 20\mu m$

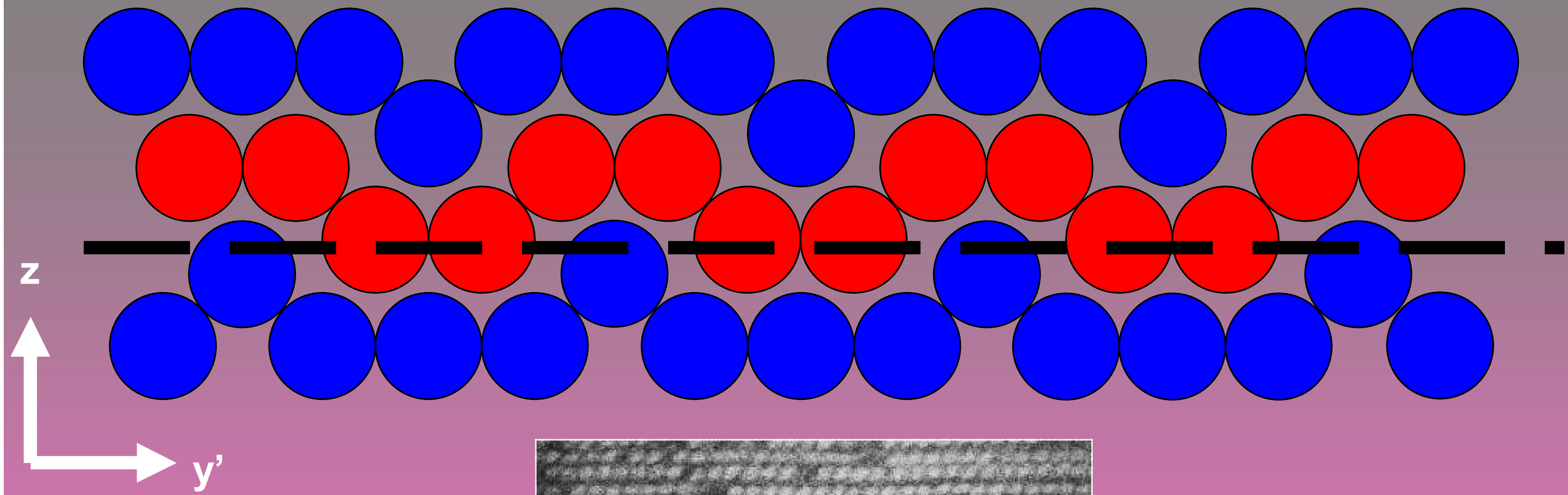
Colloids Under Confinement
Unconfined system:

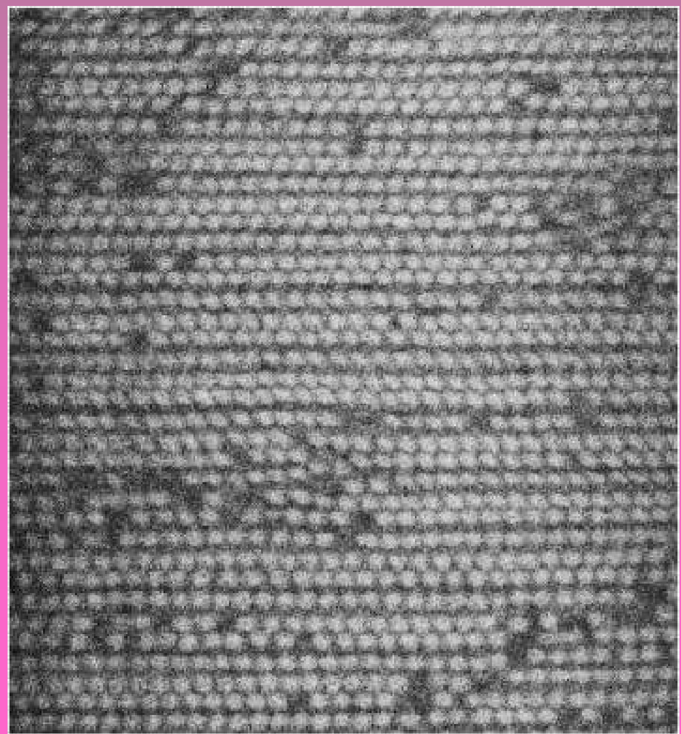


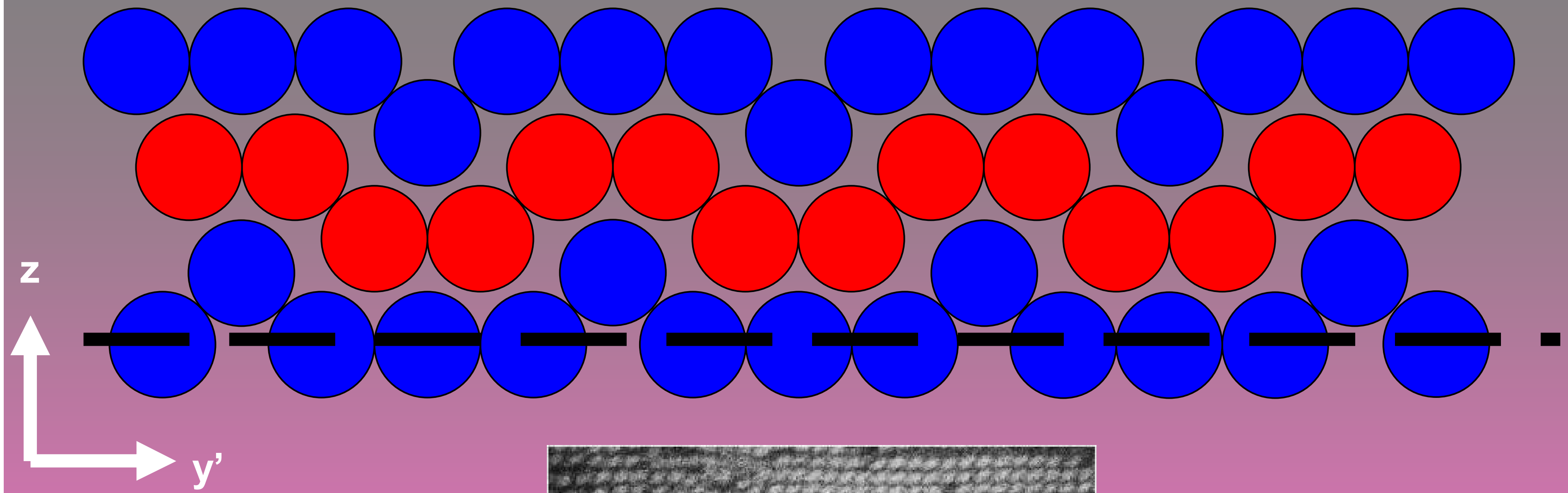

z
y'
y
y'
x

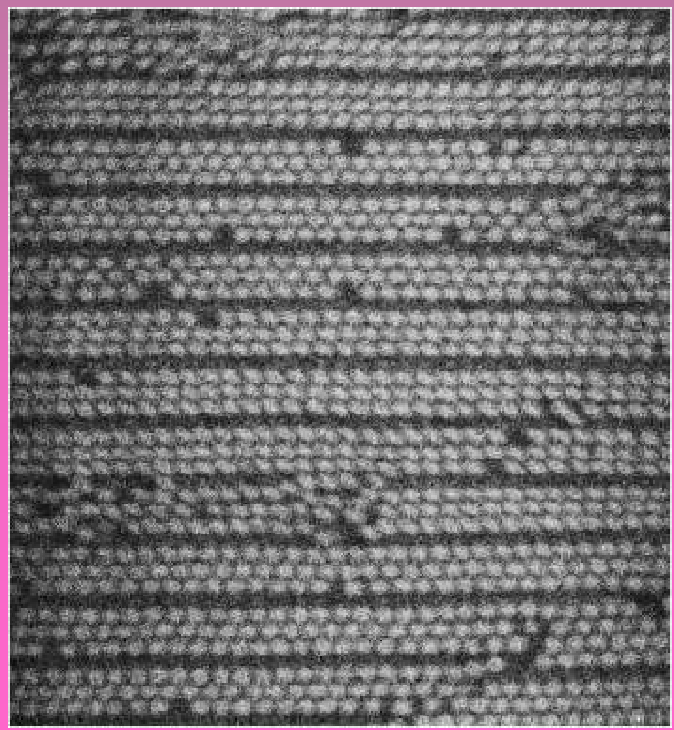

z
y’

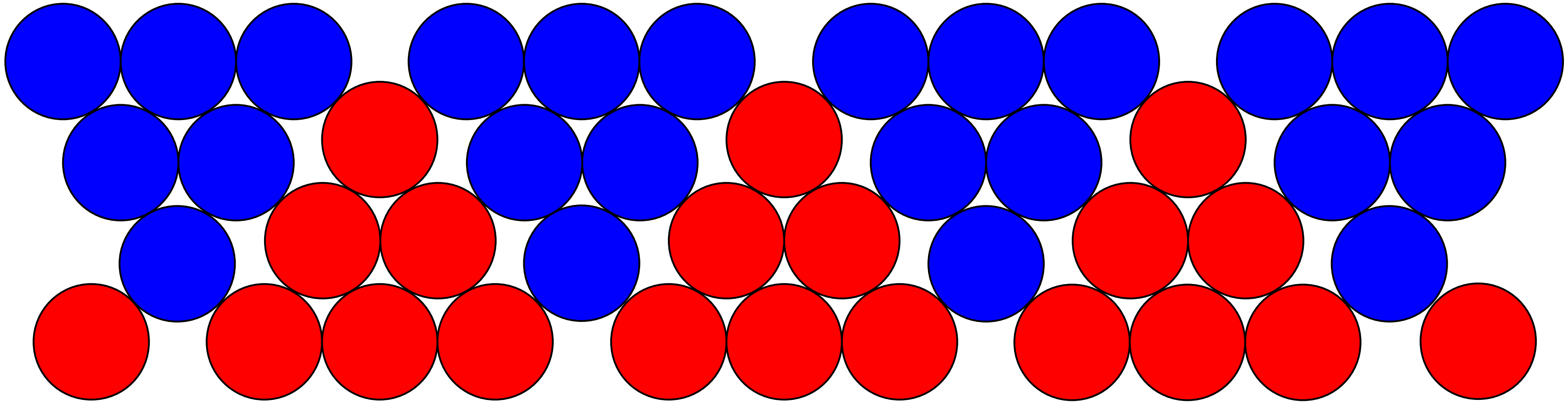



z
y’




z
y’



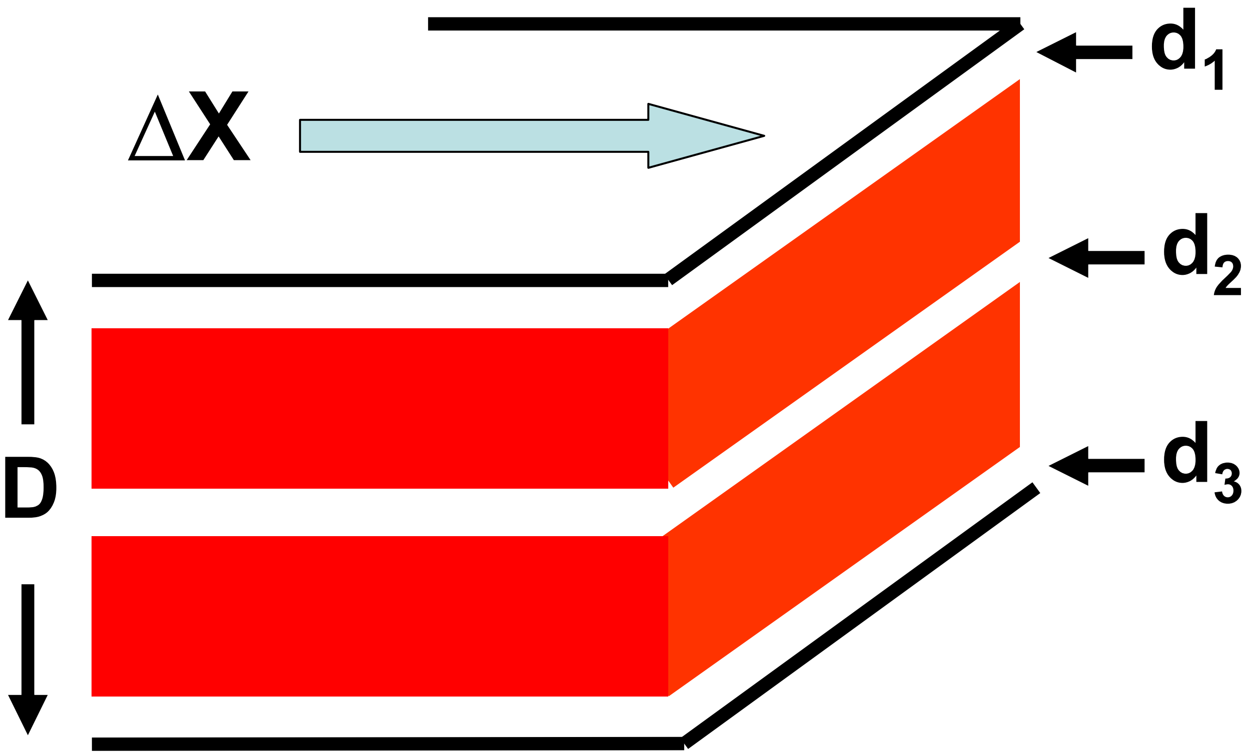


Reservoir osmotic pressure important

Densest Incommensurate Packing in 2-D

Piotr Pieranski & J. Finney, Acta Cryst **A35** 194-196 (1979)

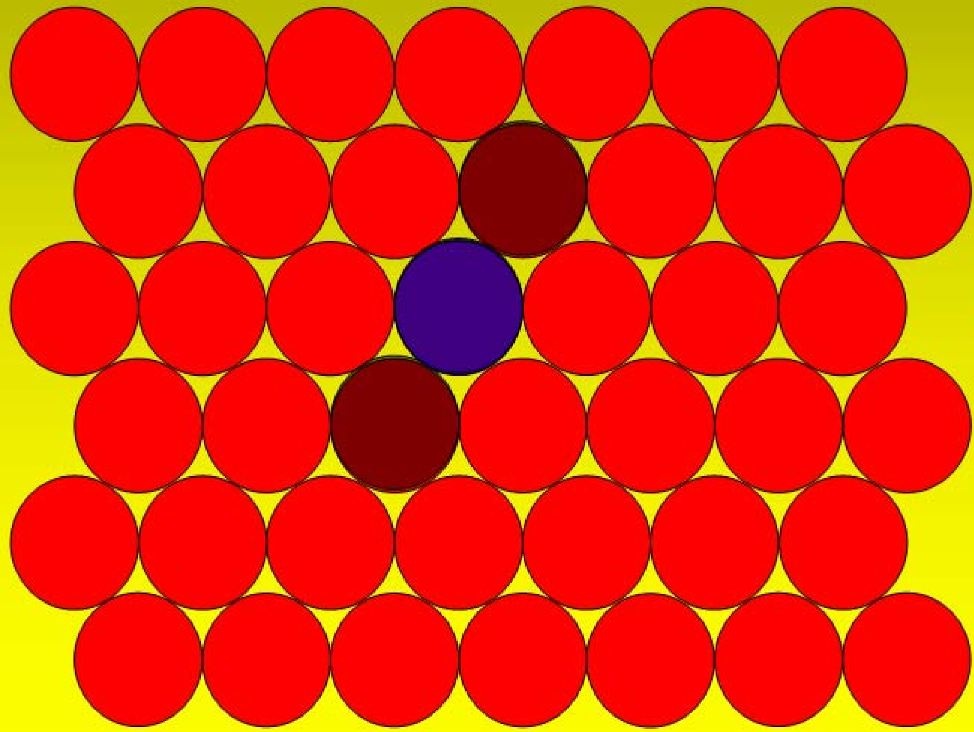
Osmotic Pressure (Π) $\Leftrightarrow$ Shear Stress

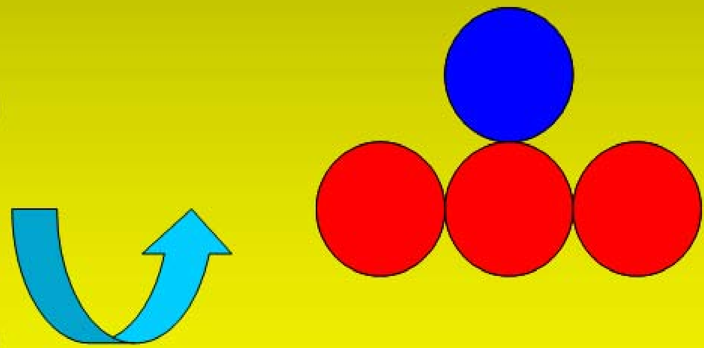


$$\eta_{eff} = \eta_0 * (D/(\Sigma d_i))$$

Structure → Ambiguity Straight

$d_i = 0$

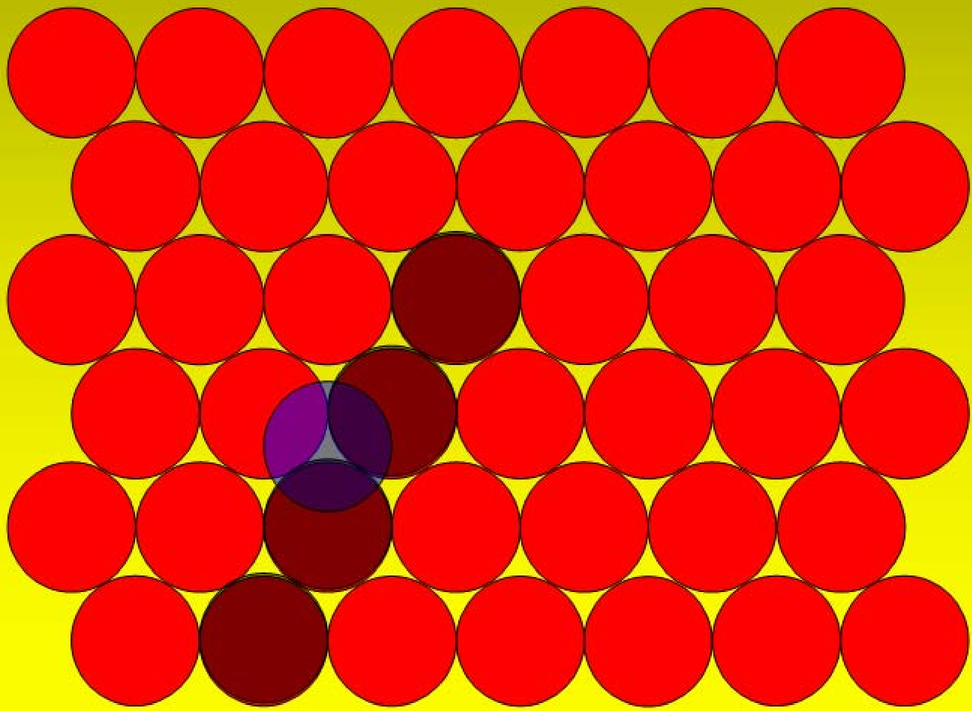


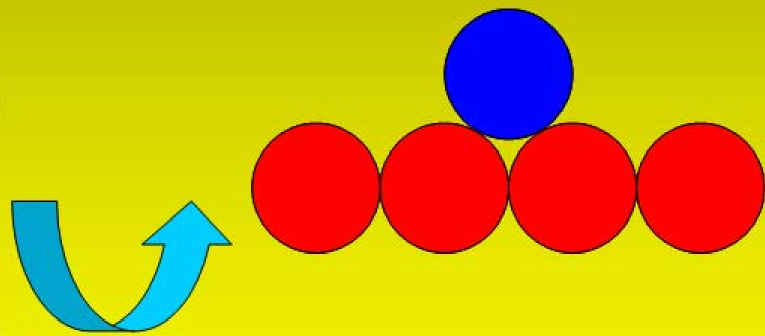


Inter-layer Distance = 2a

Structure → Ambiguity
Zigzag

$d_i = 0$





Inter-layer Distance = $\sqrt{3}$ a

Estimate Shear Stress

$\eta_{eff}\,\gamma f = \tau$ (stress)

$\Pi(\phi)$ → Literature

$\tau \sim 5\Pi_{HS} \sim 6$ dyn/cm^2

Building up a model

$$\Pi_\tau \cong \tau = \eta_{eff}\, \gamma\, f$$

$$(\Pi_\tau + \Pi)_{\text{shear zone}} = (\Pi_\tau + \Pi)_{\text{reservoir}}$$

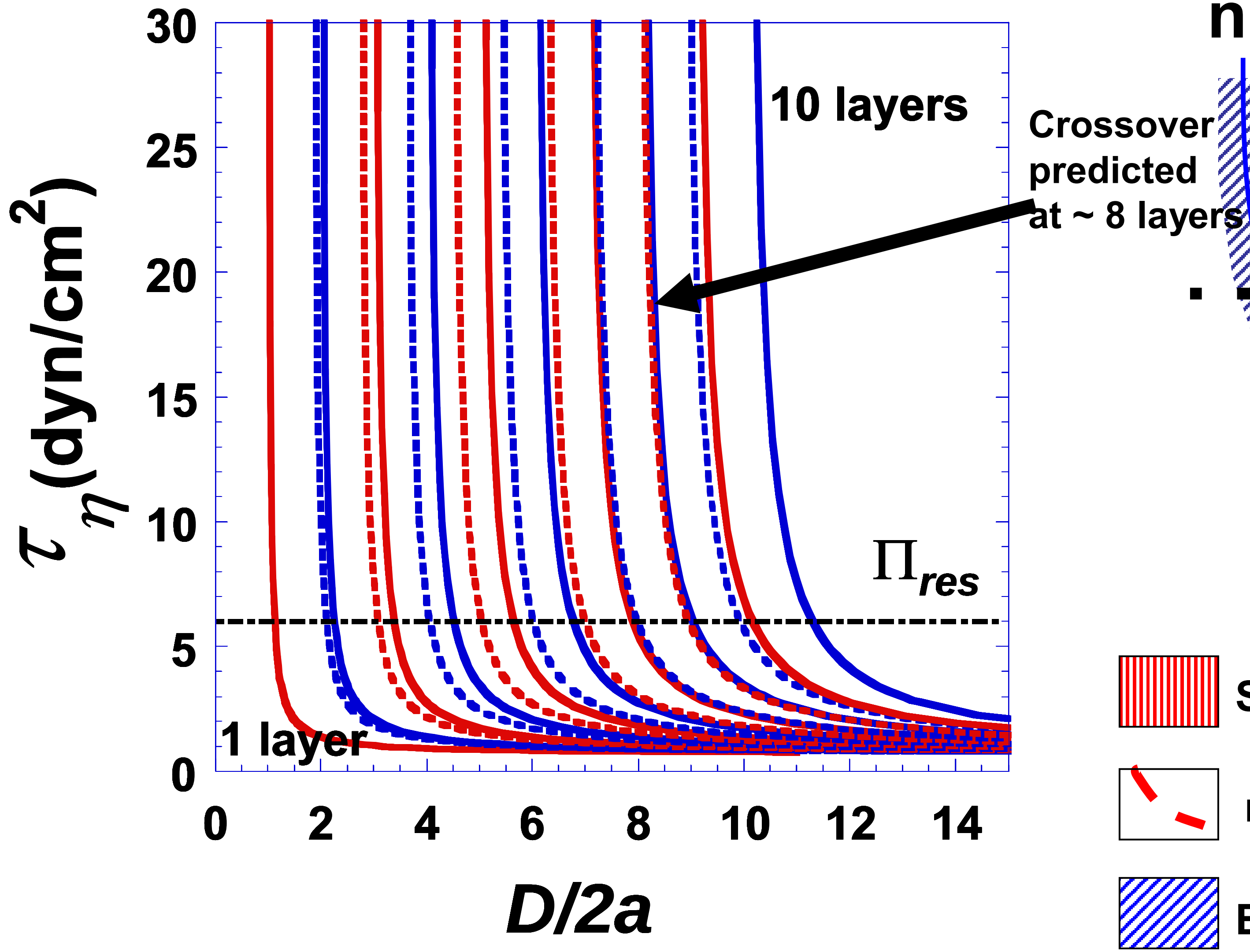
If gap ↑ η_{eff} ↓ since d_i ↑

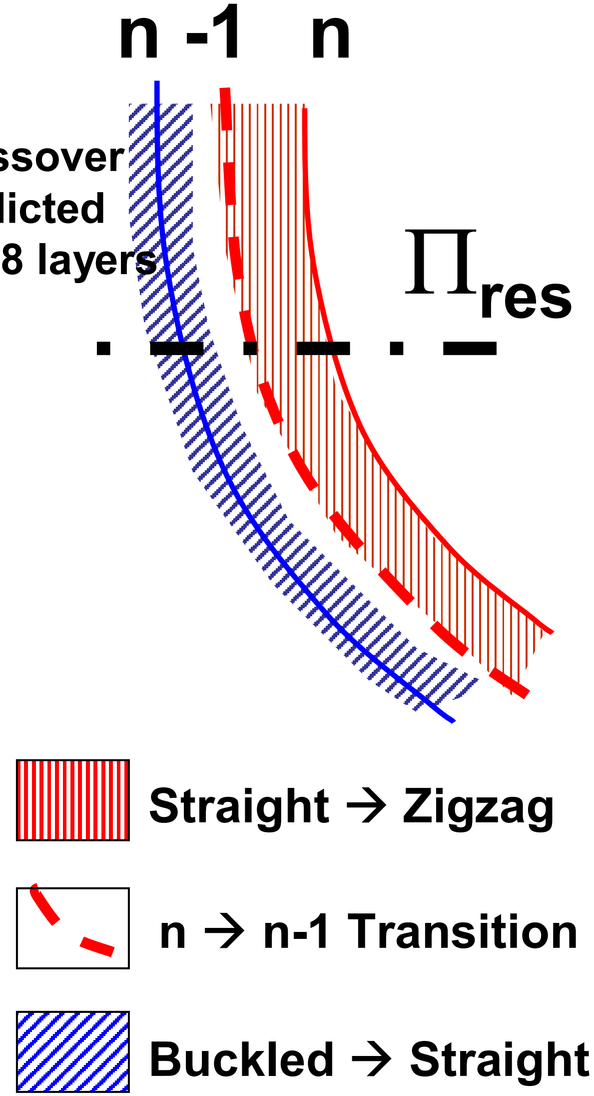
Enforce $\Pi_{res} = \Pi_\tau$, &D↑: Sheets Buckle

to keep d_i & η_{eff} constant

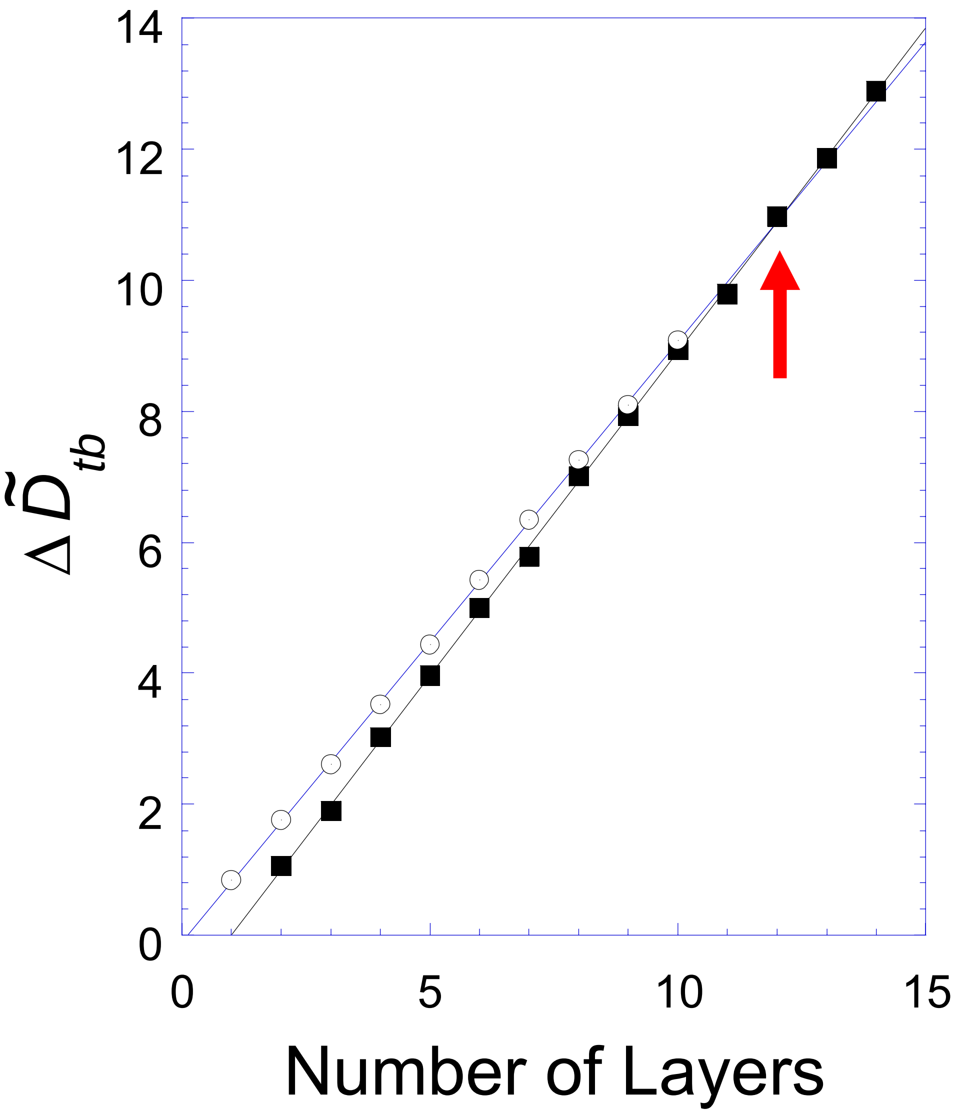
$\Pi_{res} = \Pi_\tau$: given D, γ, f → # of layers and transition mechanism

Can predict # of layers





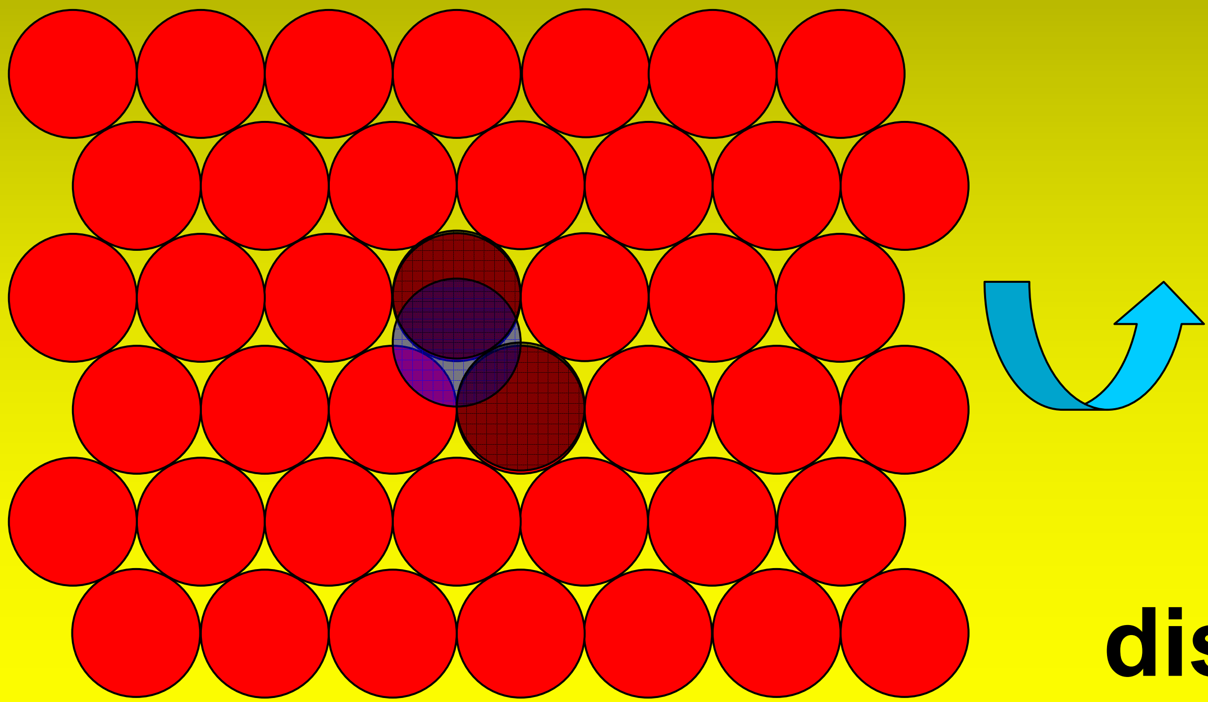
Measurement of Crossover



Crossover occurs at ~ 12 layers

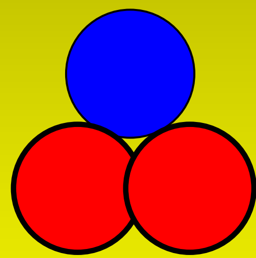
Why?

Straight But Registered



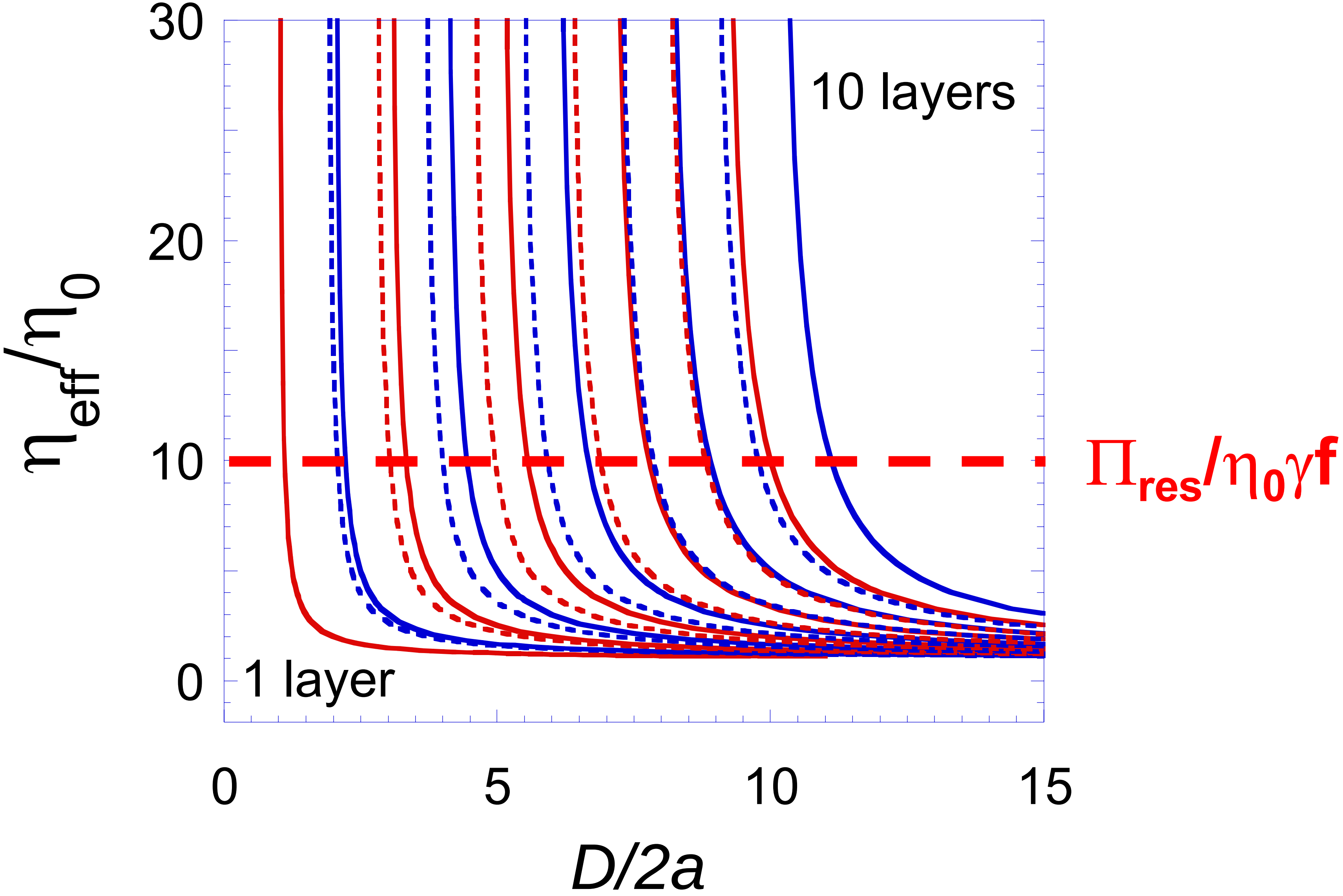
$d_i = 0$

Crossover occurs at ~ 13 layers

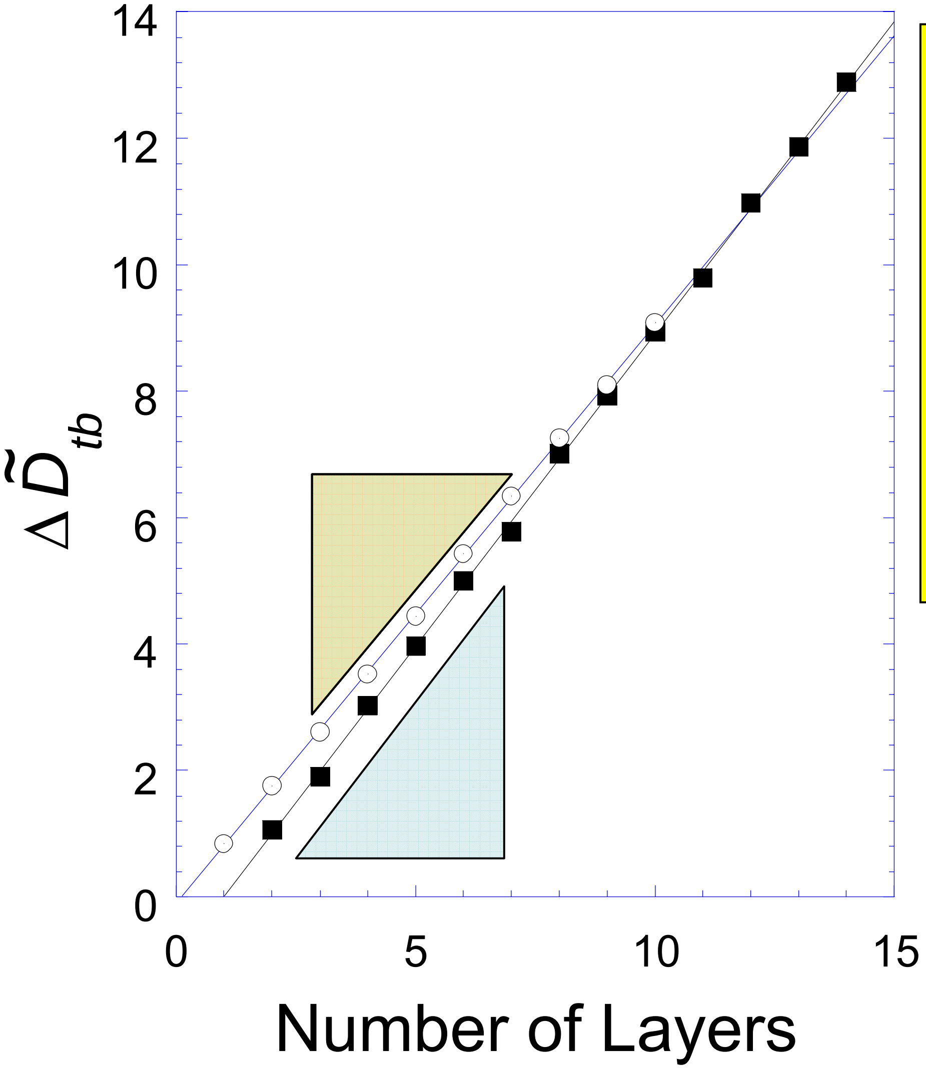


Inter-layer distance = 1.88a

Predict Shear Rate Dependence



Predict inter-layer distance



Model:

$\gamma f = 30 s^{-1}$

0.95

$\gamma f = 0.30 s^{-1}$

0.87

Measured:

$\gamma f = 30 s^{-1}$

0.92±0.05

$\gamma f = 0.30 s^{-1}$

0.89±0.05

γf	Slope flat layers	Slope buckled layers
0.3	0.98	0.89
5.0	0.98	0.90
10.0	0.99	0.90
20.0	0.99	0.91
30.0	0.99	0.92

Perspective

Three limits to colloid rheology:

1) **Low Pe # in both shear zone & reservoirs**

   Osmotic pressures balance

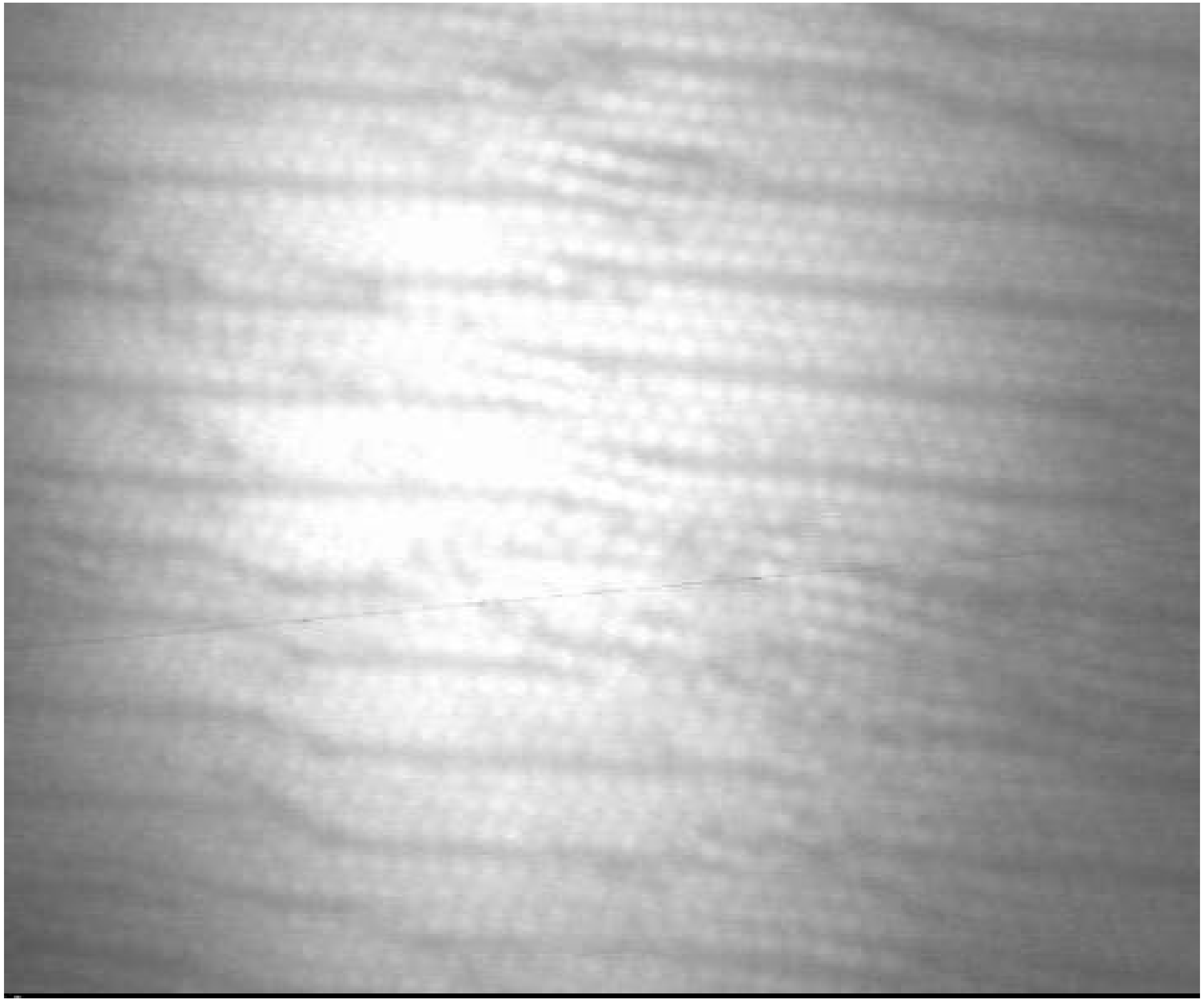
2) **High Pe # in both shear zone & reservoir**

   Π_τ balances ?????

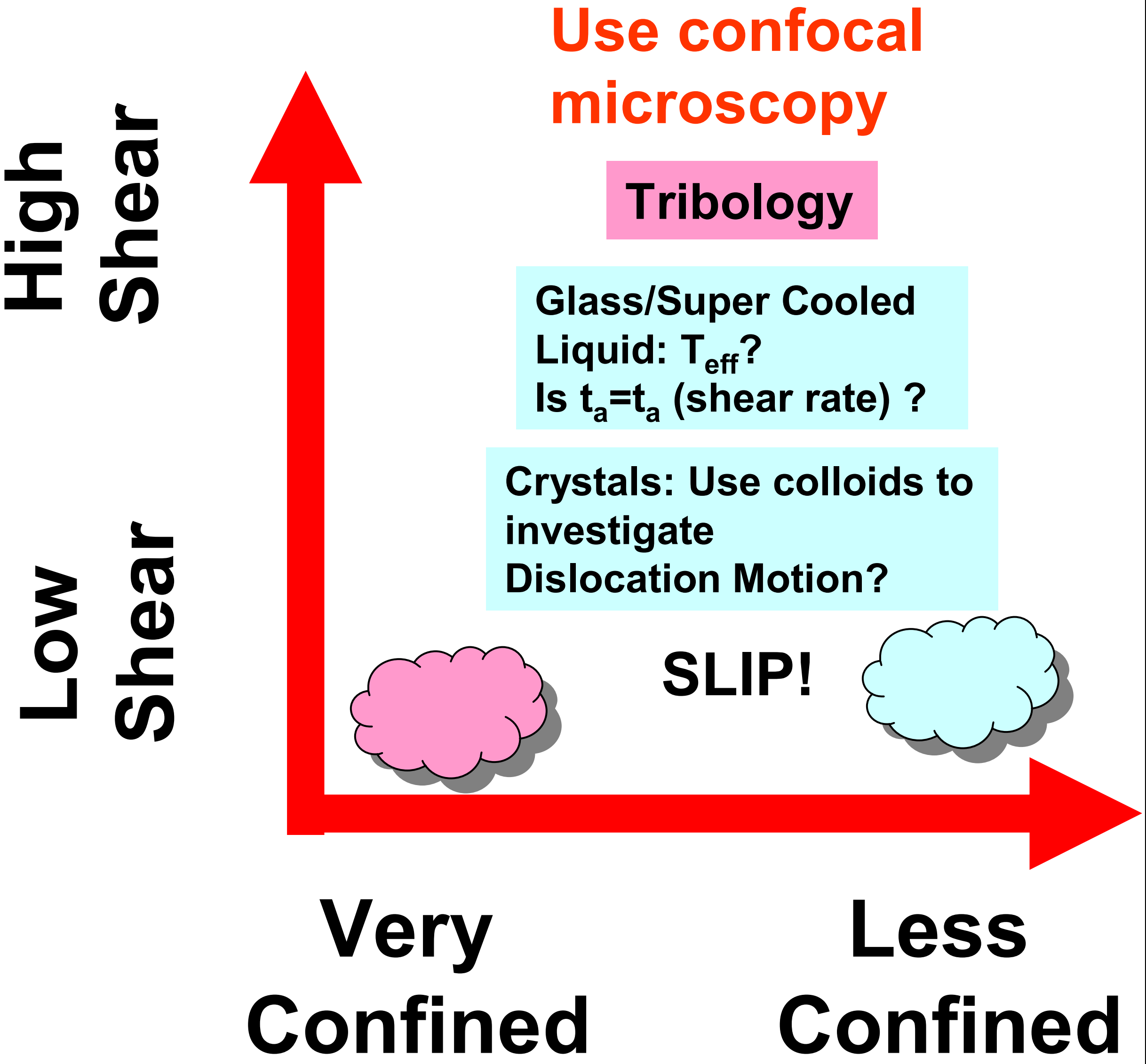
3) **High Pe # in shear zone, low Pe # in reservoir**

   Π_τ balances Π_{res}

Grain Boundary Hydrodynamics



Slow Shear

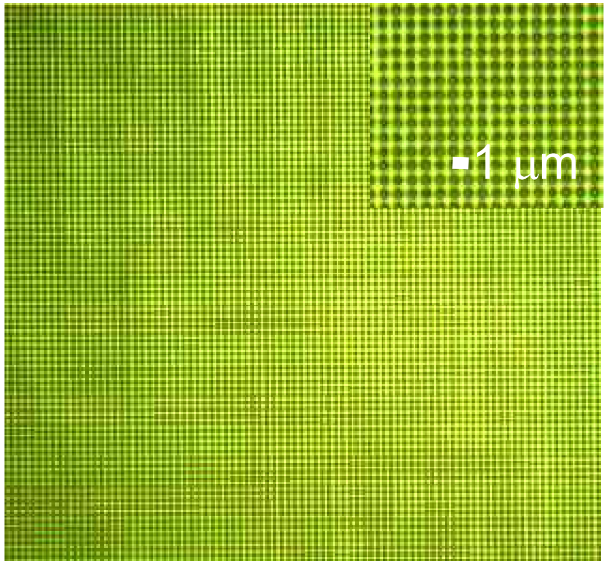


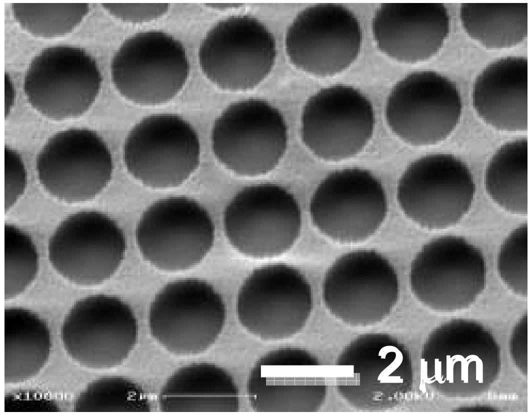
$f \cong 10^{-5}$ Hz
Amp. < 30μm
$0 < \gamma < 30$
Gap < 20 μm

$f \cong 10^{-5}$ Hz
Amp. < 30μm
$0 < \gamma < 1.5$
Gap > 20 μm

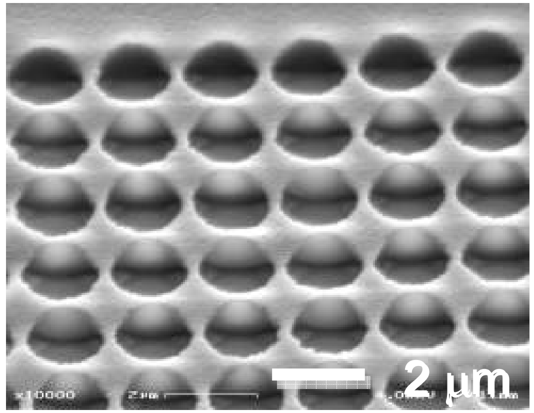
Pattern Plates to Access Slow Shear

- Stamping (optical gratings)
- Photo Lithography → (5mm X 5mm region)





Top View



Isometric View

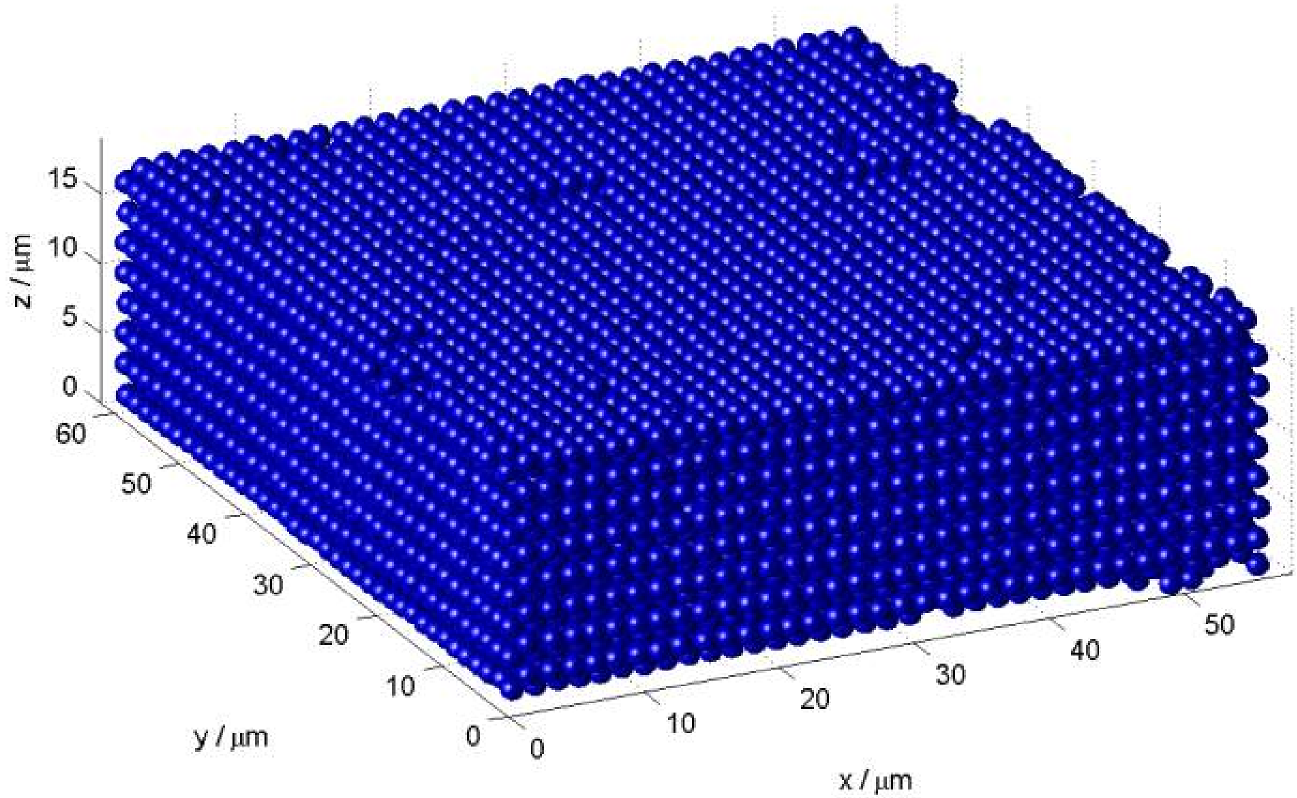
Tribology, Glasses, Dislocations

Dislocations (Peter Schall)

- Highly constrained systems
  - Nano: Smaller is harder/tougher
  - Cannot study dislocations in constrained atomic systems
  - Can we study them in colloids?
- Particle Shape: Spheres, diameter = 1.6 μm
- Particle interaction: Hard Spheres
- Volume fraction: $\Phi \cong 70\%$
- Boundary conditions: Patterned surface

Grow Perfect FCC crystals

Grow crystals “epitaxially” by sedimentation



Missmatched lattice → Misfit dislocations

Grow crystal on mismatched lattice with

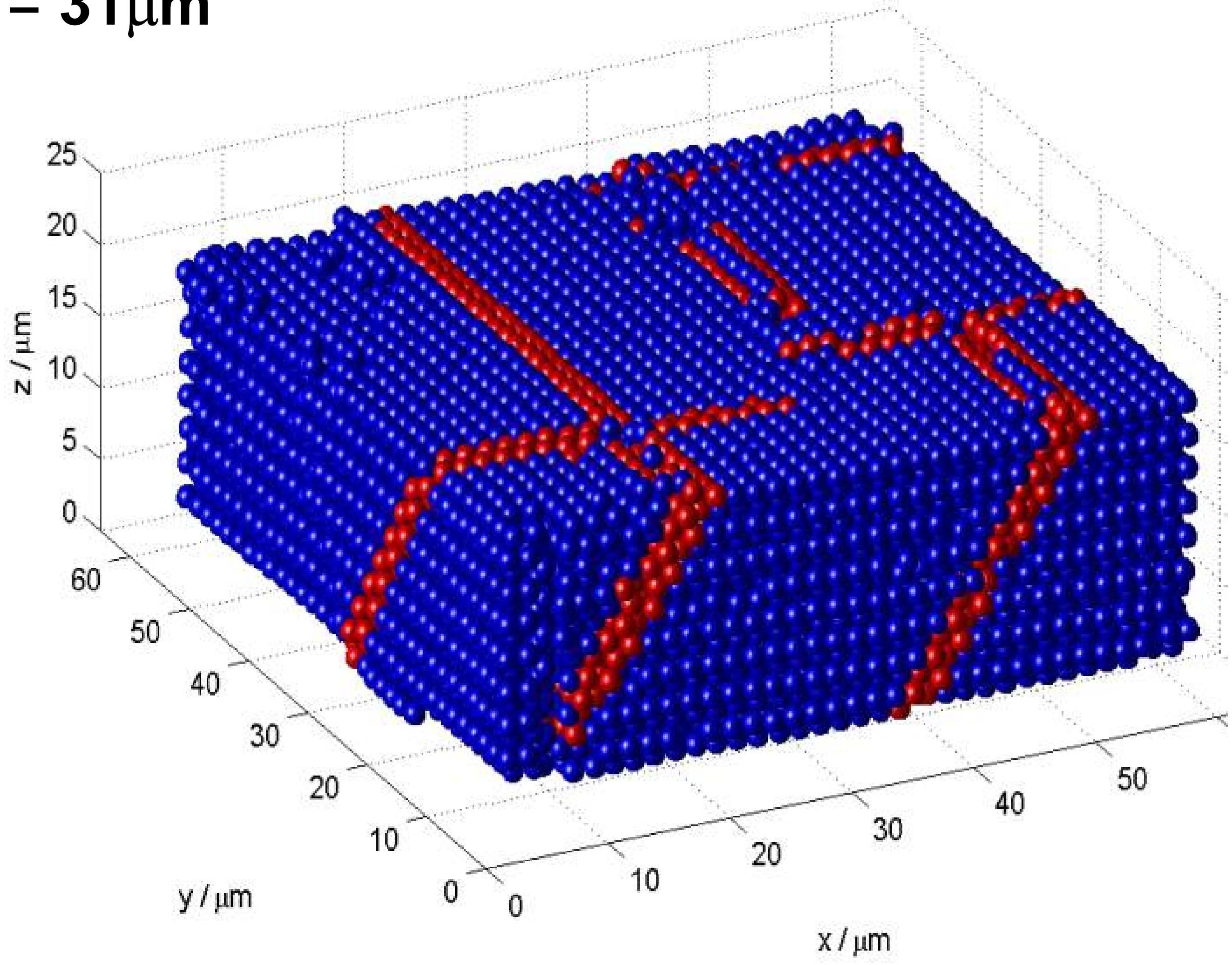
ε_0=0.015

When crystal height, h < 22μm

Crystal is defect free

Missmatched lattice → Misfit dislocations

When h = 31μm



Isolate stacking faults

When h = 31μm

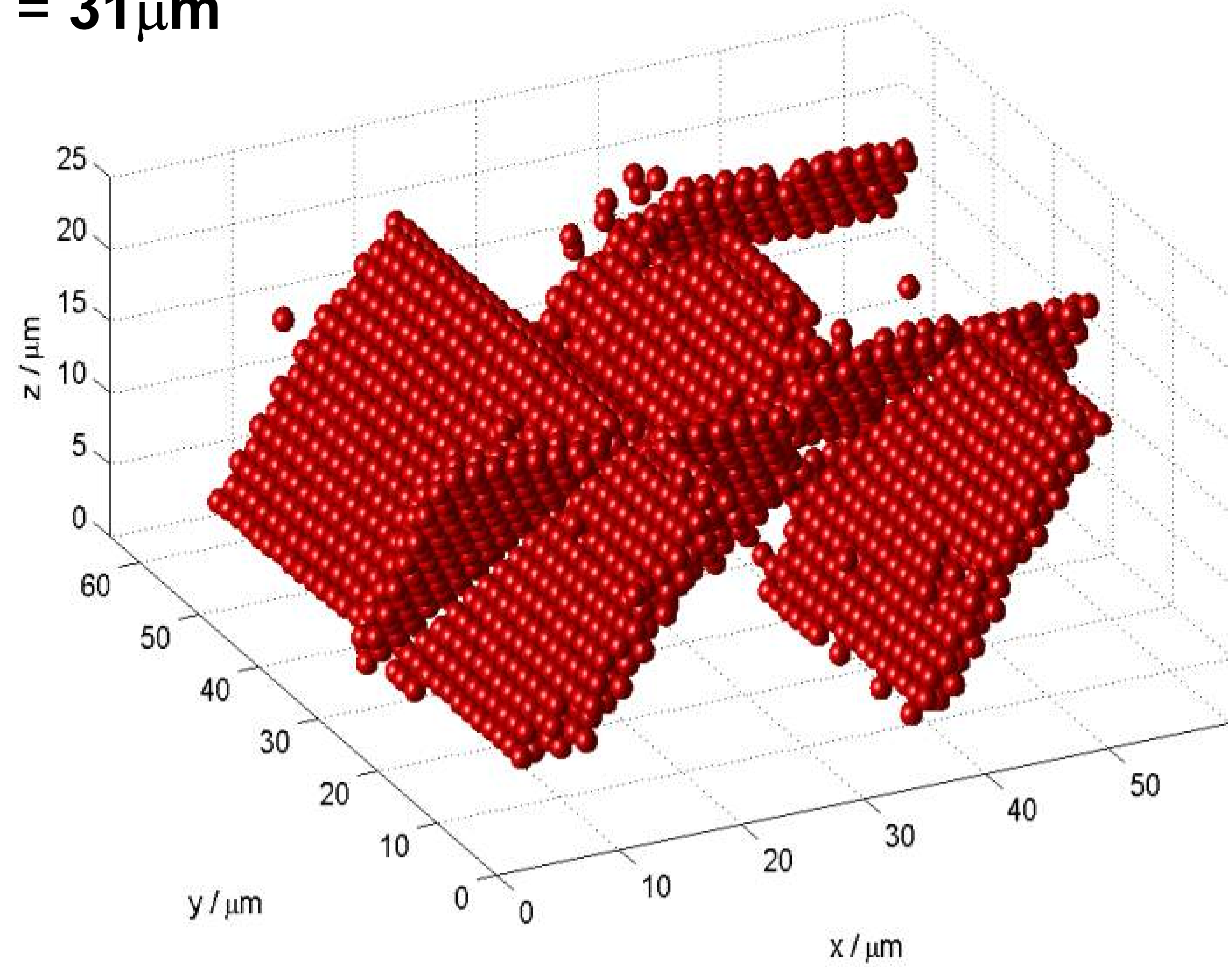
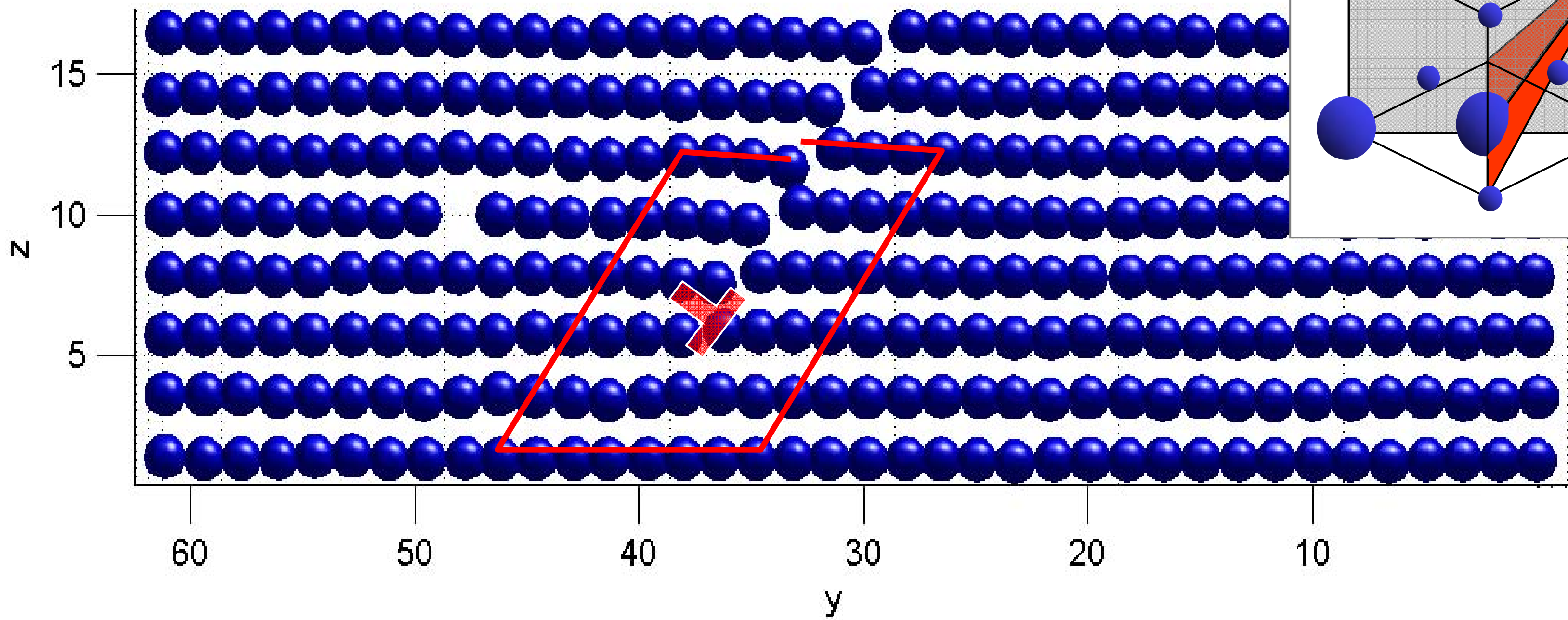
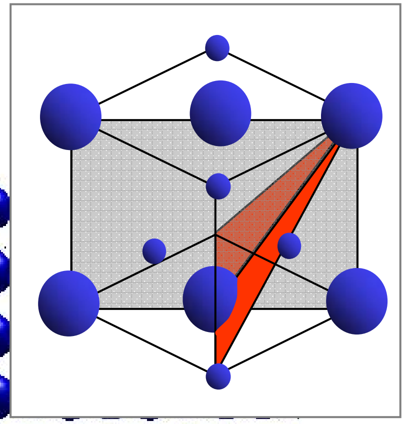


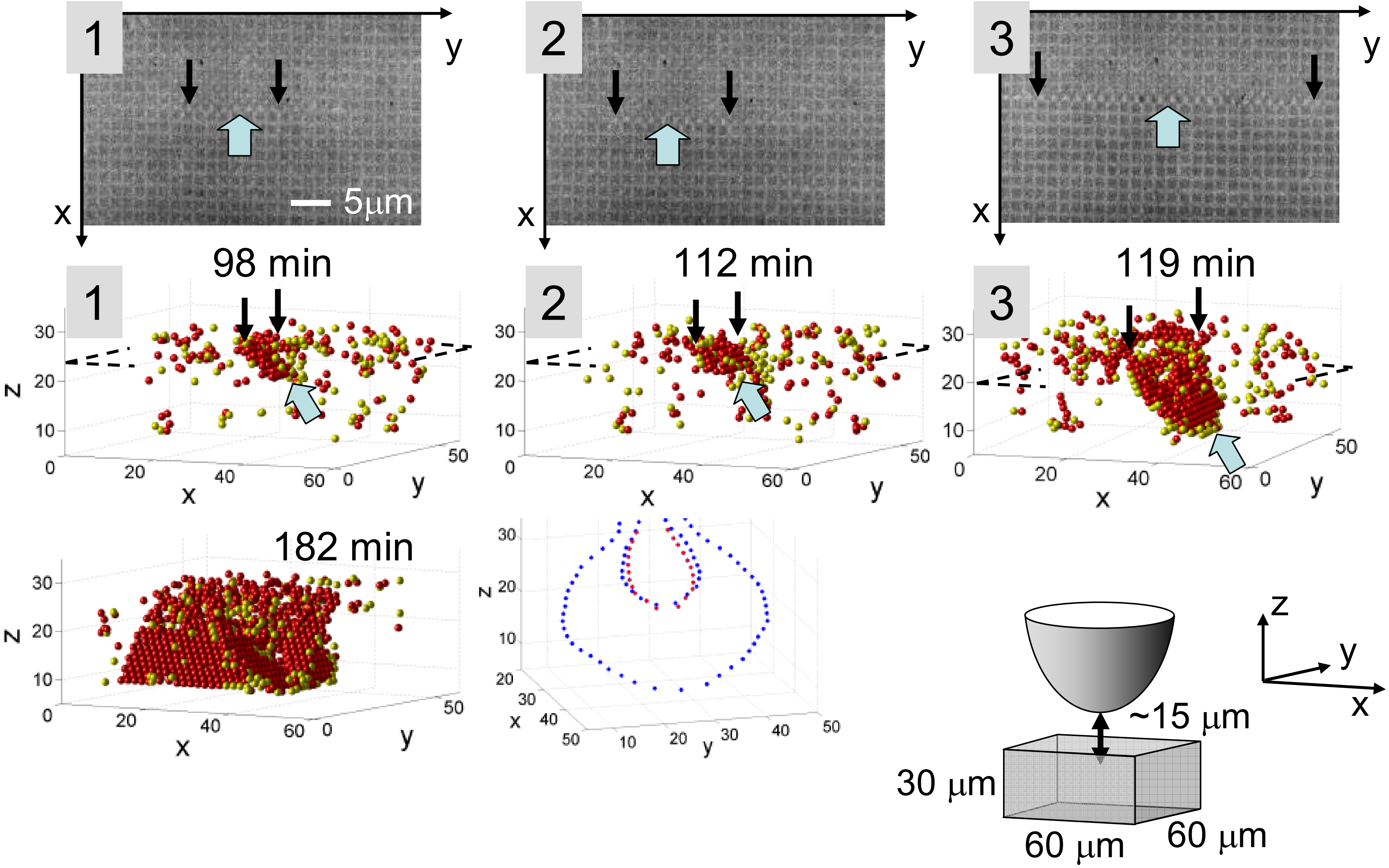
Image a cut through the crystal



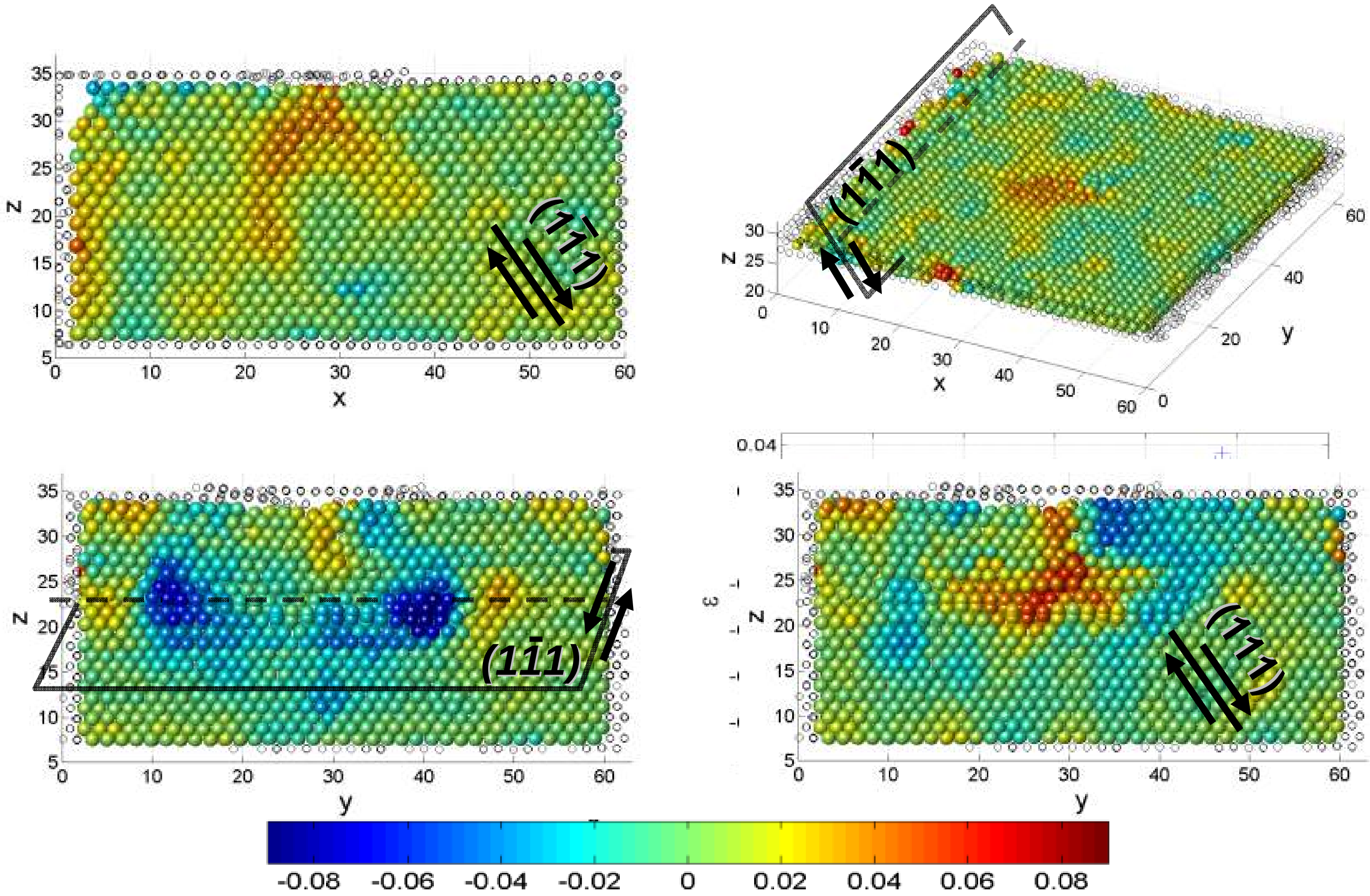


- Burger's vector: b = 0.94μm oriented ~54° to y axis
- Shokley partial dislocation (usually paired in metals)

Nanoindentation on micron scale



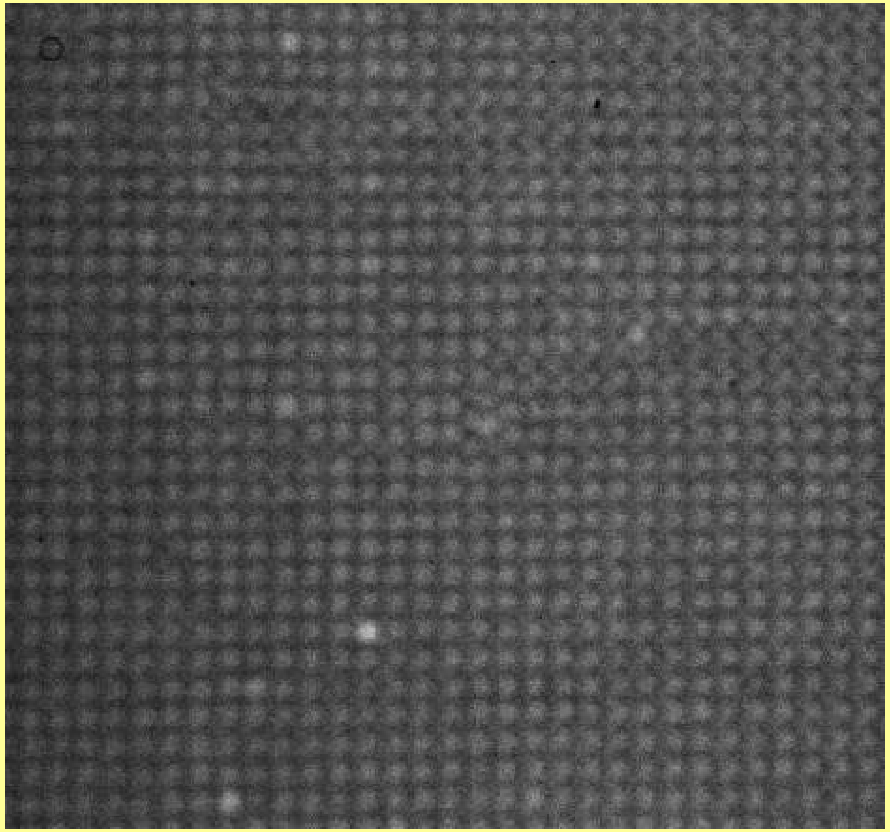
Visualizing Strain



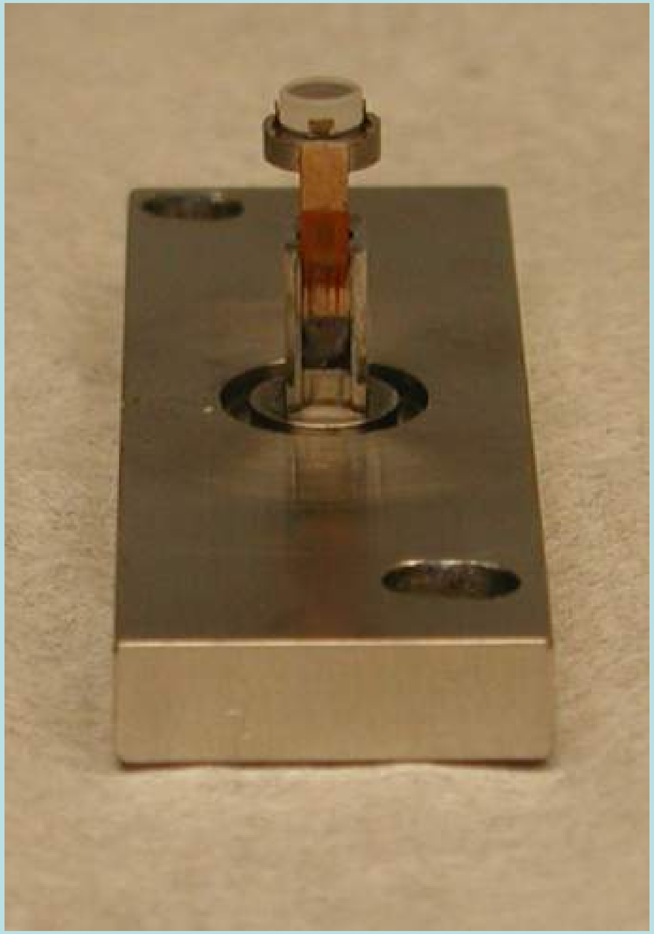
ε'_{ij}
x' (1,-1,-2)
z' (1,-1,1)
$\gamma \equiv 2\varepsilon'_{x'z'}$

γ'

Shearing Colloidal Crystal Films

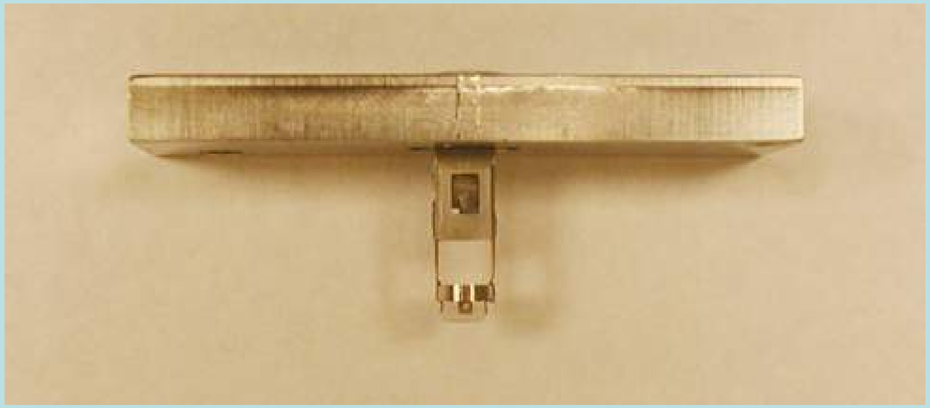


Sharon Gerbode

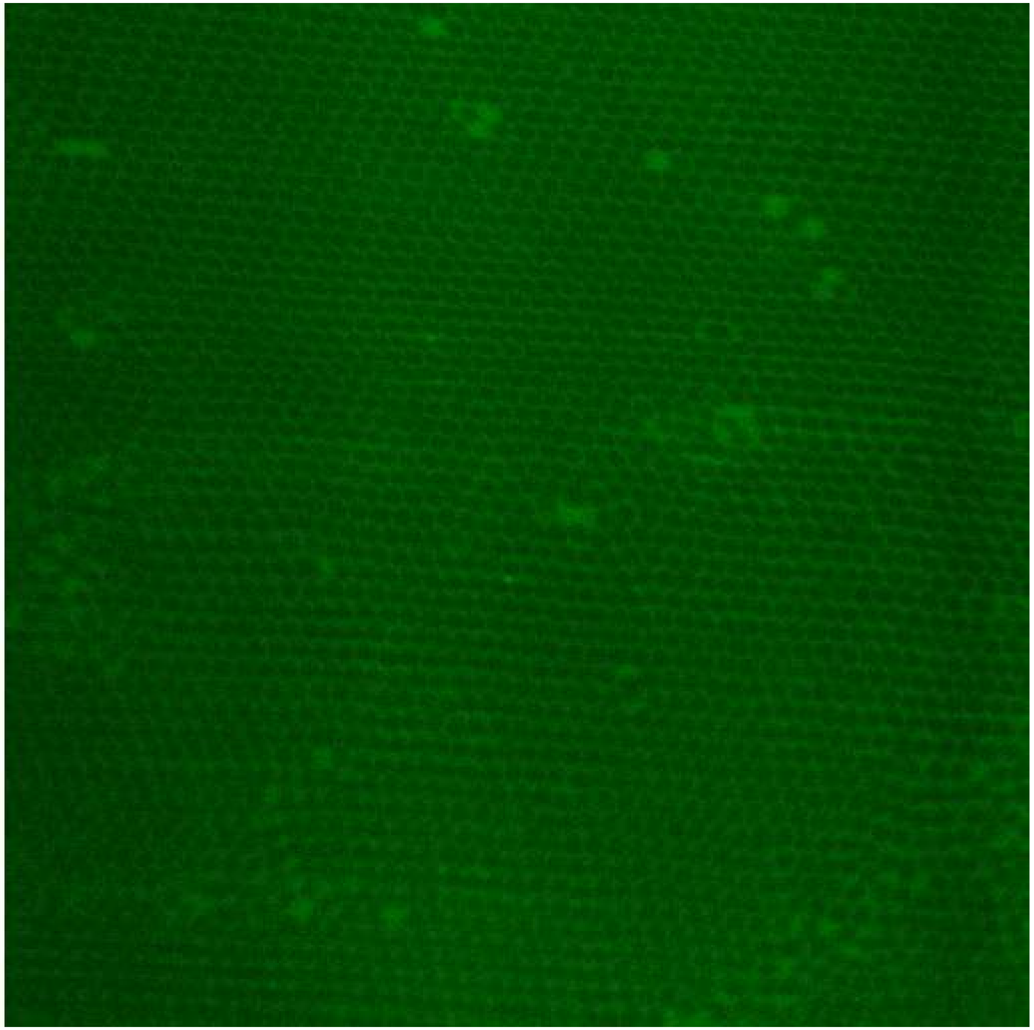


Shear Thickening Flows

Mark Buckley



Intermittent Flows



The Future

- Particle shape (discs, dimers, tetramers,…)
- Particle interaction (depletion forces, E&M)
- Volume fraction (different phases)
- Boundary conditions (plate roughness)
- Shear rate / confinement parameter space

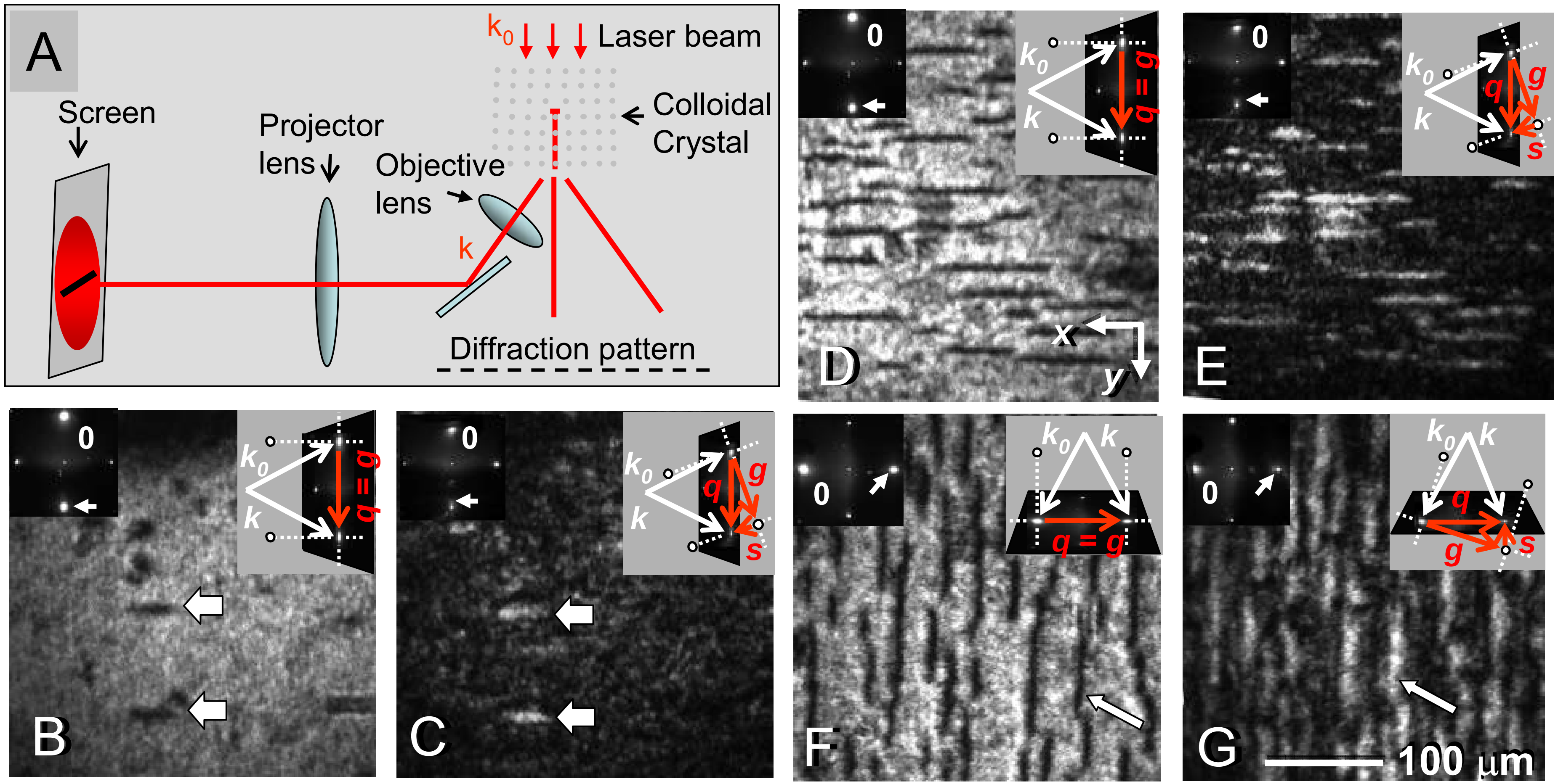
Measure transmitted stress

– (Jacob Israelachvili)

Thanks:

David Weitz (Harvard) Thomas Mason (UCLA) Jacob Israelachvili (UCSB) Frans Spaepen (Harvard) Michael Brenner (Harvard) Peter Schall (Amsterdam)	Principal investigators
Benny Davidovich (Harvard) Dan Blair (Harvard)	Post. Docs
Mark Buckley (Cornell) Sharon Gerbode (Cornell)	Graduate students

Laser Diffraction Microscopy (LDM)



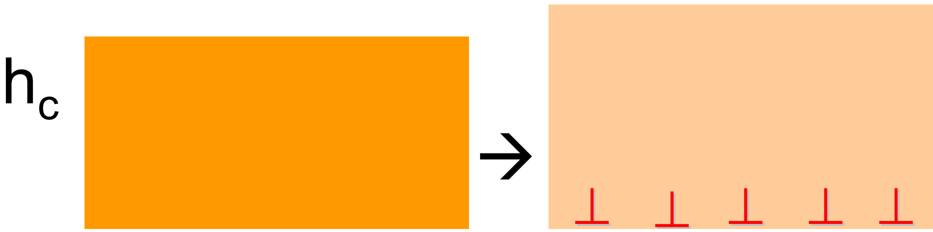
Nearly ideal lattice

Determine defect density

Stretched lattice

Test continuum theories

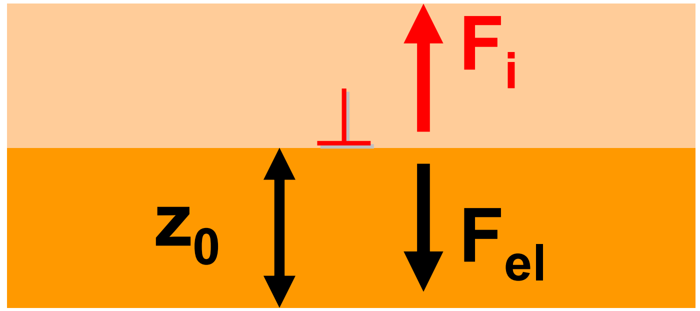
Prediction for h_c
1-d dislocation models:



$U_{el} \propto h$

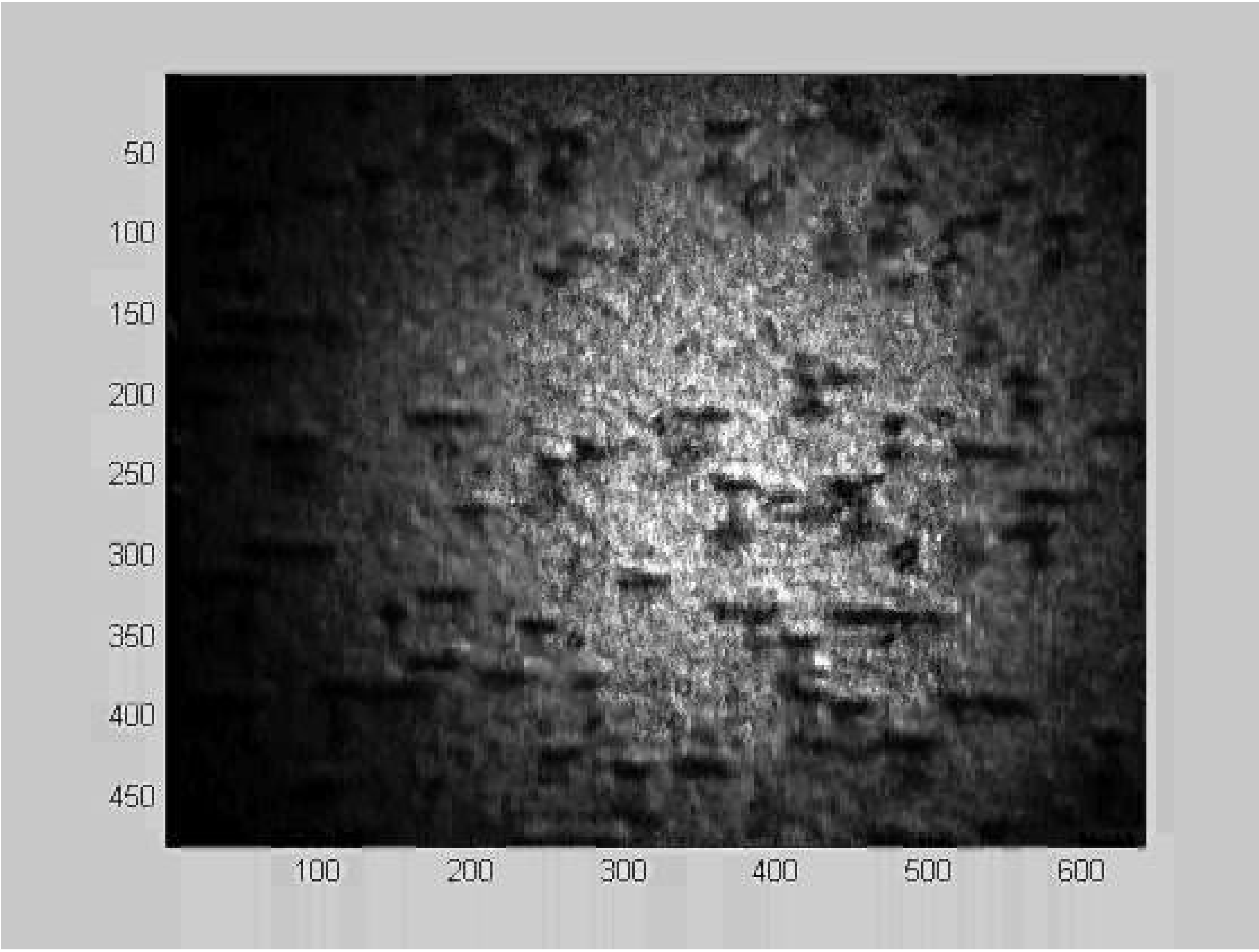
- Minimize $U_{el}+U_I$ with respect to ρ
- $h_c = b\ln(R/r_c)/8\pi\varepsilon_0(1-\nu^2)\cos\alpha$
- $h_c = 22\mu m$ (consistent)

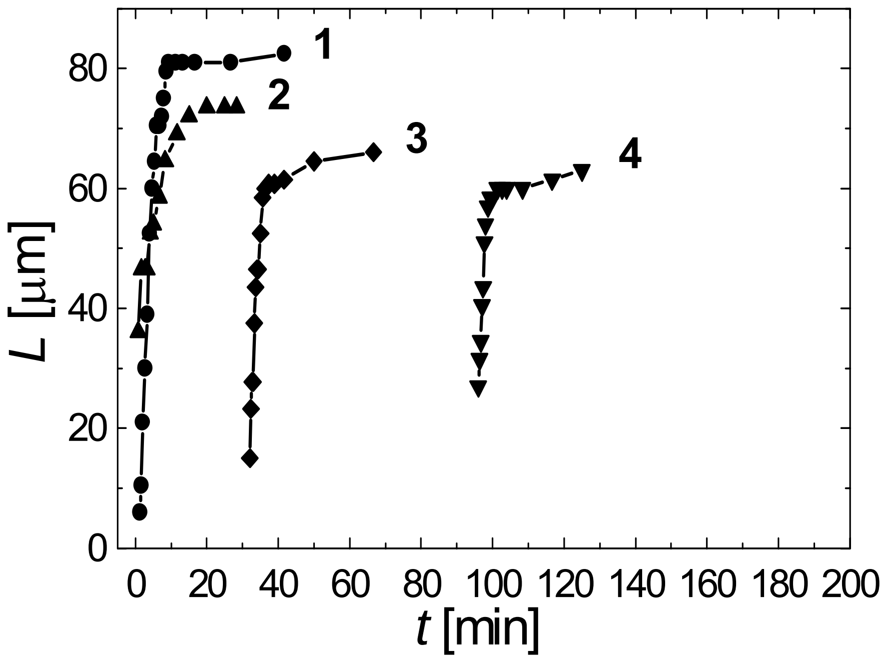
Prediction for dislocation resting height z_0

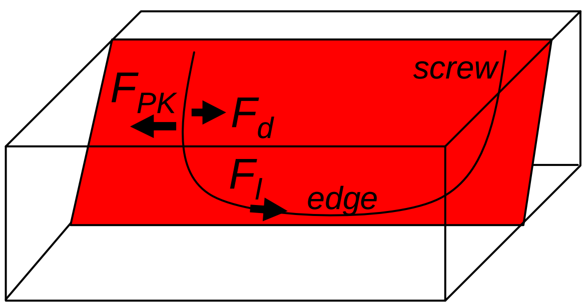


- Balance F_{el} and F_i
- $z_0 = (b\cos\alpha)^2\rho/4\pi(1-\nu^2)\varepsilon_0^2$
- $z_0 = 2.1\mu m$ (observe $3\mu m$)

LDM movie of growing dislocation







From Continuum Theory:

F_{pk} = force due to elastic strain

F_l = force due to line tension

F_d = drag force on dislocation

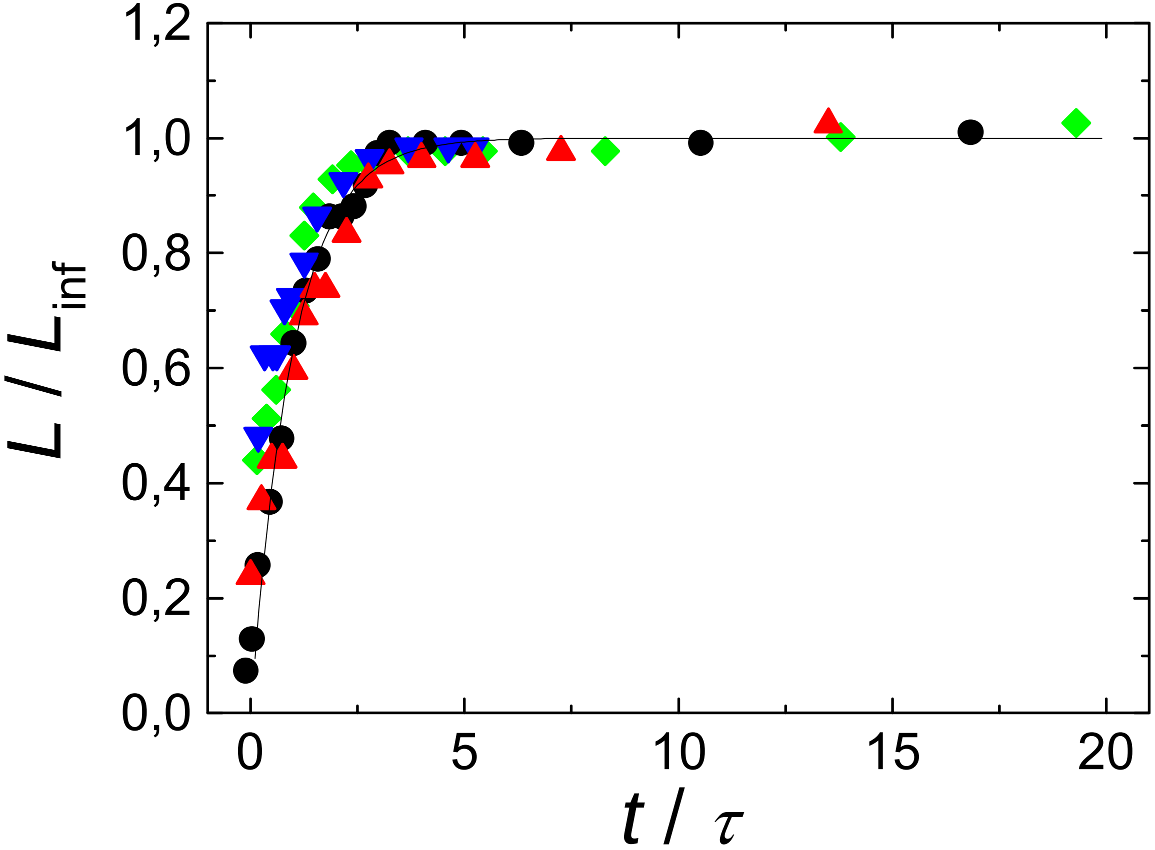
As dislocation length grows elastic strain, ε, is relieved.

$\varepsilon(t) = \varepsilon_{inf}(1- \exp(-t/\tau))$

since $\varepsilon \propto L$

$L = L_{inf}(1 - \exp(t/\tau))$

Using continuum theory calculations to collapse data



τ = 130 ± 40 s → Elastic modulus ≅ 0.3Pa √

Frenkel & Ladd, Phys. Rev. Lett. **59**, 1169 (1987)

Nano indentation at the micron scale