Rheology of lamellar and smectic phases

S. Komura, T. Kato (Tokyo Metropolitan University)

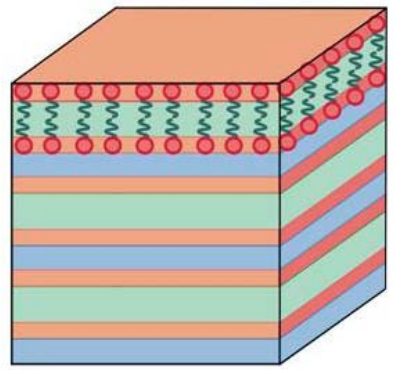
S. Fujii (Nagaoka University of Technology)

Y. Ishii (Waseda University)

C.-Y. D. Lu (National Taiwan University)

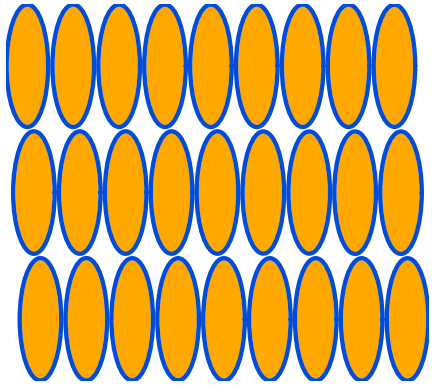
Outline

- Background
- Rheology of lamellar phase
- Rheology of smectic phase close to transition point
- Summary

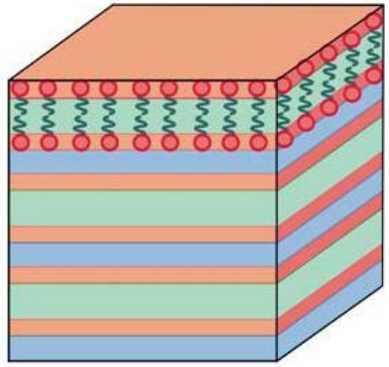


1D layered structures

- 1D solid + 2D fluid
- Thermotropic smectic phases (Sm A, Sm C)
- Lyotropic lamellar phases ($L\alpha$, $L\beta$)

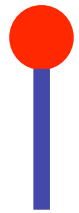


thermotropic
smectic phases



lyotropic
lamellar phases

surfactant



hydrophilic

hydrophobic

Elastic energy

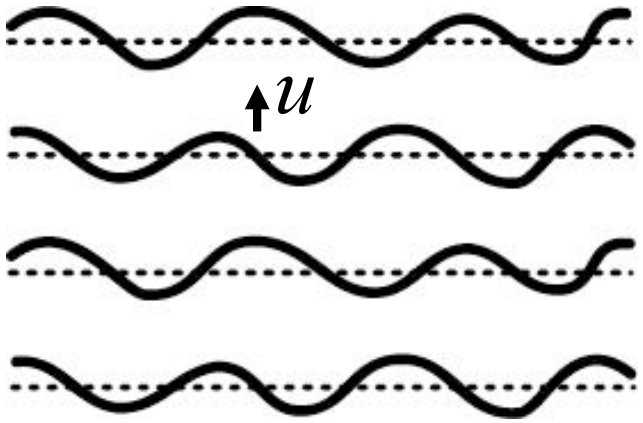
de Gennes (1969)

- Layer displacement field:

$$u(x, y, z)$$

- Elastic energy density:

$$f = \frac{K}{2}(\nabla_{\perp}^{2} u)^2 + \frac{B}{2}\left(\frac{\partial u}{\partial z}\right)^2$$

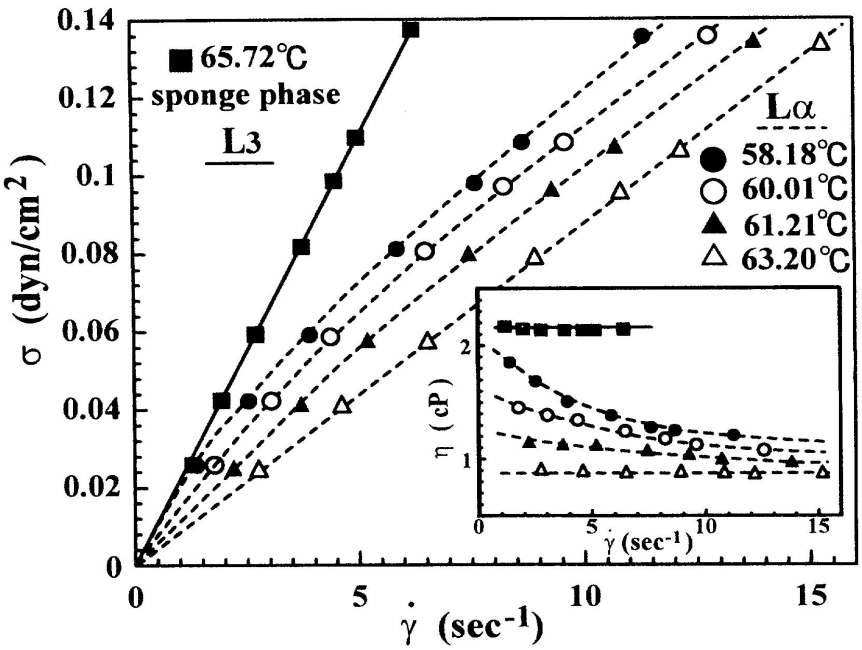


K : bending constant

B : layer compression modulus

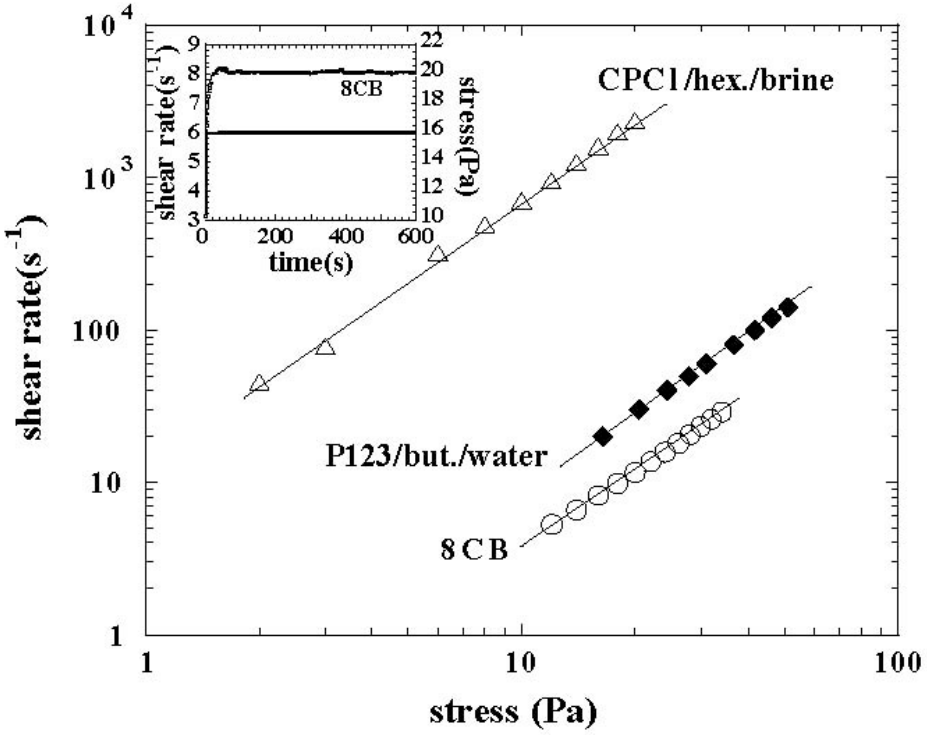
Shear thinning behavior of smectic phases: universality?

Yamamoto, Tanaka (1995)



C12E5
1.8 wt%

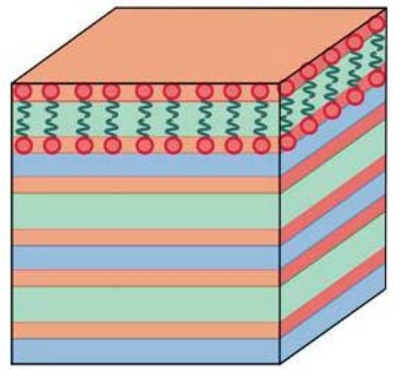
Meyer, Asnacios, Kleman (2001)



shear thinning $\dot{\gamma} \sim \sigma^m$ $m = 1.67 \pm 0.1$

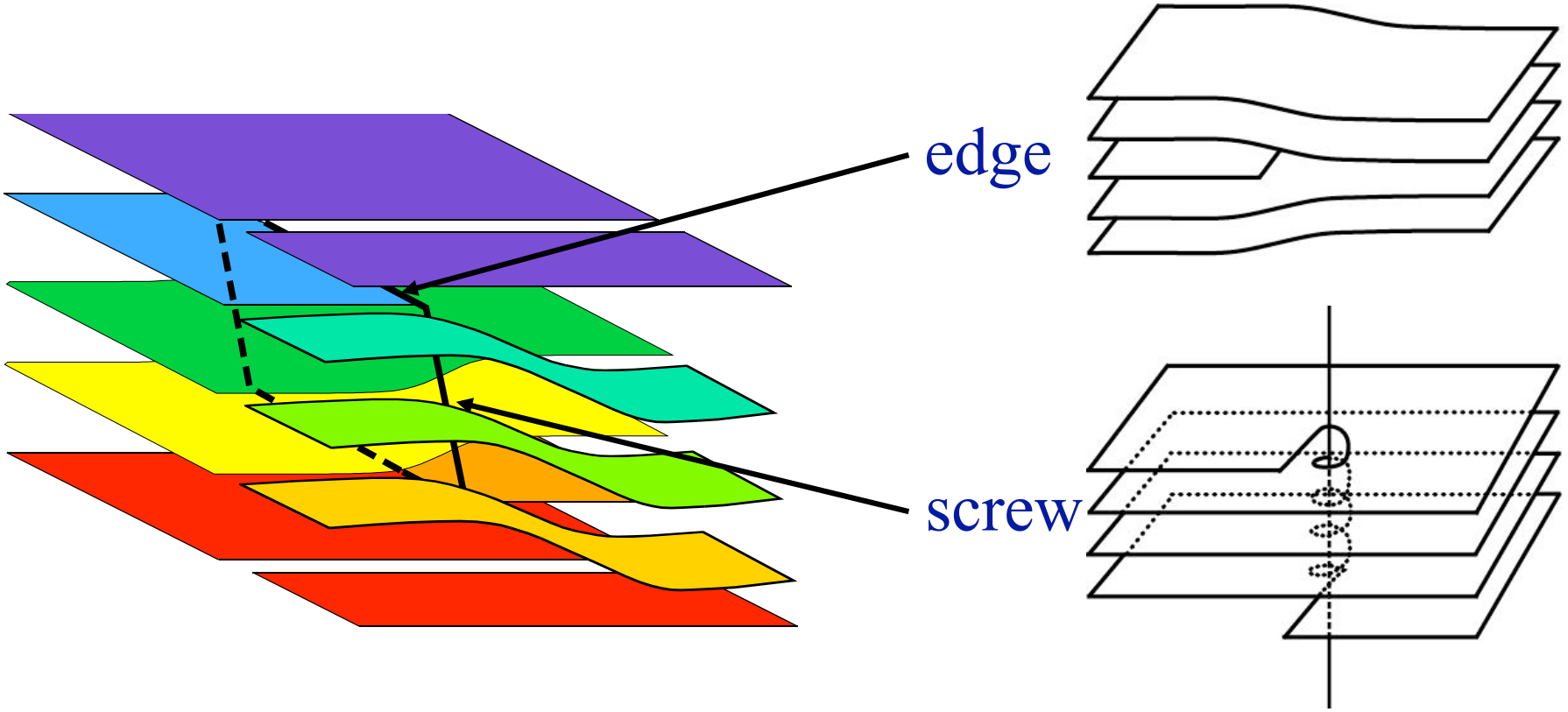
Outline

- Background
- Rheology of lamellar phase
- Rheology of smectic phase close to transition point
- Summary



Dislocation loops in lamellar phases

- Dissipation due to motion of dislocations

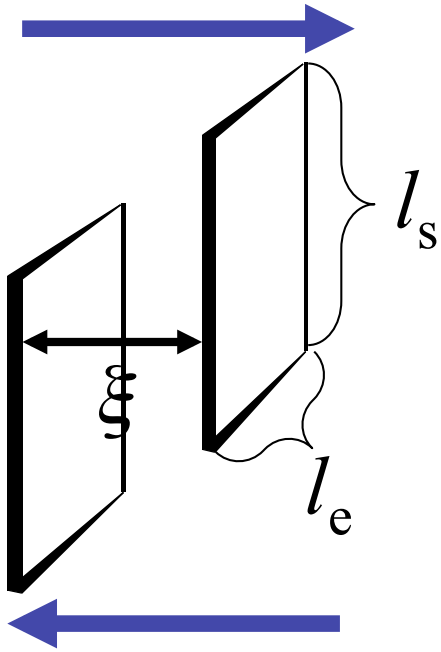


Lu *et al.* (2008)

Dynamics of dislocation loops

- Steady state stress: $\sigma \sim \rho_s \, \tau_e$

ρ_s : screw density $\quad \tau_e$: edge line tension



- Birth and sink of dislocations:

$$\frac{\partial \rho_s}{\partial t} = (\dot{\gamma} / b l_e) - (\dot{\gamma} \, l_s / \xi) \rho_s$$

- Steady state: $\rho_s \sim (\dot{\gamma} / b \mu_e \tau_e)^{2/3}$

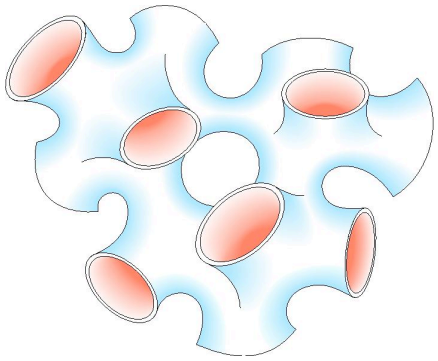
- Stress scaling: $\dot{\gamma} \sim (b \mu_e / \tau_e^{1/2}) \, \sigma^{3/2}$ $\qquad m = 3/2$

μ_e : edge climb mobility

Strey *et al*. (1990)

Phase diagram of C12E5

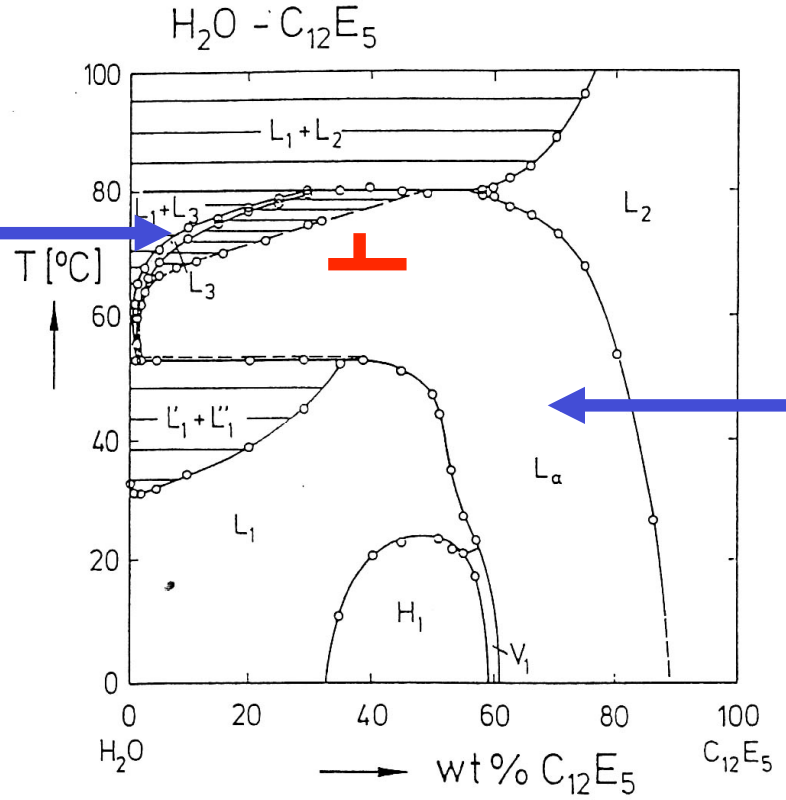
- Concentration:
  - 30~45 wt%
- Temperature:
  - 66~71 ℃ (339~344K)

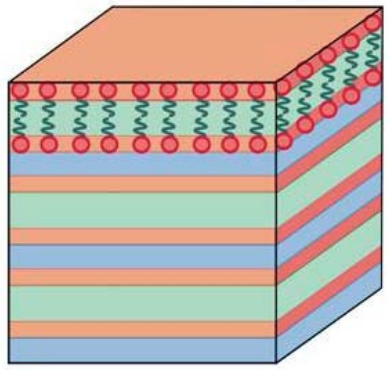


sponge

Newtonian

Snabre, Porte (1990)





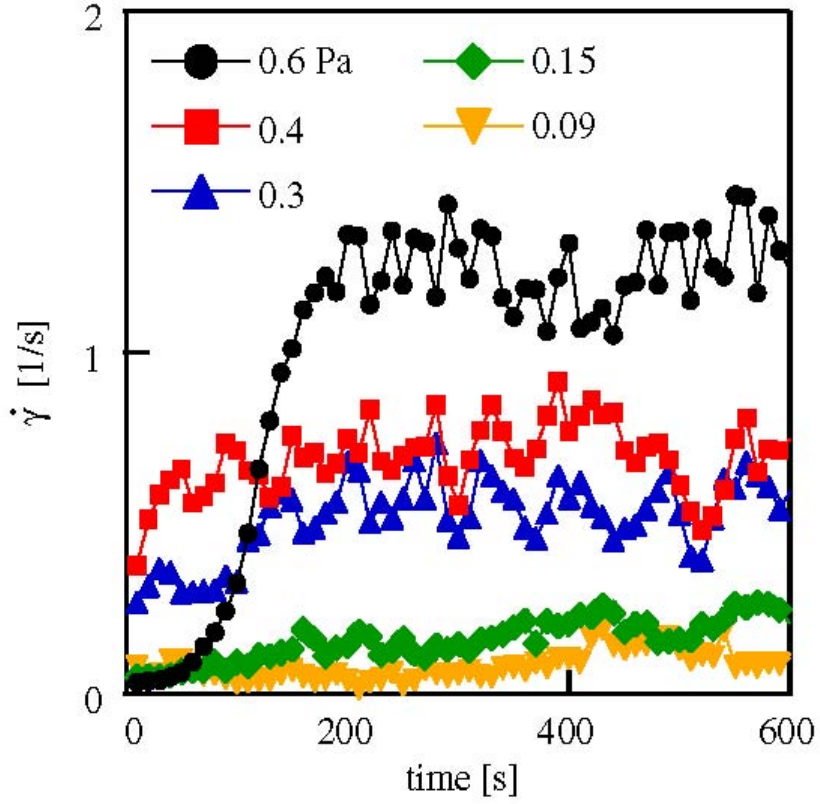
lamellar

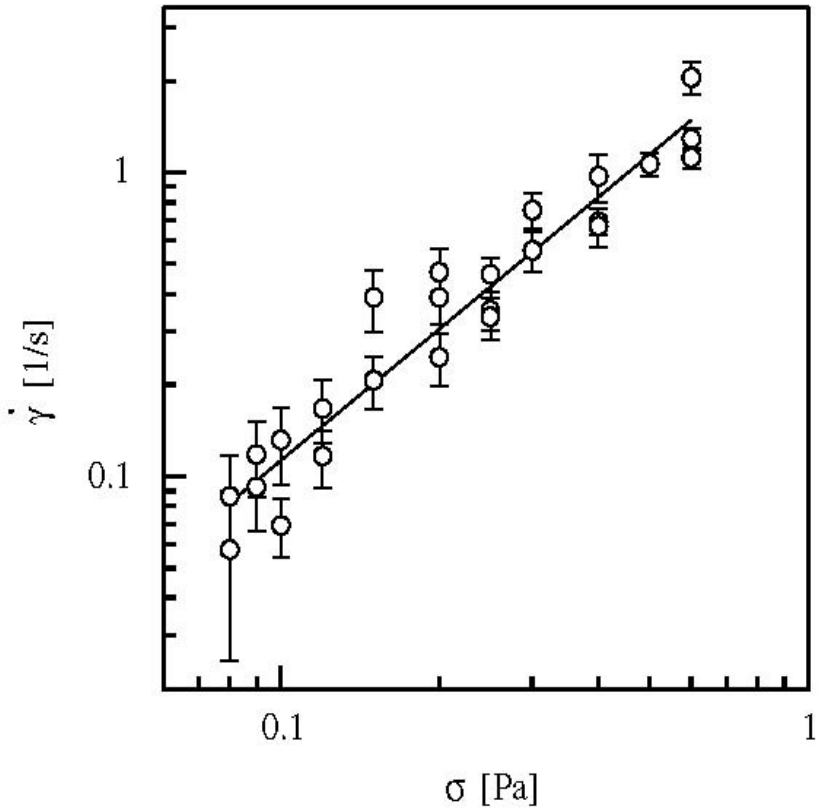
Flow curves

Lu *et al*. (2008)

35 wt% 339 K

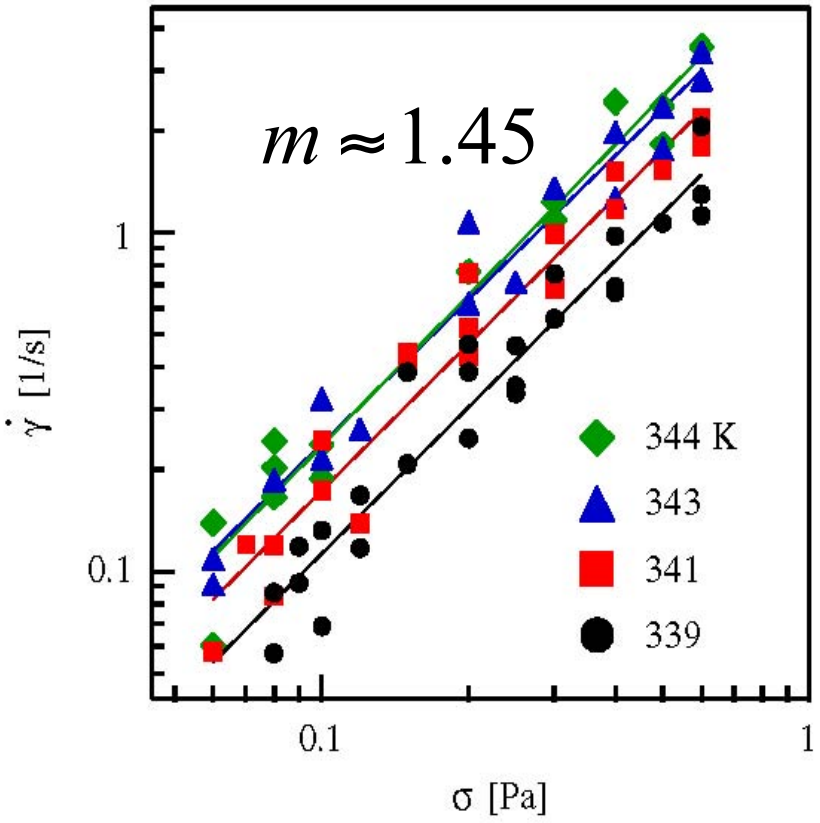
$\dot{\gamma} \sim \sigma^m$ $m = 1.44 \pm 0.08$

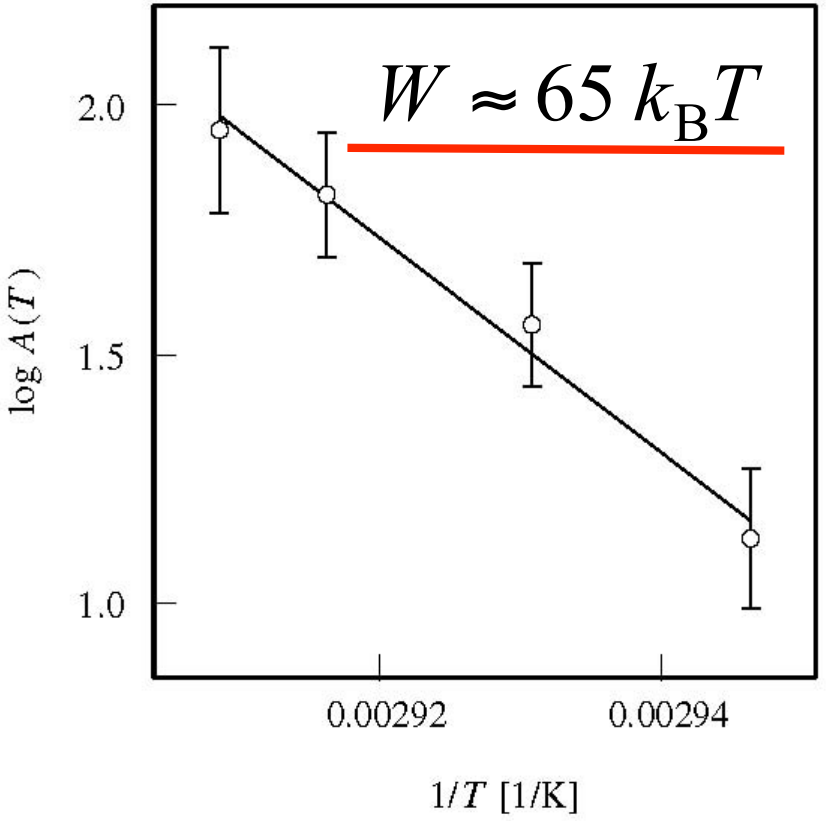




Temperature effect

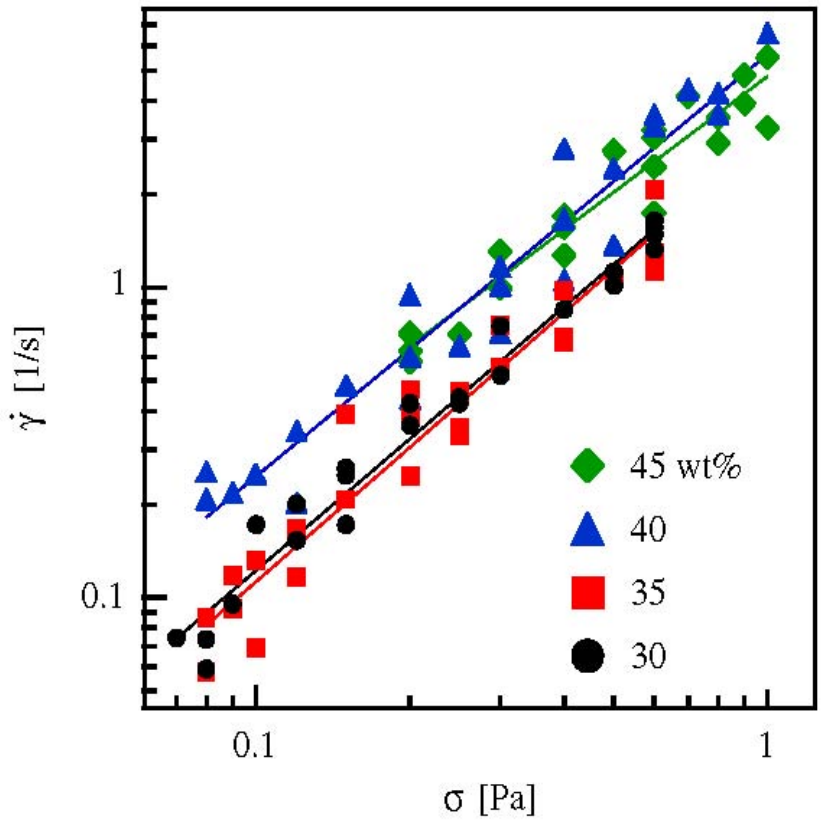
35 wt% $\dot{\gamma} \sim A(T)\sigma^m$ $A(T) = A_0 \exp(-W / k_B T)$



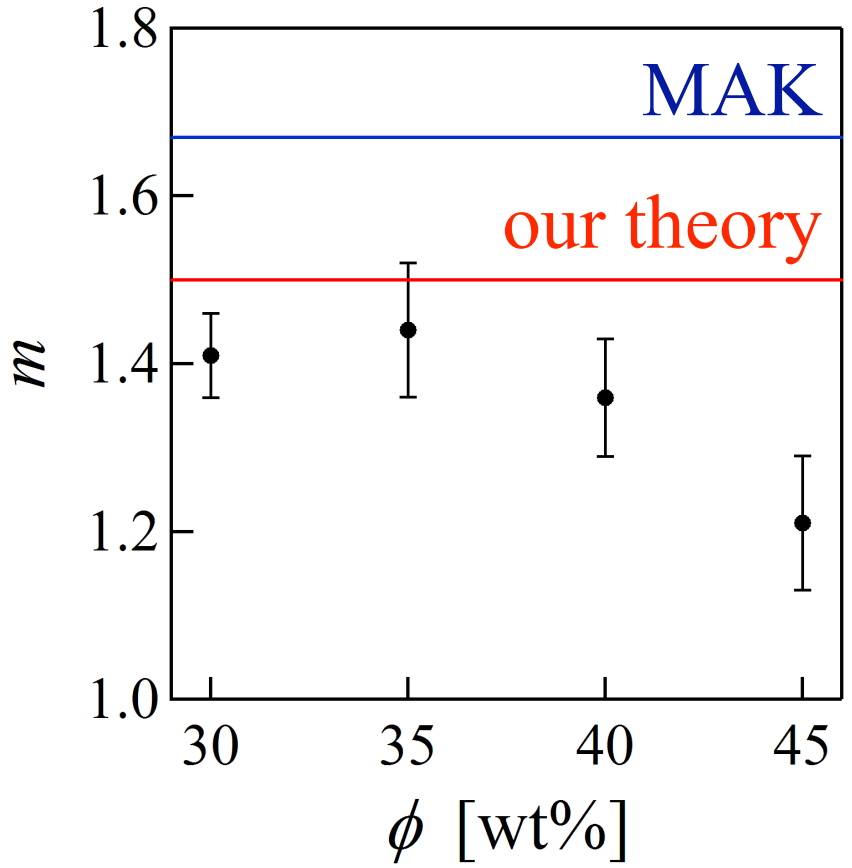


Concentration effect

339 K

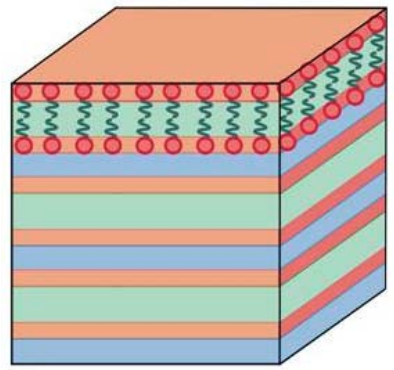


$\dot{\gamma} \sim \sigma^m$



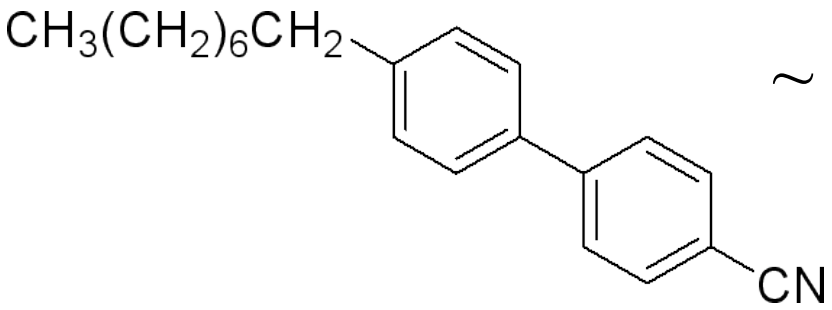
Outline

- Background
- Rheology of lamellar phase
- Rheology of smectic phase close to transition point
- Summary

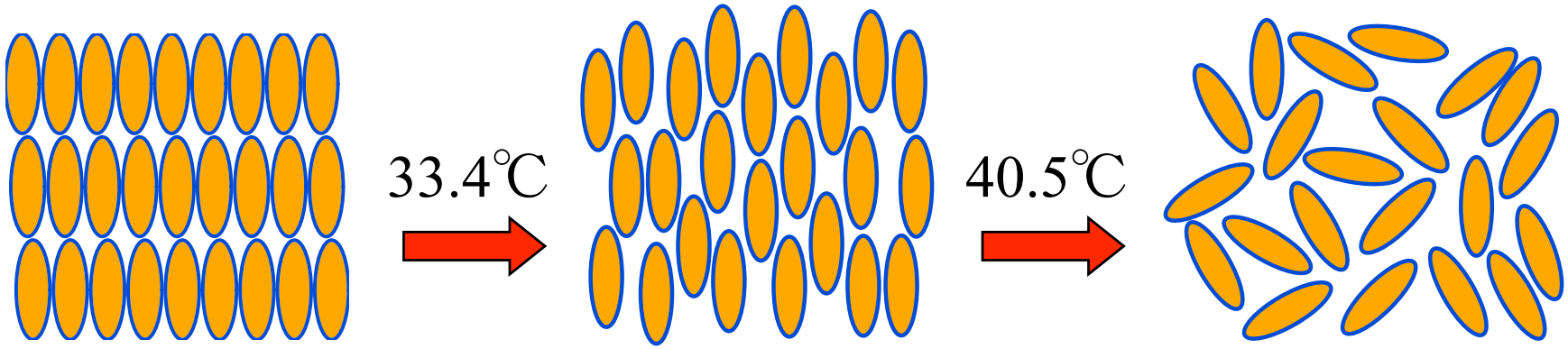


Thermotropic LC: 8CB

- 4-n-alkyl-4’-cyano-bipheny (8CB)

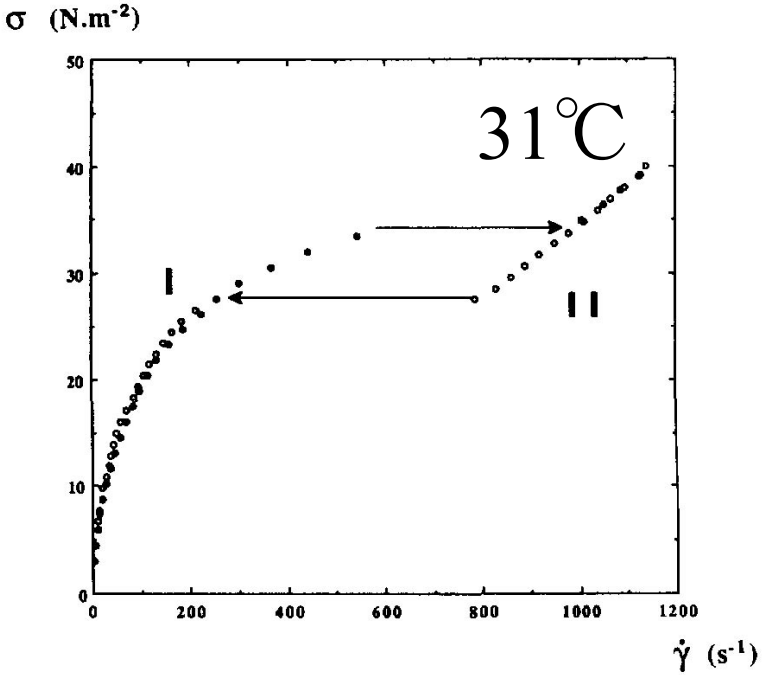


~ 2nm



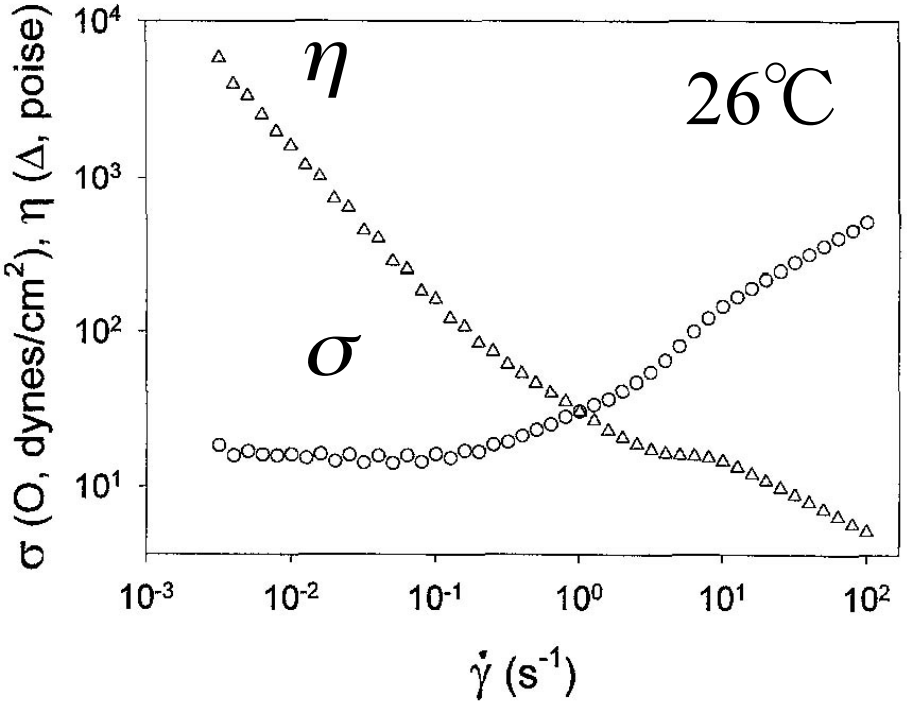
Rheology of 8CB

Panizza, Archambault, Roux (1995)



$$\dot{\gamma} \sim \sigma^{m} \qquad m = 2$$

Colby *et al*. (1997)



Universality ?

Helfrich (1978)

Nelson, Toner (1981)

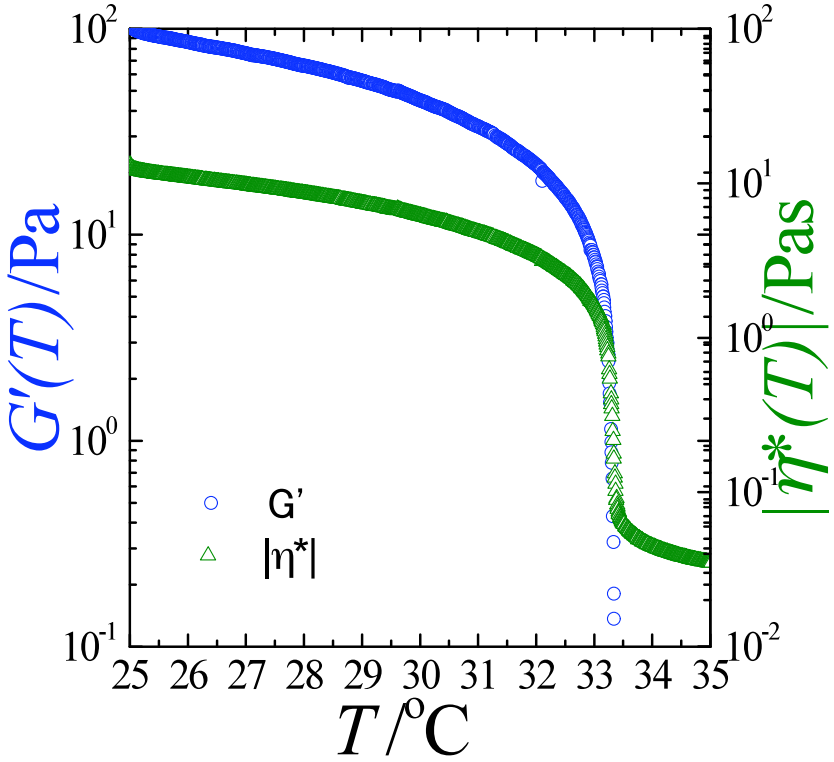
Smectic-Nematic transition

- Dislocation loop-mediated smectic melting
- Dislocation unbinding transition
- Free energy of a loop: $F = \tau\ell - k_{\mathrm{B}}T(\ell/b)\ln p$

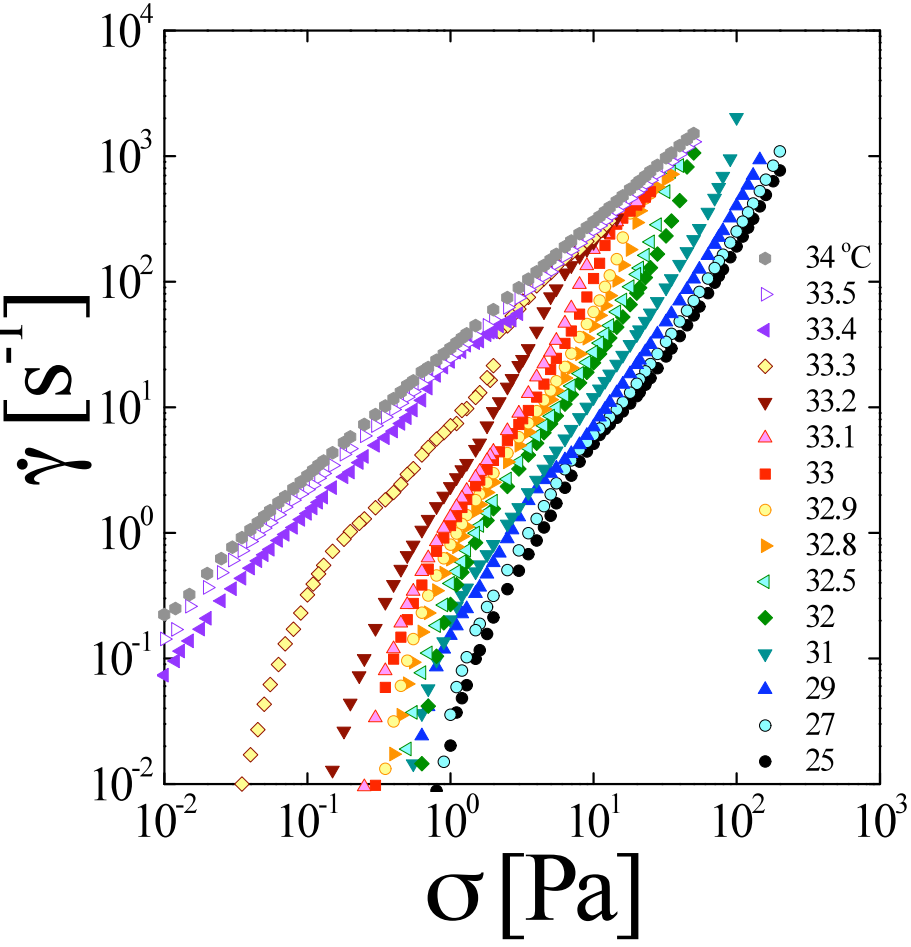
  τ : line energy p : coordination number
- Transition temperature: $T_{\mathrm{SN}} = \dfrac{\tau b}{k_{\mathrm{B}}\ln(p)}$
- Divergence of defect size

Fujii *et al.* (2010)

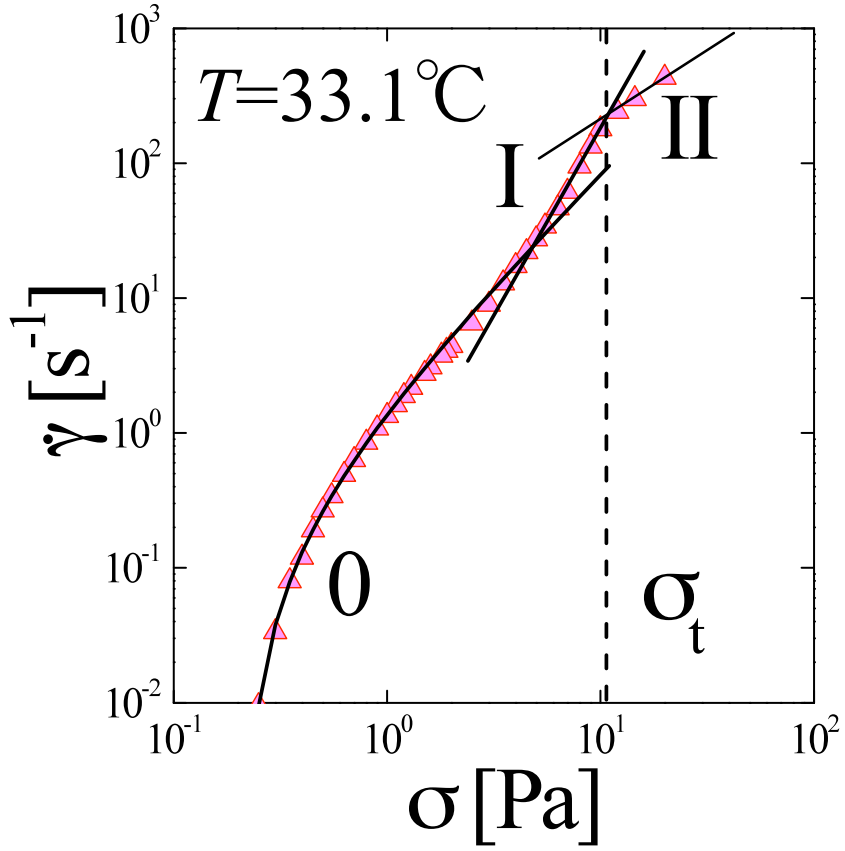
Flow curves of 8CB



T_{SN}=33.4℃



Three different regimes



- Regime 0: Hurschel-Bulkely model

$$\sigma = \sigma_y + A\dot{\gamma}^n$$

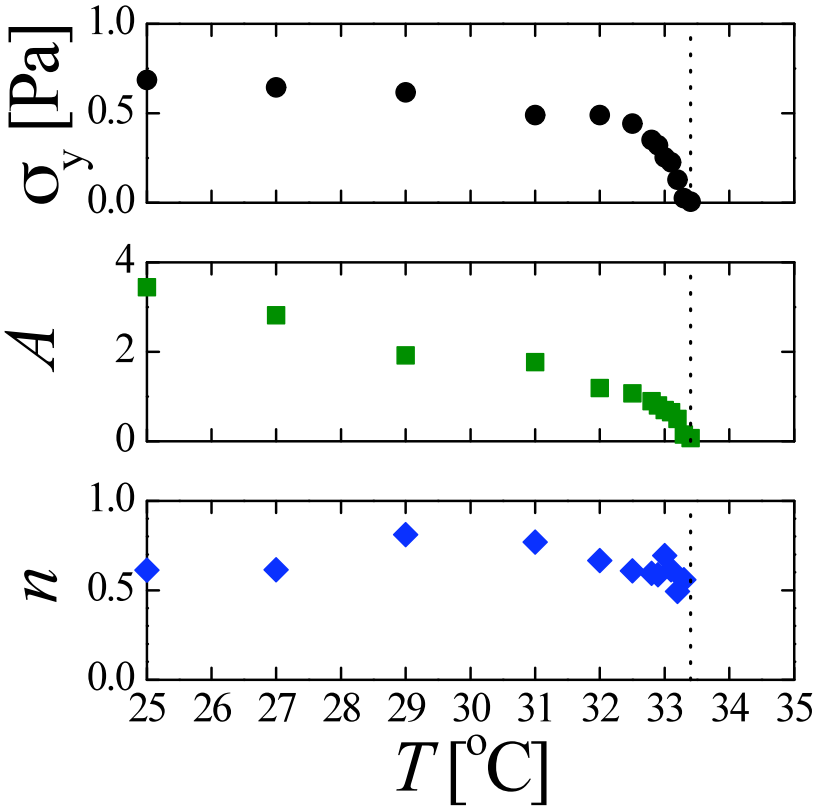
- Regime I: power law behavior

$$\sigma = C\dot{\gamma}^{1/m}$$

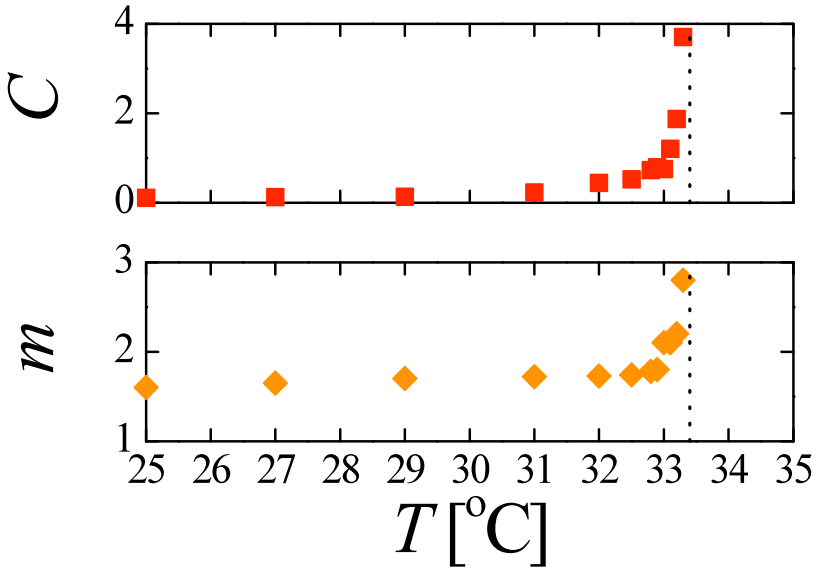
- Regime II: Newtonian

Obtained parameters

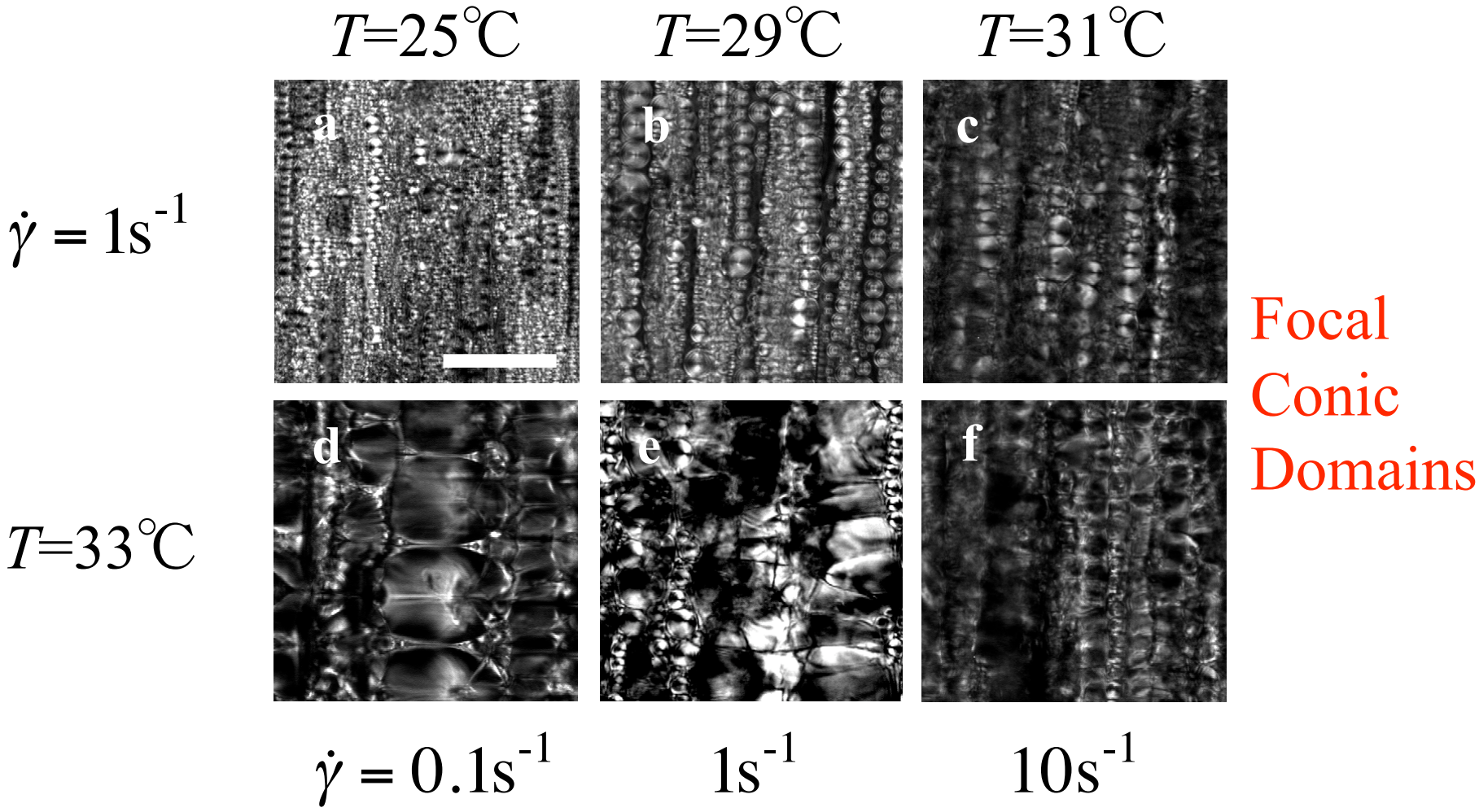
Regime 0



Regime I



Microscope observation



Yield stress

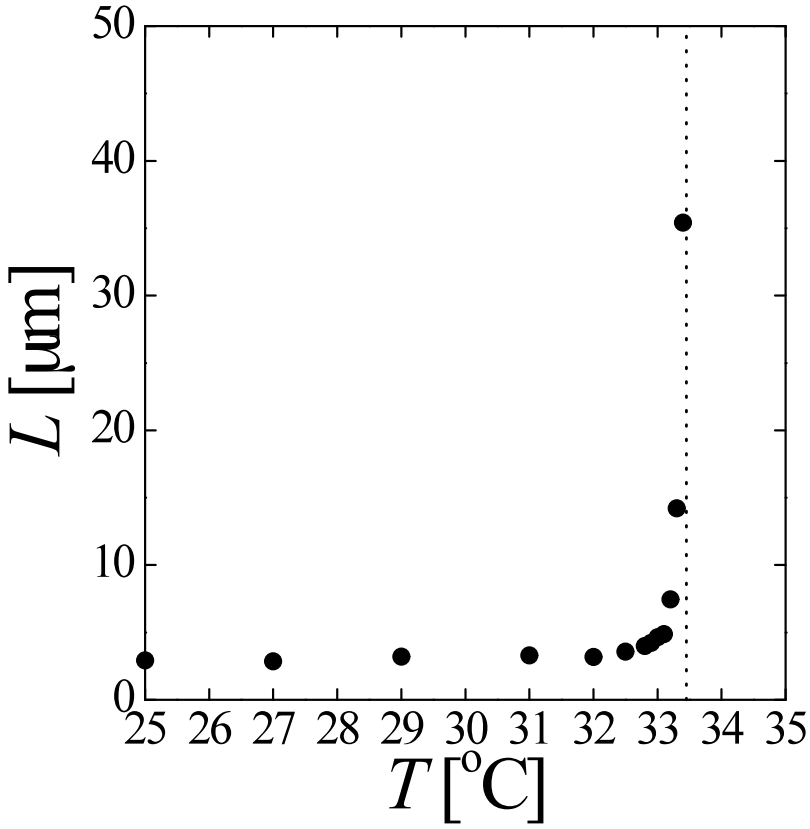
Horn, Kleman (1978)

Fujii *et al*. (2010)

- Network of focal conic domains with size L
- Needed stress to deform network

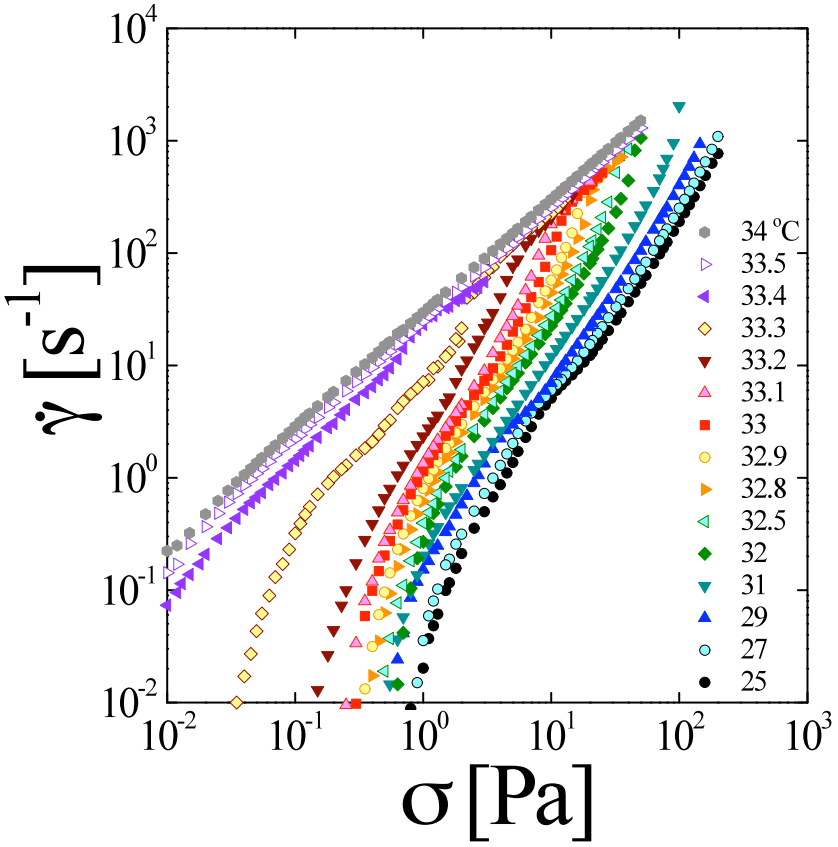
$$\sigma_y \approx K / L^2$$

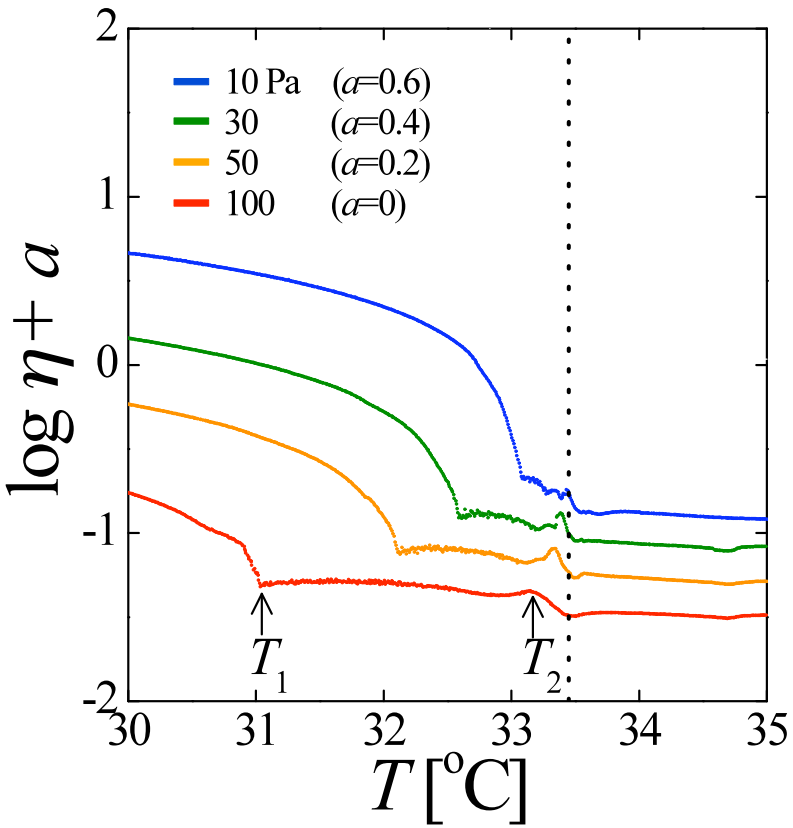
- Constant K
- Unbinding behavior?



High shear stress region

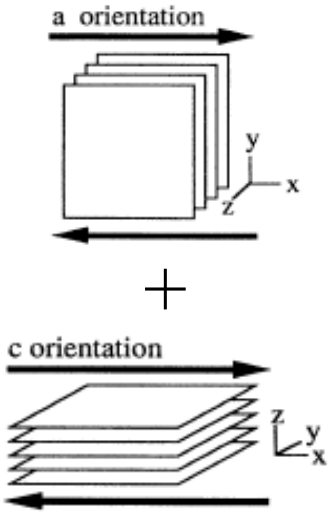
heating rate=0.05K/min

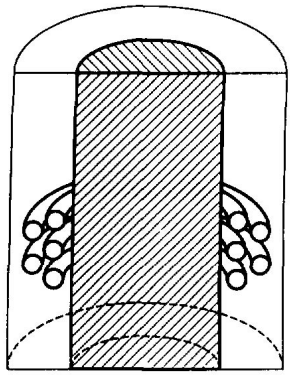


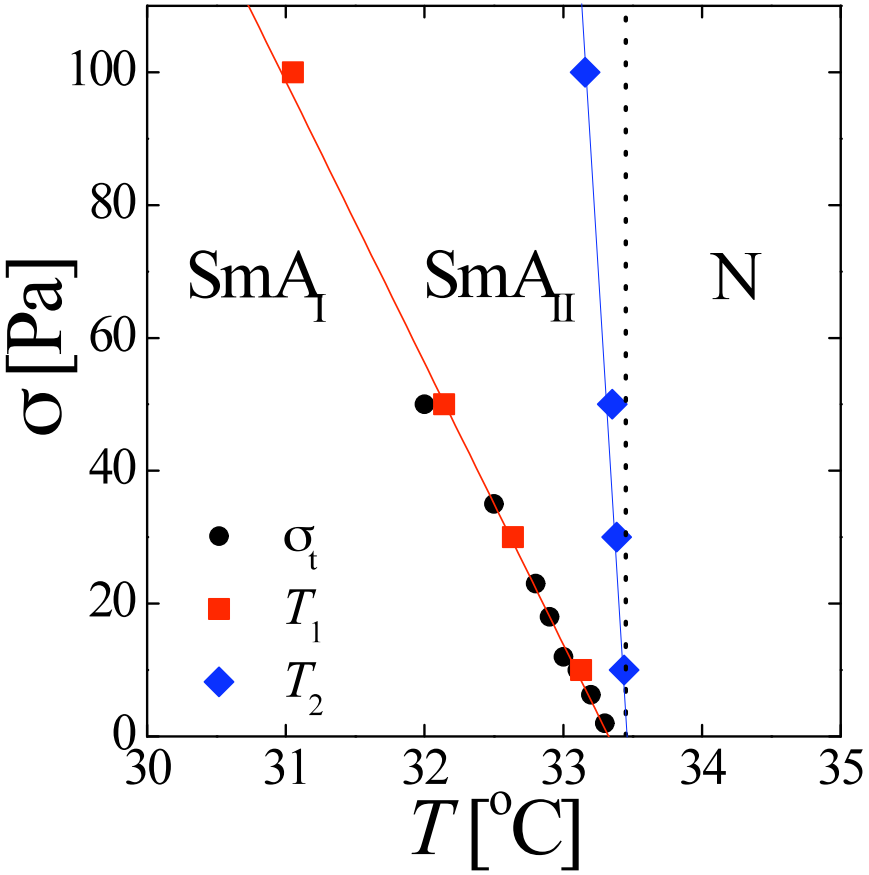


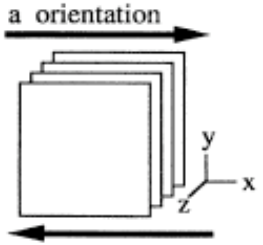
Fujii *et al*. (2010)

Dynamic phase diagram







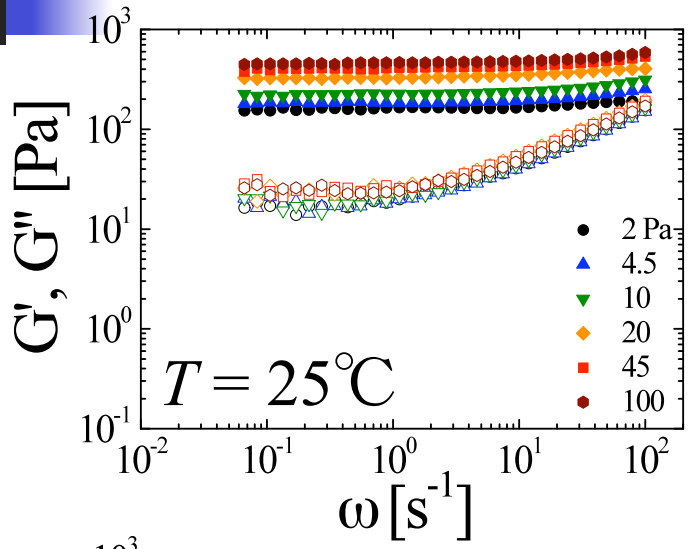


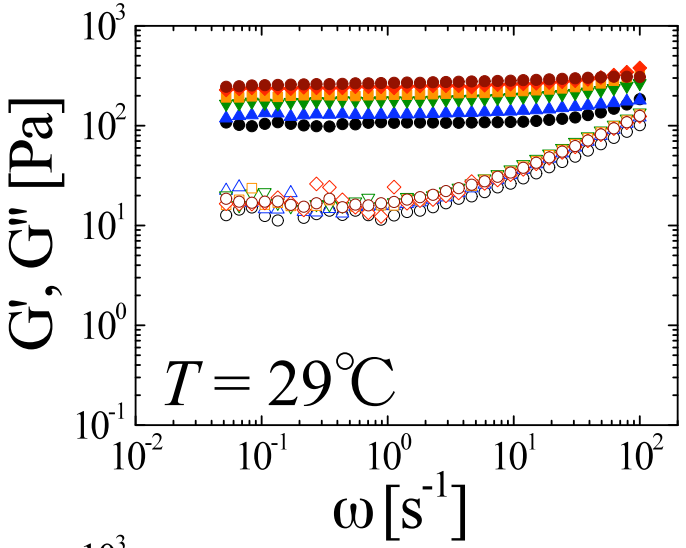
perpendicular

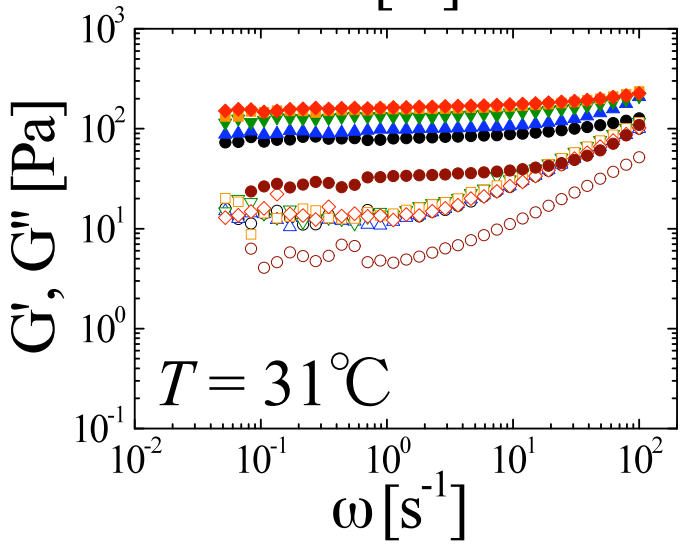
leek?

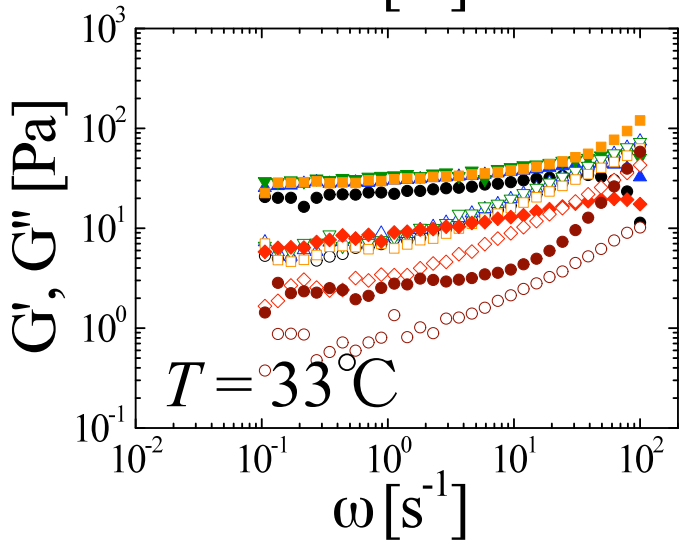
cf. Safinya, Sirota, Plano (1991)

Viscoelasticity of 8CB

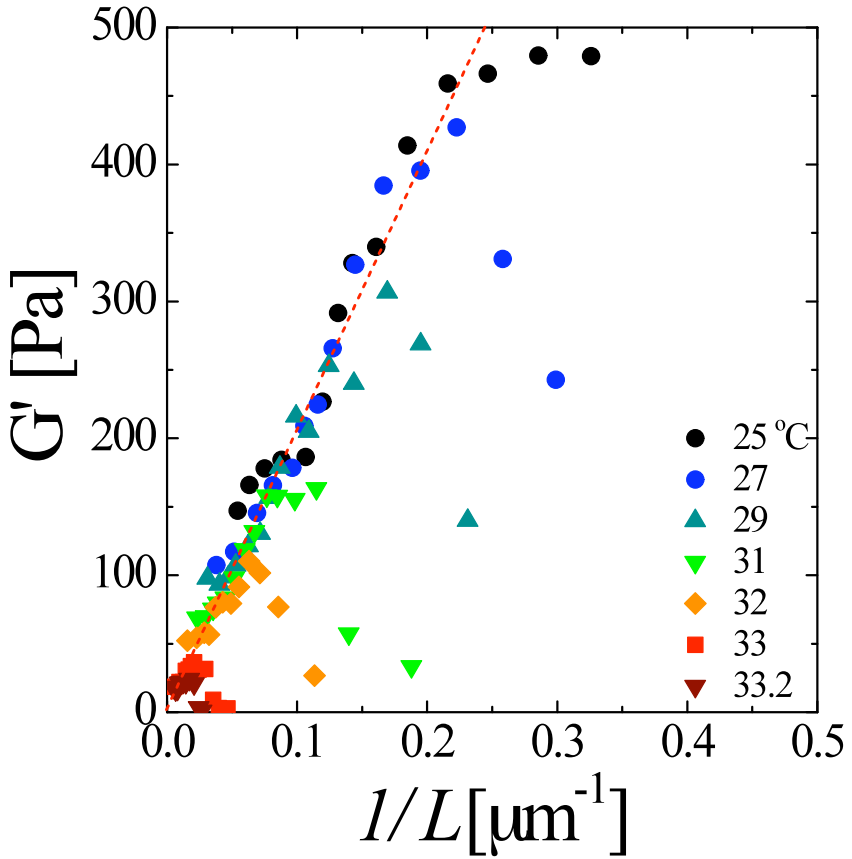








Scaling of *G'* with *L*



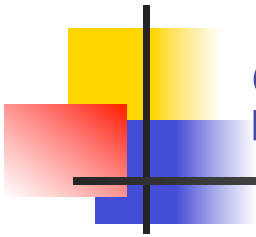
- Relation between *G'* and FCD size

$$G' \sim 1/L$$

- Effective surface tension

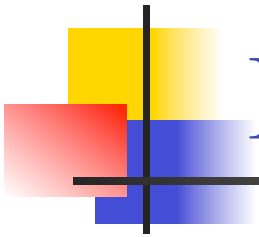
$$\sigma_{\text{eff}} \sim \sqrt{KB}$$

- Similarity to onion phases



Summary

- Defect mediated rheology in lamellar and smectic phases (structural rheology)
- Lyotropic lamellar phase
  - motion of dislocation loops
- Thermotropic smectic phase close to T_{SN}
  - growth of FCD
  - effective surface tension



References

- C.-Y. D. Lu, P. Chen, Y. Ishii, S. Komura, and T. Kato, *Eur. Phys. J. E* **25**, 91-101 (2008).

- S. Fujii, Y. Ishii, S. Komura, and C.-Y. D. Lu, *Europhys. Lett.* **90**, 64001 (2010).