Pattern Formation in Co-Assembled Cationic and Anionic Amphiphiles

Monica Olvera de la Cruz

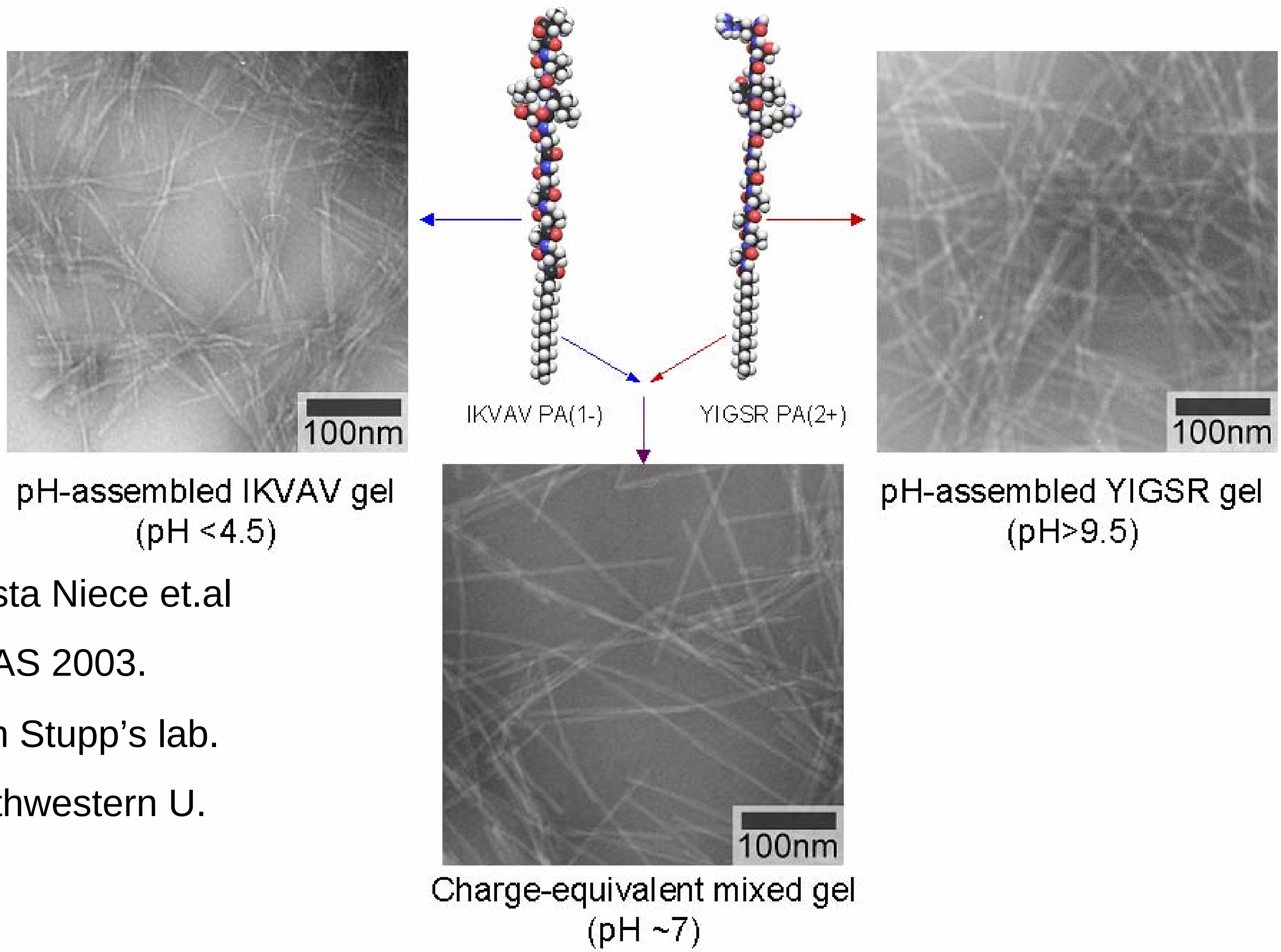
F. J. Solis (calculation in cylindrical aggregates)

S. I. Stupp (experiments)

Y. Velichko and S. Loverde (simulations cylinder and plane)

E. Raspaud (motivation from related work)

Experimental Work



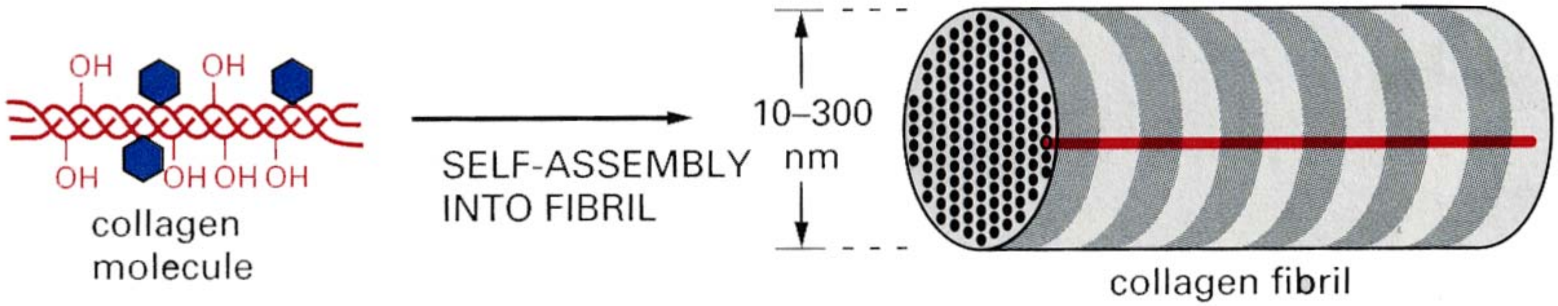
Krista Niece et.al

JCAS 2003.

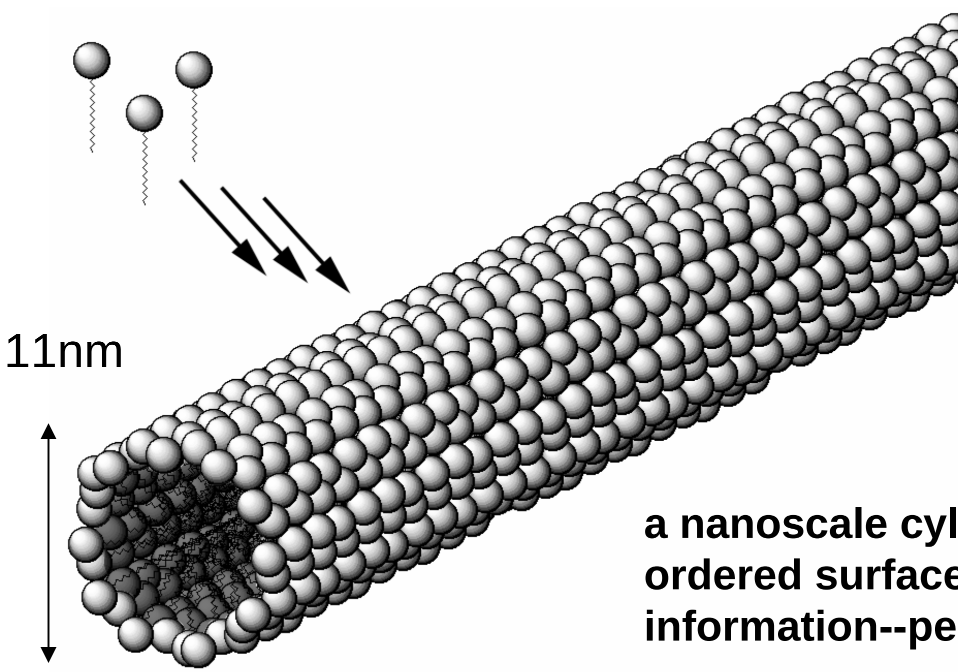
Sam Stupp’s lab.

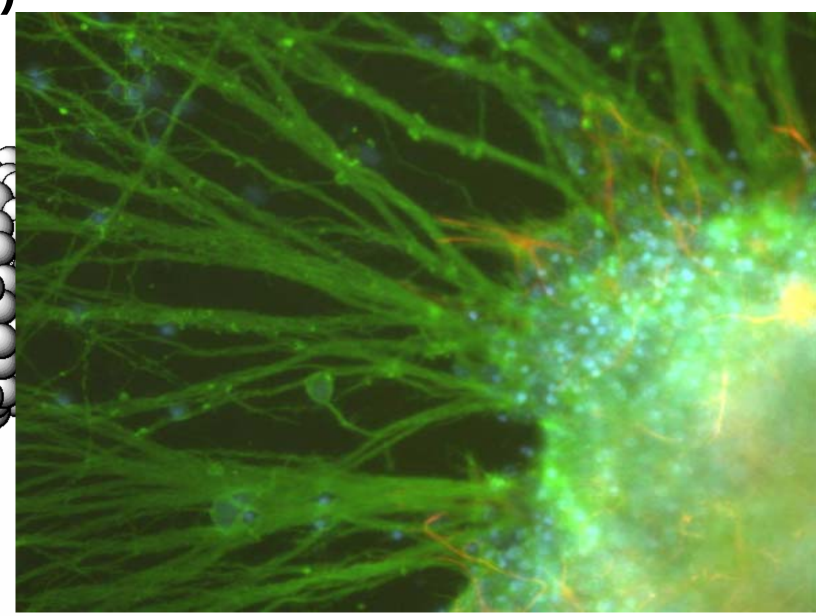
Northwestern U.

Collagen Fibril Architecture



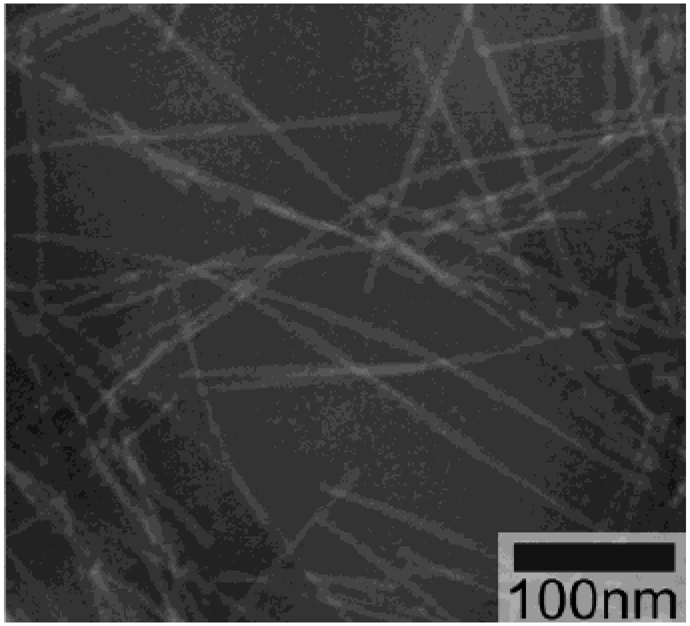
Peptide Amphiphiles (Stupp et al. **01, 02)**
Cells read surfaces (Stupp, 03, 04)





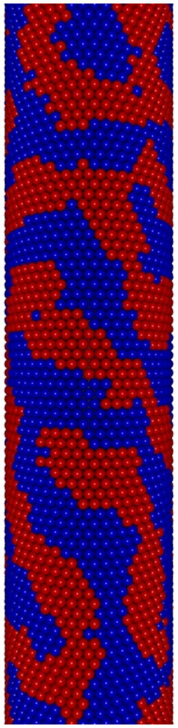
a nanoscale cylinder with highly ordered surface to deliver biological information--peptides

Peptide Amphiphiles

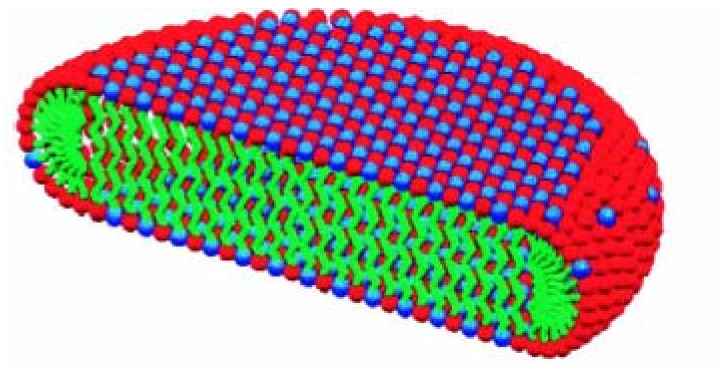


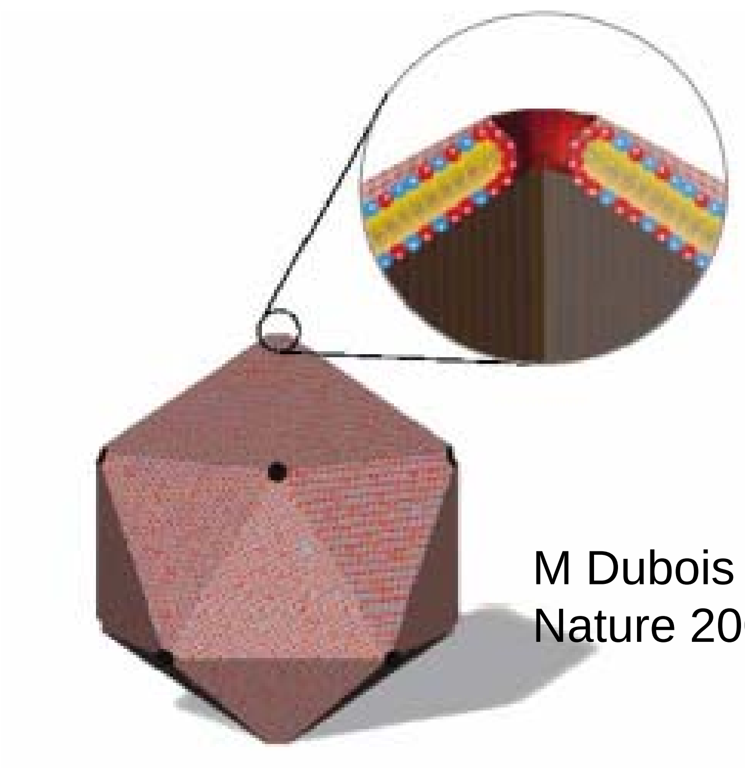
Niece et al. JACS, 2003.

- Mixture of cationic and anionic PAs:
- Competition between short range net repulsion among chemically different PAs and electrostatics leads to surface charge heterogeneities

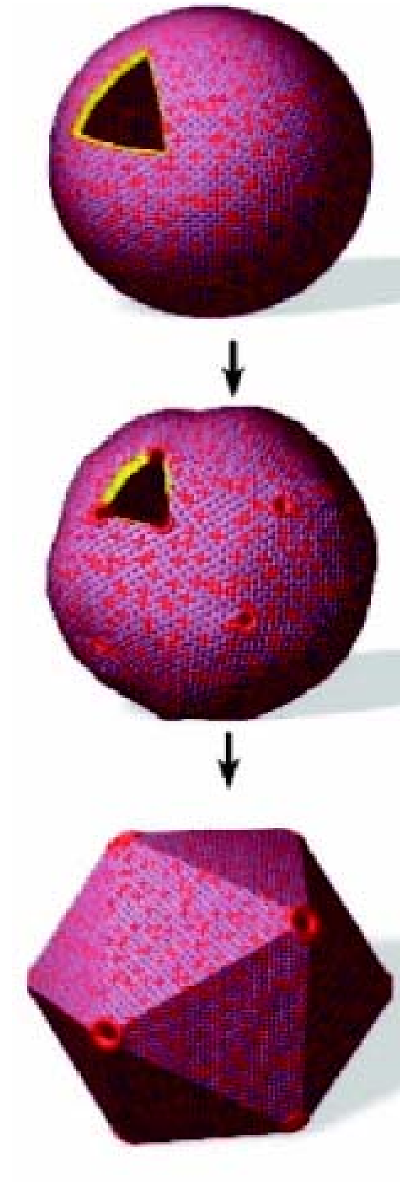


Co-assembled cationic and anionic surfactants T. Zemb et al Science 1999,





M Dubois et al Nature 2001

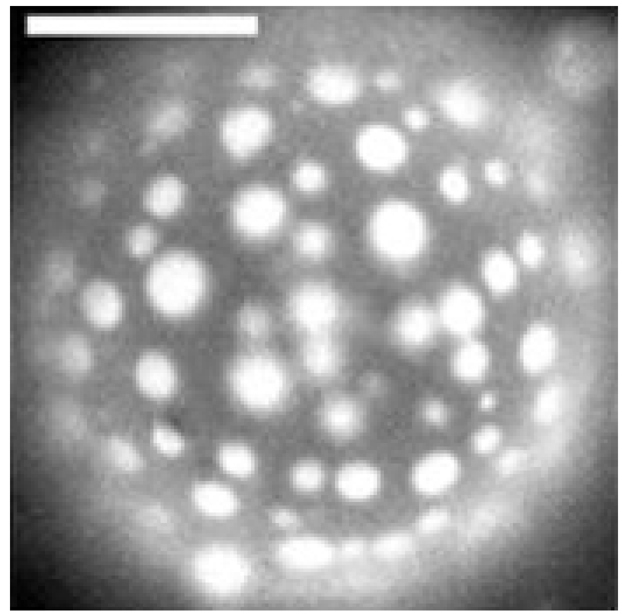


M. Dubois et al PNAS 2004

Phase segregation in neutral co-assembled vesicles

From Sarah Keller's group webpage.

20 microns

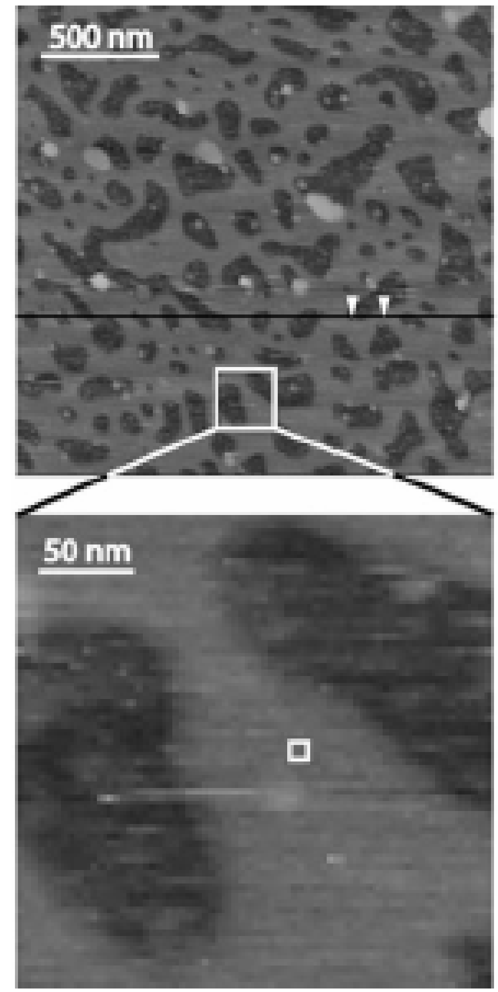


Structural transitions in vesicles of two component lipids leads to phase segregation between the two types of components

Surface Patterns

- Absorption of cationic surfactants onto negatively charged substrate.
- Hydrophobic tail assembles surfactants into domains with excess + charge
- Electrostatics restrict their growth and nanopatterns form on the surface

E.E. Meyer et al PNAS May 2005
DODA in Mica



Patterns in 2D due to competing interactions

- In Ising model with dipole interactions in 2D

- In Cationic (+) and Anionic (-) co-assembled mixtures is due to Coulomb interactions

- In binary films due to strain energies

Motivation

- Why co-assembled cationic and anionic amphiphiles are stable at low salt?
- What is the relative importance of electrostatic attraction and short range net repulsion among chemically different components?
- What patterns can result due to the charged heterogeneities along the surface of the aggregates?

Outline

- Determination of the structures in 2D (plane) in the strong and weak segregation limit: Effects of fraction of area coverage and screening

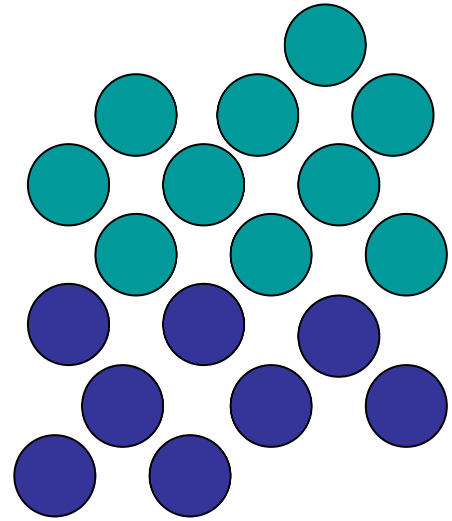
- Cylindrical geometry effects

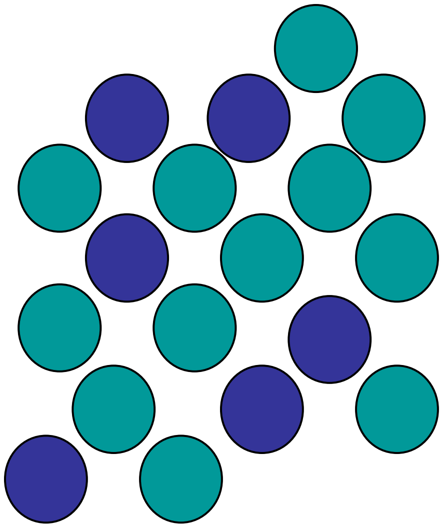
- Fluctuations

Planar Surface

MACROPHASE SEGREGATION

Immiscibility



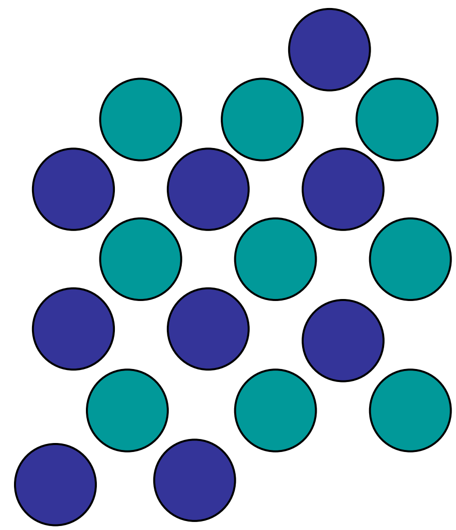


DISORDERED STRUCTURE

Entropy

IONIC CRYSTAL

Electrostatics



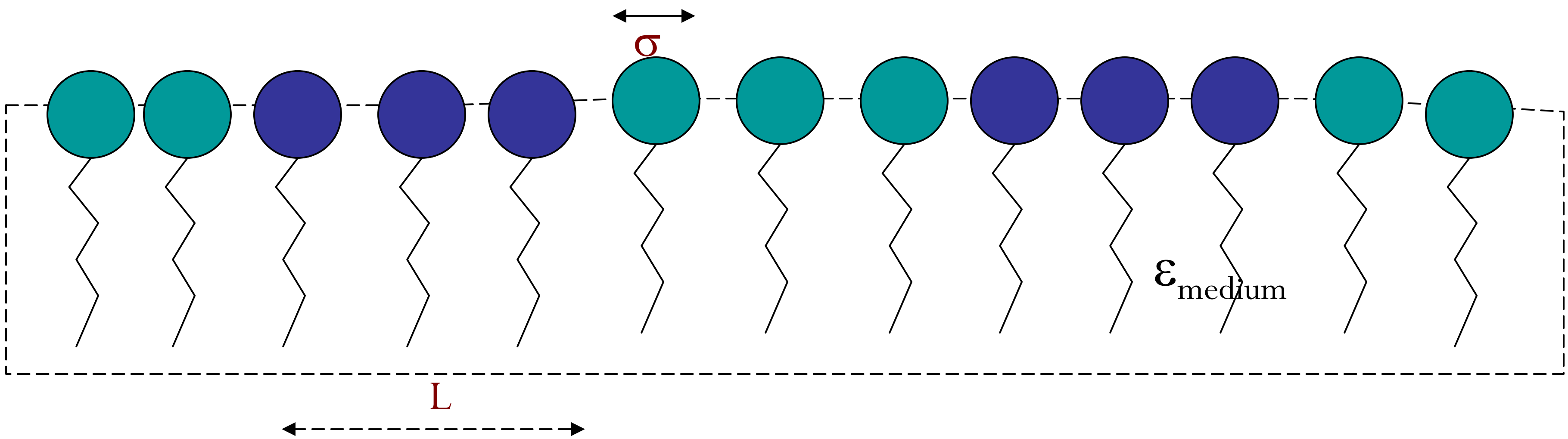
Length Scale of Interactions

$$l_B = \frac{e^2}{4\pi\varepsilon\varepsilon_r k_B T}$$

$\varepsilon_{water} \sim 80$

WATER

SIZE OF HEADGROUP



SIZE OF DOMAIN

MEDIUM OF LOWER
DIELECTRIC CONSTANT

Interactions

- Electrostatic

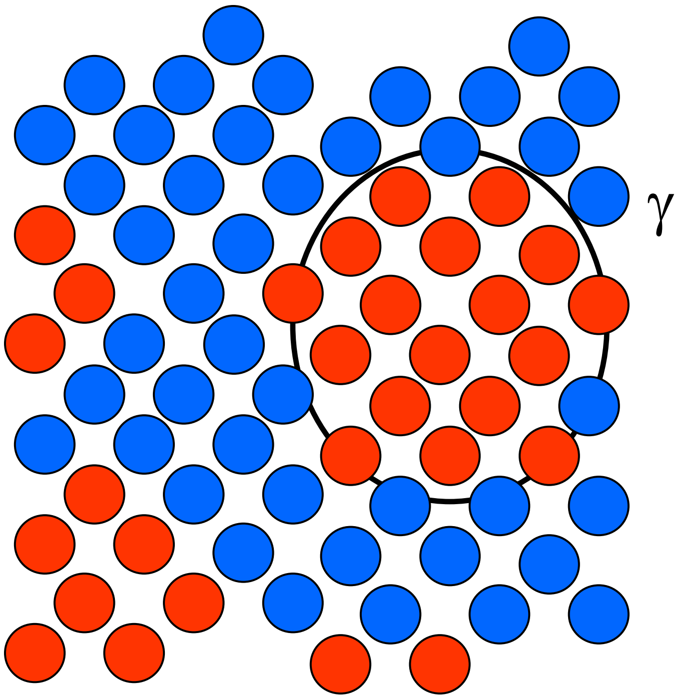
$$U_C(r_{ij}) = \frac{l_B k_B T}{r_{ij}} q_i q_j$$

- Short range: off-lattice use Van der Waals

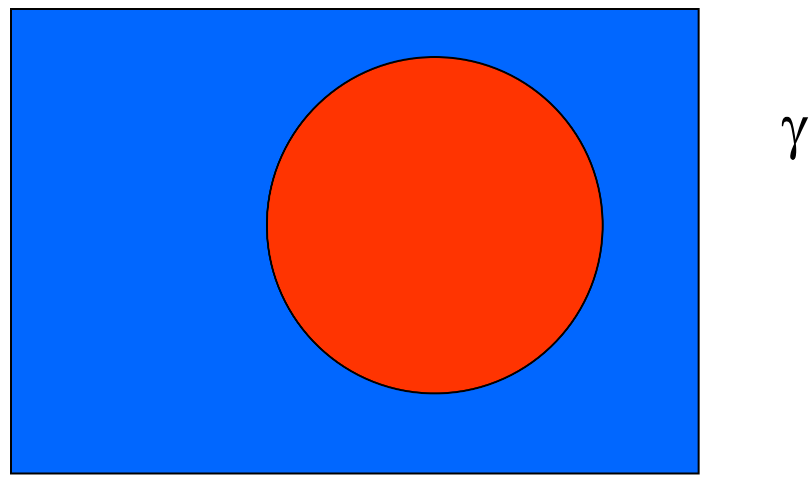
$$U^{LJ}(r_{ij}) = 4\varepsilon\left[\left(\frac{\sigma}{r_{ij}}\right)^{12} - \left(\frac{\sigma}{r_{ij}}\right)^{6}\right]$$

On lattice hard core plus net n.n. attractions among ++ pairs

Nano-segregation at low T



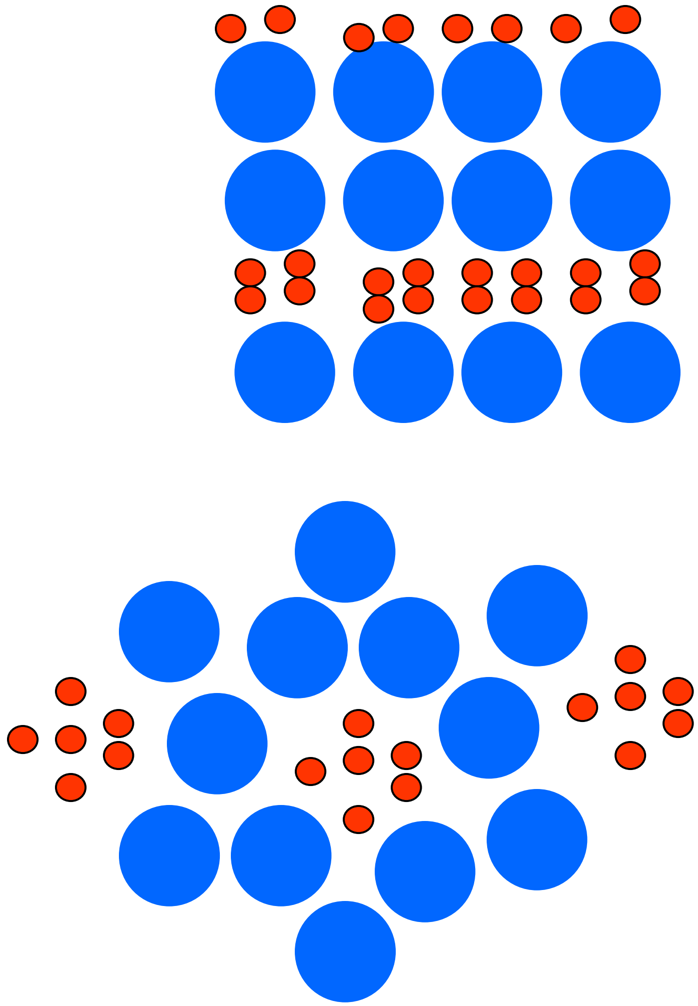
- **Strong segregation limit (no entropy)**
- **Line tension, γ, is linearly proportional to ε, magnitude of short range attraction.**



Coarse grained model

Area fraction coverage

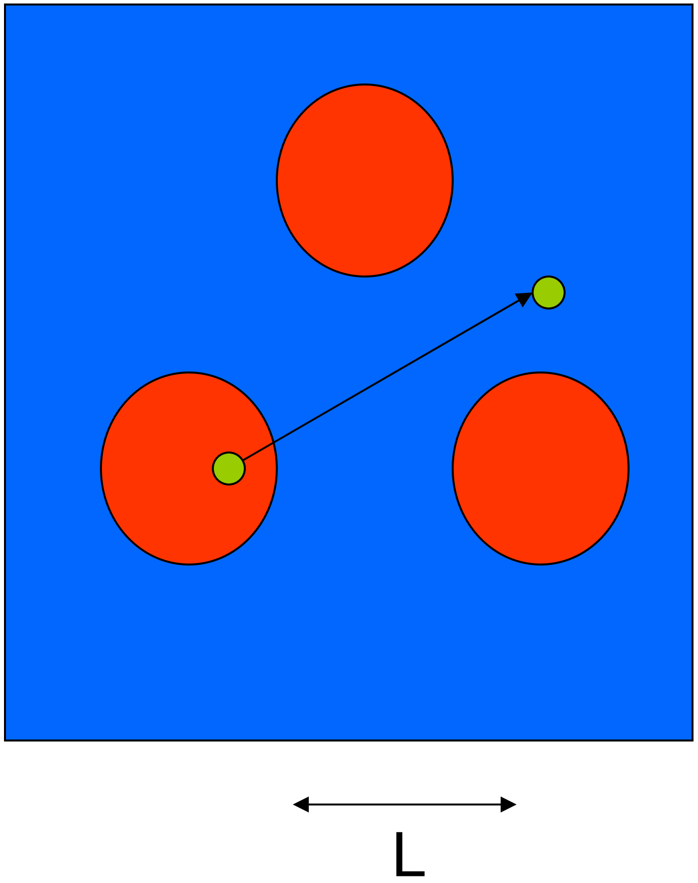
$f = A_1/(A_1+A_2)$



We consider the surface coverage not as a packing problem but in its impact on the surface tension.

Tuning the electrostatic interaction

Consider all molecules ionized, and thus, within each region, the charge density σ is constant.

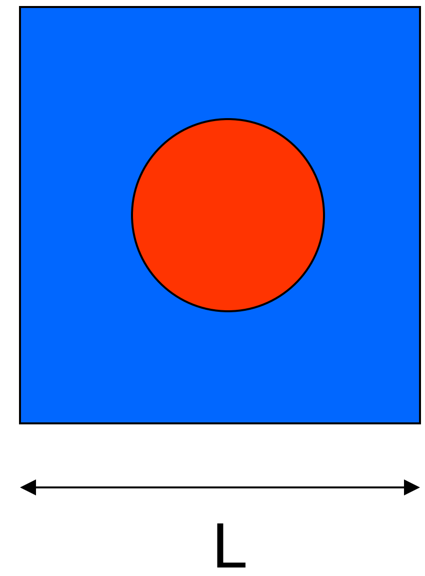


F=(1/2)✎ $d^2r\ d^2r'$ ♦🗁 (r) V(r-r') ♦🗎 (r')

Periodic: Ionic Nanocrystal

(N♦)^2/LN ✪ L (N ~ L^2); cohesive energy ~ L

The free energy



Calculate the free energy F in the unit cell divide by A $=L^2$

Number of particles~ A

The line tension energy ✪ ♑L

V(r) for electrostatics ✪ (♦A)^2/ L

$$s_1 = (4\pi f)^{1/2}$$

$$\frac{F}{A} = [s_1 \gamma L + s_2 l_B (\sigma L^2)^2 / L] / L^2$$

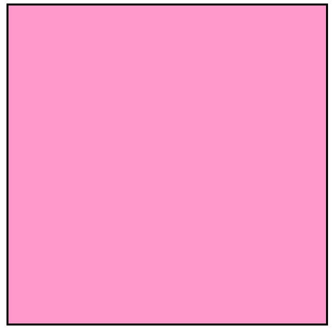
Minimized

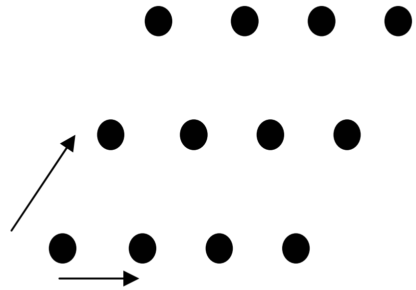
get dimensions L_o

$$L_o^{\ 2} \propto \frac{\gamma}{\sigma^2 l_B}$$

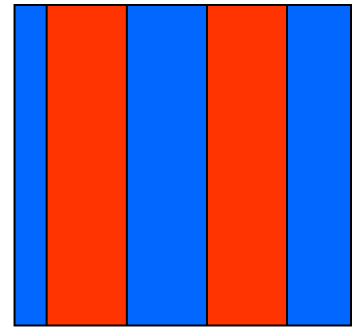
Patterns on the Plane

Homogeneous, lattices, or lamellar structures.



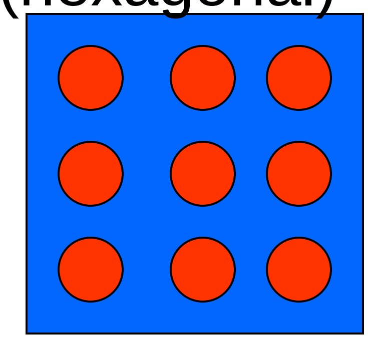


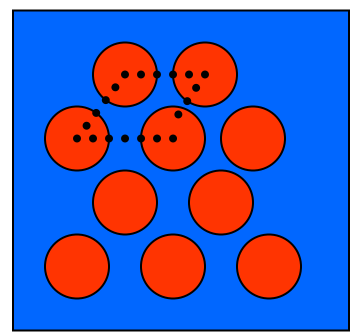
rhombic



Choose local structure within a cell

❑=□/2 (square), □/3 (hexagonal)





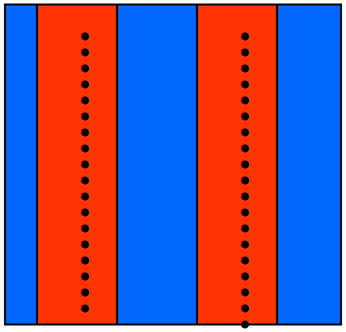
The characteristic size $d=L/L_o$

$$\frac{F}{A} = \frac{F_o}{A_o}\left(\frac{s_1}{d} + ds_2\right) = \frac{F_o}{A_o}\left(F'\right)$$

The structure is determined as a function of form of the potential via s_1 and s_2 and the size of the dimensionless unit cell $d=L/L_o$

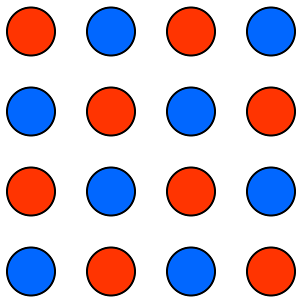
$$d = (s_1/s_2)^{1/2}$$

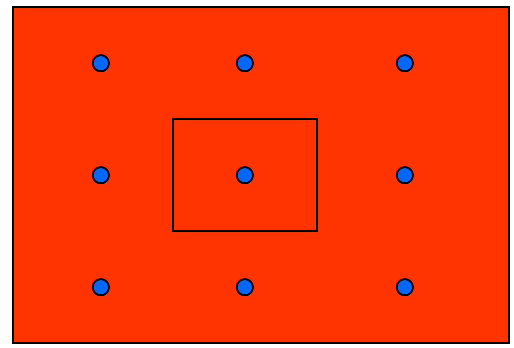
$$F' = 2(s_1 s_2)^{1/2}$$



$S_1=2$

Electrostatic contribution





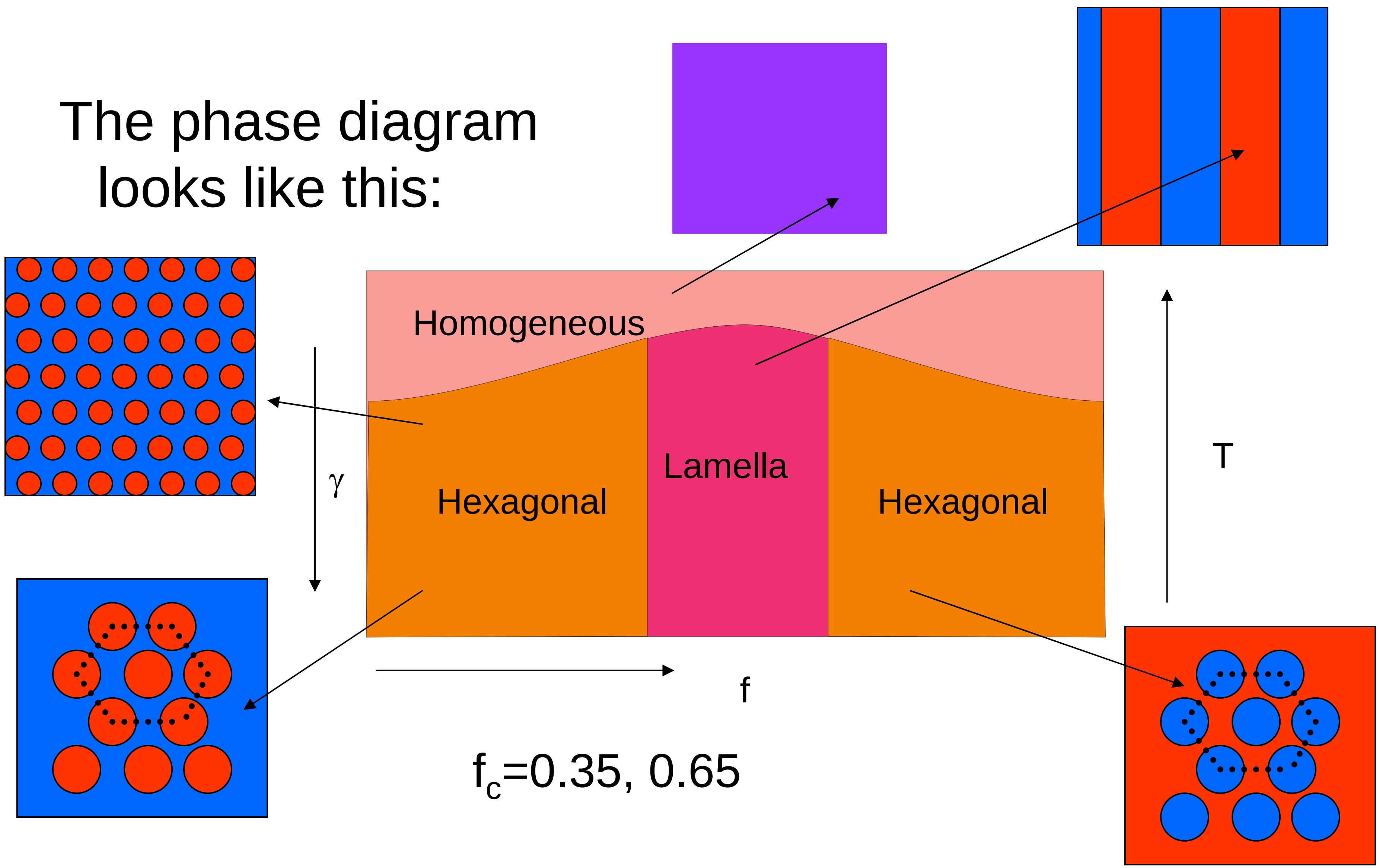
Solid state physics: Madelung and Wigner

Free energy is simplified in reciprocal space.

$$s_2 = \sum_G \hat{\sigma}'(G)\hat{V}'(-G)\hat{\sigma}'(G)$$

Results for the flat case

The phase diagram looks like this:



f_c=0.35, 0.65

Isotropic State with Weak charge Fluctuations (High T): charge density ♐(r)

$$\Delta F / k_B T \sim \sum |\phi_{\mathrm{q}}|^2 / S_o(q)$$

$$S_o^{-1}(q) = \left(\frac{1}{\phi(1-\phi)} - 2\chi + \kappa q^2 + \frac{8\pi l_B \sigma^2}{q} \right), |\,\mathrm{q}\,| = 2\pi/\lambda$$

$$\chi \sim \varepsilon \;\text{ and } \kappa \sim \chi l^2$$

$$q^* \sim \left(\frac{l_B \sigma^2}{\chi} \right)^{\frac{1}{3}}$$

$$S_0(q = q^*, \chi_{\mathrm{c}}) = \infty$$

Fluctuations destroy the critical point:
in 3D is first order transition to periodic structures
In 2D ??

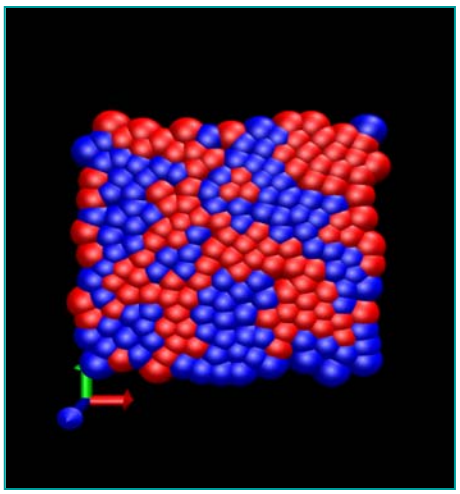
Simulations (expresso*):Effect of Increasing Short Range Attraction

$$\lambda_o \sim \left(\frac{\varepsilon}{l_B}\right)^{\frac{1}{3}}$$

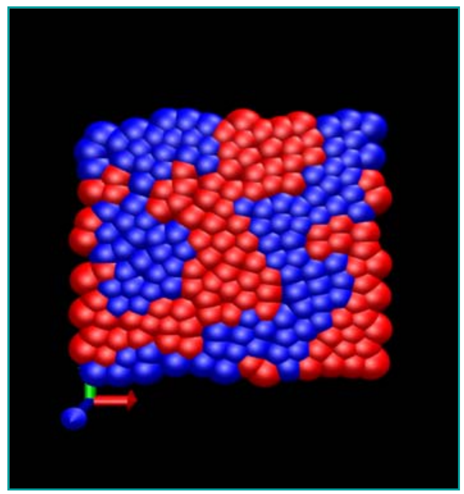
SCALING FROM WEAK SEGREGATION

$$L_0 \sim \left(\frac{\varepsilon}{l_B \sigma^2}\right)^{\frac{1}{2}}$$

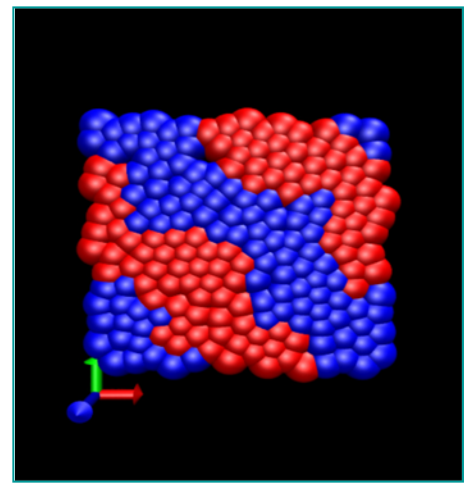
SCALING FROM STRONG SEGREGATION



ε=1.0
l_B=0.2



ε=1.5
l_B=0.2



ε=2.0
l_B=0.2

Short range attraction increases. Appearance of correlated domains.

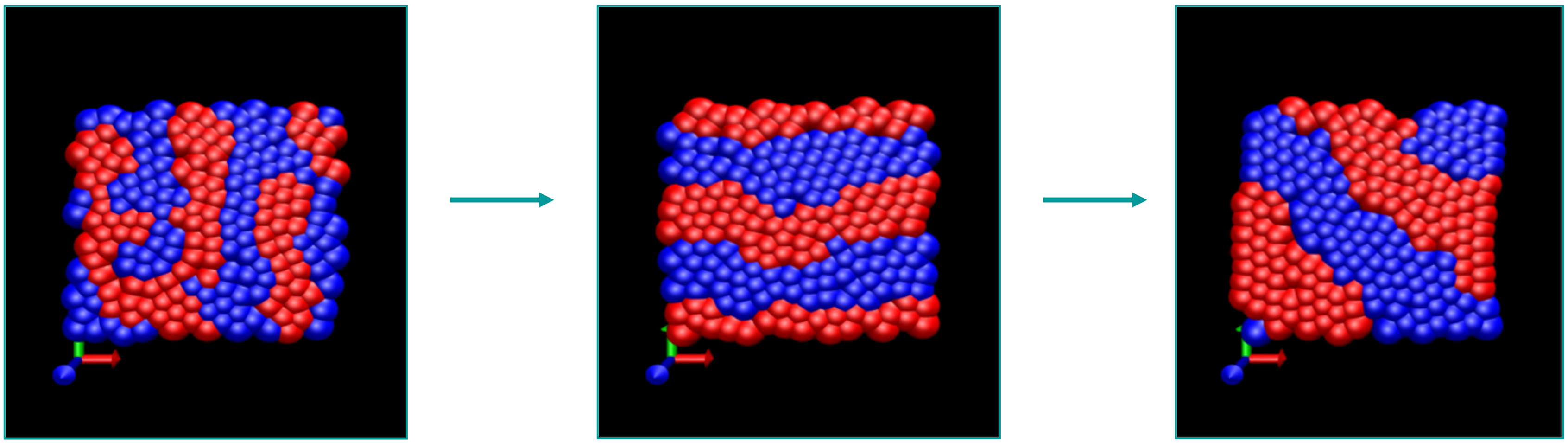
*Arnold, Joannis, Holm. JCP, 2002.

Effect of decreasing electrsoatics

$$U_C(r_{ij}) = \frac{l_B k_B T}{r_{ij}} q_i q_j$$

$$L_0 \sim \left(\frac{\varepsilon}{l_B \sigma^2}\right)^{\frac{1}{2}}$$

SCALING FROM STRONG SEGREGATION



ε=3.0	ε=3.0	ε=3.0
l_B=1.0	l_B=0.5	l_B=0.2

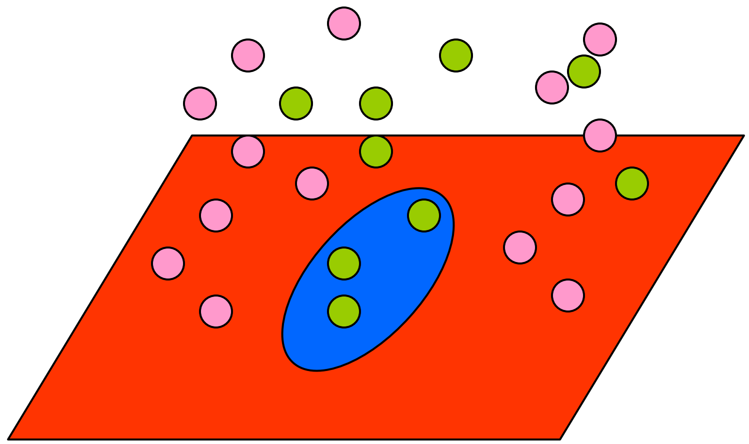
Electrostatics becomes less important. Stripes grow wider.

Screening effects

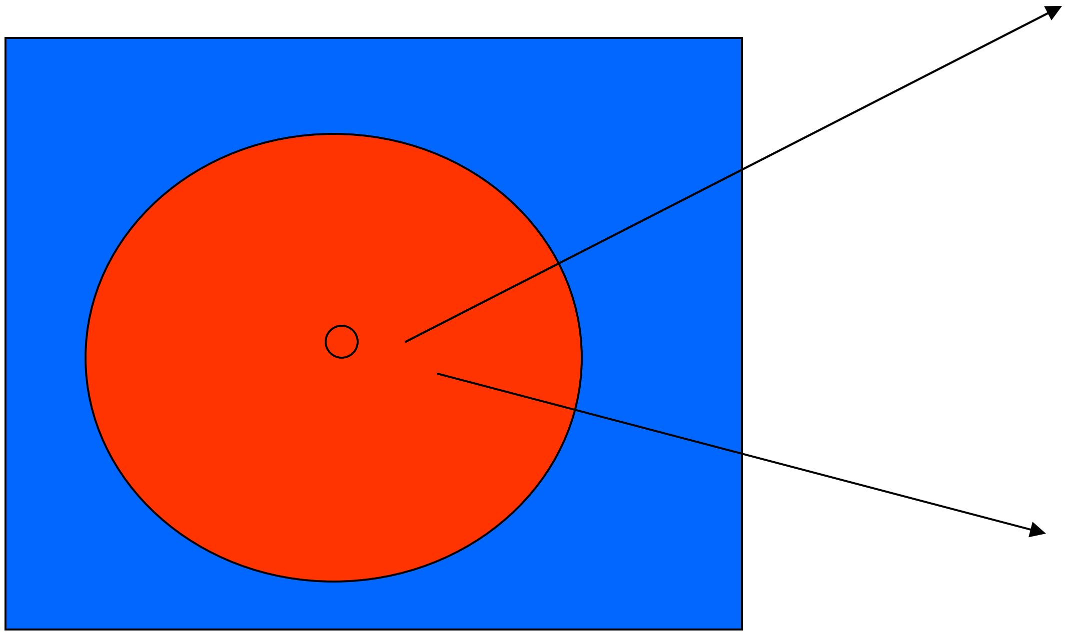
In a salty medium, the Coulomb interaction is replaced by a screened electrostatic interaction:

$$V(r) = \frac{1}{r} \quad \rightarrow V(r) = \frac{e^{-\kappa r}}{r}$$

Why?



Screening kills structure



Pure
Coulomb

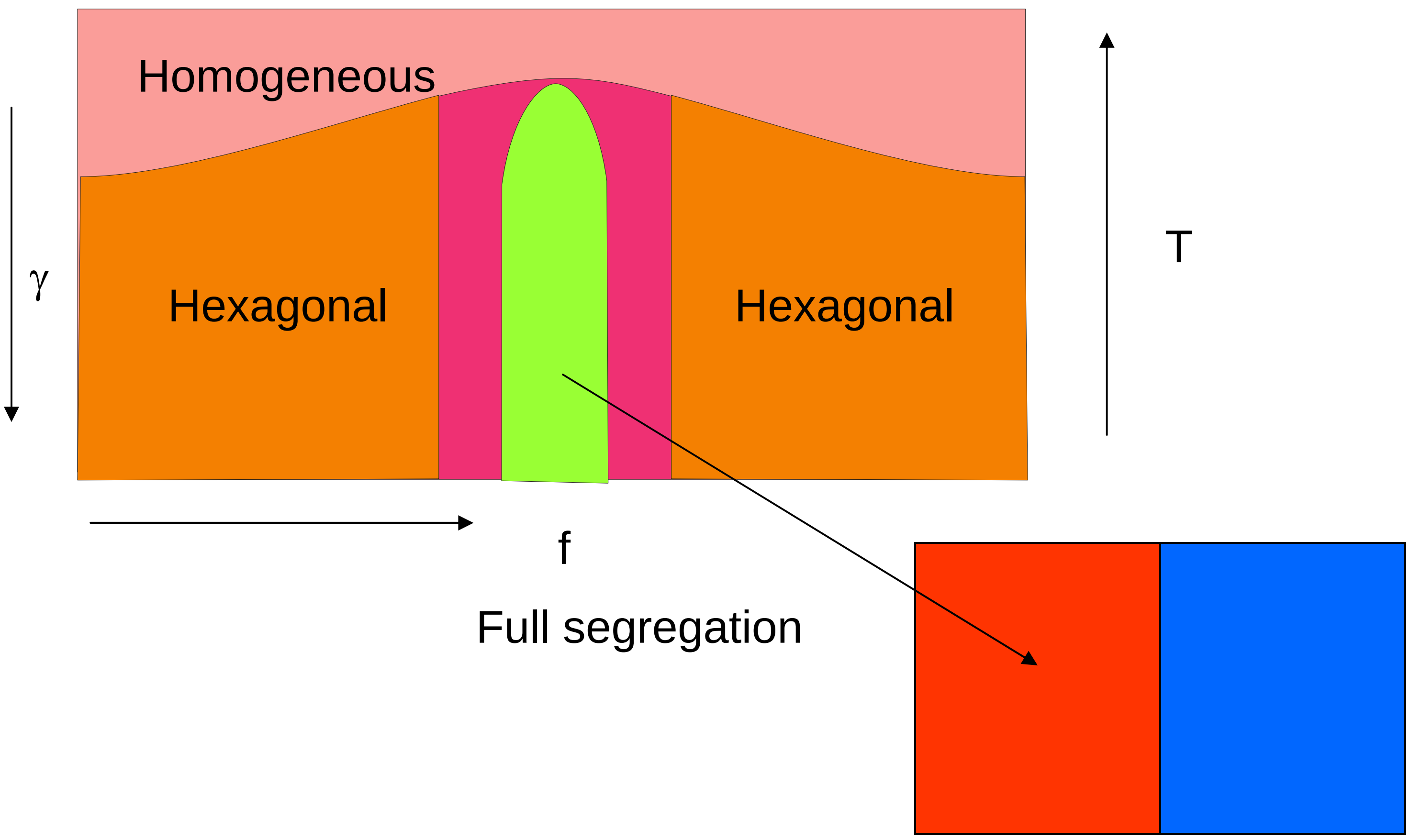
$F \sim L$

Screened

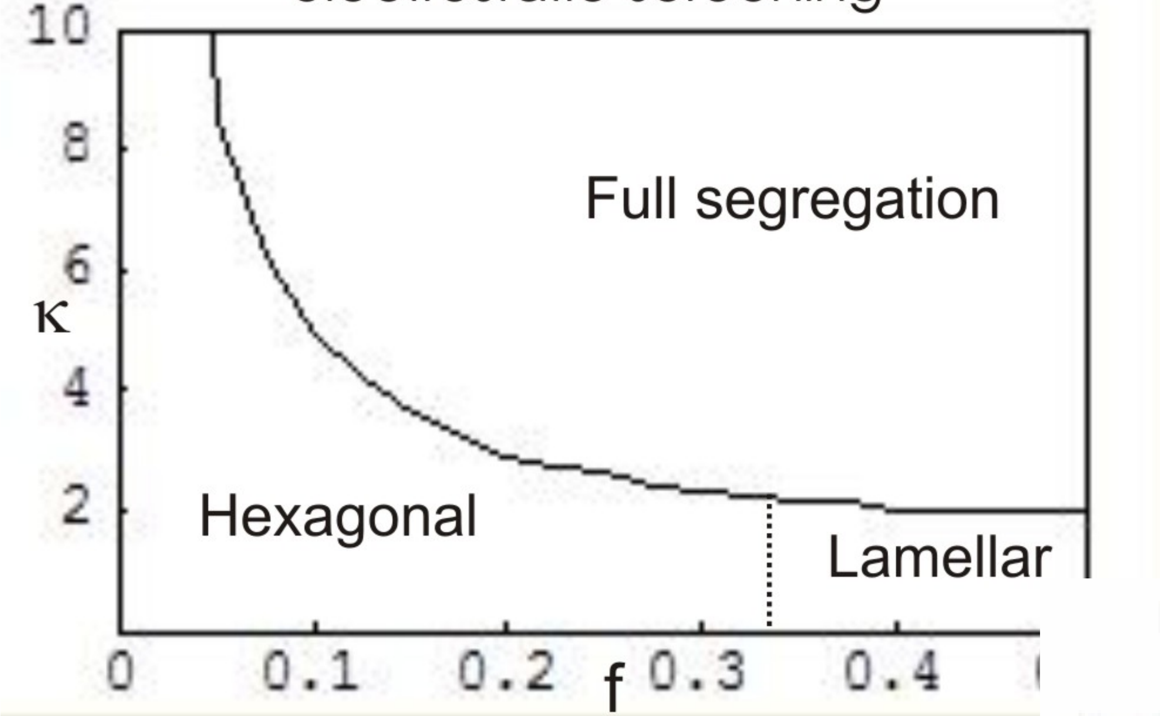
$F \sim L,\ L<1/\kappa$

$F \sim 1/\kappa,\ L>1/\kappa$

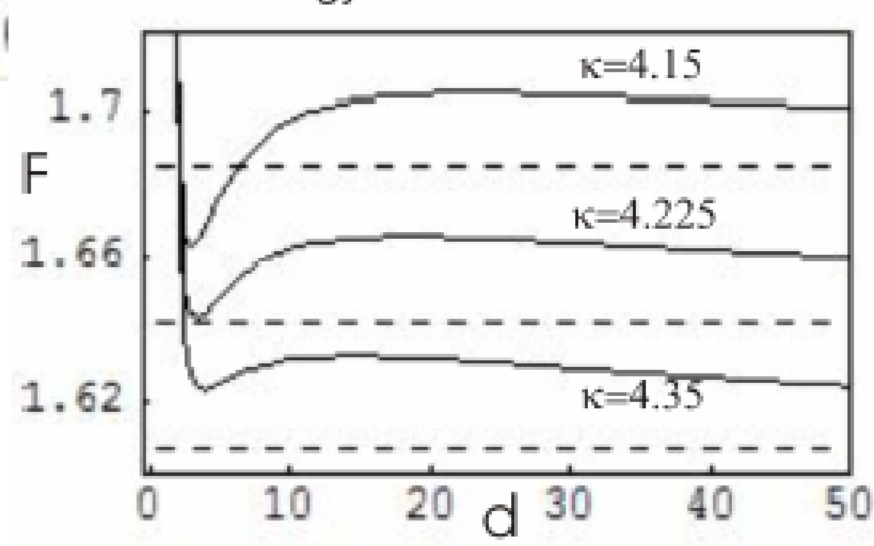
Screening produces full segregation: first order transition



Phase boundaries in the presence of electrostatic screening



Free energy as a function of cell size

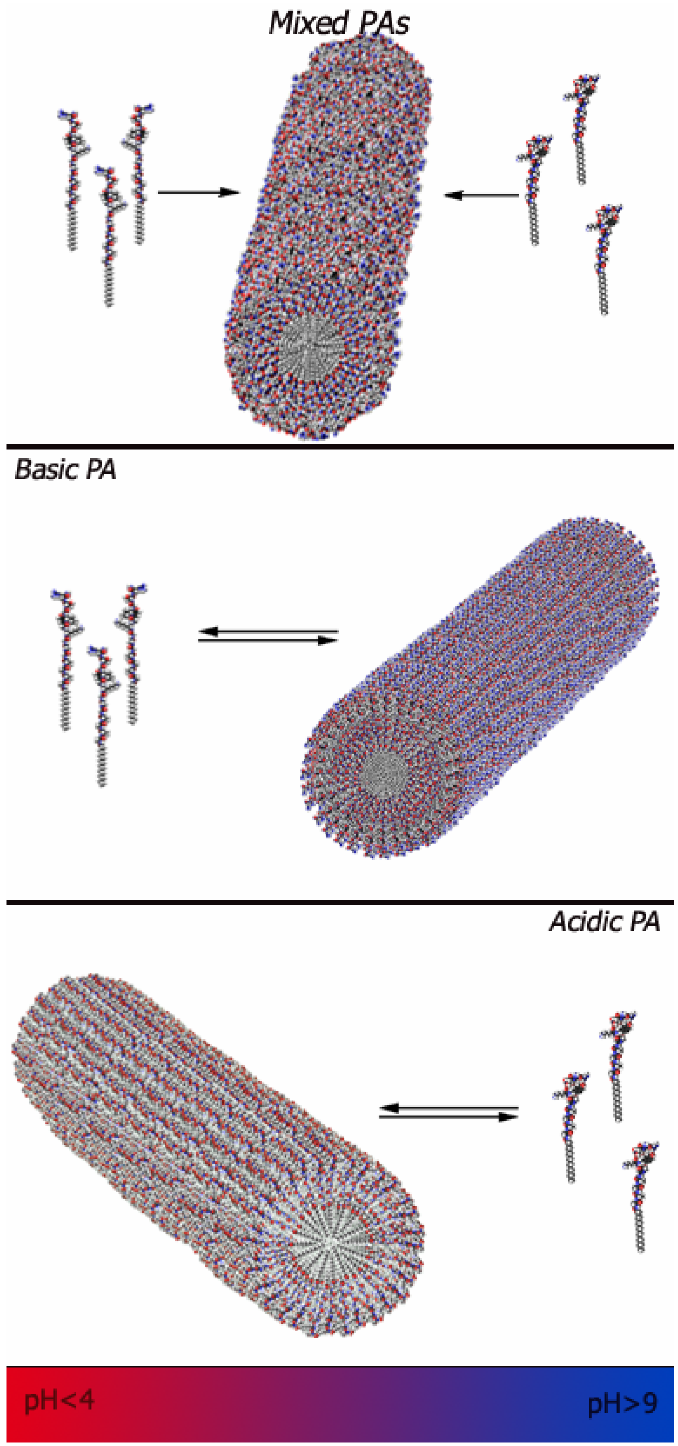


Co-assembly of cationic and anionic peptide amphiphiles

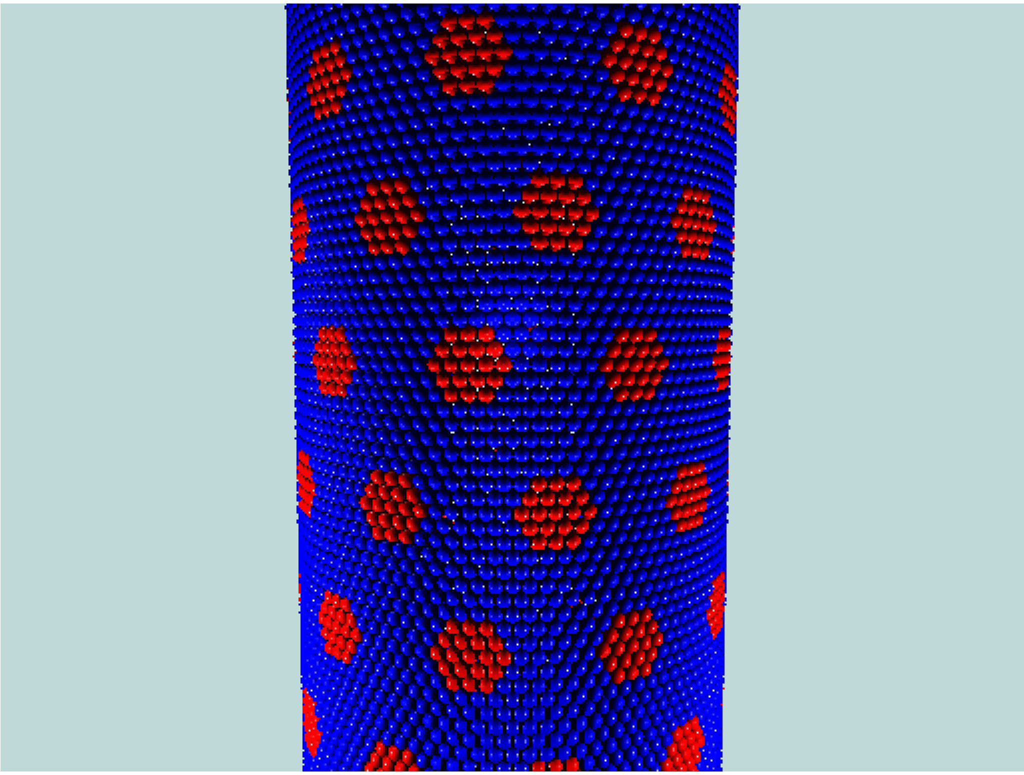
How will phase segregation develop along the nanofibers?

J. Chem. Phys. 122, 054905 (2005)

When do cationic-anionic co-assembly leads to stable micelles and vesicles?

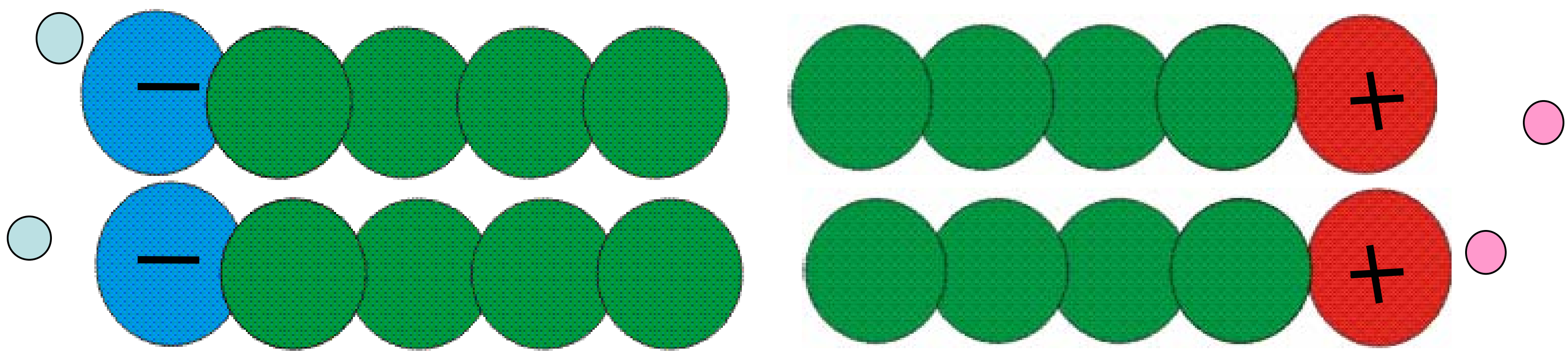


Pattern formation on cylindrical surfaces (T=0)



Multi-component micelles

Two different head species, oppositely charged, but otherwise immiscible.



Not model hydrogen bonding, hydrophobic effects, etc. : only the net repulsion among + and – chains and charges confined to surface

Cylinders

Issues:

Topological constraints.

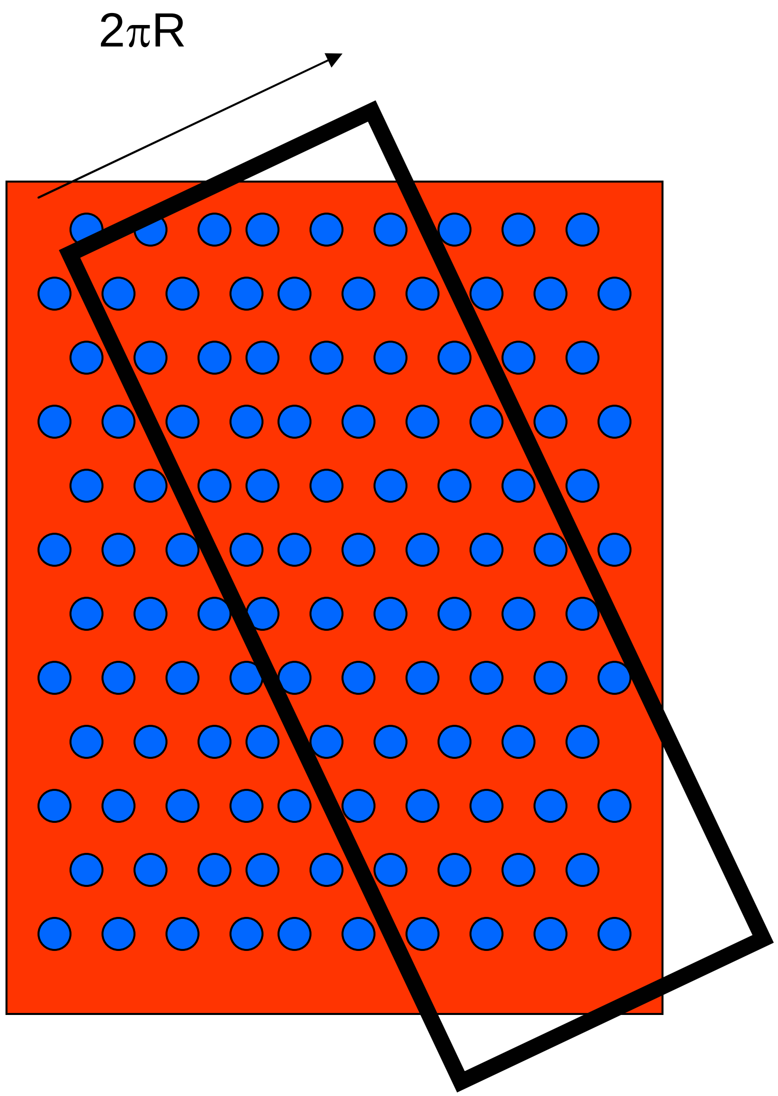
Change of interaction (cylindrical Coulomb).

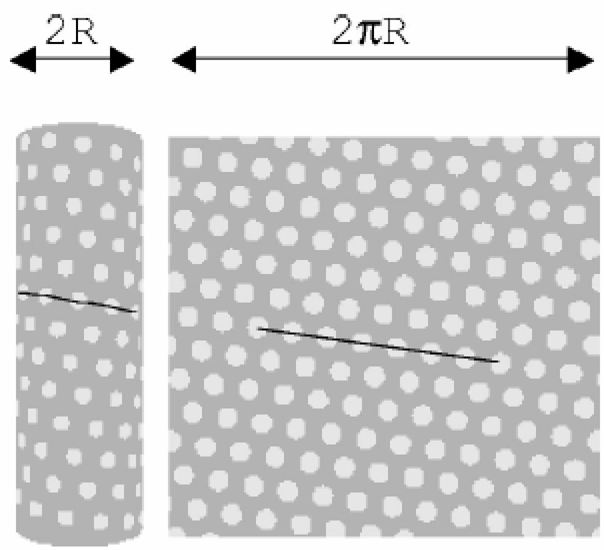
Topological constraints.

For regular patterns, we need to make sure that a given structure can placed in the cylinder.

For small cell sizes, this is easy.

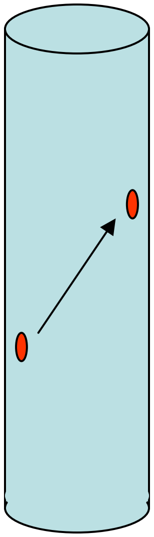
For large cell sizes it is not possible: the only alternative is lamellar order.

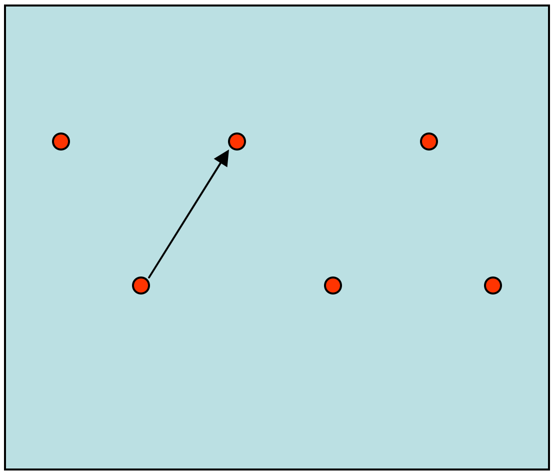



2R
2πR

Electrostatic energy in the cylinder

Calculate an equivalent problem in the plane lattice.

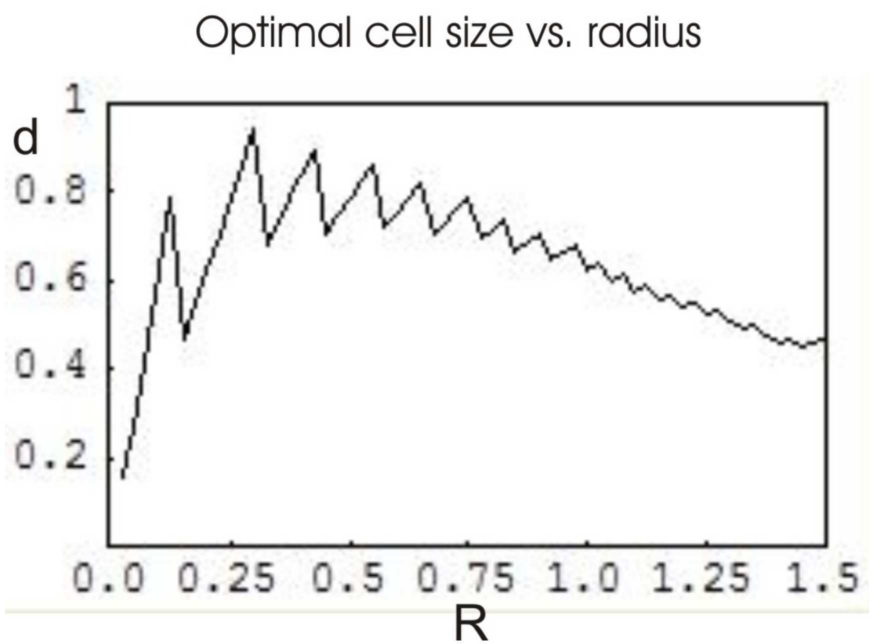


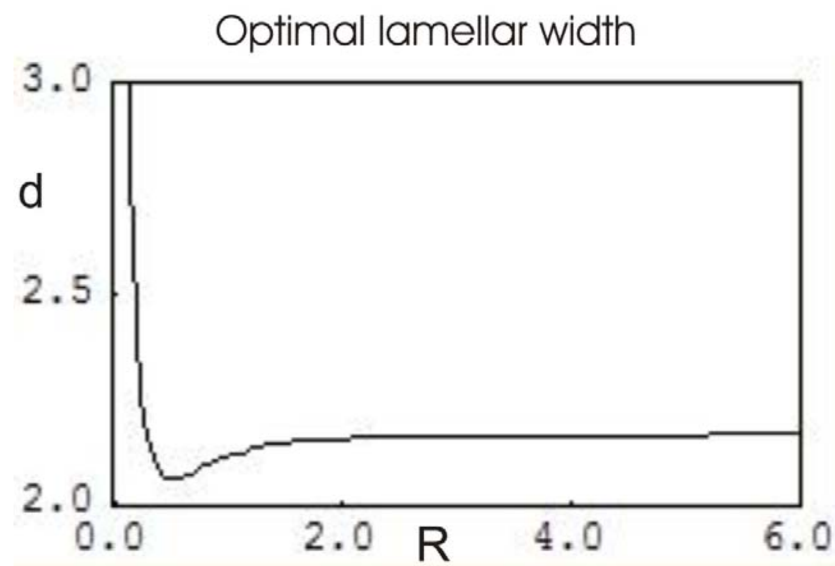


$$V(z,\theta) = \frac{1}{\sqrt{z^2 + 4R^2 \sin^2(\theta/2)}}, \quad -\pi < \theta < \pi$$

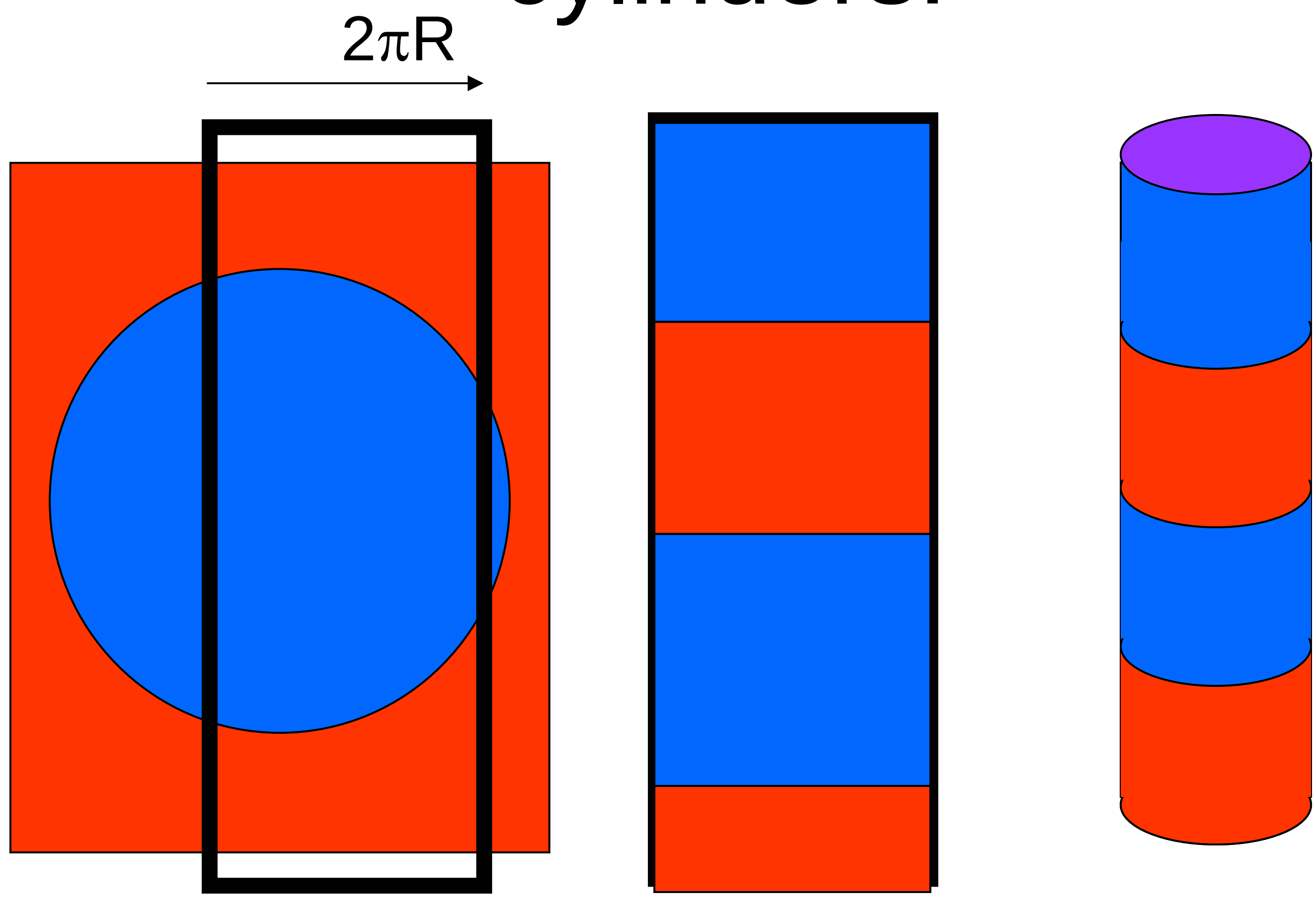
$$V_p(x,y) = \frac{1}{\sqrt{y^2 + 4R^2 \sin^2(x/2R)}},$$

Finite size effects: choosing a hexagonal cell size.

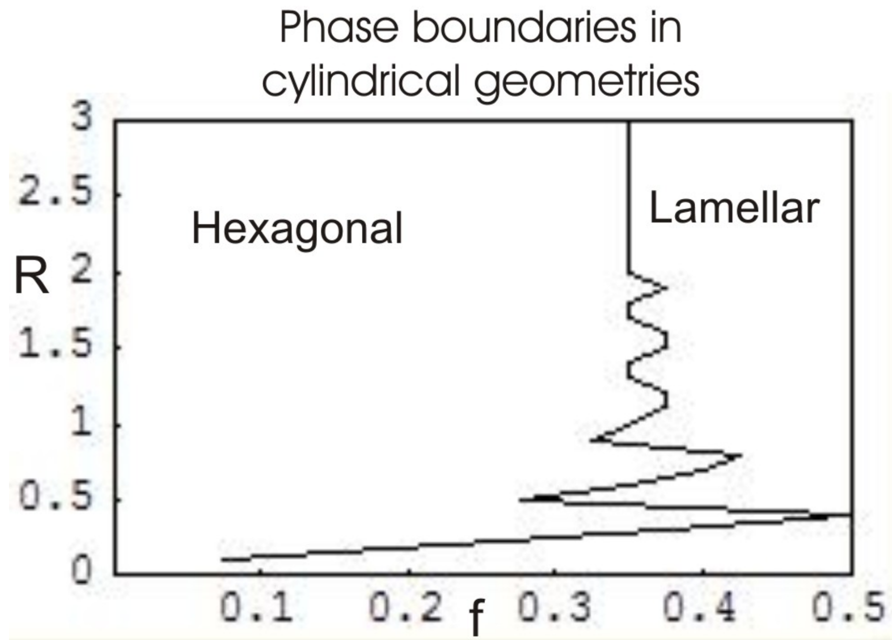




Topological constraints, for small cylinders.

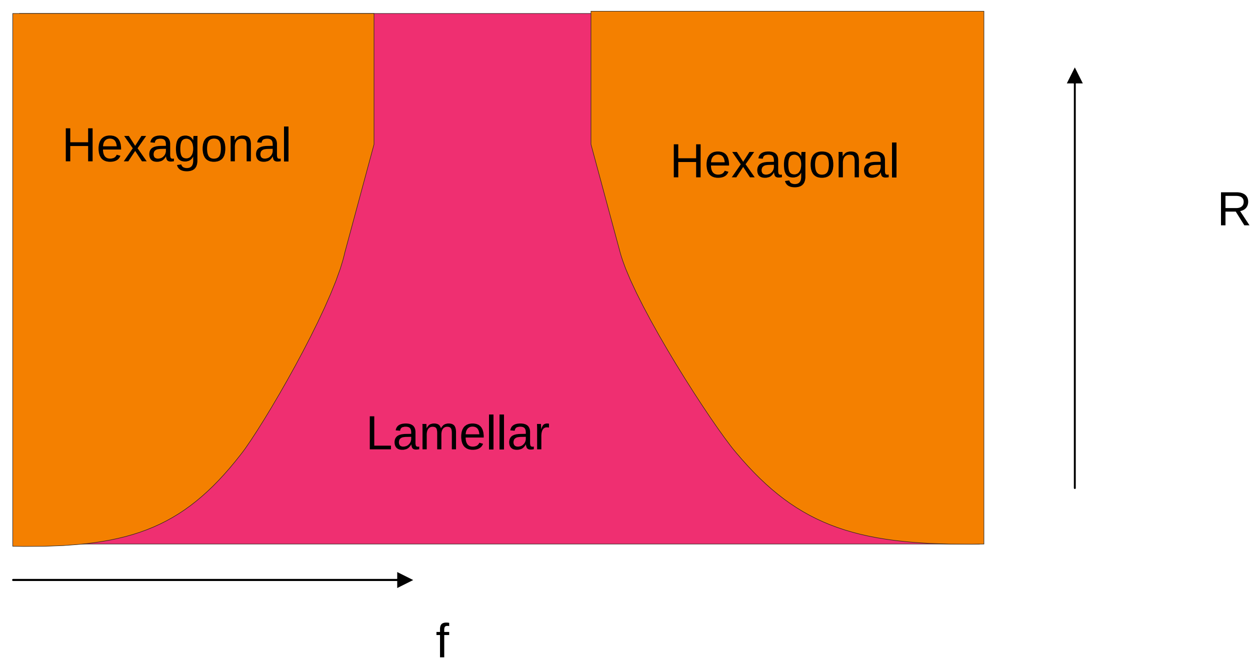


Calculated boundaries.



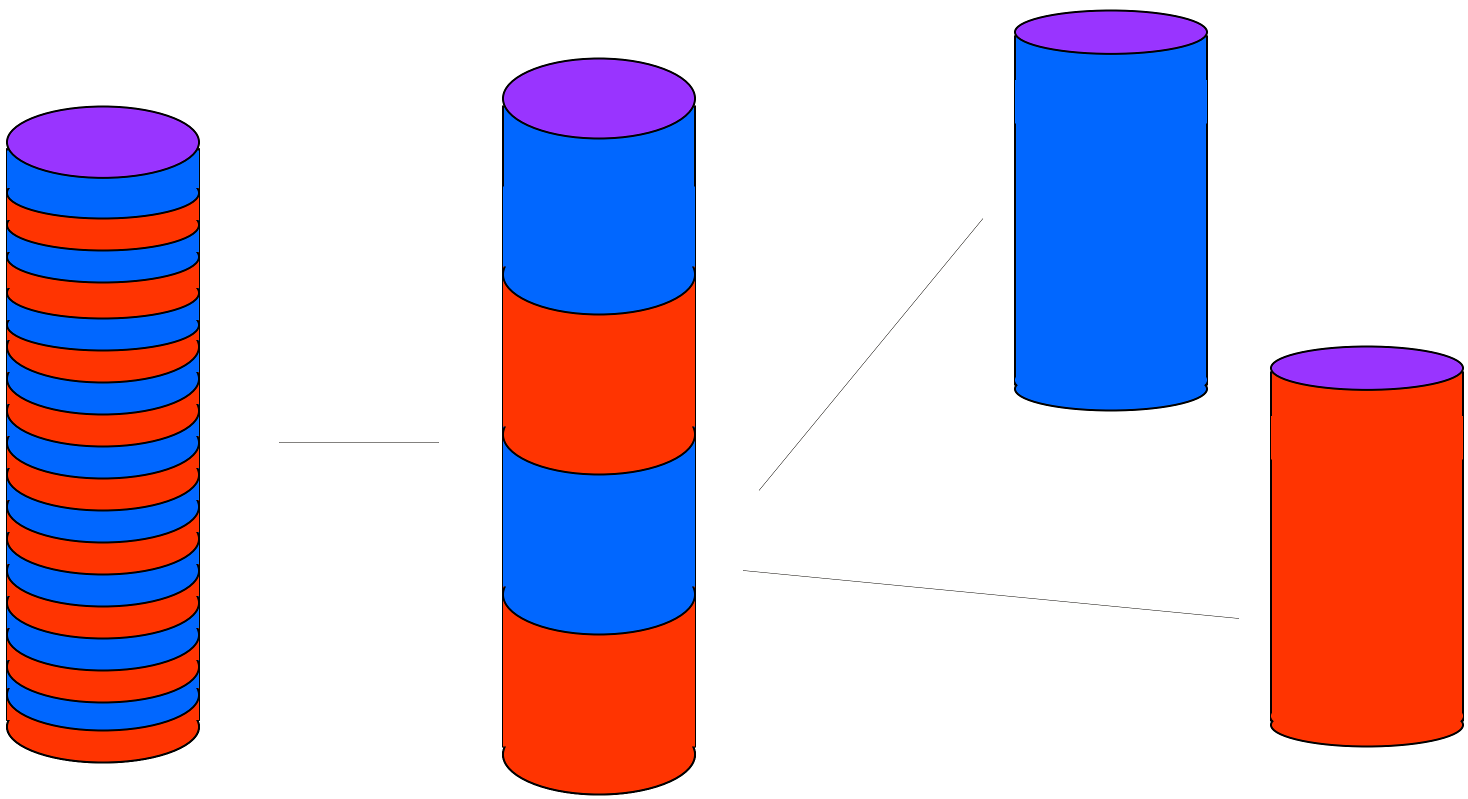
Defects are very easily formed, and what we might optimistically expect is that strong correlations will survive as well as the form of the local structure.

Phase diagram vs. Radius.



Stability with Salt

Screening leads to macroscopic segregation, which might lead to micelle breakage.



Fluctuations: MC simulations

1. Cylindrical geometry

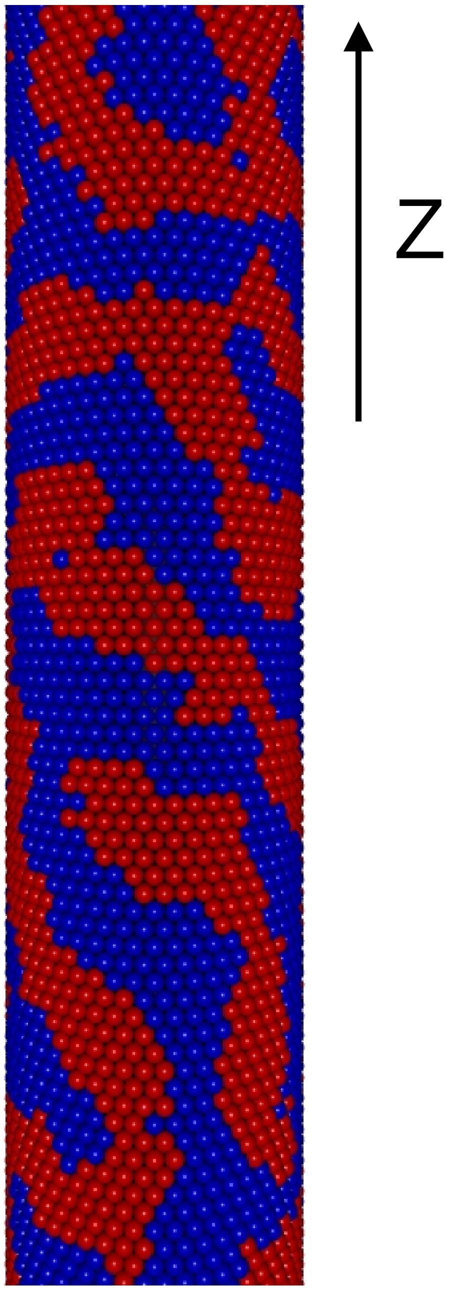
   (radius of the cylinder R_C)

2. Electrostatic forces

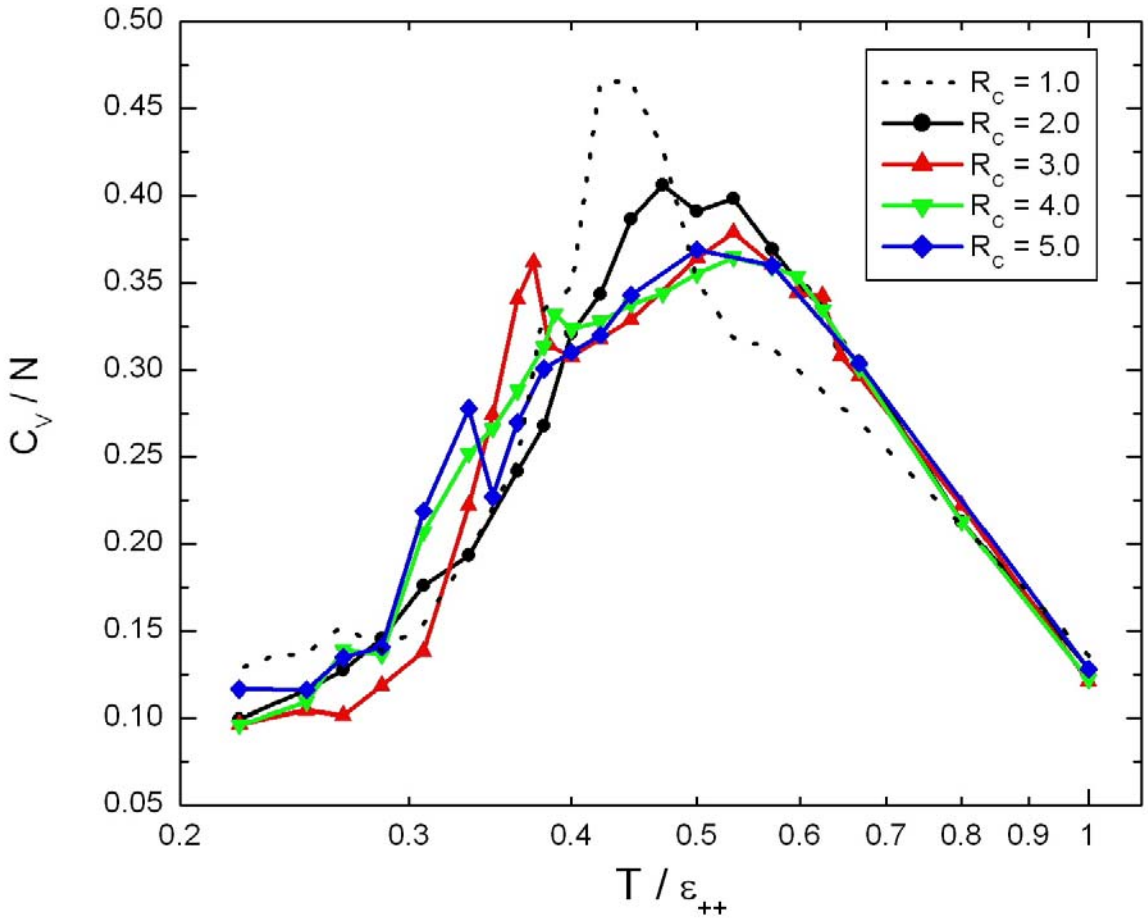
   (charge value, dielectric constant of the media)

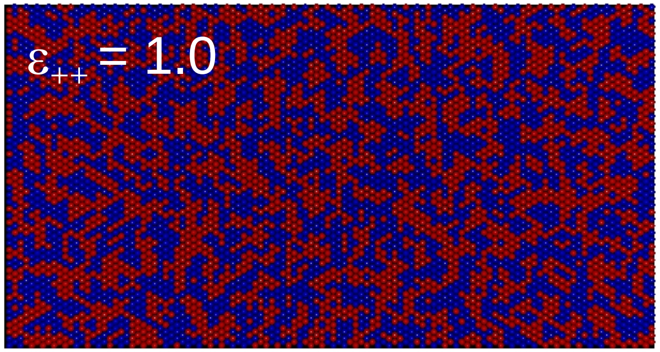
3. Chemical difference

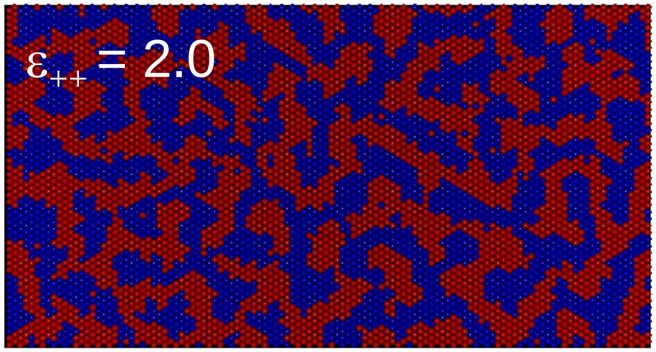
   (different size, net incompatibility)

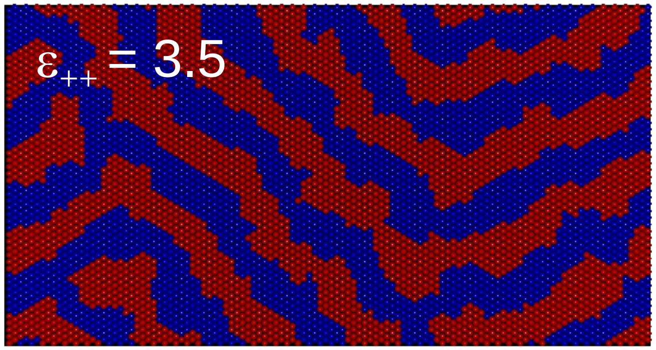


Heat capacity





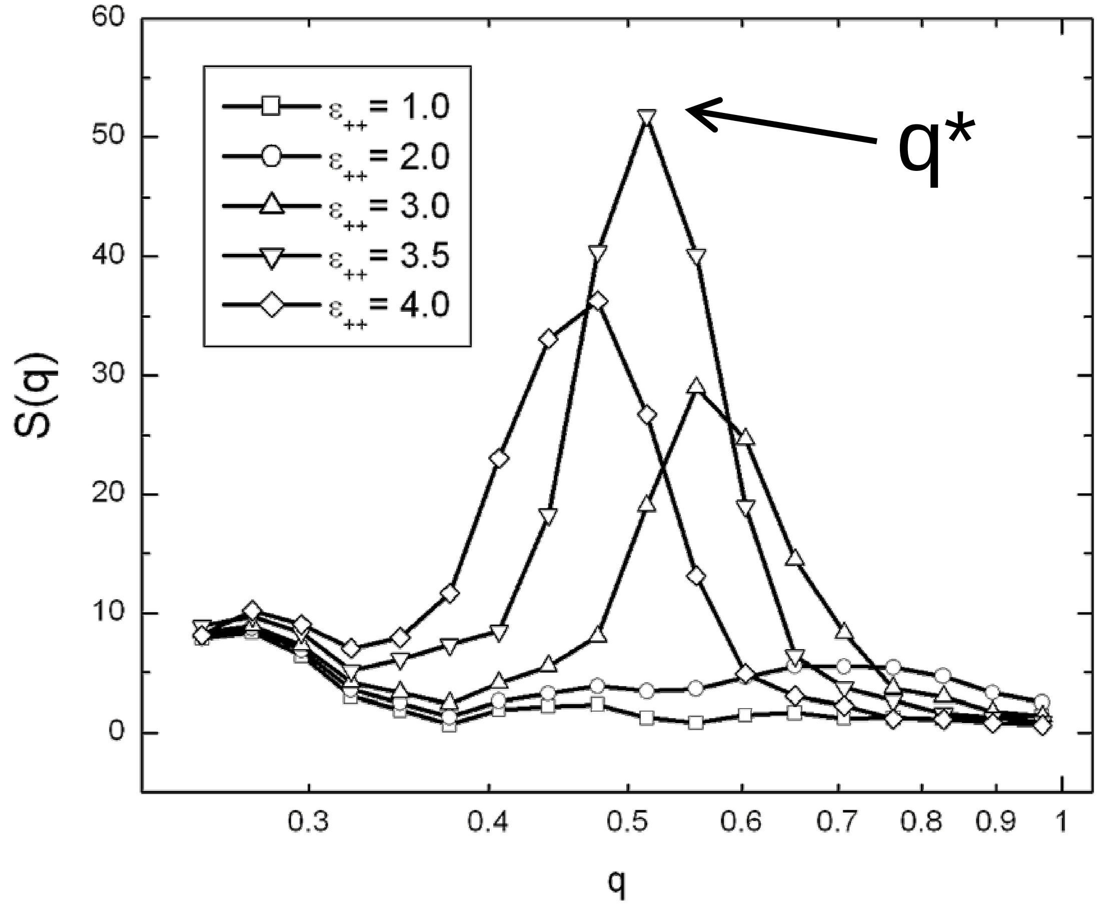




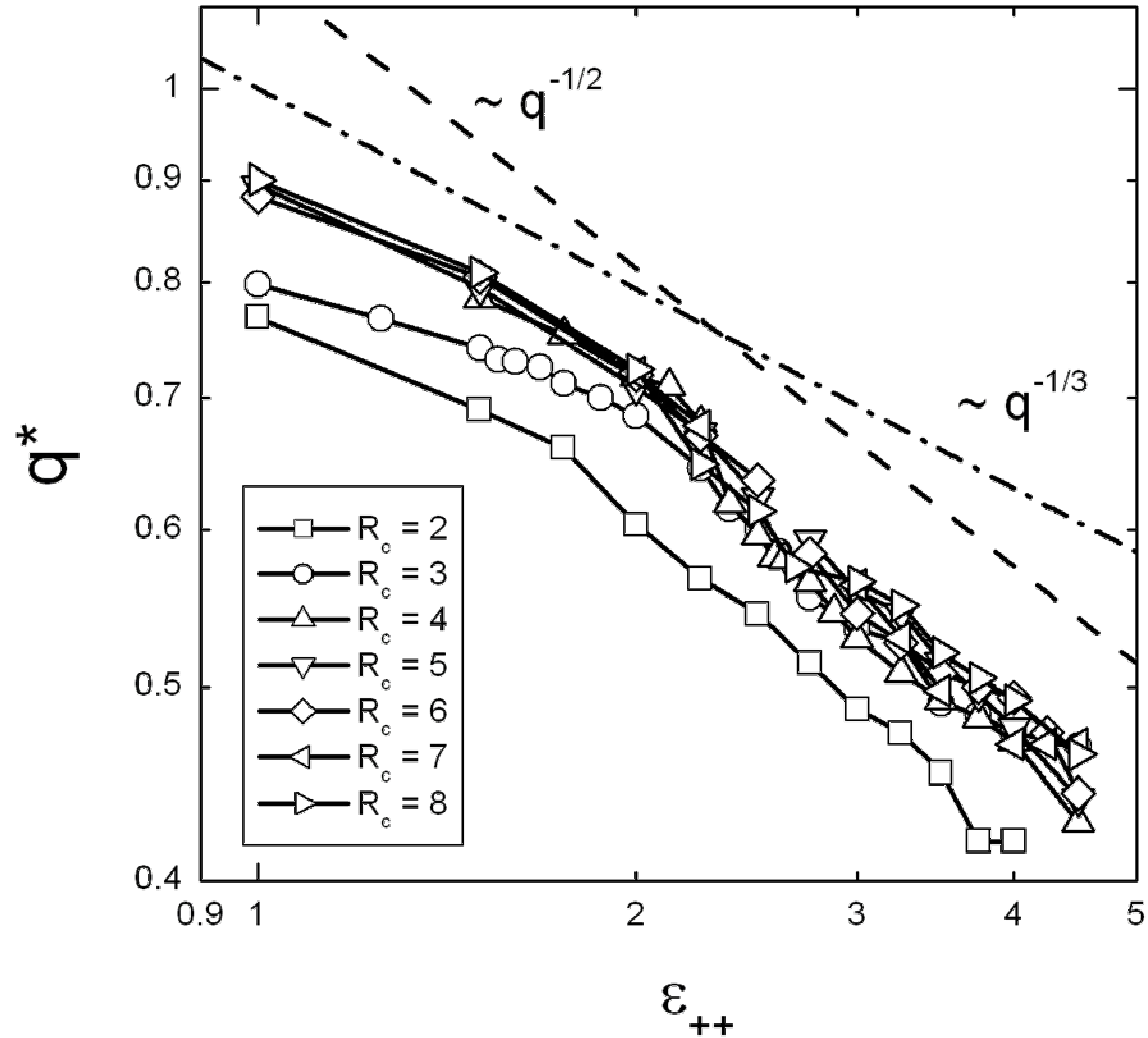
Static structure factor

$$S(\vec{q}) = \frac{1}{N}\sum_{i}^{N}\sum_{j}^{N}\exp\left(-\iota\vec{q}\Delta\vec{r}_{ij}\right)$$

$$\Delta\vec{r}_{ij} = \vec{r}_i - \vec{r}_j$$

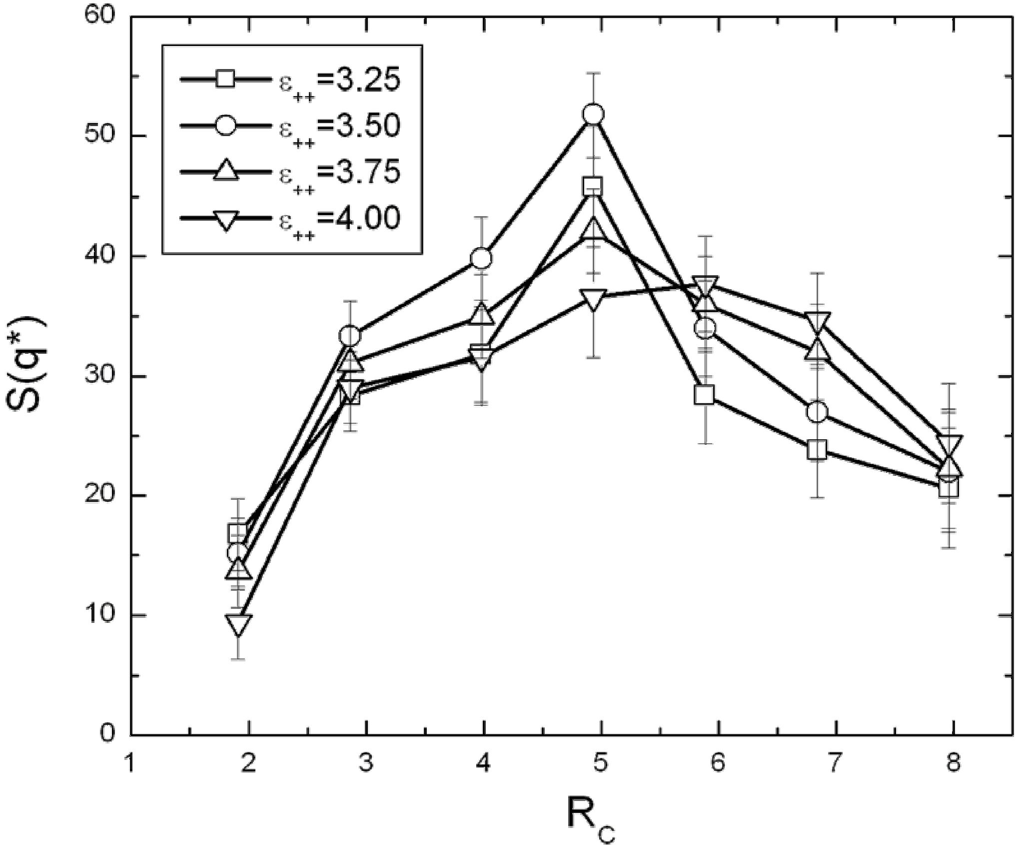


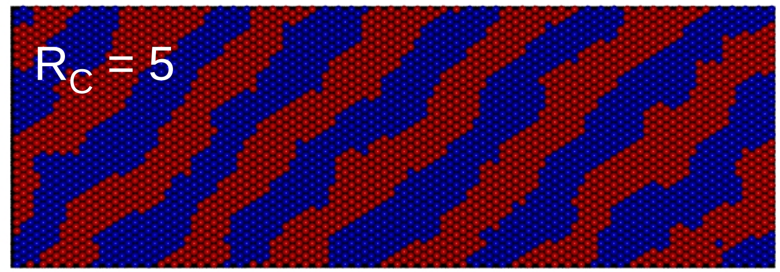
Domain size, L=2π/q*

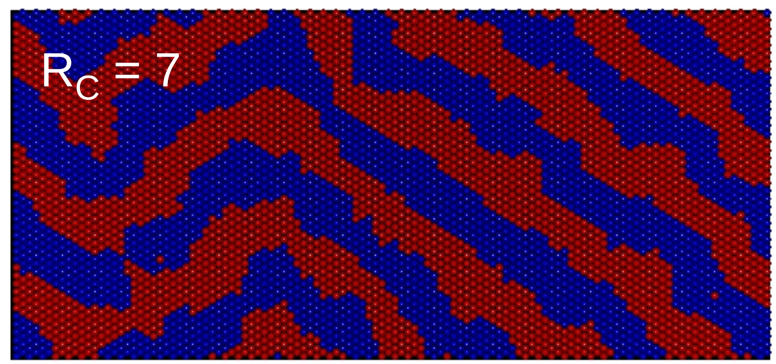


High T $\sim 1/\mathfrak{m}_{++}$
fluctuating or
weakly
segregated

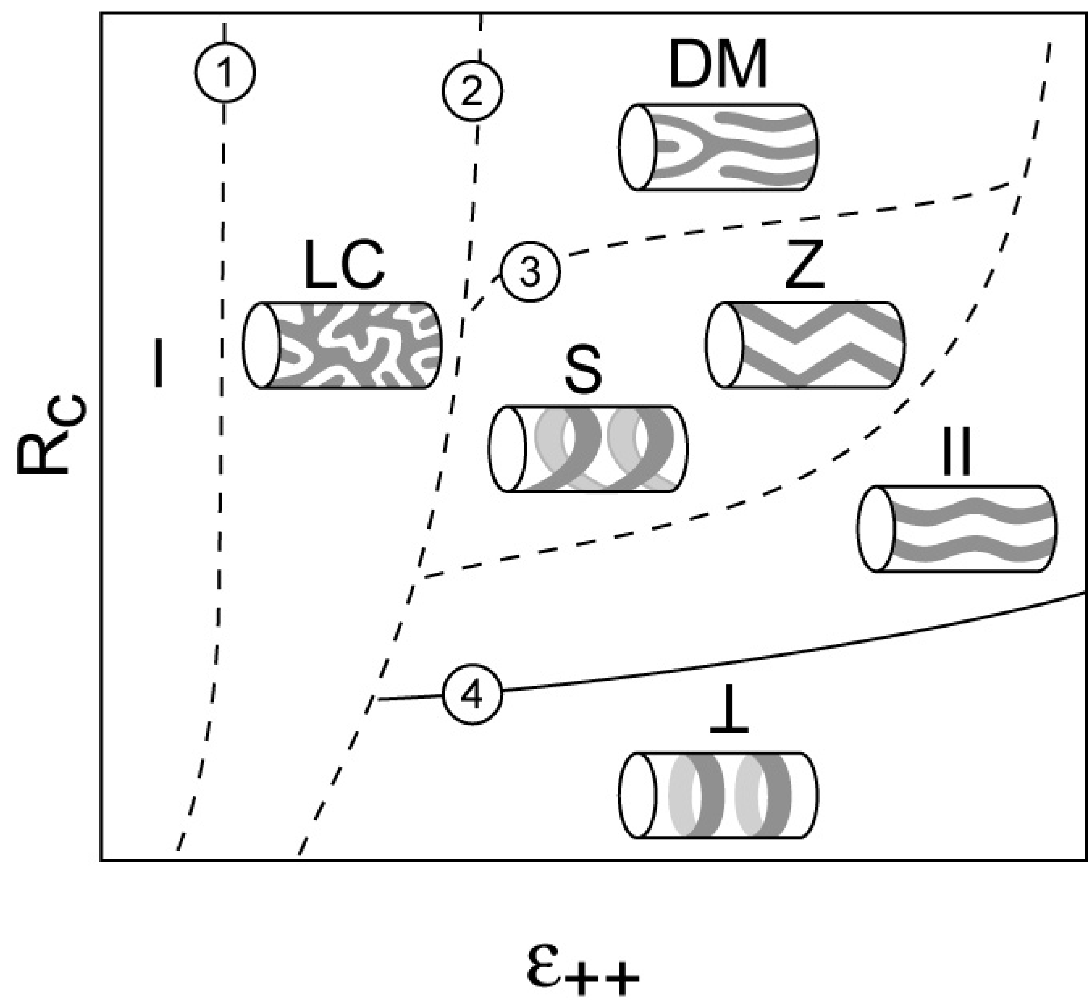
S(q) vs. R_C





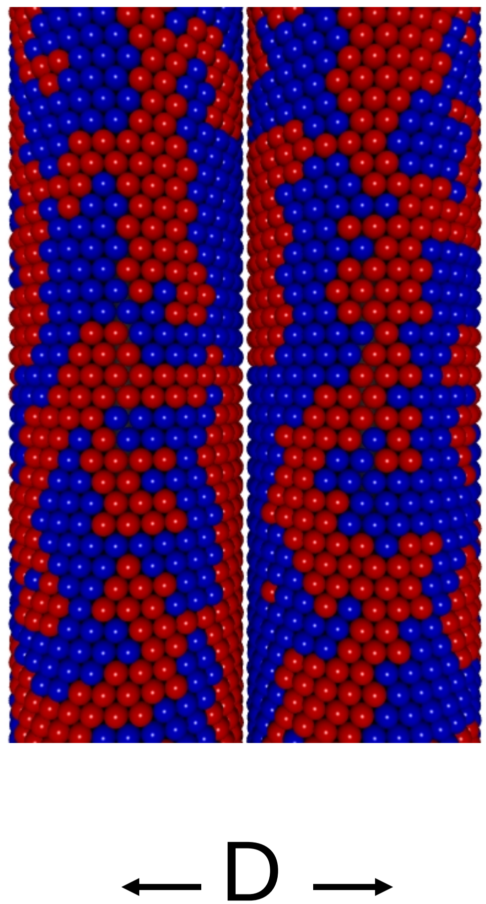


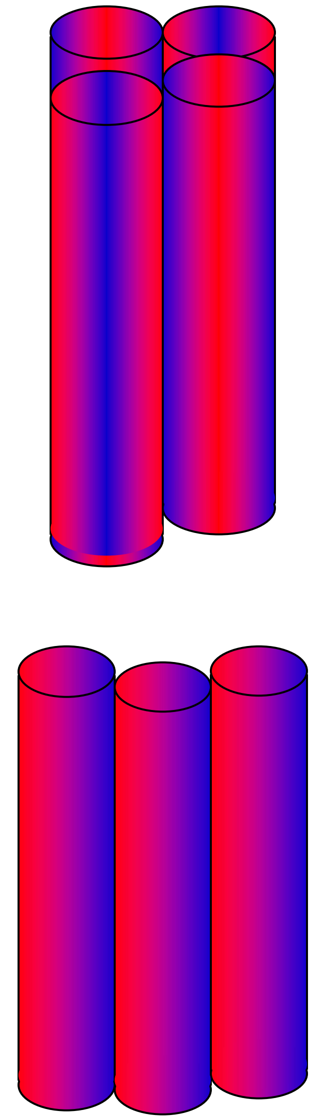
Phase diagram



Fiber-fiber interaction

How to determine the degree of bundling?



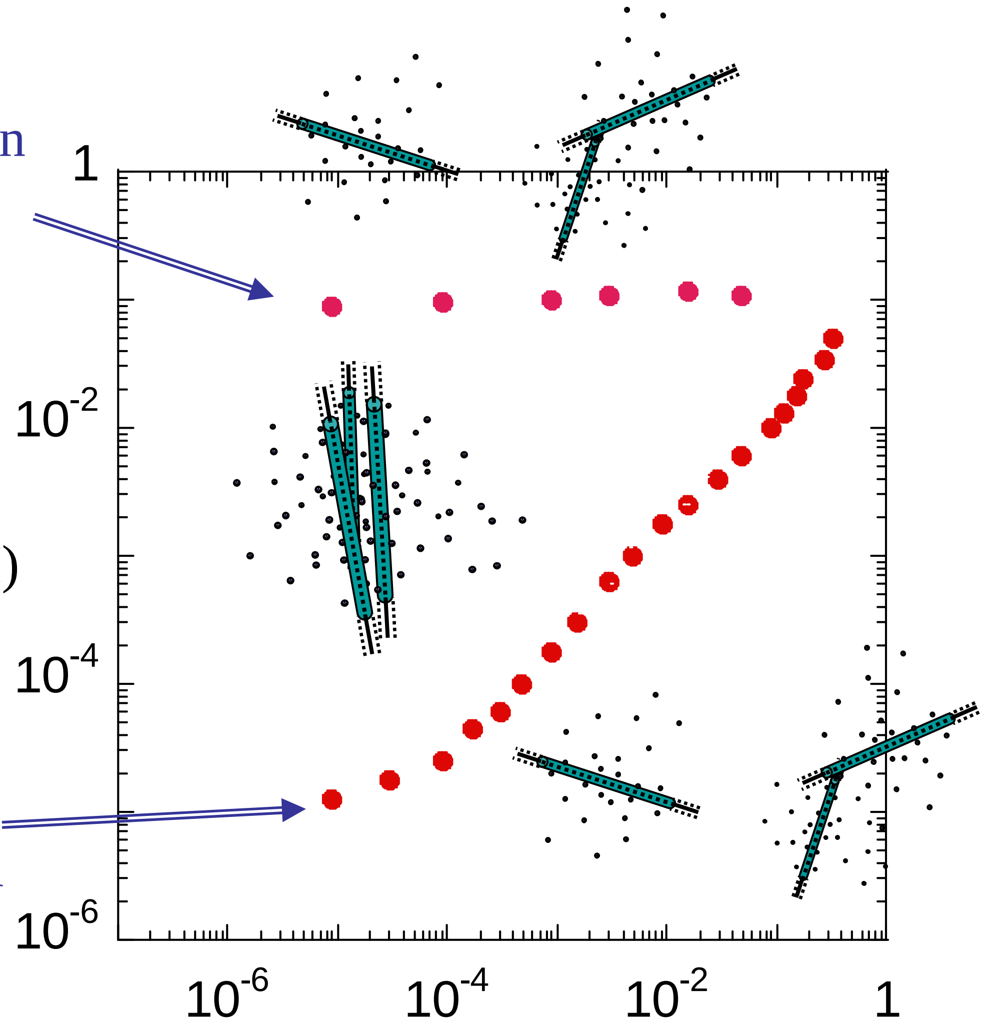


Phase diagram: nearly universal

DNA redissolution in excess of spermine

Spermine Concentration (M)

DNA precipitation

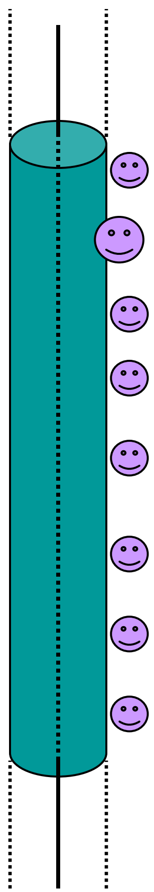


DNA concentration (M)

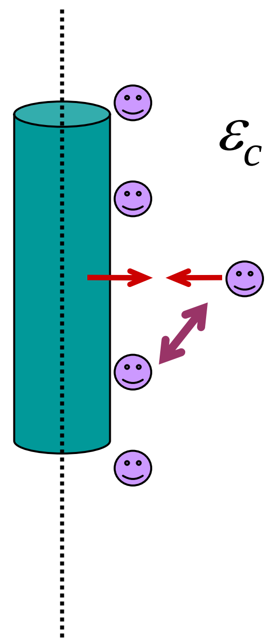
In the precipitated region the chains form an ionic crystal

(Raspaud et al., 1998-99)

Two-dimensional lattice of the **multivalent** counterions around the surface (Rouzina and Bloomfield 1996) and around rods Polarizability (Solis and Olvera de la Cruz, 1999)

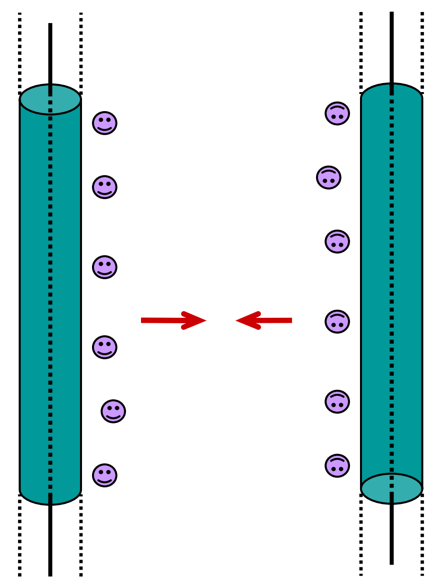


Correlation energy ε_c
per ion < 0 (attractive)



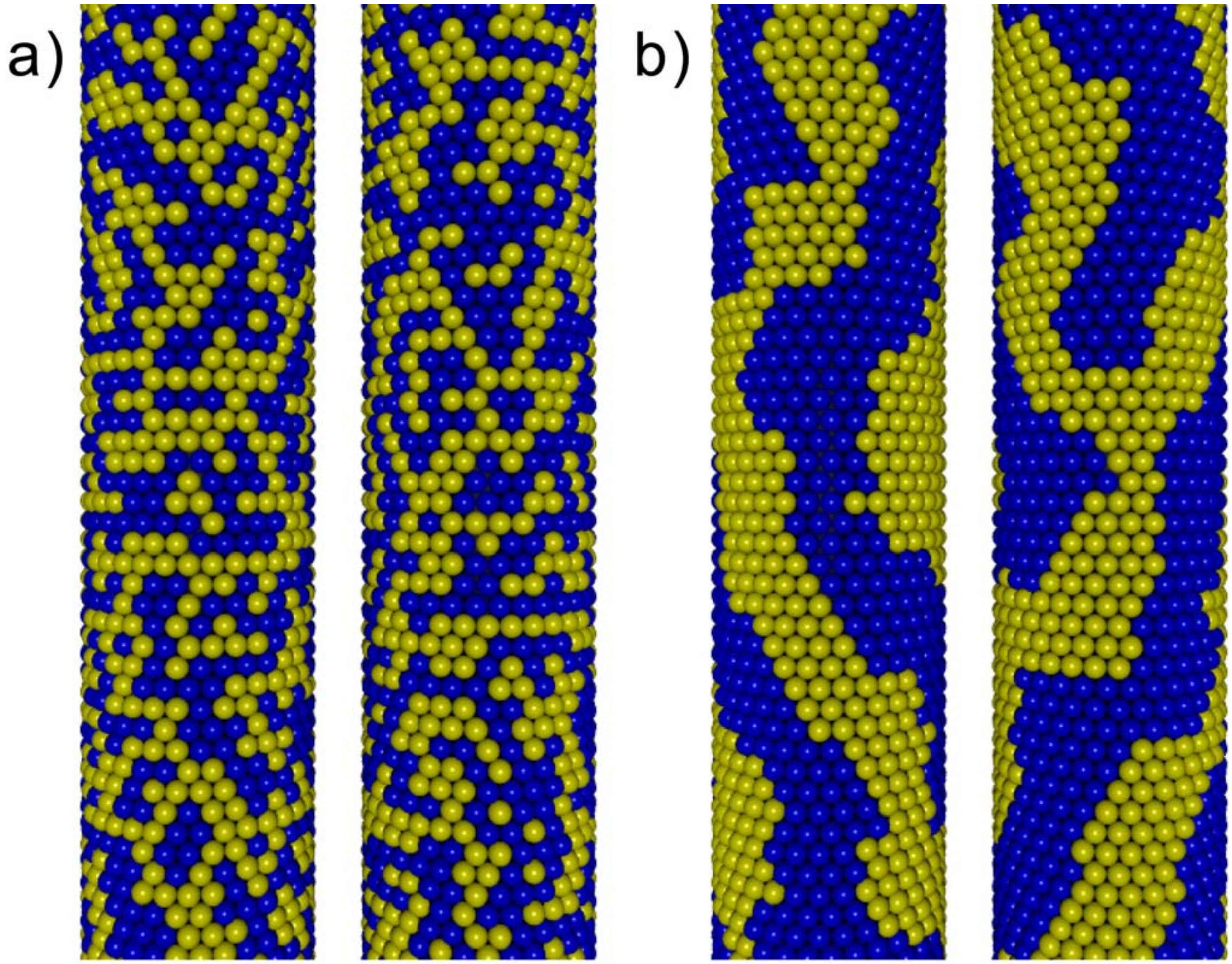
$$\varepsilon_c \approx -W_c$$

If n : local concentration of
the correlated liquid

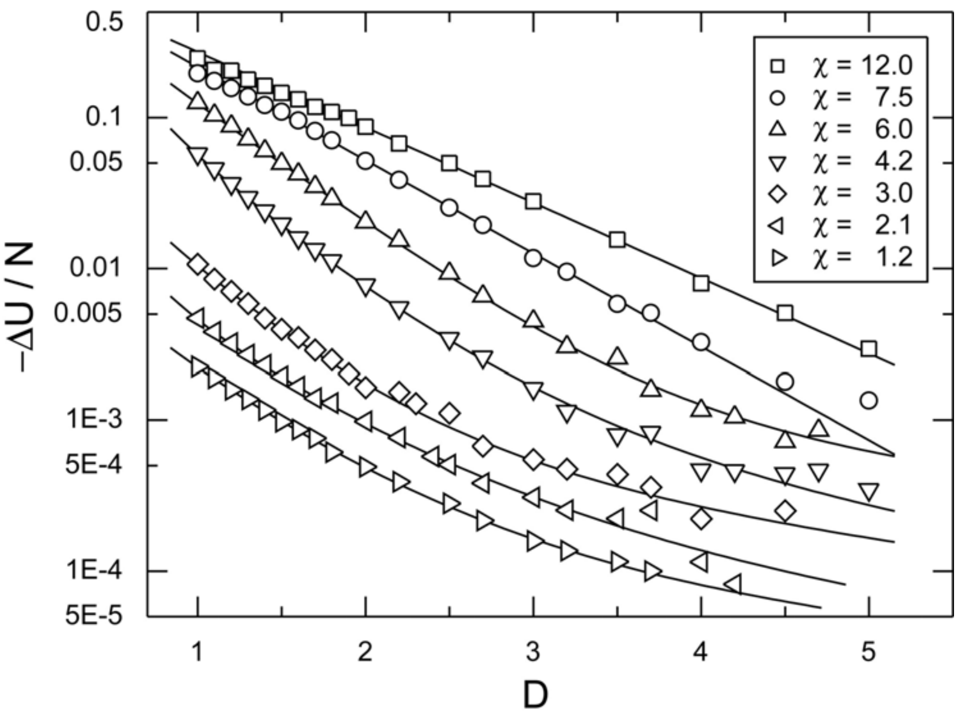


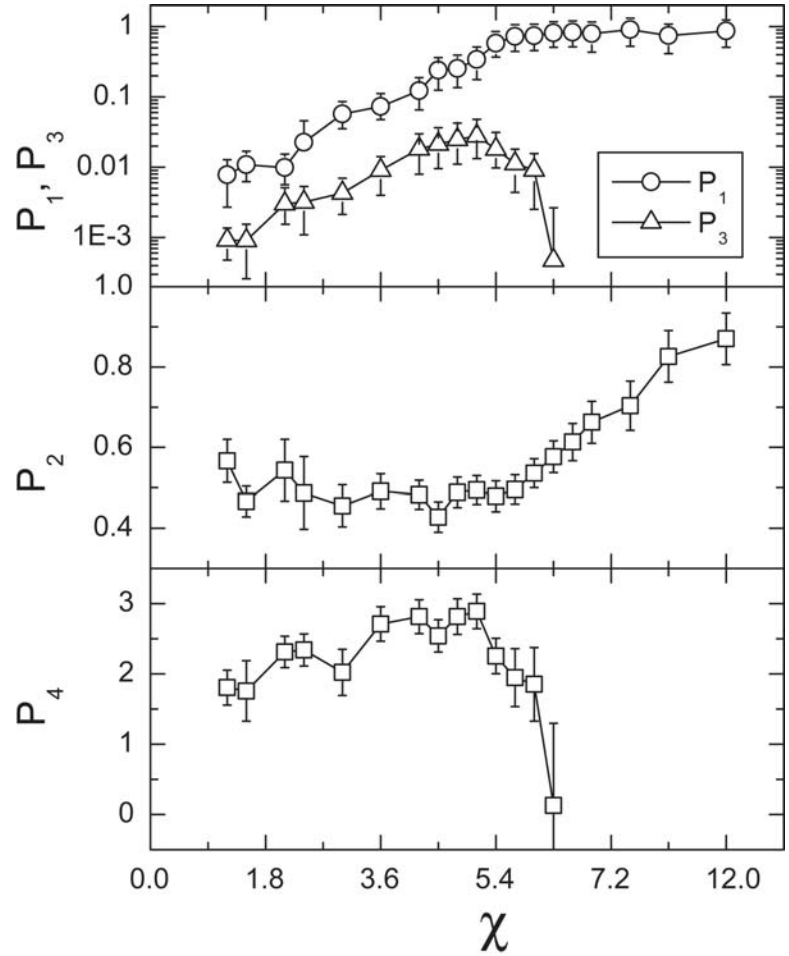
$$\varepsilon_c(2n) < \varepsilon_c(n)$$

Attraction between chains

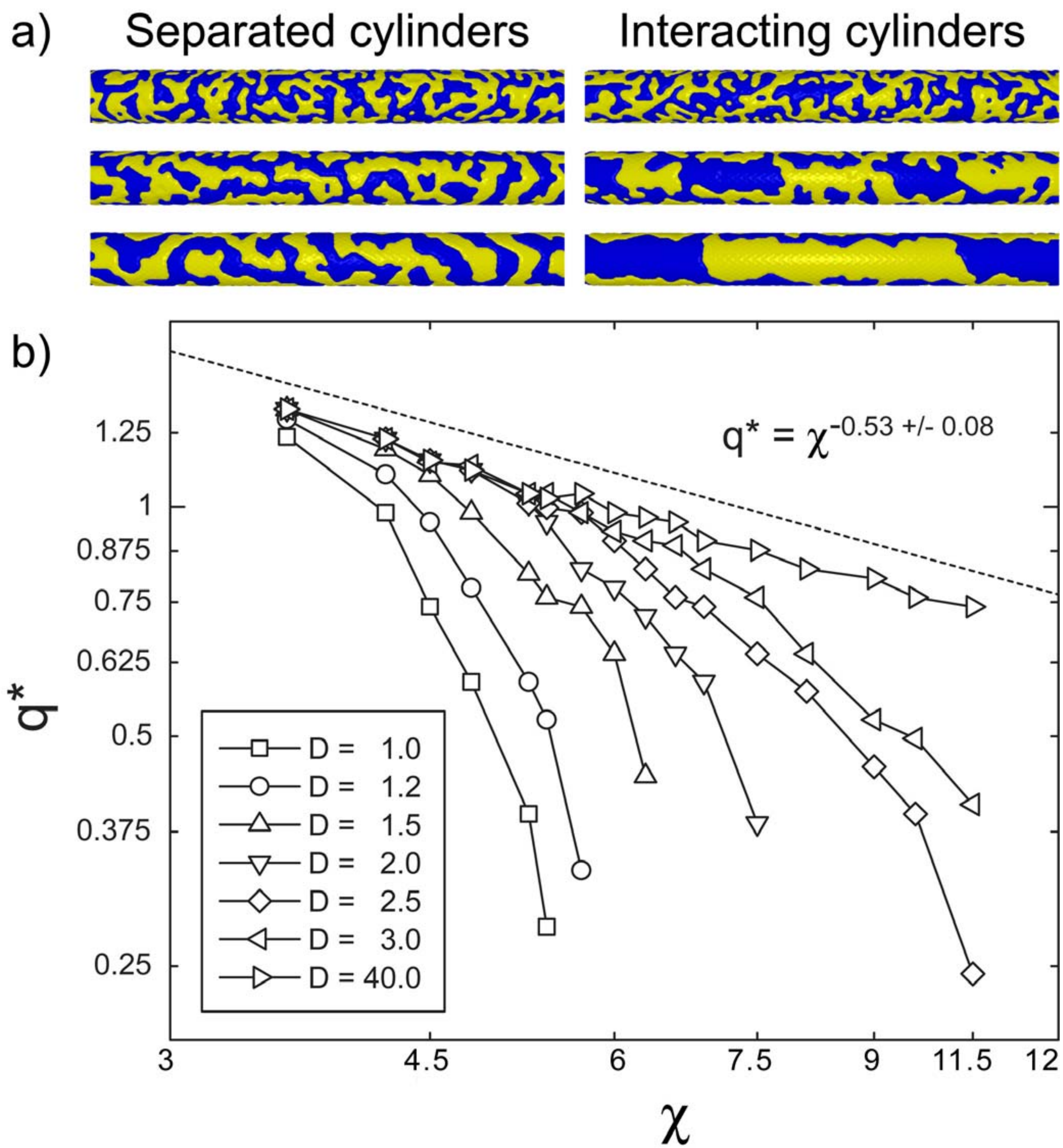

a)
b)

Fiber-fiber attraction



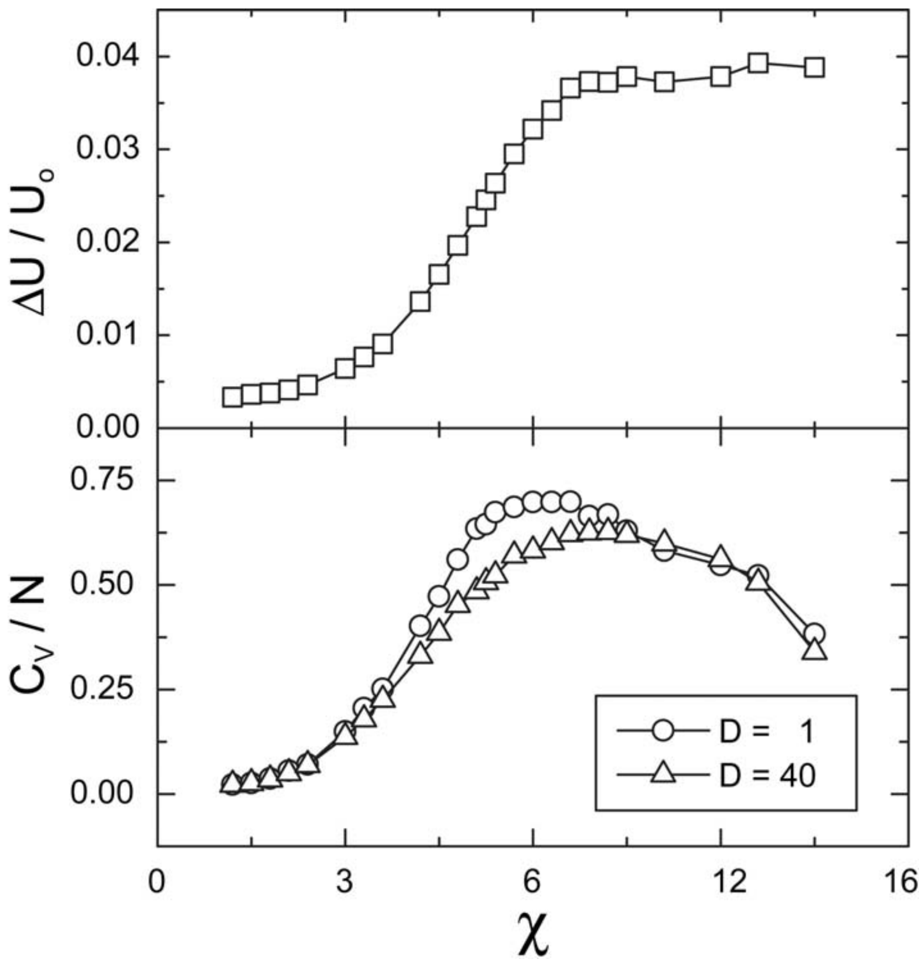


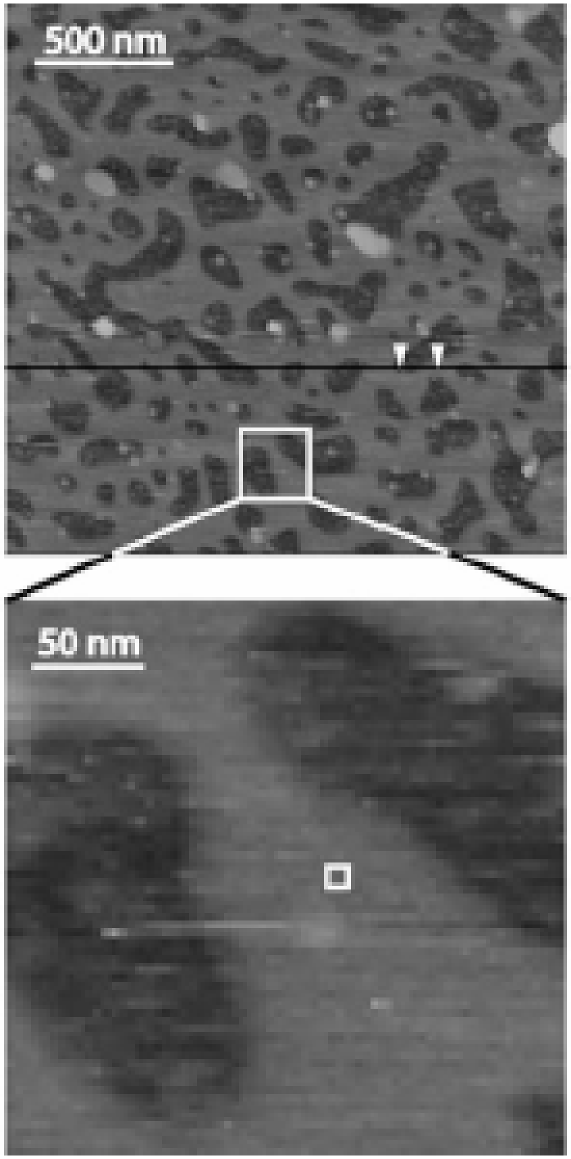
$$\Delta U \propto \begin{cases} T \to \infty & P_3 / D^{P_4} & P_4(\chi) \approx 2 \\ T \to 0 & P_1 \exp(-P_1 D) & P_1 \approx q^* \end{cases}$$



a)
Separated cylinders
Interacting cylinders
b)
q* = χ^-0.53 +/- 0.08
q*
χ
D = 1.0
D = 1.2
D = 1.5
D = 2.0
D = 2.5
D = 3.0
D = 40.0
1.25
1
0.875
0.75
0.625
0.5
0.375
0.25
3
4.5
6
7.5
9
11.5
12

Fiber-fiber attraction





E.E. Meyer et al PNAS
May 2005

DODA in Mica