Colloidal Systems

(Lecture 1)

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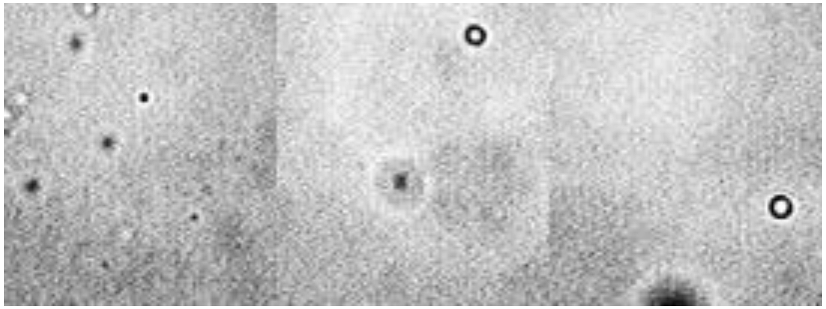

IoP, Durham, April 2017

Colloidal systems

Outline:

- Examples-Applications
- Main phenomena – Forces - Time scales
- Phase behavior: Thermodynamic phases, Metastable states (glasses and gels)
- Microscopic Dynamics (Scattering-Microscopy)

- Mechanical properties (Rheology) -> 2nd lect.
- Rheology of suspensions and glasses -> 2nd lect.
- Rheology of attractive colloids and gels -> 3rd lect.

Colloidal systems

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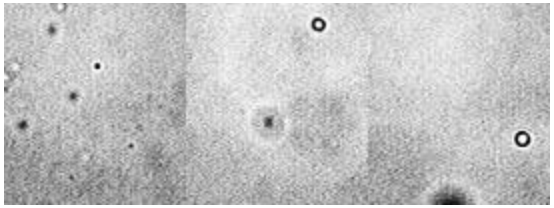
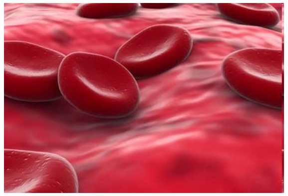
Colloids –Examples

Example: Particles with size few nm to few μm suspended in a liquid



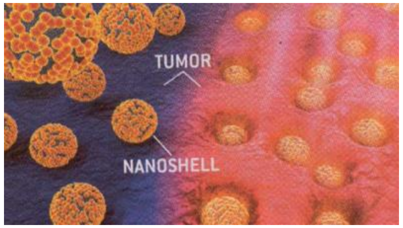
Paints, Inks, lubricants, shampoo, foodstuff, blood, …



Biological systems and applications:
Protein crystallisation, macromolecular crowding in biological cells, drug release, etc

Figure 1 Crowded interior. This three-dimensional reconstruction shows part of the cytoplasm of an intact motile *Dictyostelium discoideum* cell. The orange linear complexes are actin filaments; ribosomes and other macromolecular complexes are in grey; membranes are in blue. Reprinted with permission from ref. 3.

biomaterials



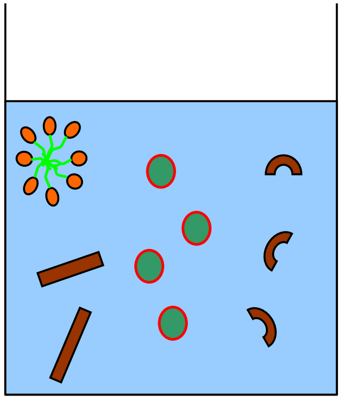
Colloidal Systems

Which systems are colloidal?

General Definition: Two immiscible component mixtures

Dispersed phase (gas, liquid, solid) in suspending medium (gas, liquid, solid)

Size of dispersed particles: ~10 nm to ~5 µm



Brownian motion keeps them from sinking

$$\Rightarrow k_B T > m_B\, g\, R$$

$$\Rightarrow radius\ \ R \leq 1-5\ \mu m$$

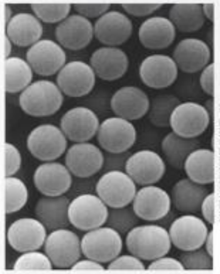
Examples:

Solid particles suspended in a liquid (paints, blood, milk …)

Liquid particles in a liquid medium (emulsions,…)

Solid particles in gas (aerosols,…)

Gas in liquid (foams,…)…. etc.. ..



Uniform silica microspheres (1 µm diam, × 10,000).

BANGS LABORATORIES (CARMEL, IN)

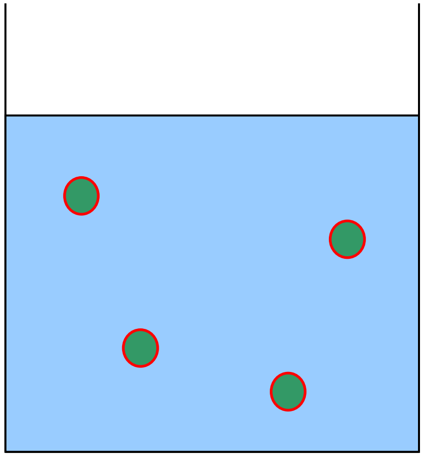
all combinations .. but one.

Colloidal Systems

States: Liquids, Crystals, Glasses, Gels

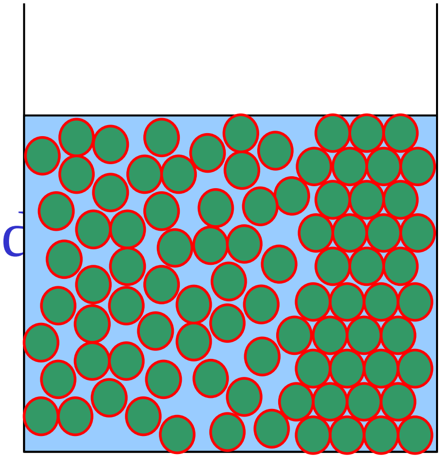
Dilute:

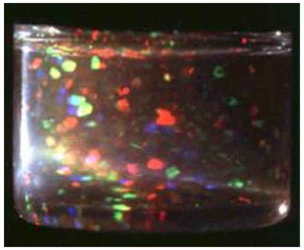
Colloidal
“gas”



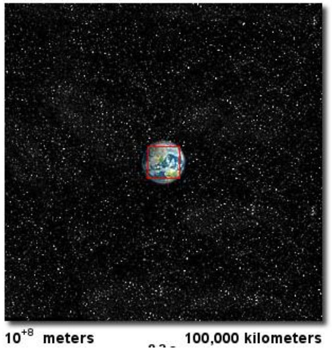
Concentrated:

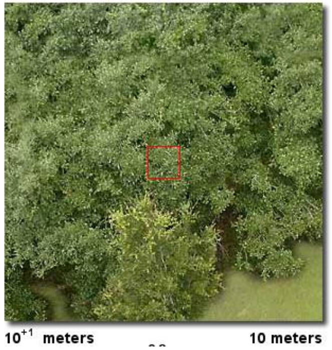
Colloidal liquid
or solid



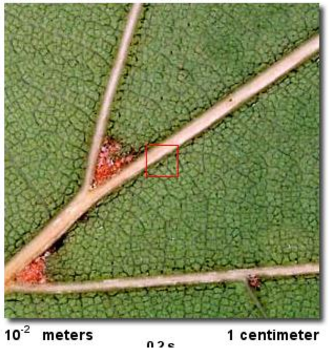


The middle world: Mesoscopic phenomena


The Earth from 100,000 Kilometers.


Top of large Oak tree.


Oak tree branch with leaves.

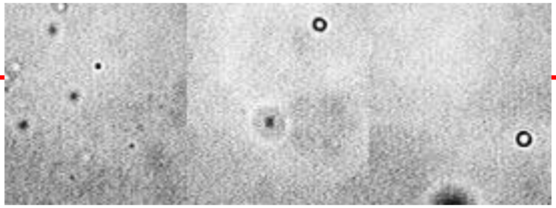

Surface of an Oak leaf magnified 10 times.

Macro - world

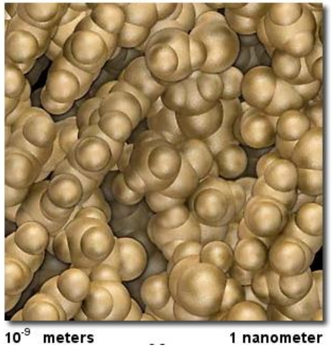
Brownian Motion : “The restless heart of matter and life”
M.D. Haw

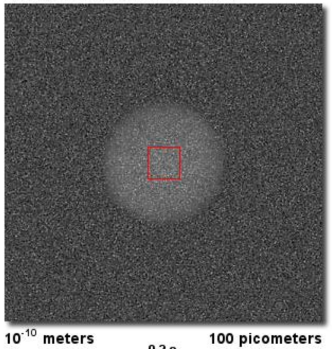
Middle – world

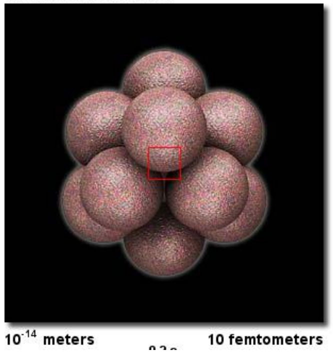
10 nm – 10 μm



atomic world


DNA nucleotide building blocks.


Outer electron cloud of a carbon atom.


Nucleus of the carbon atom.

Colloidal Suspensions as model mesoscopic systems

“Colloids as large atoms” (P. N. Pusey)

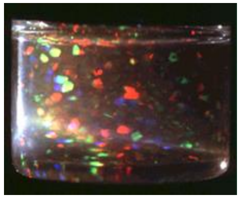
- Collection of interacting particles – can tune interactions
- Can reach thermodynamic equilibrium – colloidal gases, liquids and solids
- Can be trapped in metastable, non-ergodic states– glasses, gels

•Can study phenomena of generic interest:

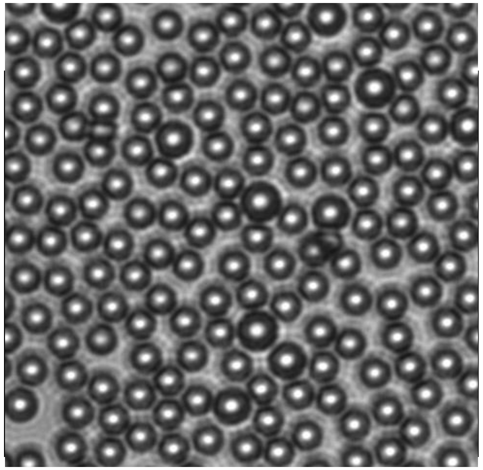
crystallization, glass formation and melting, ageing etc.

Colloidal solids are weak and “slow”

Model Systems: Hard-sphere colloids



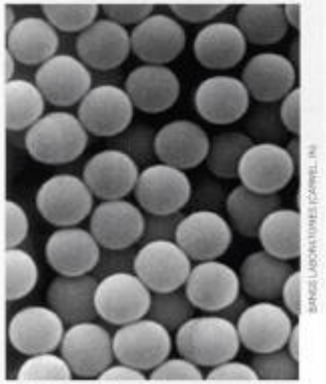
Sterically-stabilised poly-methylmethacrylate (PMMA) colloidal “hard spheres”



- Suspend in mixture of organic liquids – nearly transparent samples even at high concentrations
- No attraction, nearly hard-sphere repulsion
- Radius $R \approx 0.2\ to\ 1\ \mu m$

“Plastic Brownian billiard balls”

Other “hard” spheres: Silica particles (small steric layer, PS particles (charged stabilized + salt to screen interactions)



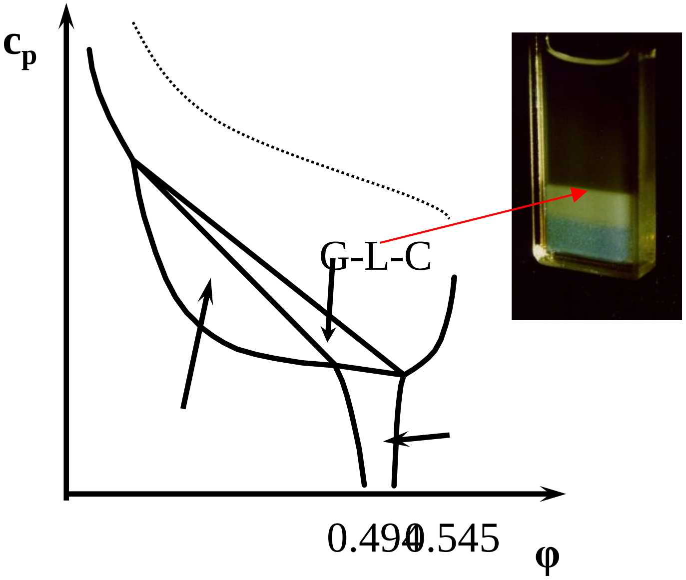
Uniform silica microspheres (1 μm diam. × 10,000).

Colloids as “Large Atoms”

Phase behavior

Dynamics of Crystallization

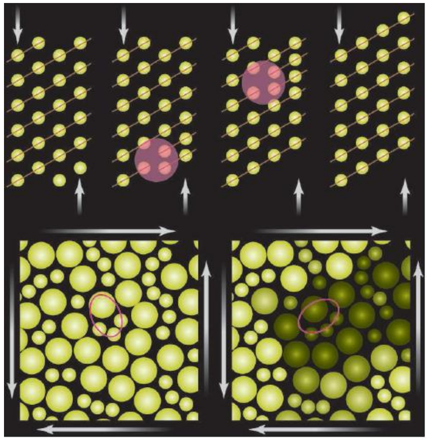
Non-ergodic states (glasses, gels)



Flow of glassy and crystalline molecular systems

Metallic glasses

SCIENCE VOL 318 21 DECEMBER 2007



The role of defects. (Top) In crystals, flow is determined by dislocations,

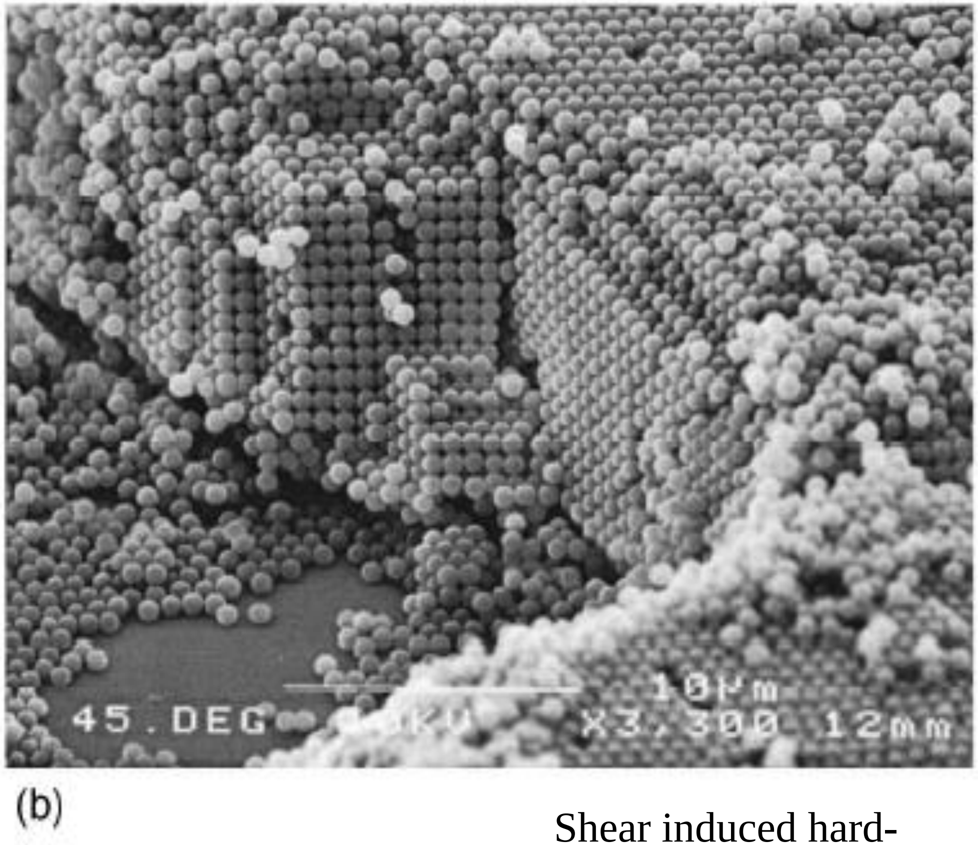
Applications - Why are colloids interesting ?

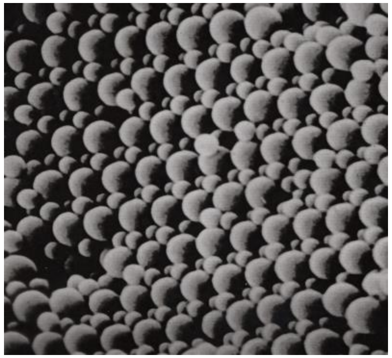
- **“Colloid engineering”**

New materials, e.g. photonic or phononic crystals from colloidal precursors

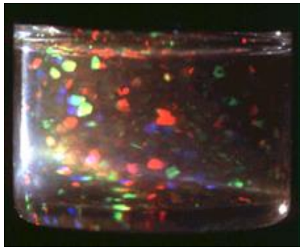
high precision filters, controlled porosity substrates from colloidal precursors.

Scanning electron microscope pictures of dried sample





Binary Colloidal Crystal
AB_2 $R_B/R_A = 0.58$

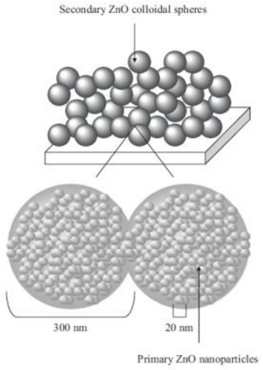


Shear induced hard-Sphere FCC Crystal

R.M. Amos et al., PRE **61**, 2929 (2000)

More applications of colloidal systems

- **Nanocomposites (colloids in polymeric matrices) photovoltaics and other applications**



Chu et al. Adv. Materials, 2007

- **Magnetic particles in 2D,**

Magneto-rheological fluids

- **Optofluidics (flow induced structures for optical applications)**

NATURE|Vol 442|27 July 2006|doi:10.1038/nature05060

Developing optofluidic technology through the fusion of microfluidics and optics

Demetri Psaltis[1], Stephen R. Quake[2] & Changhuei Yang[1]

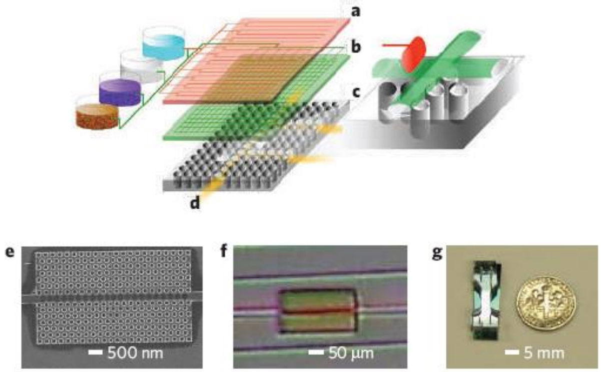
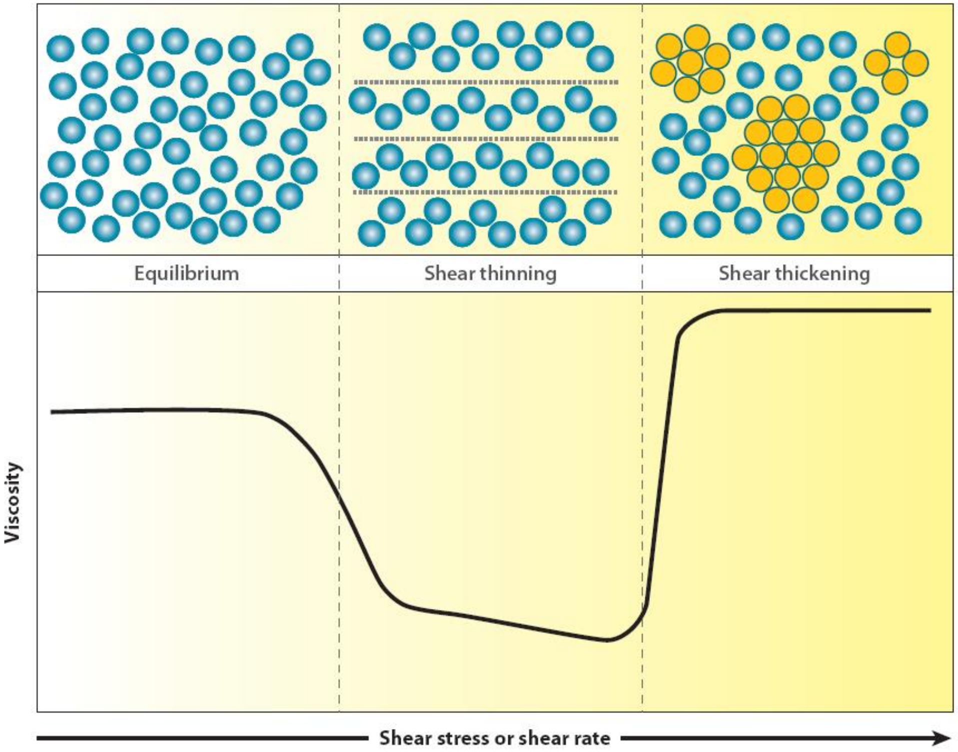


Figure 1 | A generalized layer construction of an optofluidic device. An

Applications: Rich Flow properties (colloids, grains, emulsions, etc)



Wagner and Brady

Applications

of shear thickening

Liquid Armor

Wagner, (Delaware)

Non-Newtonian fluids: thixotropy - rheopexy

http://www.youtube.com/watch?v=f2XQ97XHjVw

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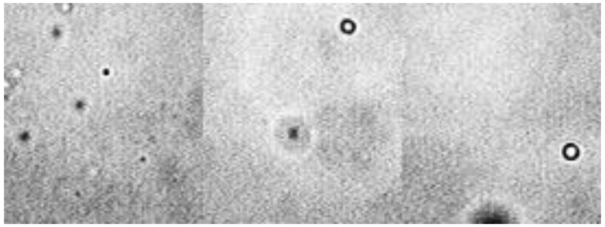
- Mechanical properties (Rheology)

Main phenomena – Brownian motion



Mean square displacement of a particle of radius R

$< \Delta r(t)^2 >= 6Dt$ Einstein-Smoluchowksi (1905), *for* $t > t_B = \dfrac{m}{6\pi\eta R}$

$D_0 = \dfrac{k_B T}{6\pi\eta R}$ Stokes-Einstein-Sutherland diffusion coefficient

for colloids time to diffuse their own radius : $t \approx 1ms ... 1s$

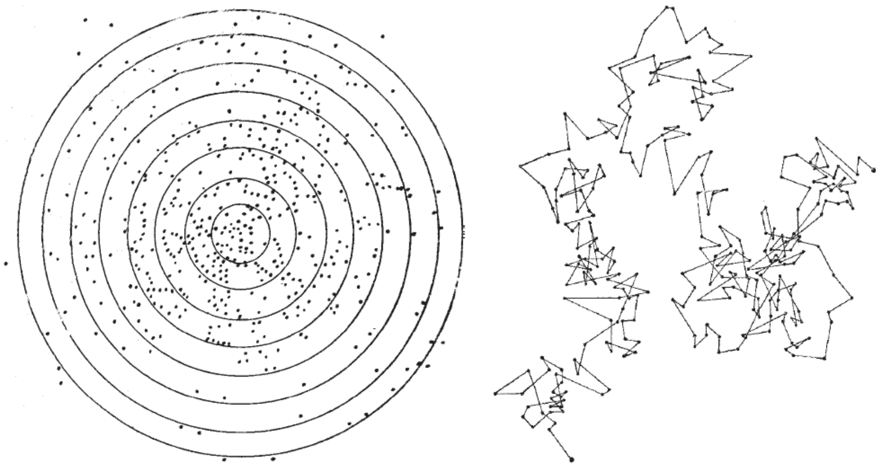


Figure 1.2. Jean Perrin's data, showing the location of colloidal particles released from the center at time zero and measured at time *t*. The right figure shows a typical trajectory of a 0.53 μm particle.

Mewis and Wagner, Colloidal suspension rheology, Cambridge, 2012

Large particles => Slow diffusion

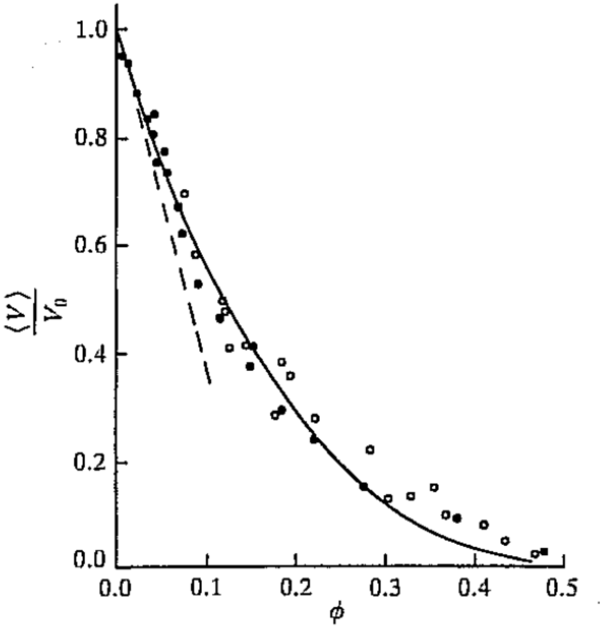
J. Perrin (Nobel prize, 1926)

Used Brownian motion to calculate

Avogadro number, N_A (=R/k_B) =>

proved existence of molecules

Main phenomena – Sedimentation



Sedimentation velocity

$$V_0 = \frac{2}{9} g R^2 \frac{\Delta\rho}{\eta}, \text{ isolated sphere}$$

For dilute concentrations < ~10% =>

Hydrodynamic interactions (two body) => slower sedimentation

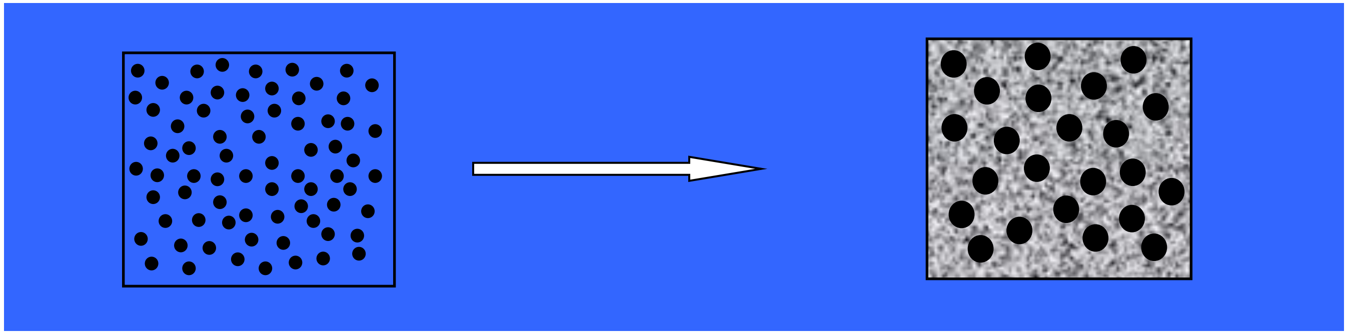
$$\langle V \rangle = V_0(1 - 6.55\phi), \quad \text{Batchelor (1972)}$$

Large particles => Fast sedimentation

Deviations from Batchelor's prediction at higher φ =>

Multi-particle HI increase velocity

Colloidal systems – Time and length scales



Atomic ***X1000*** ***Colloidal***

Time scales

$$<\Delta r(t)^2>=6Dt$$

Slow

$$D=\frac{k_B T}{6\pi\eta R}$$

$$t\approx 1ms\ldots 1s$$

Stokes-Einstein-Sutherland diffusion

$$(Atomic: t\approx 10^{-12}-10^{-10}s)$$

Mechanical response

$$\mathrm{G}\propto\frac{\mathrm{k_B T}}{\mathrm{R}^3}$$

Soft

$$G\approx 1-1000\,Nm^{-2}$$

$$(Metals: G\approx 10^9-10^{12}\,Nm^{-2})$$

Length scale

d ≈ λ
(wavelength of light)

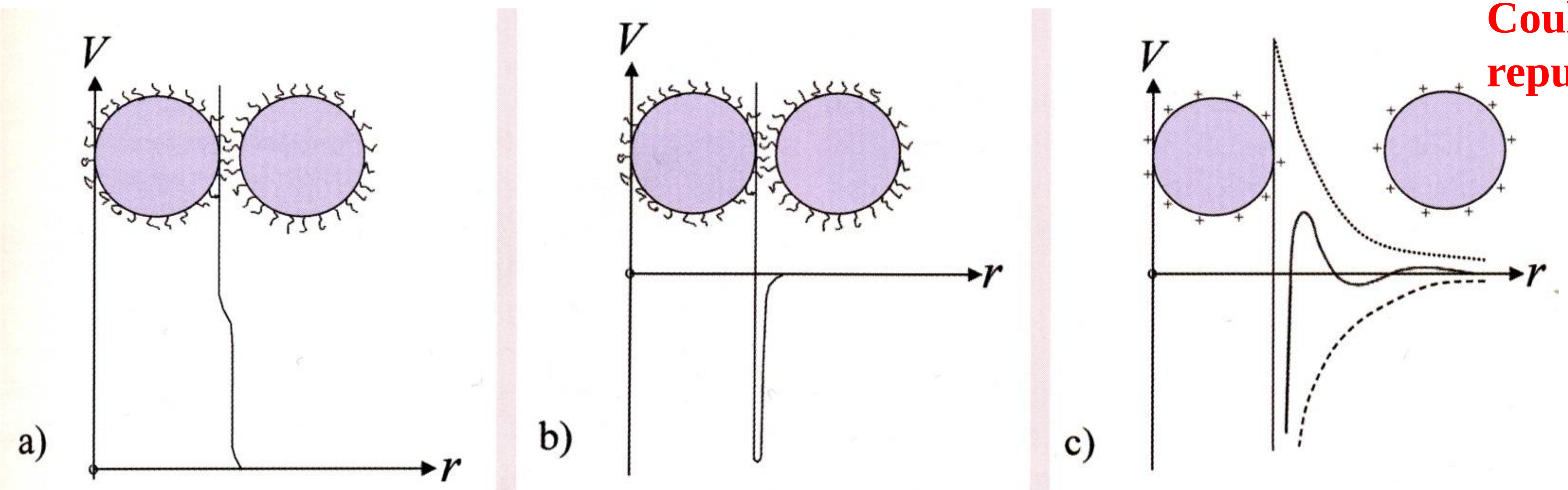
Large Enough =>

good for microscopy

and light scattering

Forces - Interactions

Coulomb repulsions



Van der Waals attractions

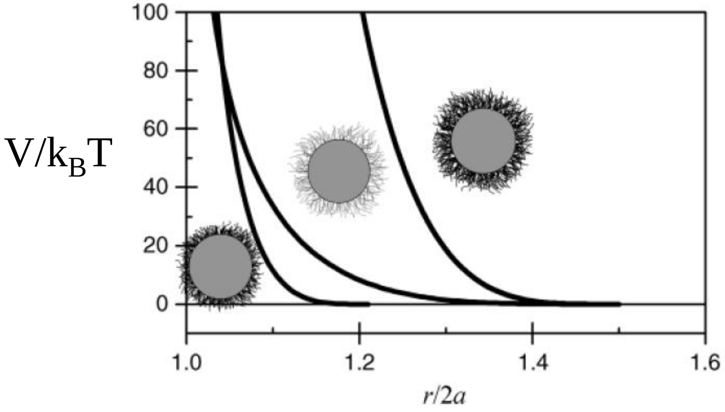
nearly hard spheres

Attractive (sticky spheres)

In bad solvent

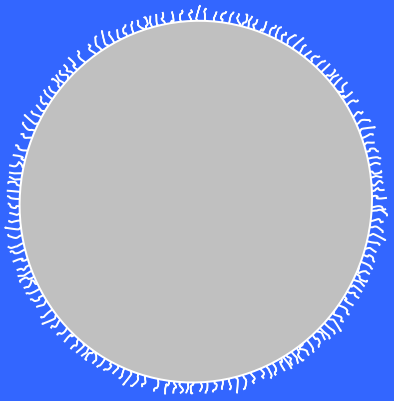
Charged colloids

(DLVO potential)



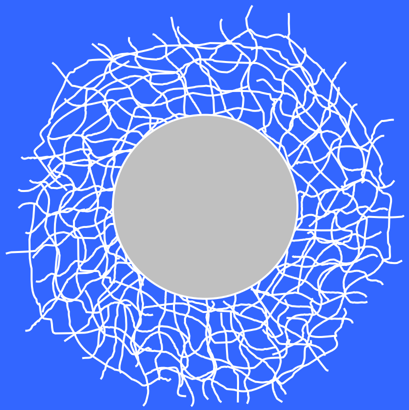
Sterically stabilized

Repulsive colloids: From hard to soft interactions



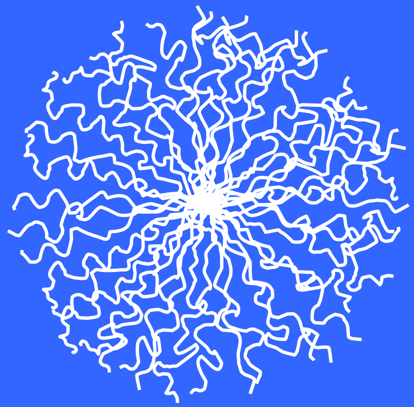
Hard spheres

(PMMA, silica particles etc.)

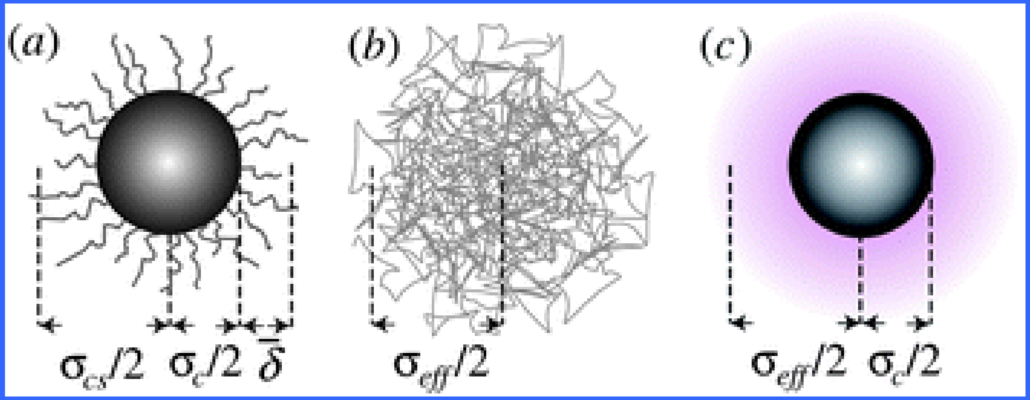


Core-shell microgels:

(example PS-PNIMAM)



Ultra soft multiarm
star polymers or
Star-like micelles



Polymer grafted particles **Crosslinked microgels** **Charged particles**

Interactions

van der Waals forces (usually attactive)

London or dispersion forces between two induced (fluctuating) dipoles

Interaction between 2 individual dipoles

$$U_{vdW}(r) = -\frac{C}{r^6}, \qquad \text{with } C = \frac{3}{4}\left(\frac{1}{4\pi\varepsilon_0}\right)^2 \alpha^2 \hbar\omega$$

Integrating for colloidal particles

Interaction per unit surface, between 2 semi-infinite solid planes at distance H:

$$U_{vdW}(H) = -\frac{A}{12\pi H^2}, \text{ with } A = \pi^2\rho^2 C, \text{ Hamaker constant (usually A>0)}$$

Interaction between 2 spheres of radius R, at surface-surface distance H:

$$U_{vdW}(H) = -\frac{AR}{12H}\left[1 + \frac{3H}{4R} + 2\frac{H}{R}\ln\left(\frac{H}{R}\right)\right], \quad for\ H << R$$

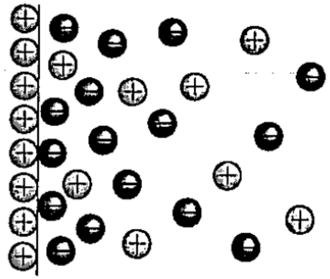
or $$U_{vdW}(r) = -\frac{16Aa^6}{9r^6}, \quad for\ r >> R$$

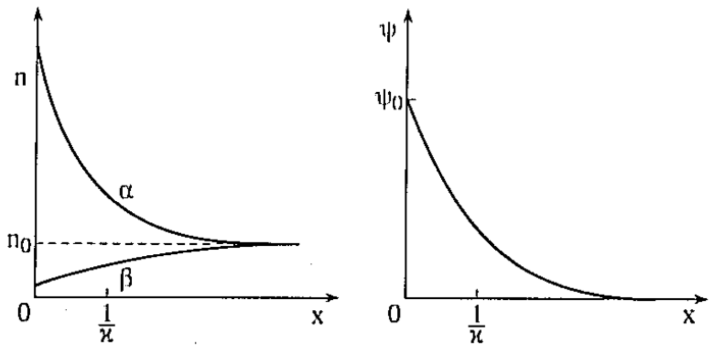
Interactions

Charged particles

Screened Coulomb repulsions in the presence of counter-ions

Diffuse double-layer model of Gouy & Chapman





Interaction potential between 2 planes

(semi-infinite solid planes):

$$U_{Cb}(H) = \frac{64 n_0 k_B T}{\kappa} \tanh^2\left(\frac{ze\psi_0}{4k_B T}\right)\exp\left(-\kappa H\right)$$

with n_0 the ion number density, z their valence,

ψ_0 the surface potential,

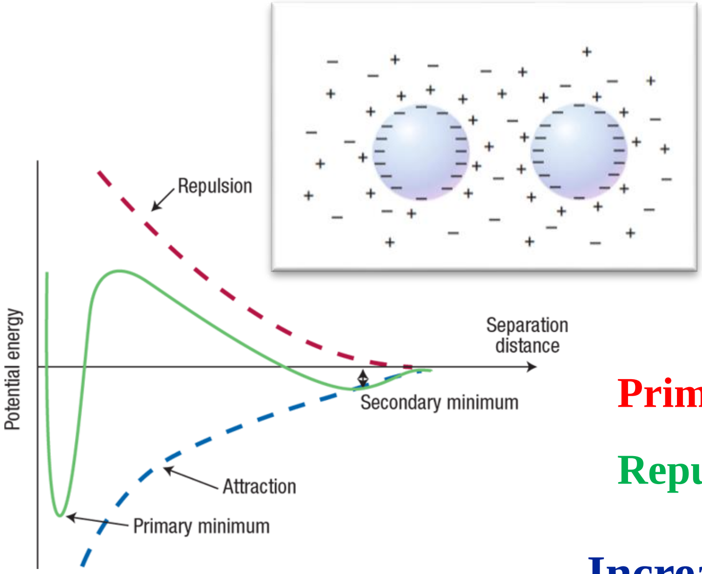
and

$\kappa^{-1} = \left(\frac{\varepsilon\varepsilon_0 k_B T}{2e^2 n_0 z^2}\right)^{1/2}$ the Debye Screening length

Interaction potential between 2 spheres: $U_{Cb}(H) = 2\pi\varepsilon R\psi_0^2 \exp\left(-\kappa H\right)$ for κR<5

Interactions

Charged particles



Charged colloids – Total interaction potential

DLVO (Derjaguin, Landau, Verwey and Overbeek)

$$U_{DLVO}(r) = U_{vdw}(r) + U_{cb}(r)$$

Characteristics:

Primary/secondary minimum=>irreversible/reversible aggregation

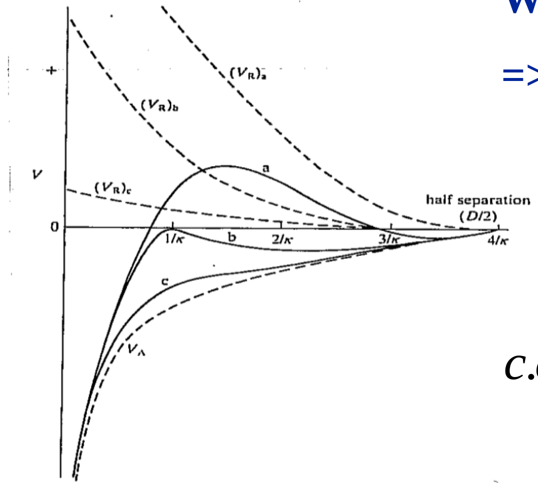
Repulsive barrier => particle stabilization

Increasing ion concentration <= e.g. addition of salt

⇓

Weakening of repulsive interactions => decrease of Debye screening length

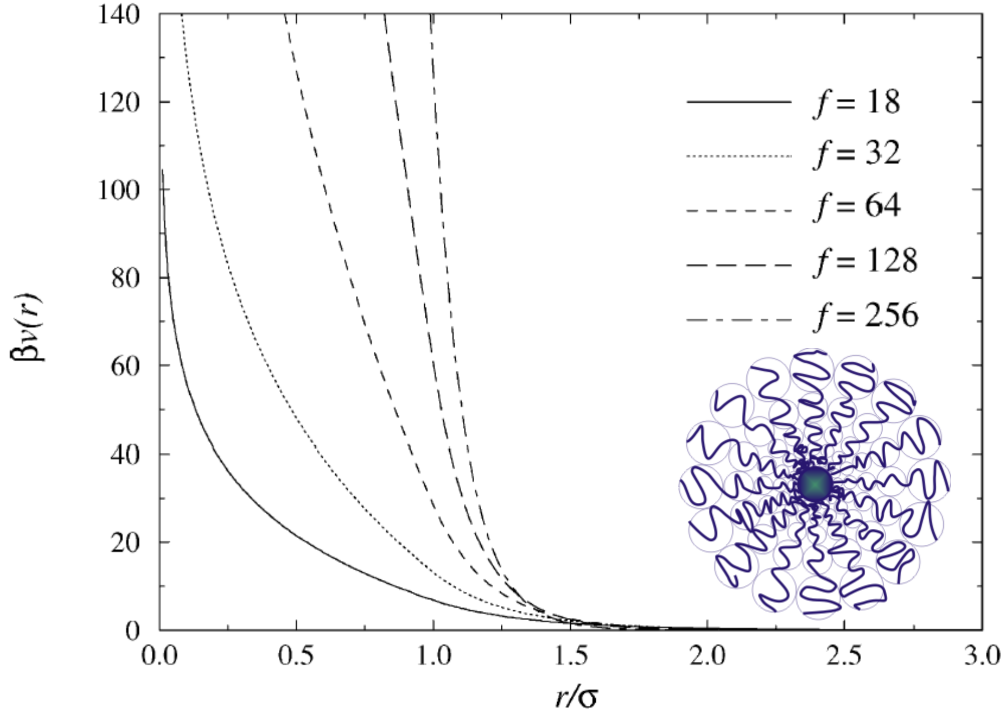
=> lowering of the repulsive barrier

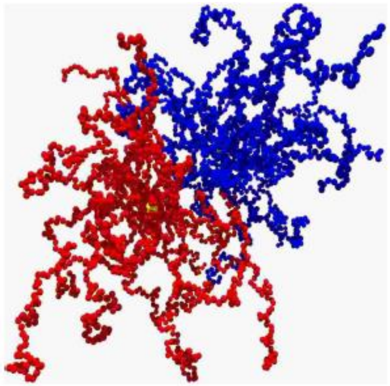


Barrier zero @ Critical coagulation concentration (ccc) :

$$c.c.c.\left[mol/lt\right] = \frac{\left(4\pi\varepsilon_0\varepsilon\right)^3 0.107\left(k_B T\right)^5}{N_A A^2 \left(ze\right)^6}\tanh^4\left(\frac{ze\psi_0}{4k_B T}\right)$$

Multiarm Star Polymers as model soft colloids





Parameters:

Functionality (number of arms) *f*

Molecular weight of arm *M*

Solvent quality

$$\frac{U(r)}{kT}=\begin{cases}(5/18)\,f^{3/2}\left[-\ln(r/\sigma)+(1+\sqrt{f}/2)^{-1}\right] \\ (5/18)\,f^{3/2}(1+\sqrt{f}/2)^{-1}(\sigma/r)\exp\left[-\sqrt{f}(r-\sigma)/2\sigma\right]\end{cases}$$

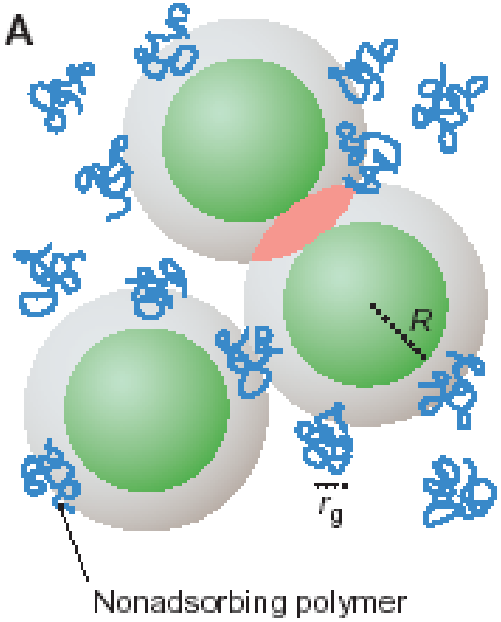
Likos, Loewen, Richter, PRL, 1998

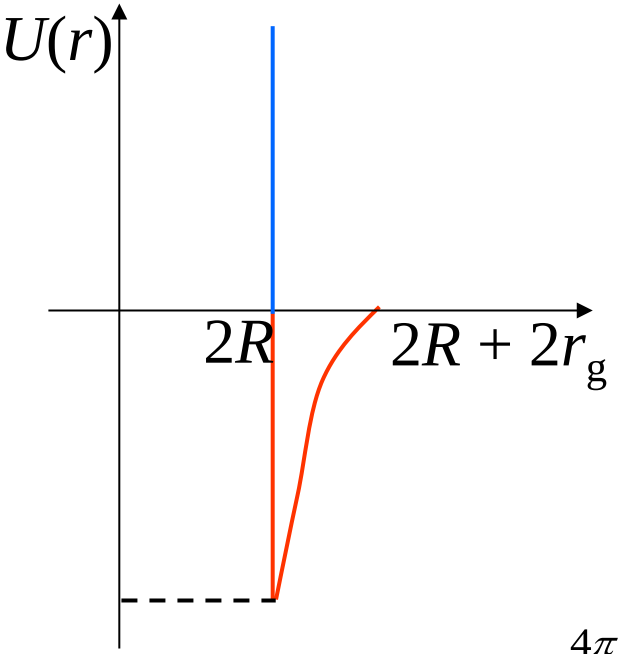
good solvent: Likos, Macromolecules, 2008

Depletion Interactions: Attractions in colloid-polymer mixtures

Induce attraction between the particles by adding non-adsorbing polymer chains

“Depletion”: - Unbalanced osmotic pressure pushes particles together
- Overlap of depletion zones gives polymer more free volume (higher entropy)





Can control
- range – size ratio r_g/R
- strength – polymer concentration

Particle radius R
Polymer radius of gyration r_g
Overlap zone $L \sim r_g$

$$V_{ov} = \frac{4\pi}{3}(R+L)^3\left(1 - \frac{3r}{4(R+L)} + \frac{r^3}{16(R+L)^3}\right)$$

$F_{dep} = -P_{osm}V_{ov}$ with $P_{osm} = \frac{N}{V}k_BT$

Asakura-Oosawa (AO) potential

Colloidal systems: Scale of main forces:

- Gravitational: $F_{gravity} \approx R^3 \Delta\rho g$
- Brownian: $F_{Brownian} \approx k_B T / R$
- Electrostatic: $F_{coulomb} \approx \varepsilon\varepsilon_0\zeta^2$
- Viscous (Stokes drag): $F_{viscous} \approx \eta R \upsilon$
- Van der Waals: $F_{VdW} \approx \mathrm{A}_{\mathrm{eff}} / R^2$
- Inertia: $F_{inertia} \approx \rho R^2 \upsilon^2$

Example:

$R = 1\ \mu\mathrm{m}\,,\quad \eta = 1\mathrm{cp} = 10^{-3}\ \mathrm{Pa\ s}$

$\rho = 10^3\ \mathrm{kg/m^3},\ \Delta\rho/\rho = 0.01$

$T = 20^o\mathrm{C}\,,\ \upsilon = 1\ \mu\mathrm{m/s}$

$\mathrm{A_{eff}} = 10^{-20}\mathrm{Joule}\,,\ \zeta = 50\ \mathrm{mV}$

$\mathrm{g} = 10\ \mathrm{m/s^2},\ \varepsilon = 100,\ \varepsilon_0 = 8.85\ 10^{-12}\mathrm{C/Vm}$

ratios of forces:

$$\frac{F_{coulomb}}{F_{Brownian}} \approx 100$$

$$\frac{F_{vdW}}{F_{Brownian}} \approx 1$$

$$\frac{F_{viscous}}{F_{Brownian}} \approx 1$$

$$\frac{F_{gravity}}{F_{viscous}} \approx 0.1$$

$$\frac{F_{inertia}}{F_{viscous}} \approx 10^{-6},\ (=\mathrm{Re})$$

Colloidal systems

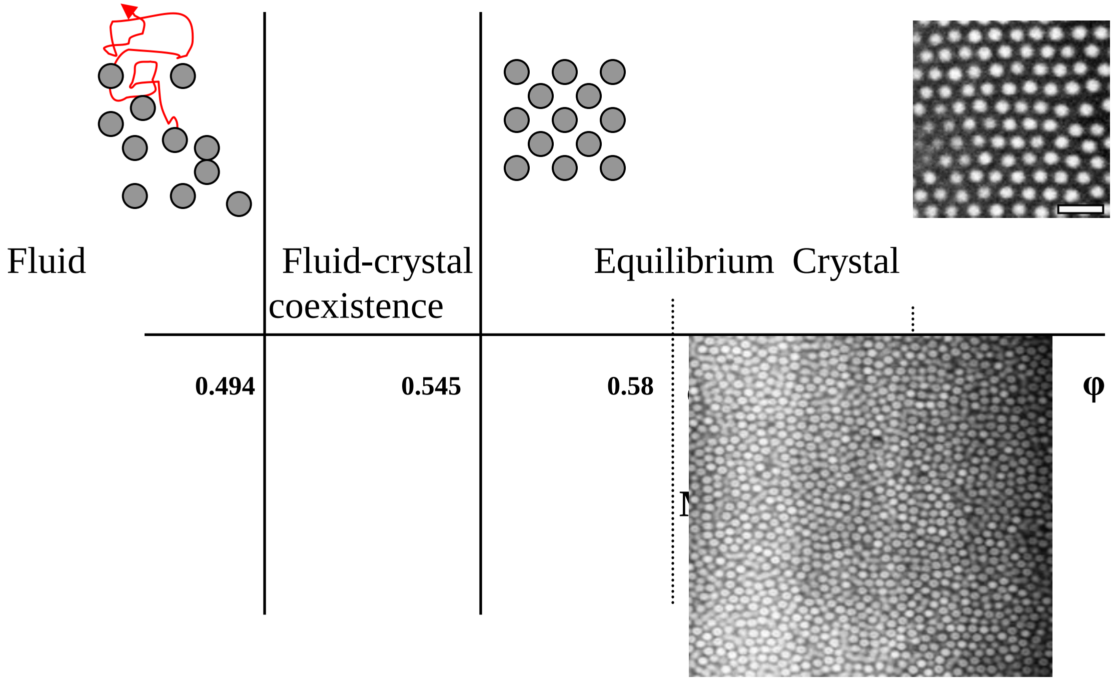
Outline:

- Definitions-Examples-Applications
- Main phenomena – Forces - Time scales
- **Phase behavior: Thermodynamic phases, Metastable states (glasses and gels)**
- Microscopic Dynamics (Scattering-Microscopy)
- Mechanical properties (Rheology)

Phase behavior – Brownian Hard Spheres

One-dimensional phase diagram

$$\phi = \frac{N}{V}\ \frac{4}{3}\pi R^3$$



Fluid

Fluid-crystal coexistence

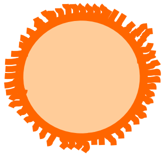
Equilibrium Crystal

0.494

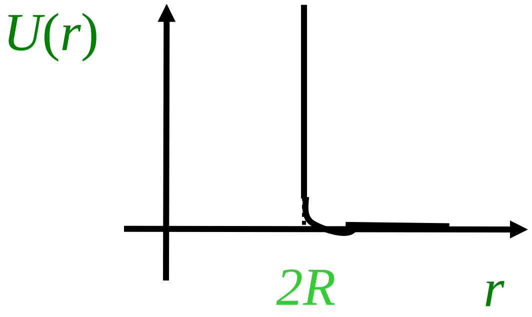
0.545

0.58

φ



PMMA spheres
Sterically stabilized
with PHSA



Entropy Driven Crystallisation

Crystal has *higher* entropy
than metastable fluid
at same concentration

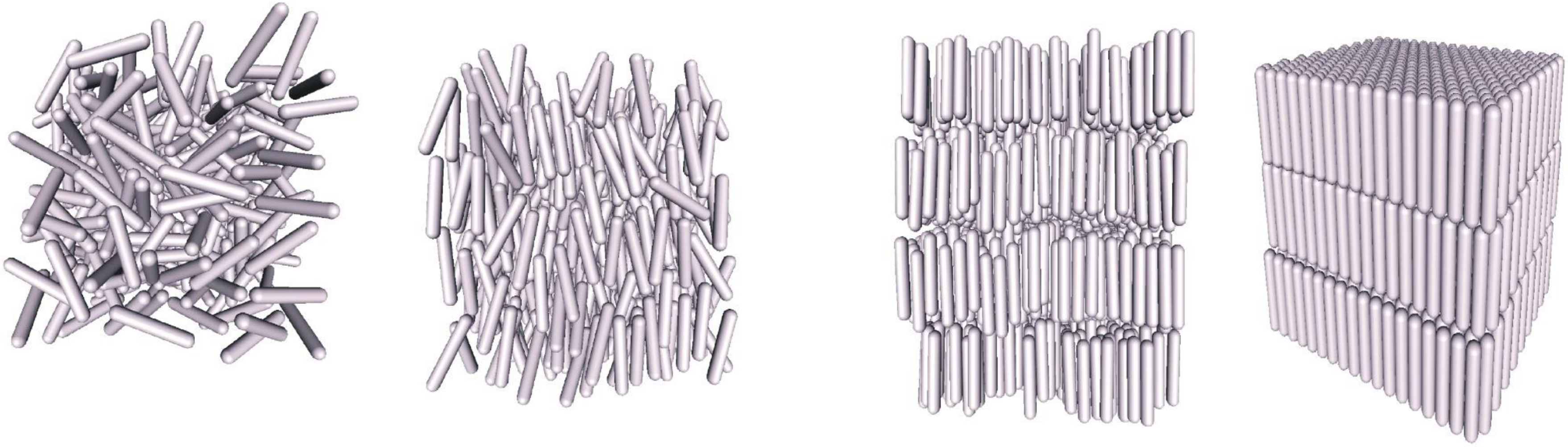
Computer simulations:
Alder & Wainwright(1957)
Wood & Jacobson (1957)
Hoover & Ree (1968)

Experiments: Pusey, van Megen, Nature, 1986

Hard-sphere colloidal crystals and glasses

Fluid	Fluid + Crystal	Crystal	Glass
$\phi < 0.494$		$\phi > 0.545$	$\phi > 0.58$

Other entropy driven transitions: Liquid crystals



Isotropic liquid

Nematic-liquid crystals

Smectic-Liquid Crystals

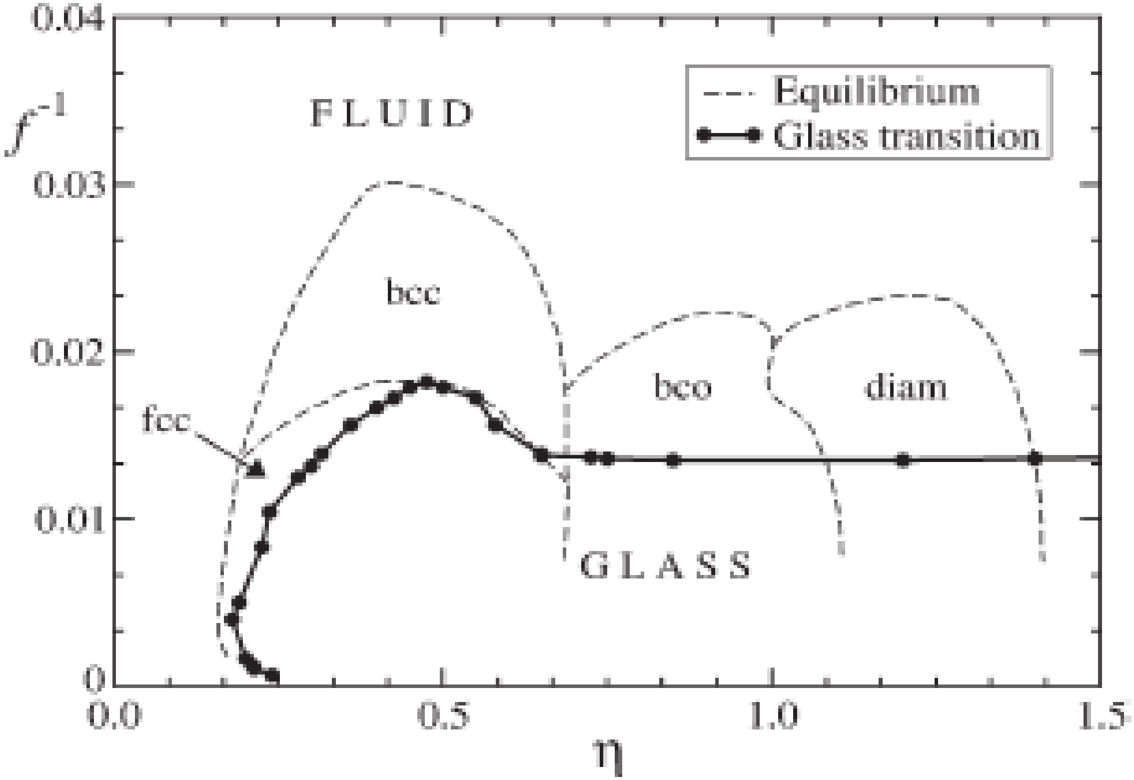
Crystal

Decreasing temperature (thermotropic)

or increasing concentration (Lyotropic)

Entropy driven ordering: Isotropic-nematic transition in Hard rods

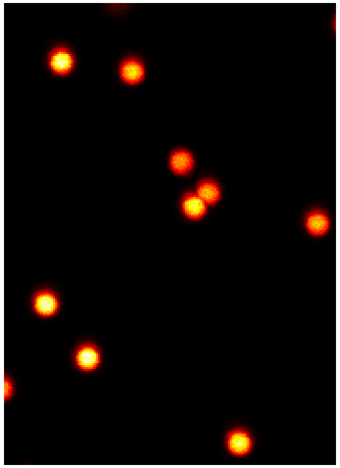
Phase behavior – Soft Multiarm Star colloids

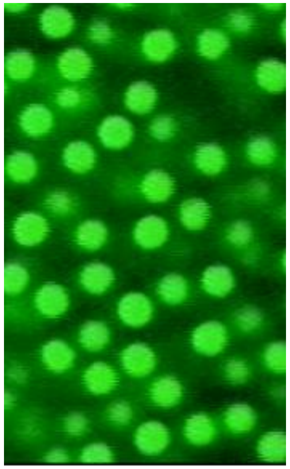


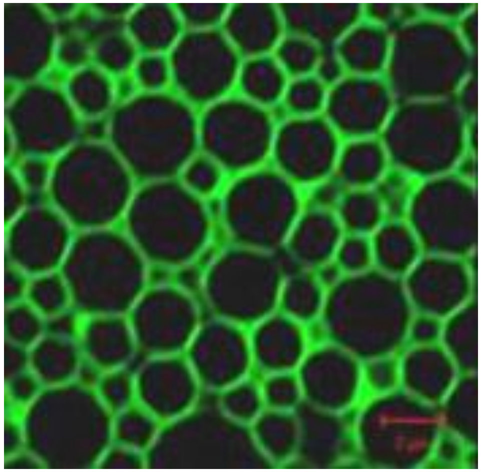
Watzlawek, PRL(1999), Foffi, PRL (2003)

Theoretical phase diagram: Liquid, crystal phases, glasses

Phase behavior of repulsive colloids







Suspension

Crystal

Glass

<u>Jammed</u>

Φ_F

$\Phi_G \approx 0.58$

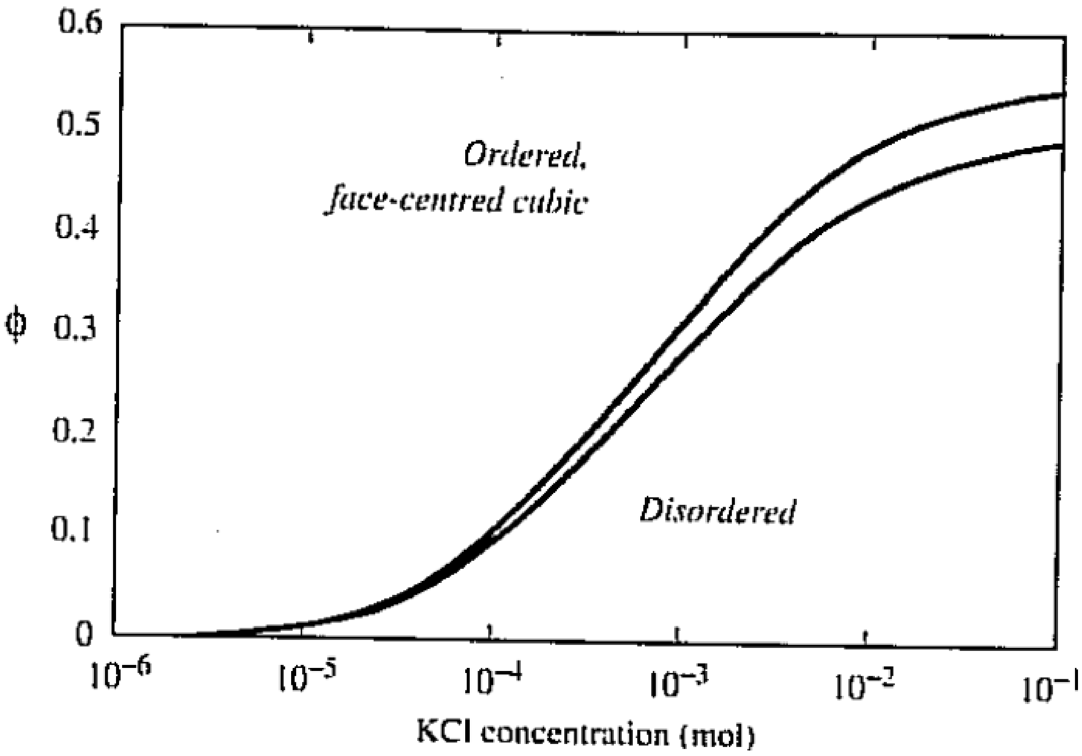
$\Phi_C \approx 0.64$

Thermally
activated
dynamics

<u>Contact forces</u>

Cloitre, 2000

Phase behavior – Charged colloids



Russel et al. (1989)

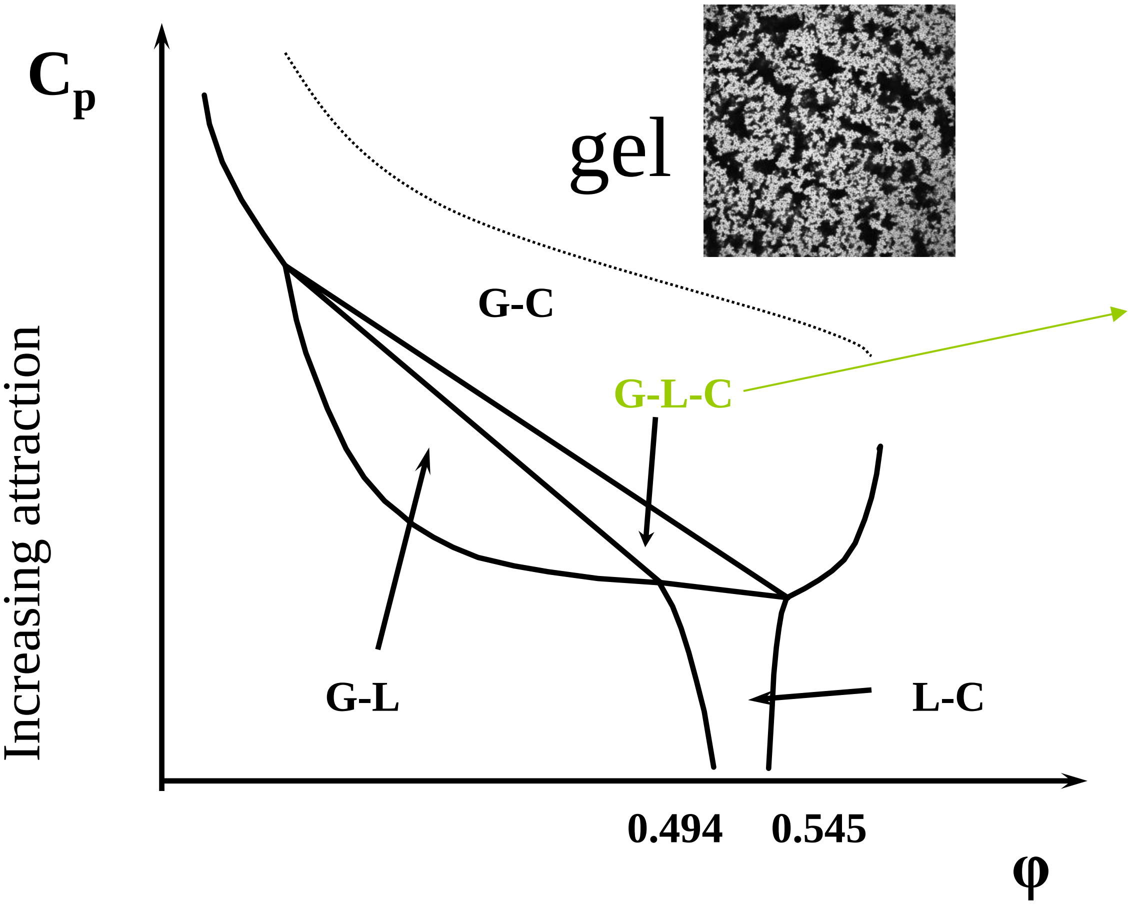
Long range repulsions =>

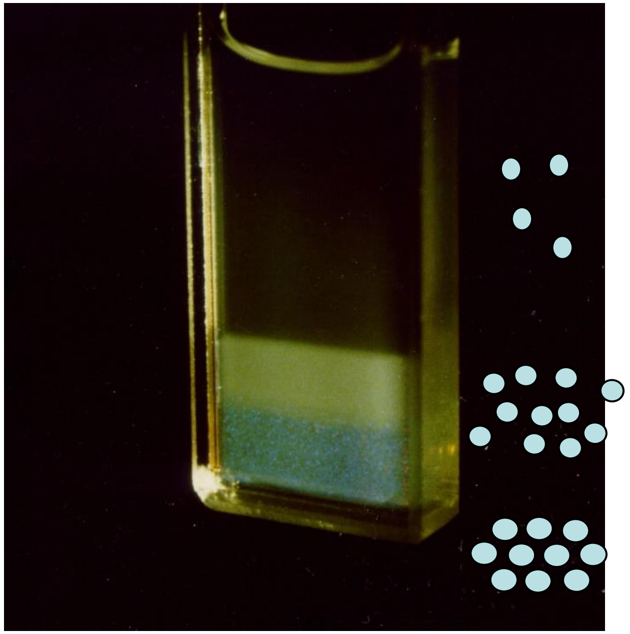
Liquid-crystal transition, coexistence and glassy states @ much lower φ than HSs

Phase diagram:
Depletion attractions

Schematic experimental phase diagram (colloid-polymer mixtures)

For size ratio, ξ>0.25 => triple coexistence

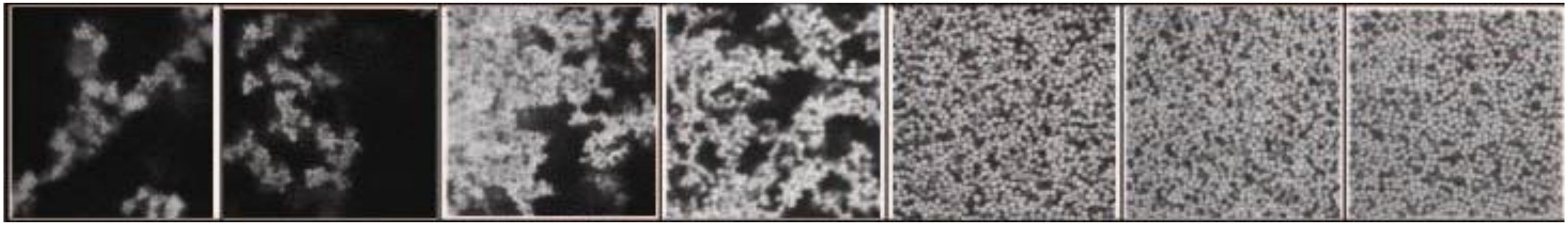




Metastable states: Colloidal gels

Increasing volume fraction

Free clusters Interconnected networks compact clusters -> attractive glass



Low volume fractions ($\varphi<0.2$) percolating network

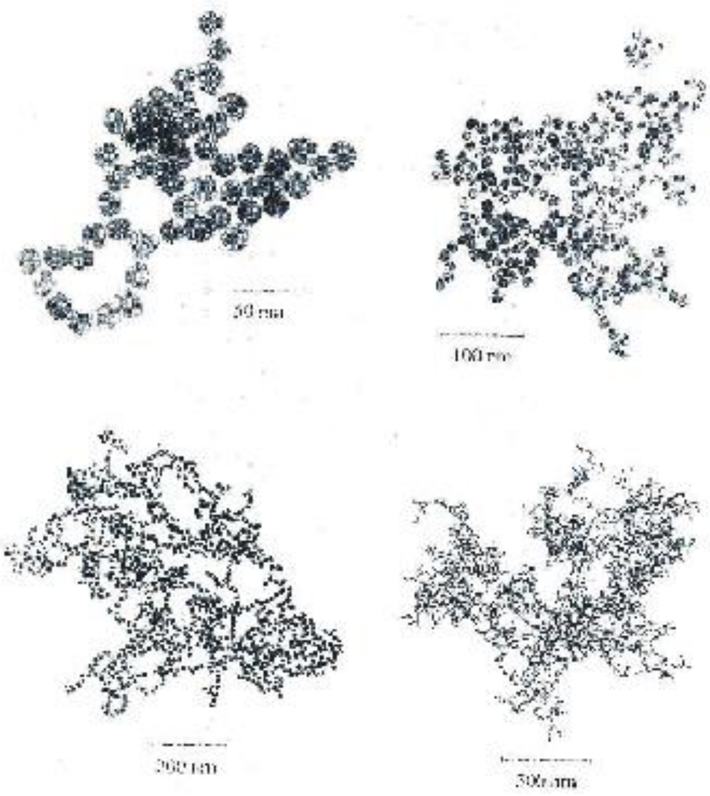
Intermediate volume fractions (0.2-0.5):

Interplay with phase separation:
- Arrested phase separation
- or equilibrium gels

High volume fractions ($\varphi>0.58$) => attractive glasses

Low volume fractions: Fractal microstructure (flocs)

Aggregate structures in 3D and 2D



$$n \propto R^{d_f}$$

n=number of particles within distance R from center of floc
d_f = fractal dimension

High attraction strength=>

Diffusion Limited aggregation

(DLCA): d_f = 1.7-1.8

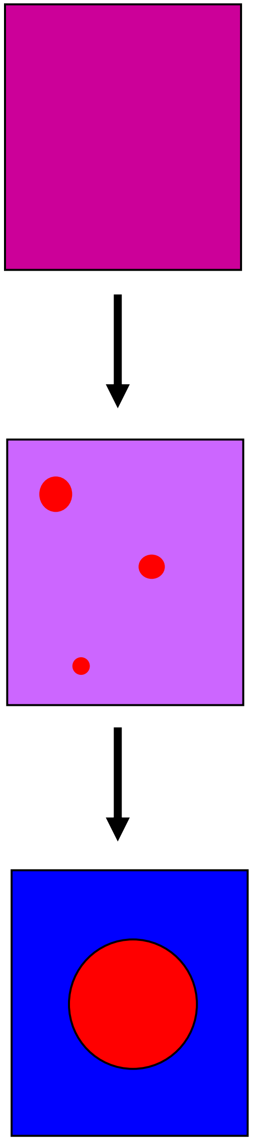
Low attraction strength=>
Reaction Limited aggregation

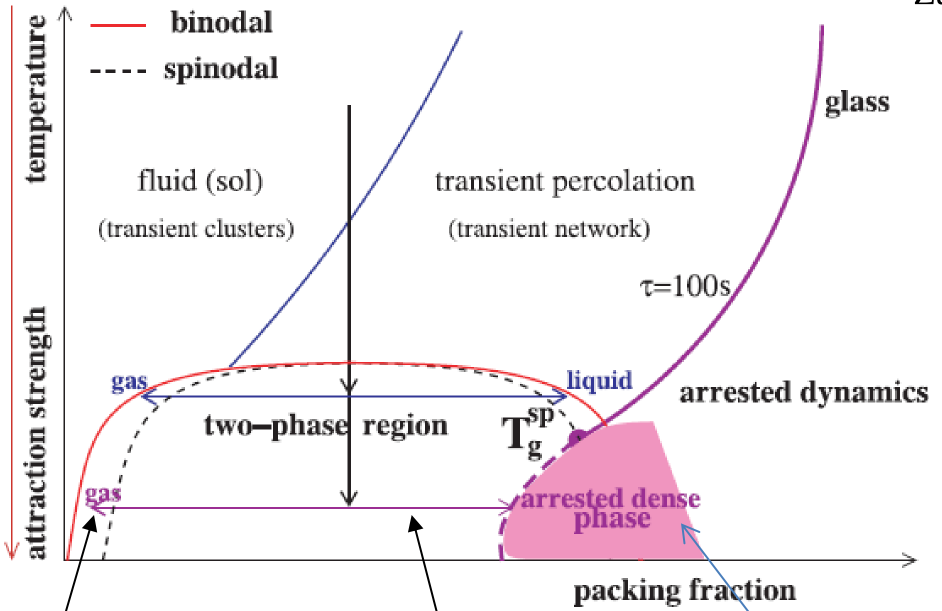
(RLCA): d_f = 2.0-2.1

Weitz and Huang, PRL 1984

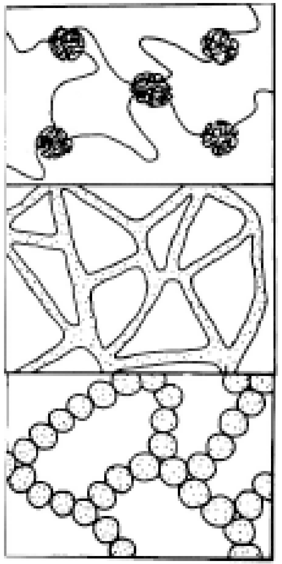
Phase transition – gelation kinetics

Zaccarelli , JPCM, 2007





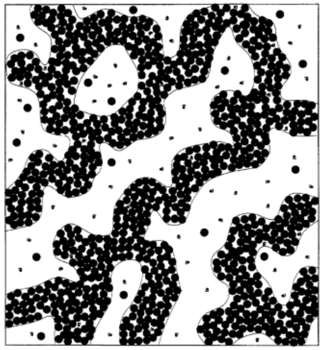
Schematic for long(er) range attractions



Metastable: **Nucleation & growth**

Unstable: **Spinodal decomposition**

Gels through Arrested phase separation



Verhaegh et al. *Physica A*

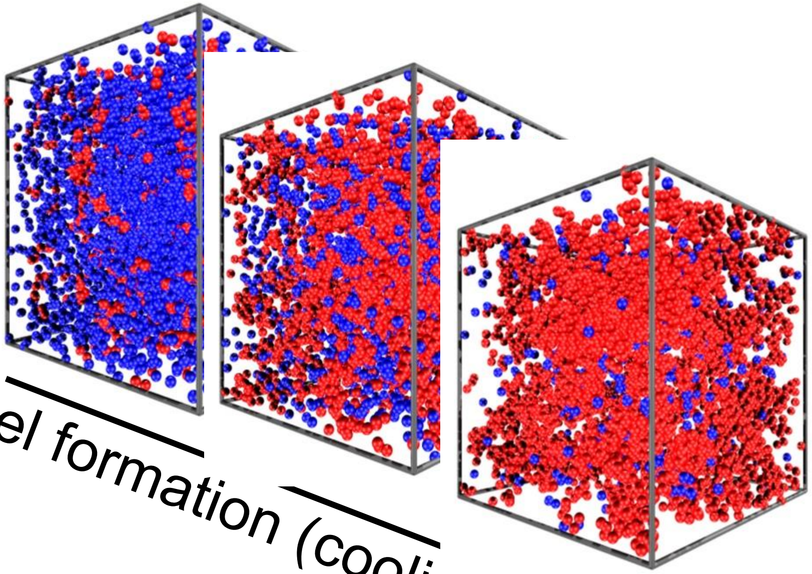
Evolution of structure during gelation

(Wagner+Mewis)

adhesive hard-spheres (AHS)
(one component)

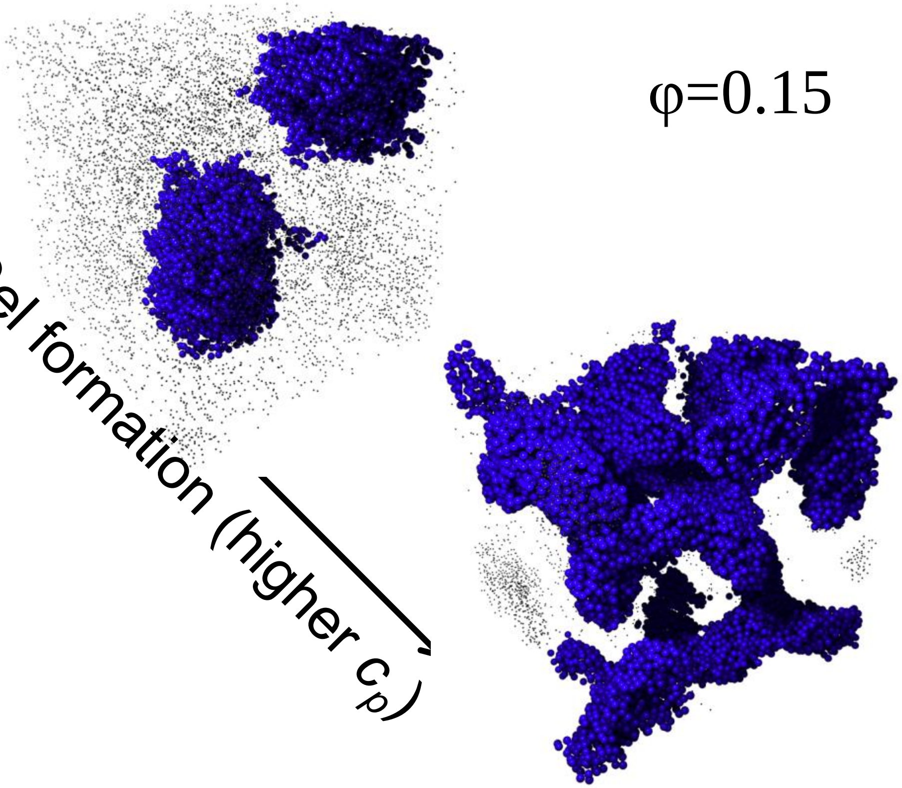
Colloid-polymer mixture
(two components)

φ=0.09



Gel formation (cooling)

Snapshots courtesy of Castañeda-Priego



φ=0.15

Gel formation (higher c_p)

Figures from Liu et al., PRL 96 (2006)

Macroscopically percolated homogenous structure

Heterogeneous structure that is arrested due to attraction

Metastable states: Colloidal gels

Ageing => coarsening of colloidal gel with waiting time

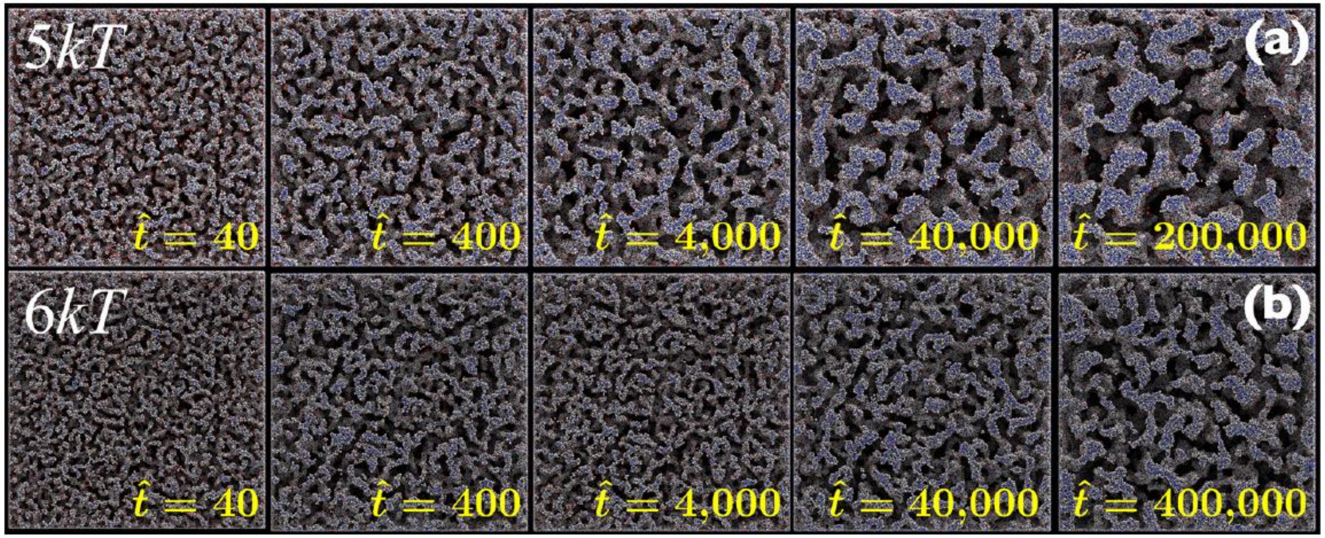


FIG. 5. Evolution of particle microstructure over time for (a) top row, 5 kT gel and (b) bottom row, 6 kT gel. The gel in each snapshot is older than the previous image as indicated.

Brownian Dynamics simulations, φ=0.2,

Zia et al, J. Rheol. 2014

Colloidal systems

Outline:

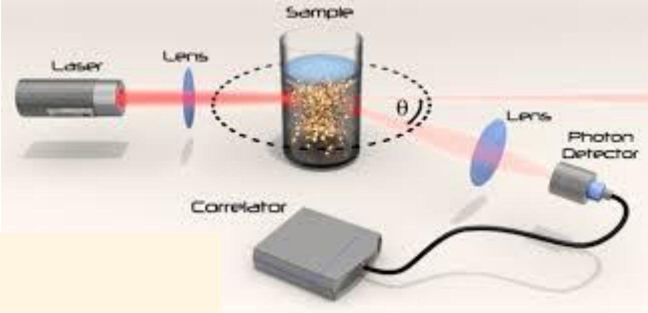
- Definitions-Examples-Applications
- Main phenomena – Forces - Time scales
- Phase behavior: Thermodynamic phases, Metastable states (glasses and gels)
- **Microscopic Dynamics (Scattering-Microscopy)**
- Mechanical properties (Rheology)

Microscopic Structure and Dynamics

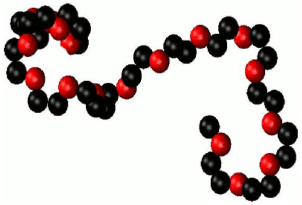
Light scattering (reciprocal space)

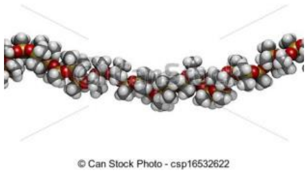
Probe fluctuations at scattering wave vector q.

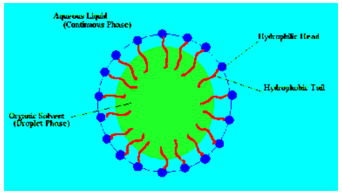
$$q = 4\pi n/\lambda \sin(\theta/2)$$

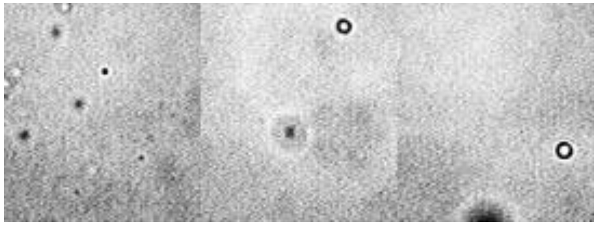


Measure structure and particle dynamics of polymers, colloids, emulsions




© Can Stock Photo - csp16532622

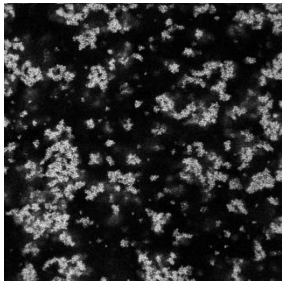


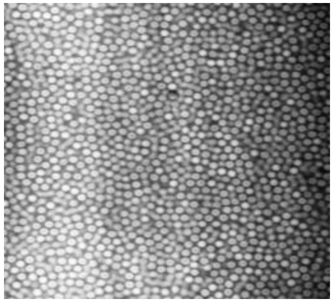


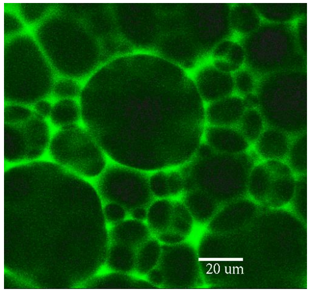
Optical Microscopy (direct space)

Measure structure and particle dynamics

State of the art: Fast fluorescence confocal microscopy follow dynamics also under shear

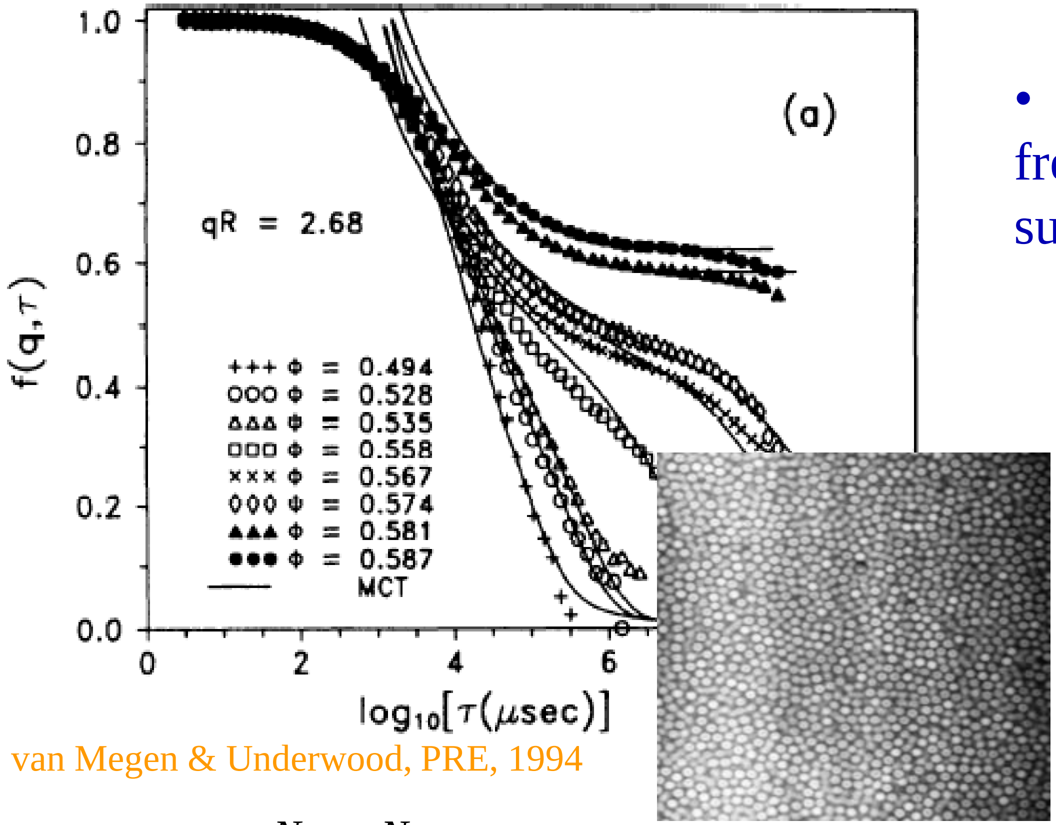






Dynamics: colloidal Suspensions

DLS for HS’s at 0.49<φ<0.59

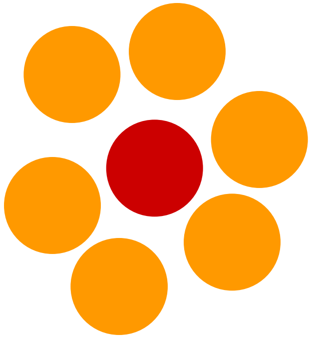


van Megen & Underwood, PRE, 1994

$$f(q,t) = \frac{1}{N}\sum_{j=1}^{N}\sum_{i=1}^{N} < \exp(i\bar{q}\cdot(\bar{r}_i(0)-\bar{r}_j(t))) >$$

$q = 4\pi n/\lambda \sin(\theta/2)$

- As ϕ increases the particles are caged more and more
- At $\phi \sim 0.58$, fluctuations partly freeze and crystallization is suppressed



Mode Coupling Theory (MCT)
predicts a transition to a dynamically arrested non-ergodic state (repulsive glass)
Götze 1980

Mean Square displacement

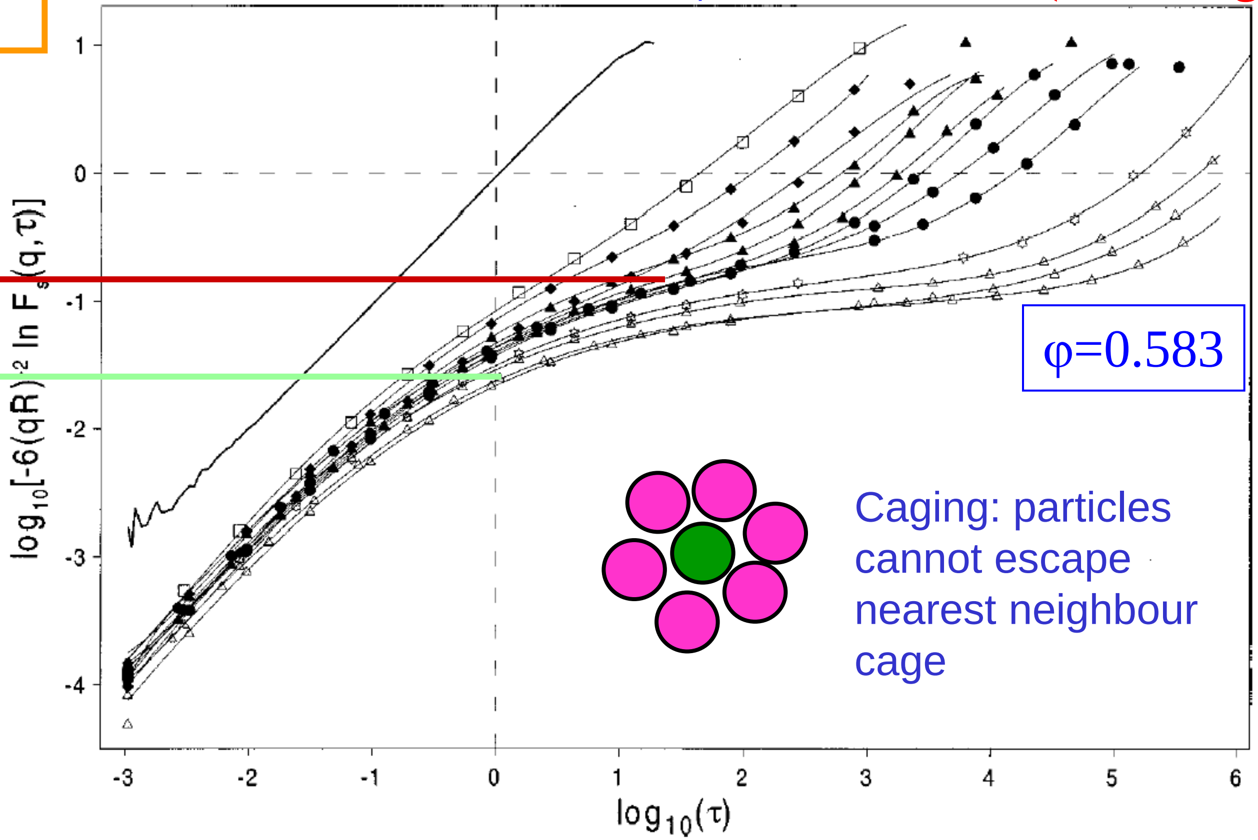
$$\left\langle \Delta r^2(t) \right\rangle / R^2$$

Long time dynamics (out of cage)

$\phi = 0.466$

$$\sqrt{\left\langle \Delta r^2(t) \right\rangle} \cong 0.28R$$

$$\sqrt{\left\langle \Delta r^2(t) \right\rangle} \cong 0.16R$$



φ=0.583

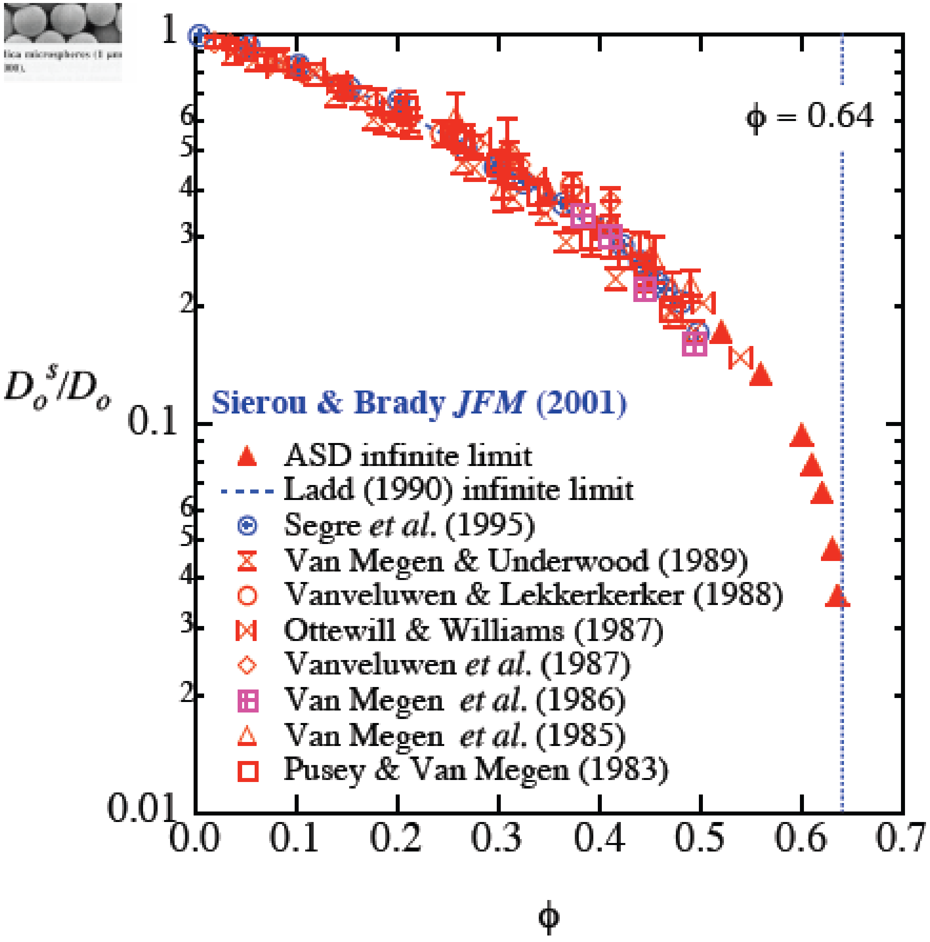
Caging: particles cannot escape nearest neighbour cage

Short time dynamics (in-cage)

(Van Megen, PRE, 1999)

Hard Spheres: Short-time self diffusion

Volume fraction dependence



Batchelor's prediction

Hydrodynamic effect at low φ,

(pair wise contributions)

$$\text{Dilute limit: } \phi \rightarrow 0$$

$$D_0^s(\phi) \sim D_0(1-1.83\phi)$$

$$\text{Close packing:}$$

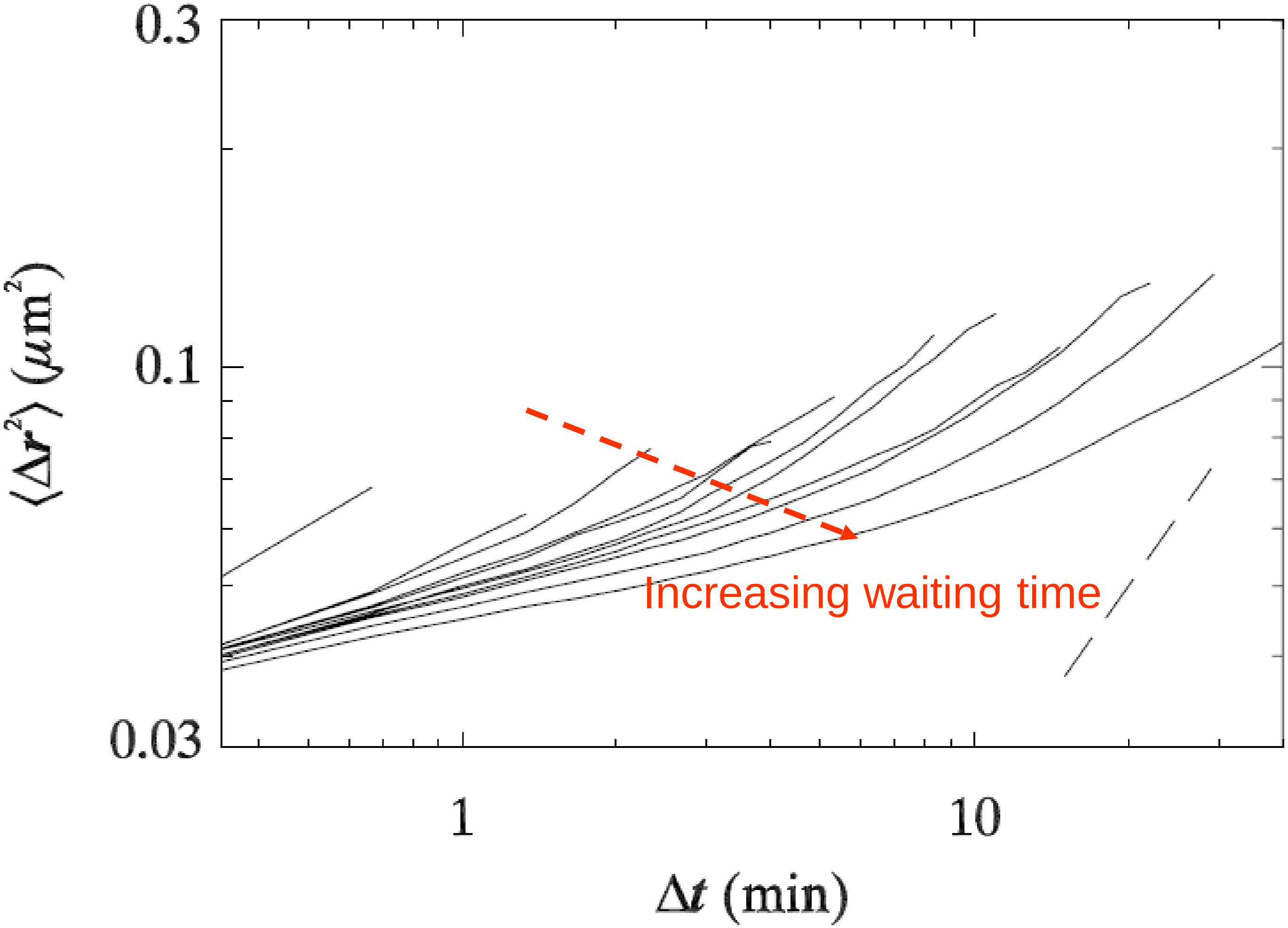
$$\varepsilon = 1-\phi/\phi_{rcp} \rightarrow 0$$

$$D_0^s(\phi) \sim D_0/\ln(1/\varepsilon)$$

In-cage diffusion decrease towards zero @ rcp (φ=0.64)

Ageing of the hard-sphere glass

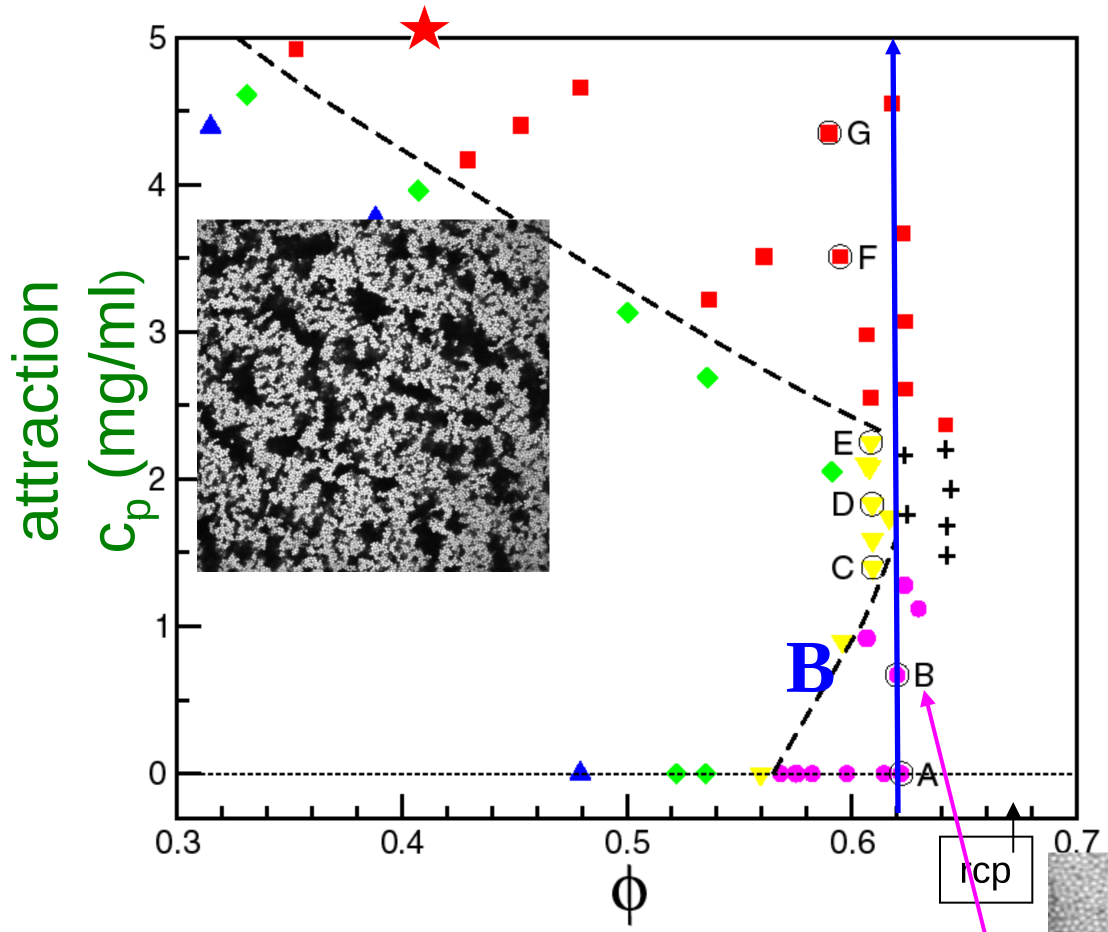
Long-time (out of cage) dynamics slow down with waiting time near the glass transition

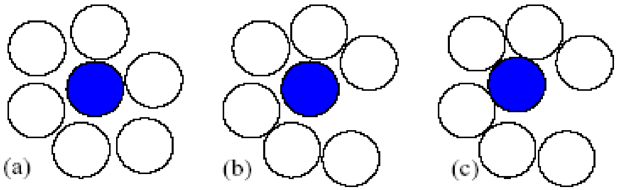


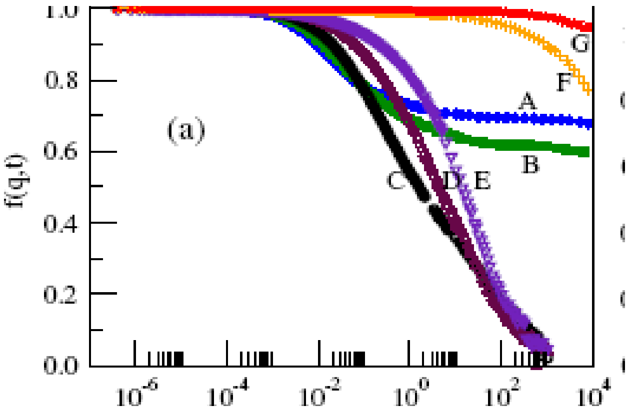
Courtland & Weeks, *JPCM* **15** S359, confocal particle tracking

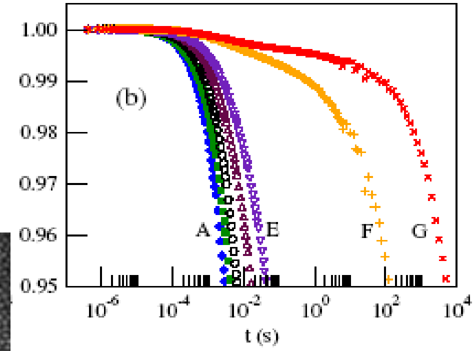
Re-entrant glass transition: repulsive to attractive glass

Attractive glass

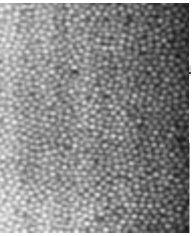








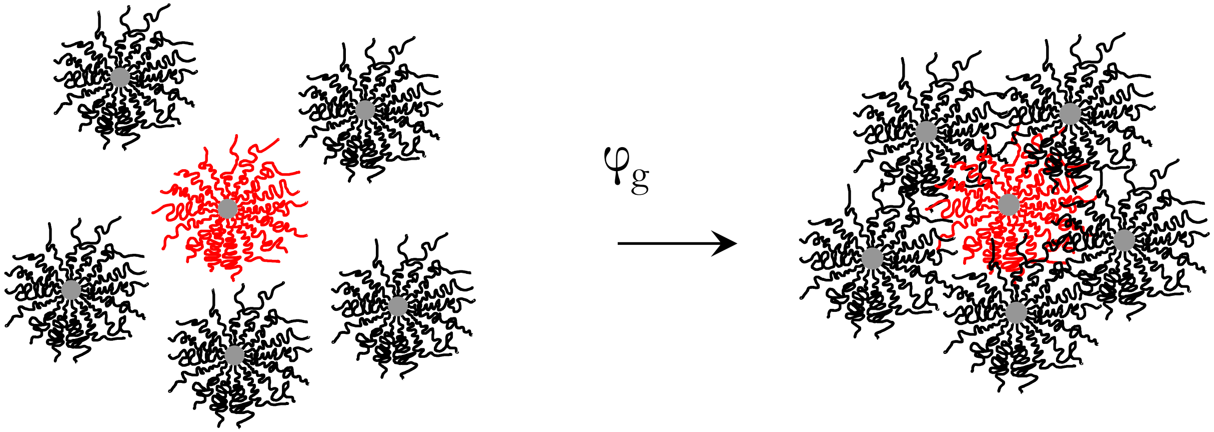
repulsive glass



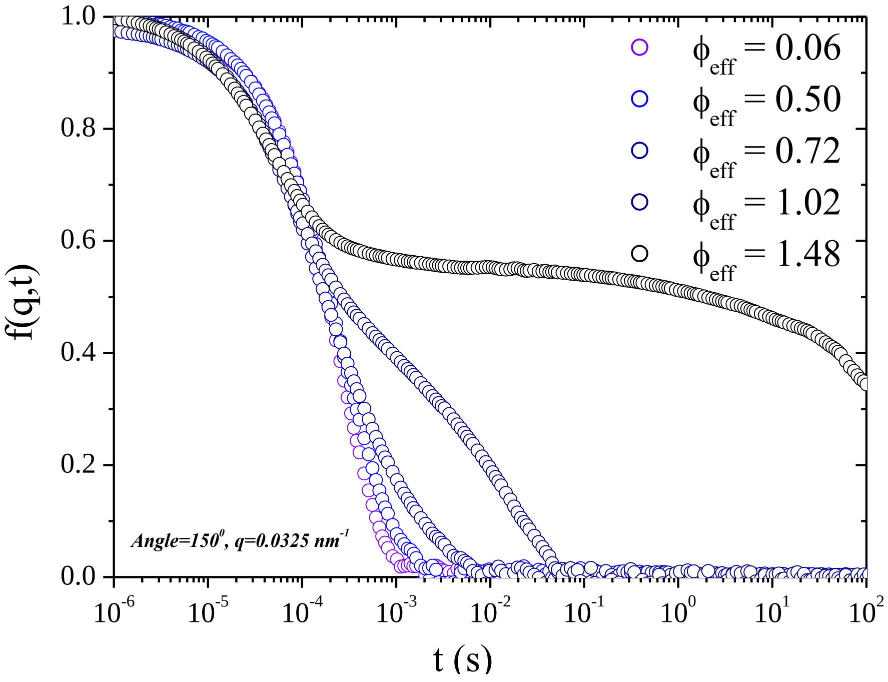
Pham et. al. Science, 2002

Soft Colloids - Dynamics approaching the glass

Multiarm Stars



Caging with increasing c or T



Colloidal systems

END of Lecture 1

- Definitions-Examples-Applications
- Main phenomena – Forces - Time scales
- Phase behavior: Thermodynamic phases, Metastable states (glasses and gels)
- Microscopic Dynamics (Scattering-Microscopy)
- Mechanical properties (Rheology) => lecture 2

Colloidal systems

Study questions (Lecture 1)

1. Define colloidal systems. Why are colloidal particles defined by size limitations from nanometers to micrometers?
2. What is the phase diagram of hard spheres, and how is it changed for soft polymer coated particles?
3. What is the role of a polymer in colloidal dispersion stability for a) Grafted or adsorbed polymer b) Dissolved, non-adsorbed polymer?
4. Describe the interaction potential and the phase diagram of charged stabilized colloids.
5. Calculate the van der Waals interaction per unit area between two semi-infinite planes.
6. Determine the critical coagulation concentration (c.c.c) (in mol/L) for two planar surfaces *(use approximately the vdW and screened Coulomb interaction between semi-infinite planes)*
7. Calculate the time needed for a colloidal particle with radius, $R=0.5\ \mu$m to diffuse it own diameter in water at 25 C in the dilute limit and at a volume fraction of $\varphi=0.1$
8. Calculate the sedimentation velocity of a particle with $R=2\mu$m and $\rho=1.2$g/cm^3 in the dilute limit and at $\varphi=0.05$ and 0.3.
9. A colloidal glass of hard spheres with R=100 nm, at $\varphi=0.6$ has G'= 80 Pa at $\omega=10$ rad/s and T=20 ^{o}C. Calculate the G' for a glass at the same φ in the case of HS with R=500 nm at T=40 ^{o}C. At which frequency ω we should make the comparison?
10. Calculate the ratio of main forces in a colloidal suspension with:

$R = 1\ \mu\text{m}$, $\eta = 1\text{cp} = 10^{-3}$ Pa s, $\rho = 10^{3}$ kg/m^{3}, $\Delta\rho/\rho = 0.01$, $T = 20^{o}$C, $\upsilon = 1\ \mu$m/s, $A_{eff} = 10^{-20}$Joule, $\zeta = 50$ mV

g=10 m/s^{2}, $\varepsilon=100$, $\varepsilon_0=8.85\ 10^{-12}$C/Vm

Colloidal systems

Study questions cont. (Lecture 1)

11. You are trying to flocculate a colloidal dispersion in a plant-size operation at 500 K using calcium oxide (CaO). In your laboratory, all you have available at the moment is sodium chloride (NaCl). At room temperature, you find that 2 mol/L NaCl is necessary to induce flocculation. Estimate the concentration of CaO necessary to flocculate the dispersion in your plant operation.
12. Determine the crystal-liquid coexistence regime for charged stabilized particles with a Debye screening length $1/\kappa = 10$ nm and radius R= 150 nm. Assume the particles behave as hard spheres with an effective radius $R + 1/\kappa$.
13. What is the difference between the behavior of power law fluids and Bingham bodies at low stress levels?
14. Can you rationalize the dependence of the Debye screening length on the thermal energy, and ion concentration?
15. What is a colloidal glass, a colloidal gel and an attractive glass?

Colloidal systems

Further reading (Lecture 1)

Books:

- W.B. Russel, D.A. Saville, W.R.Schowalter, Colloidal Dispersions, Cambridge University Press, 1989
- R. J. Hunter, Foundations of Colloid Science, Oxford, University Press, New York, 2001
- D. F. Evans, H. Wennerström, The Colloidal Domain, Where Physics, Chemistry, Biology and Technology meet, John Willey and Sons, New York, 1999.
- M.D. Haw “Middle World: The Restless Heart of Matter and Life”, 2006

Reviews:

- P.N. Pusey, in Les Houches Session 51, ed. D. Lesvesque, J. P. Hansen and J. Zinn-Justin, North-Holland, Amsterdam, (1991).
- W. C. K. Poon, J. Phys.: Condens. Matter, (2002), 14, R859–R880.
- C. N. Likos, Physics Reports 348, (2001) 267-439