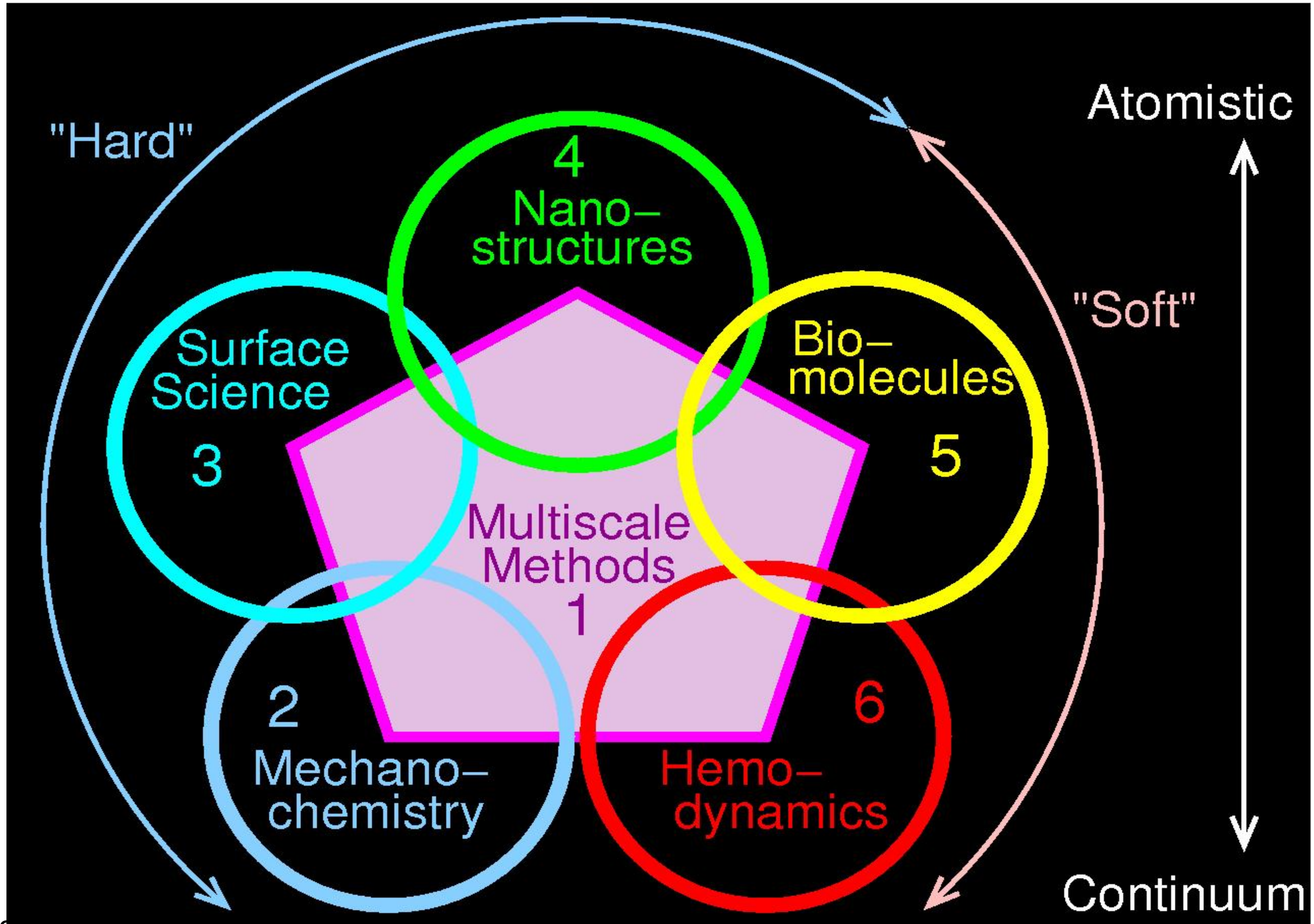
Challenges for computational physical sciences

- Can we ***predict*** from first-principles, the relevant structures – functions of complex systems?
- What are ***key features*** at each scale?
- How are they ***coupled*** in complex system?
- Variables: space, time, concentration, …
- Constants: from "first-principles"
- Parameters: adjustable

EK Research Group – Physics and SEAS

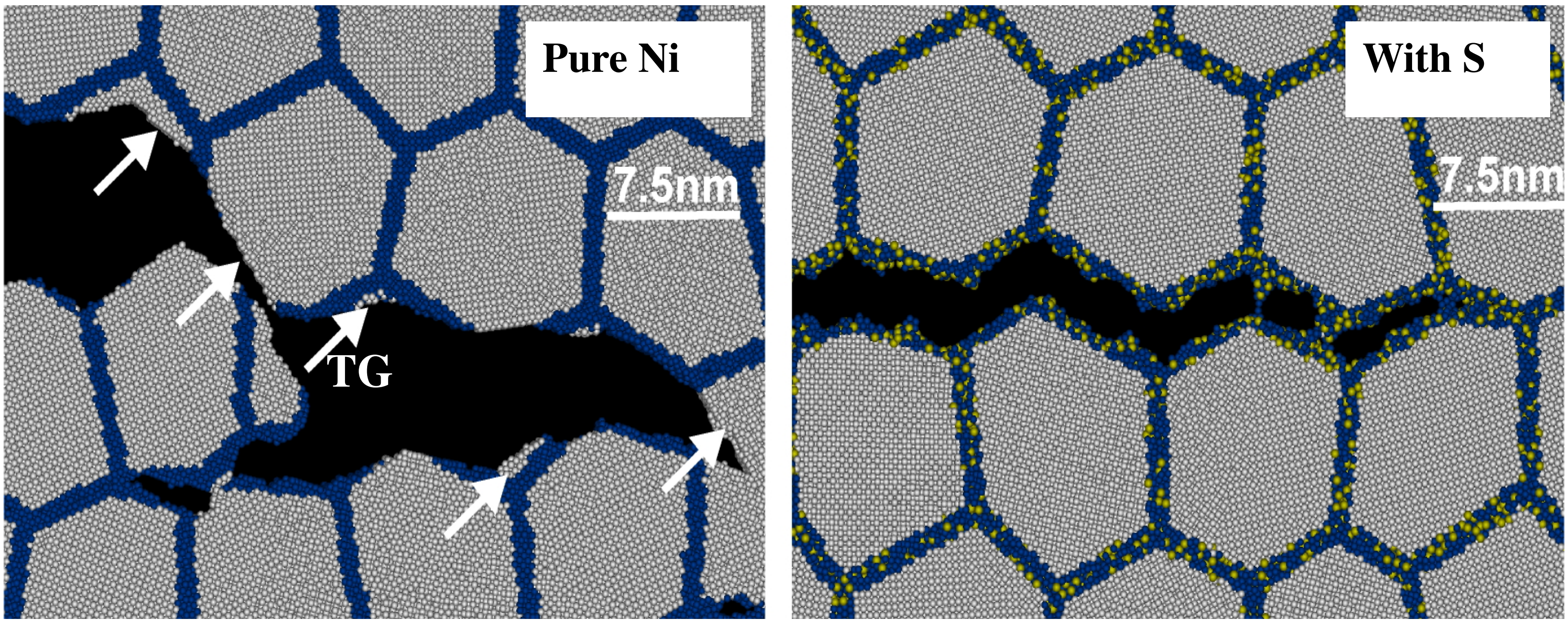



SOUTHWEST.COM

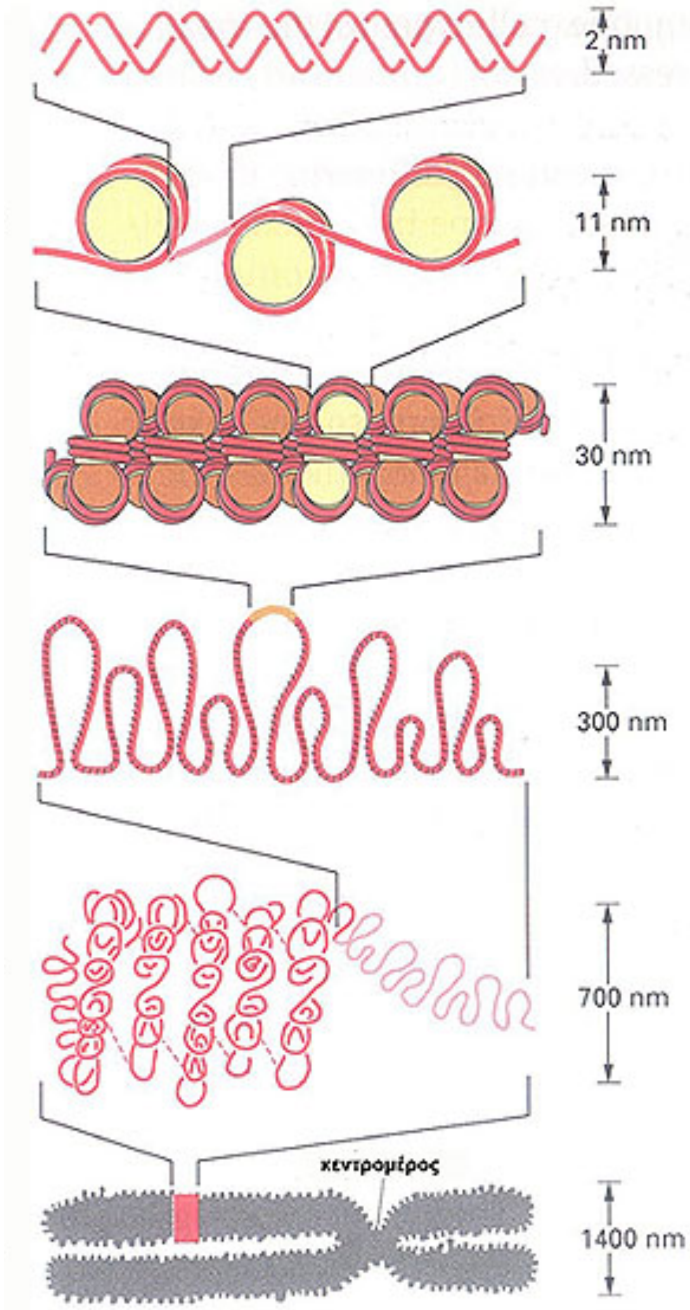
Stress Corrosion Cracking: Ni embrittlement by S impurities

- **multiscale simulations: sulfur-induced intergranular amorphization and embrittlement**

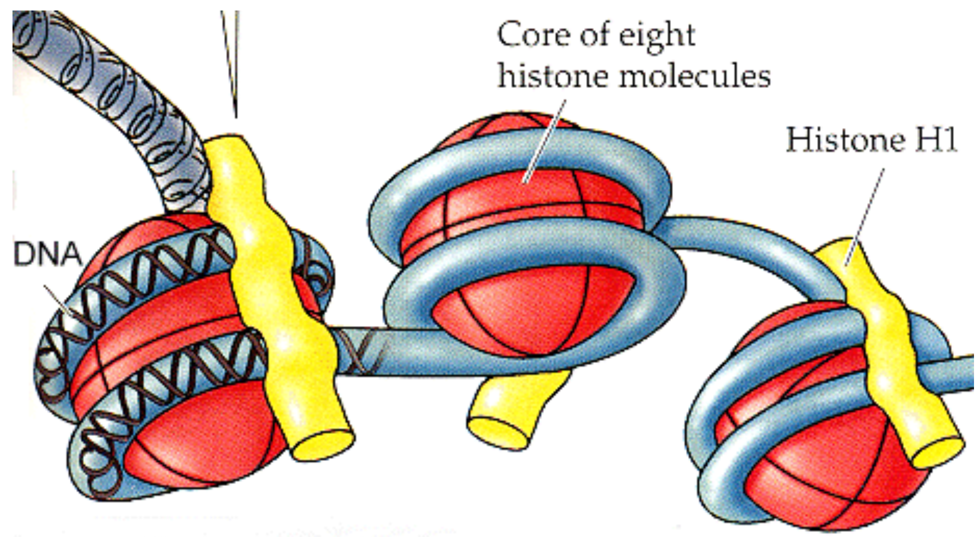
0 parameters (parameter-free model)



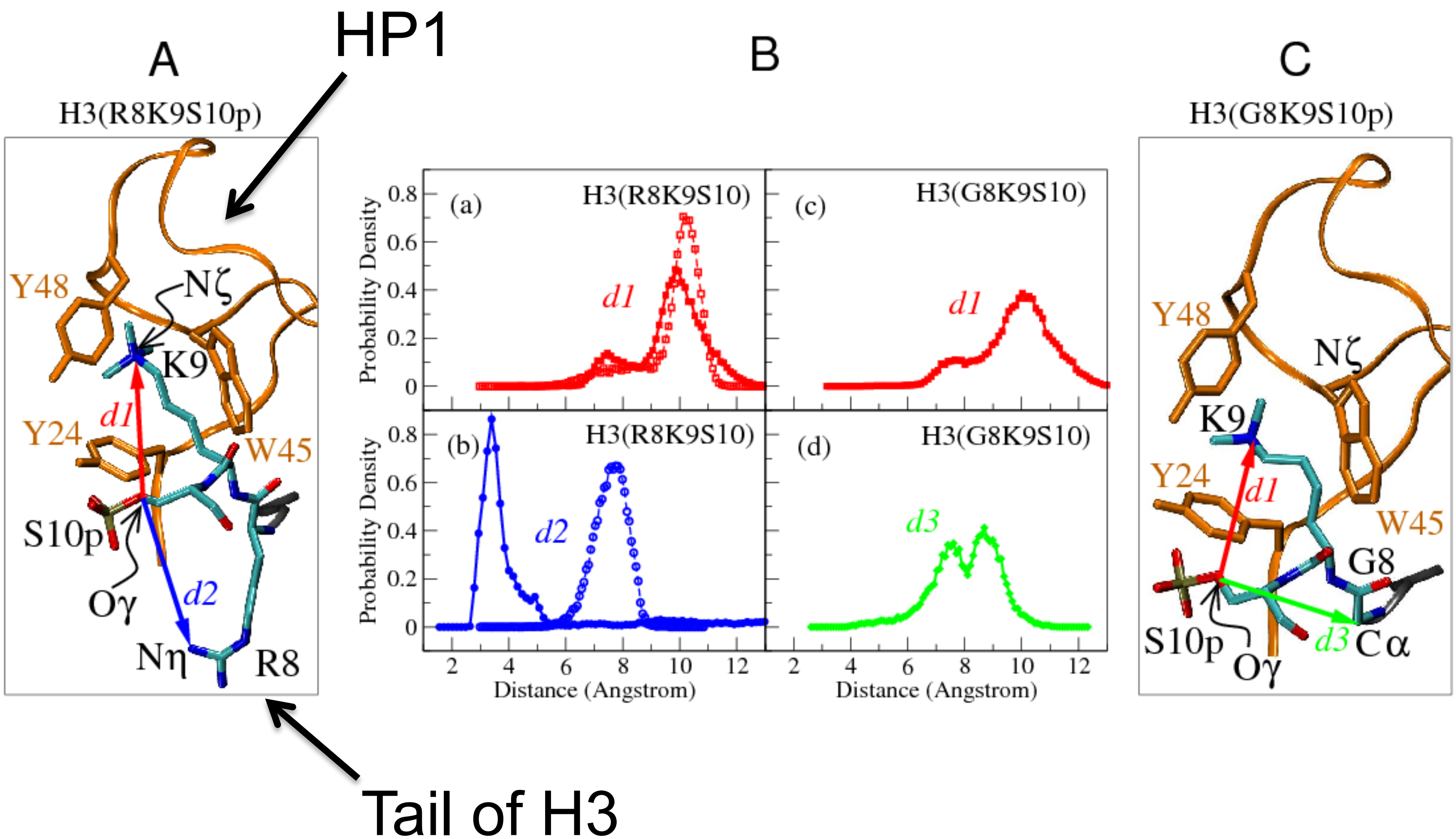
H.P. Chen, et al. Phys. Rev. Lett. 104, 155502 (2010).



Structure of DNA on several scales: from chromosome to nucleosome



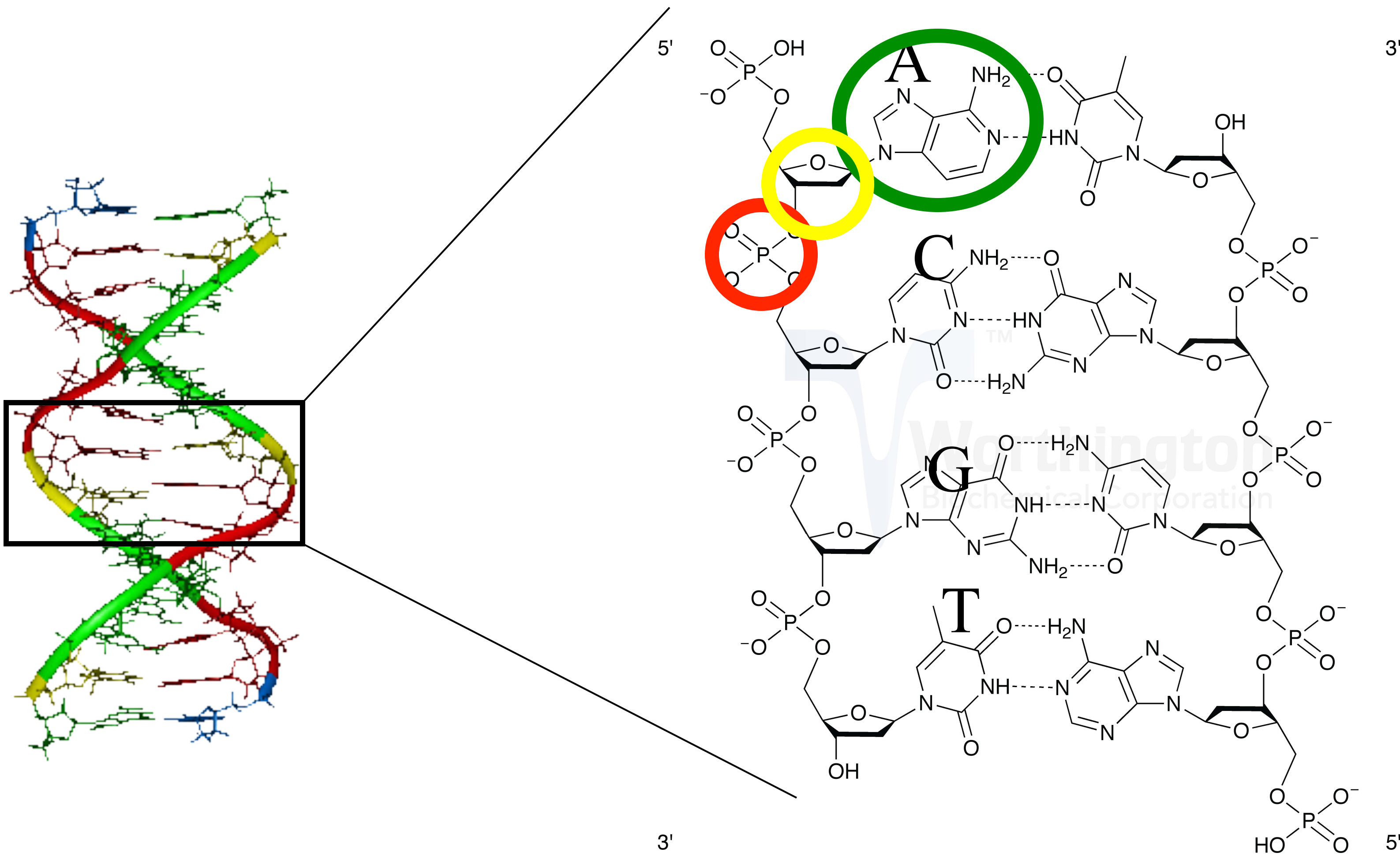
Important in **epigenetics**: genetic information not encoded in DNA base sequence



Papamokos et al., Biophys. J. (2012)

Coarse-grained potential fo DNA

Deoxyribonucleic Acid



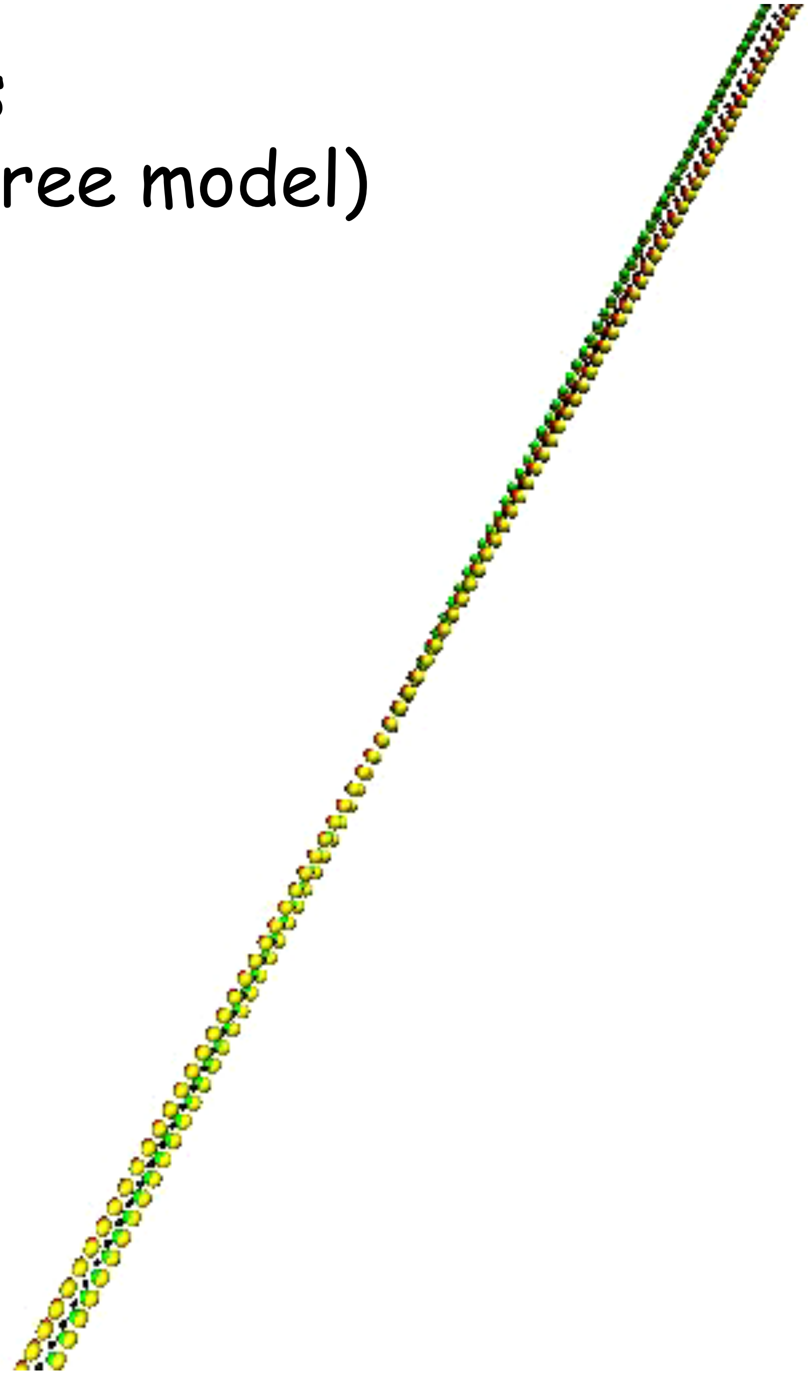
5'-Adenine-Cytosine-Guanine-Thymine-3'

W. Hsu, M. Fyta, G. Lakatos, S. Melchionna, EK (JPC, 2012)

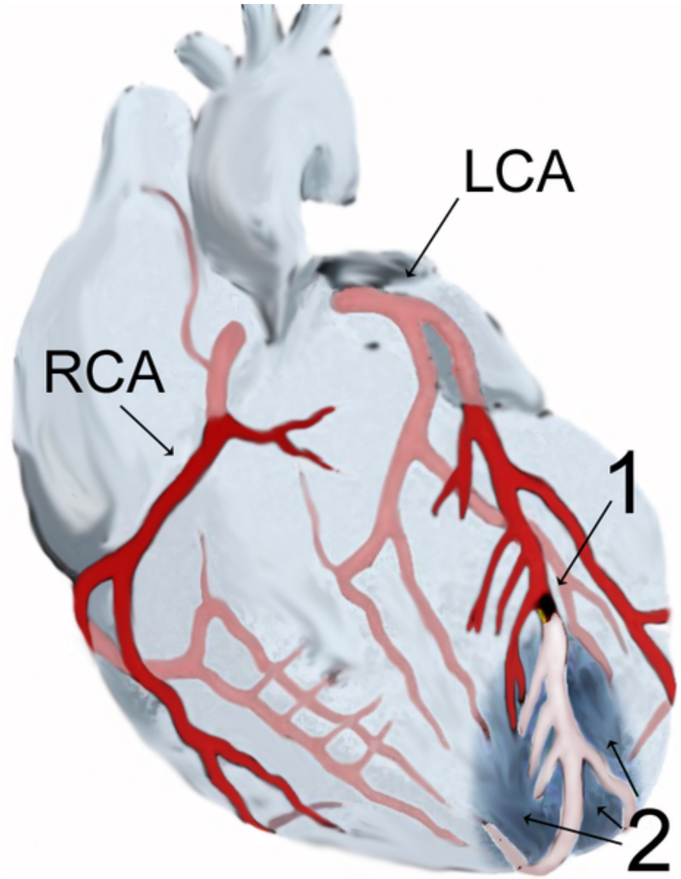
Center *for* Strategic Scientific Initiatives

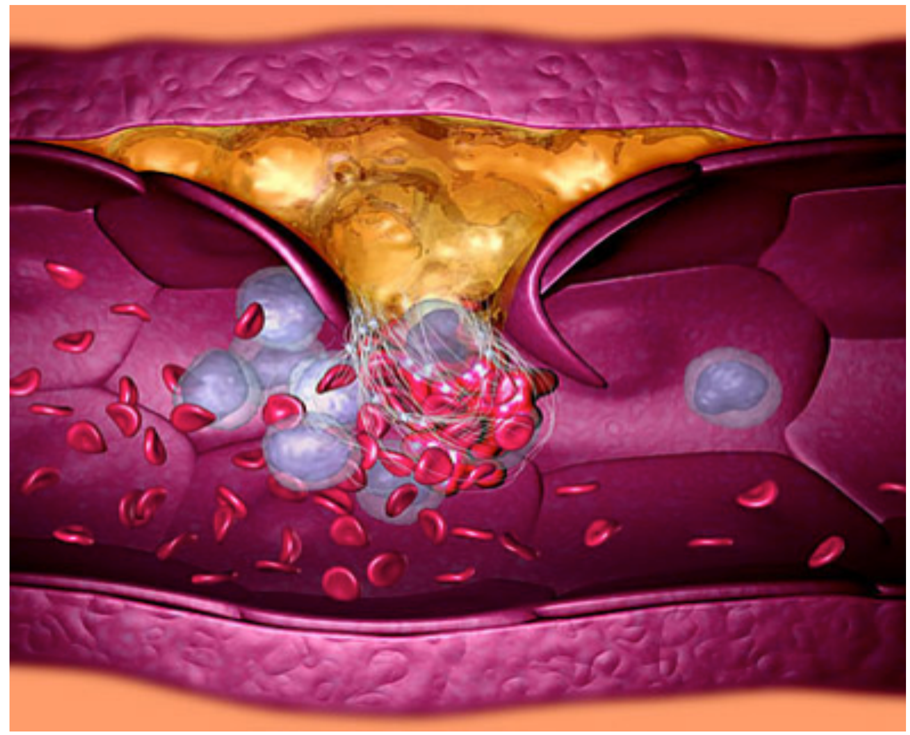
Enabling Progress in Cancer Research Through Advanced Technologies, Trans-Disciplinary Programs and Resources

0 parameters
(parameter-free model)



Acute Myocardial Infarction (heart attack)





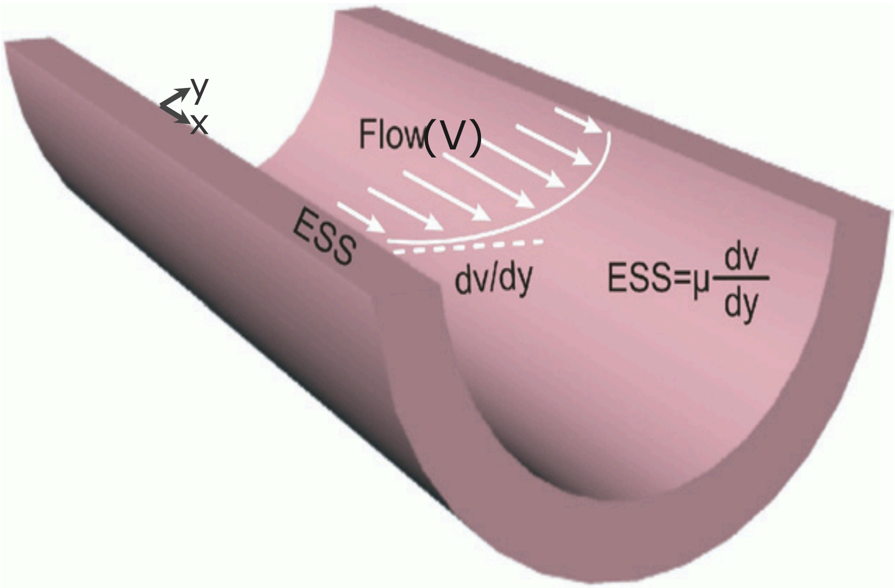
Deaths in USA:

- 35% blood flow obstruction (80% heart, 20% brain)

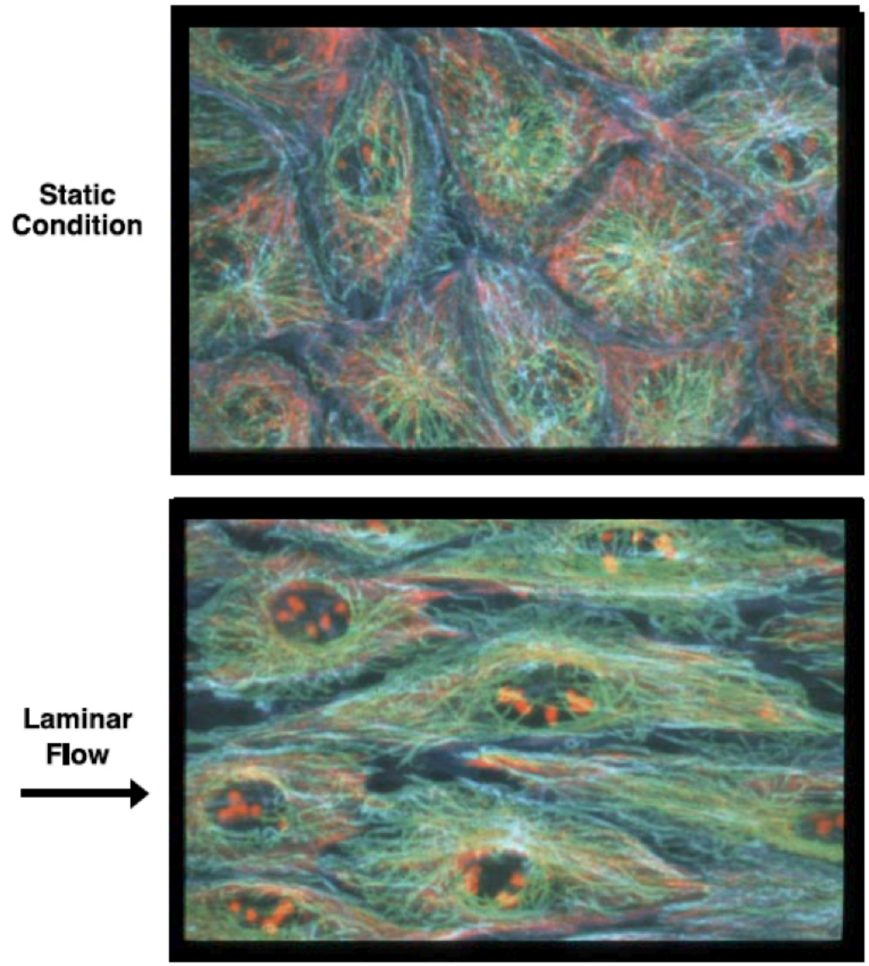
UNPREDICTABLE

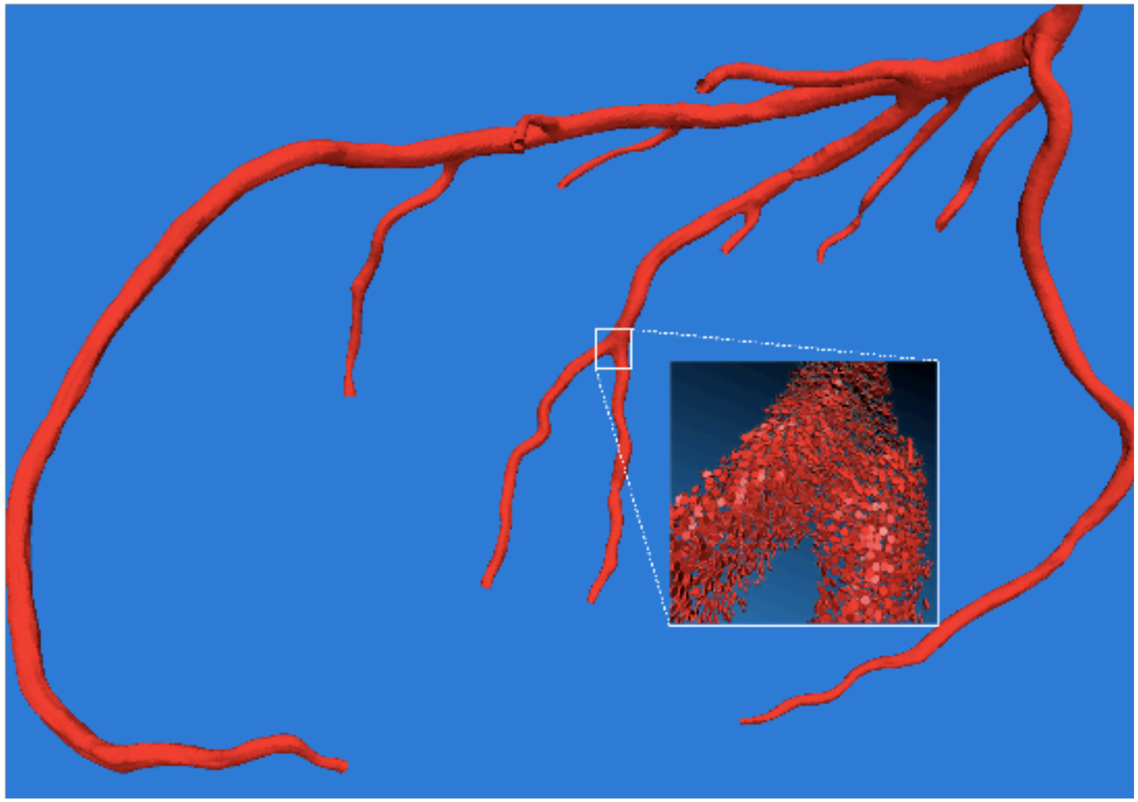
- 25% cancer (all types)

How does the flow reshape the endothelium?

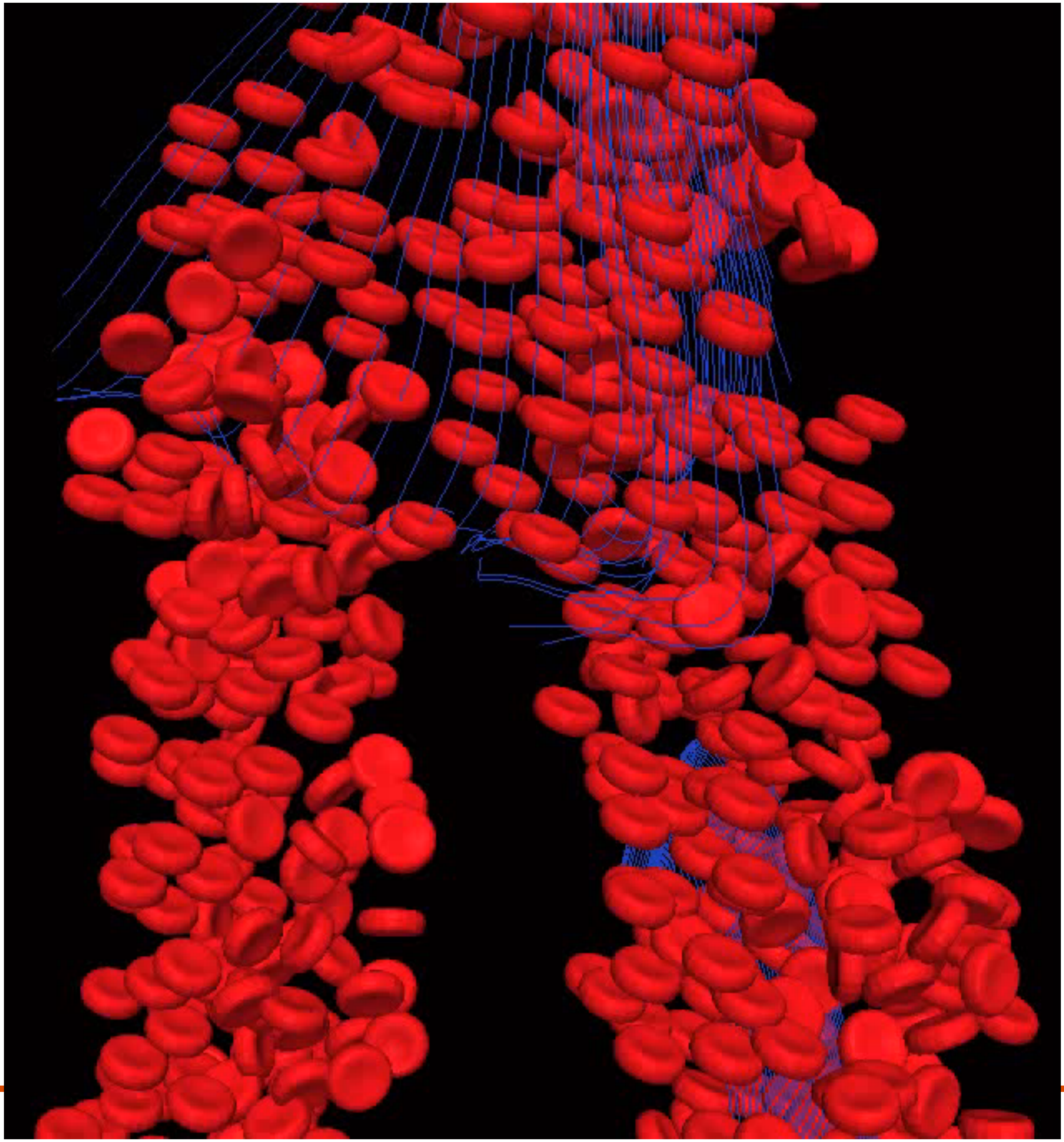


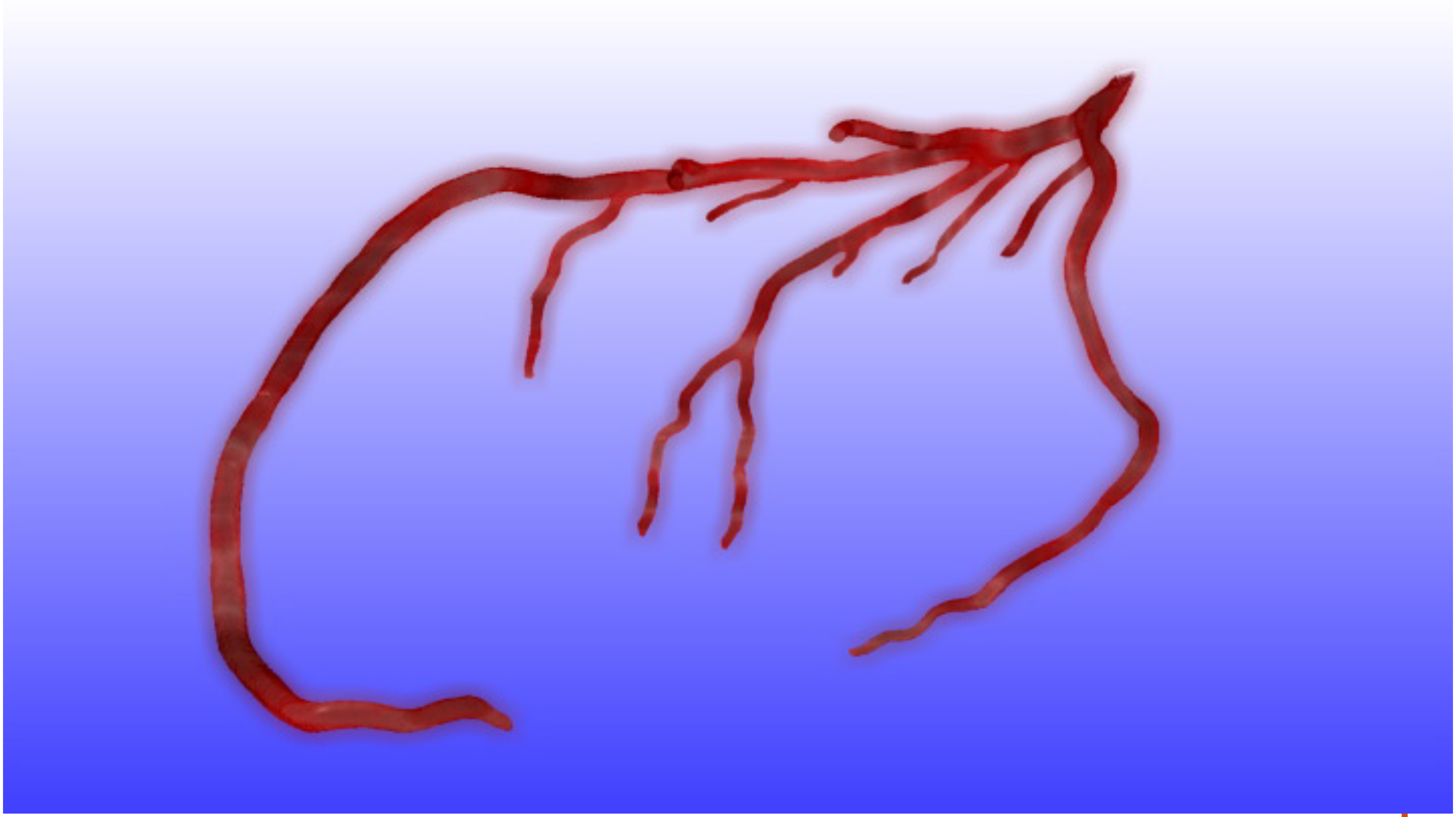
Endothelial Shear Stress

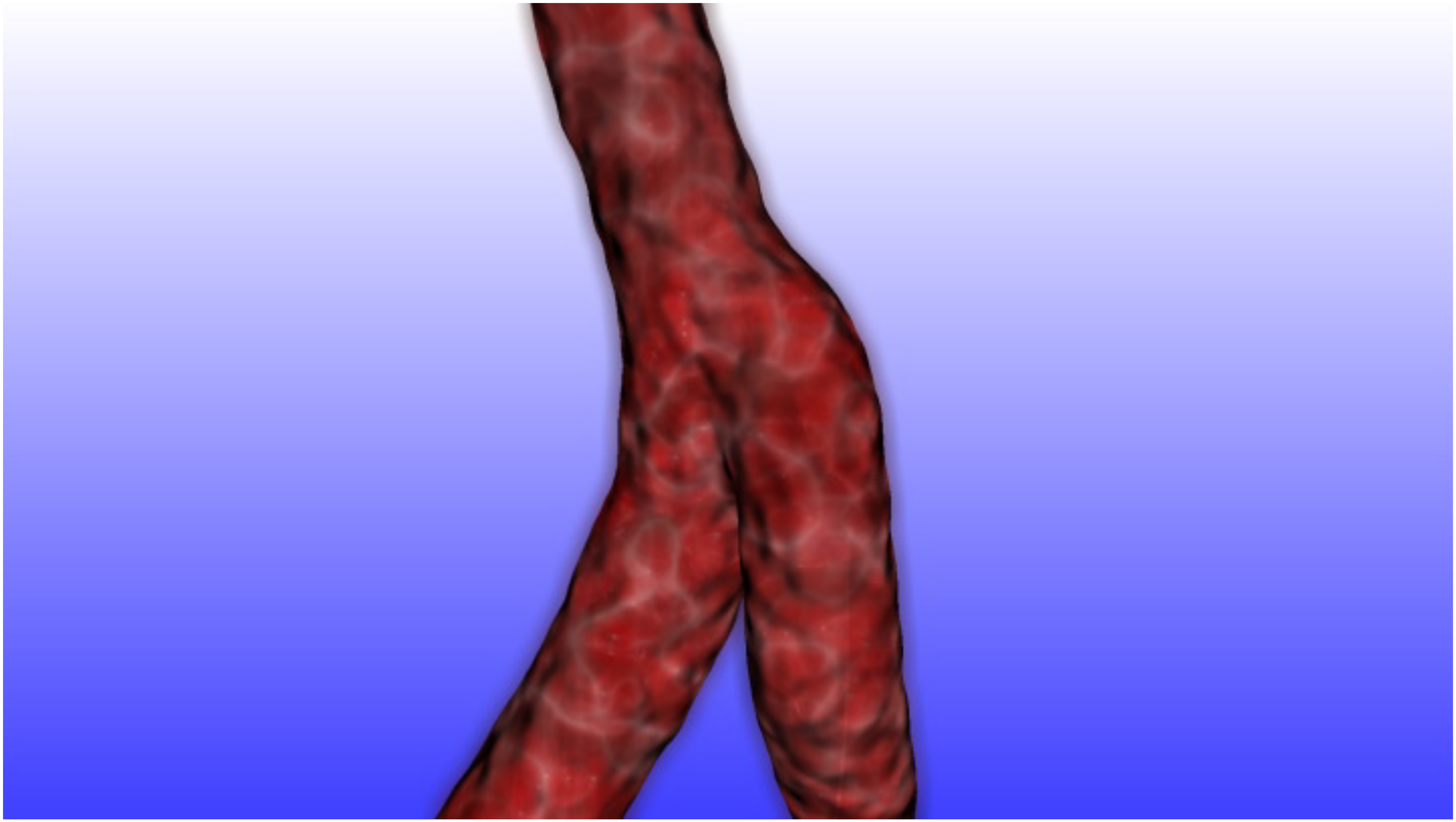




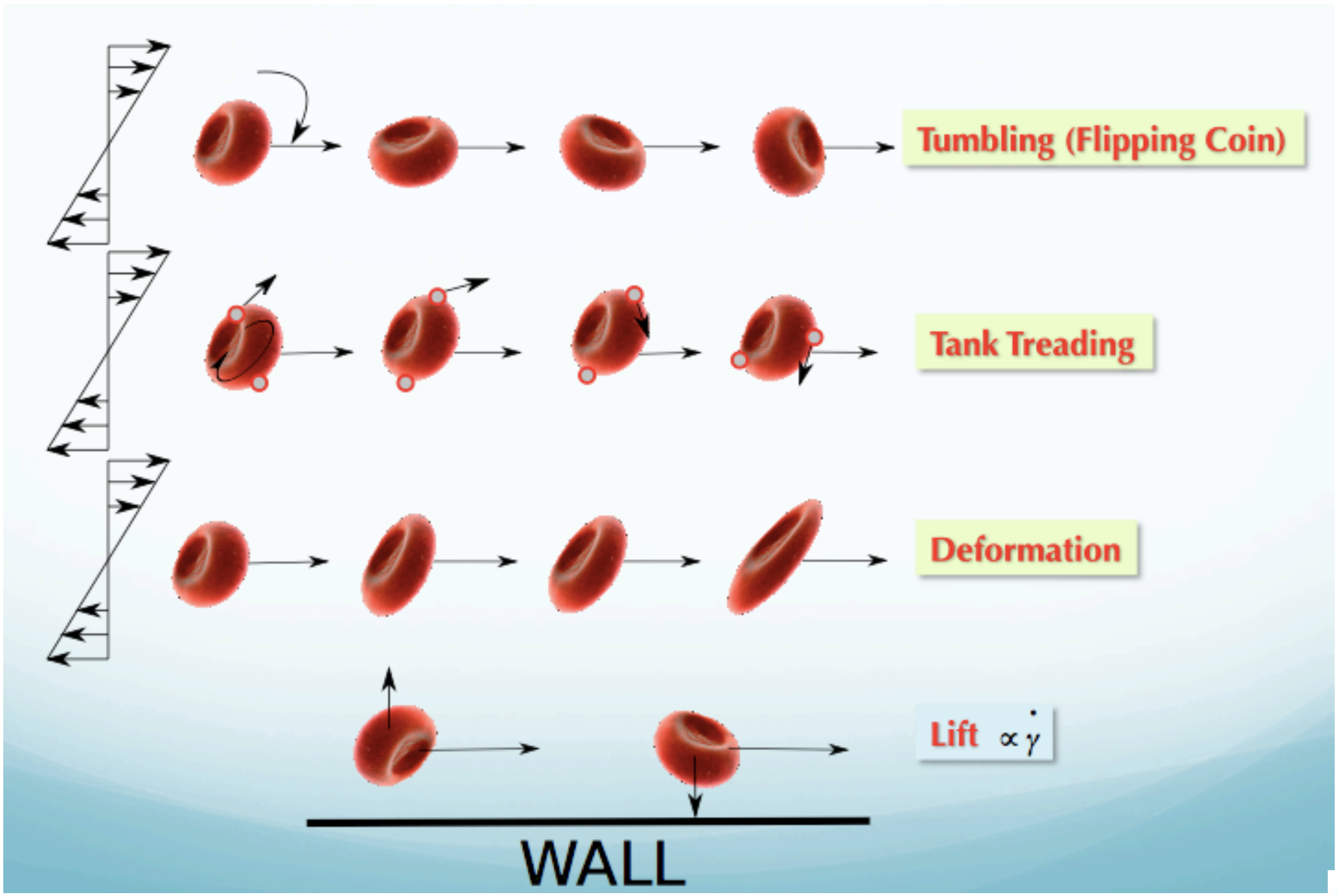
Fluid dynamics + RBC motion
(strongly coupled)
1 parameter (fluid-cell friction constant)



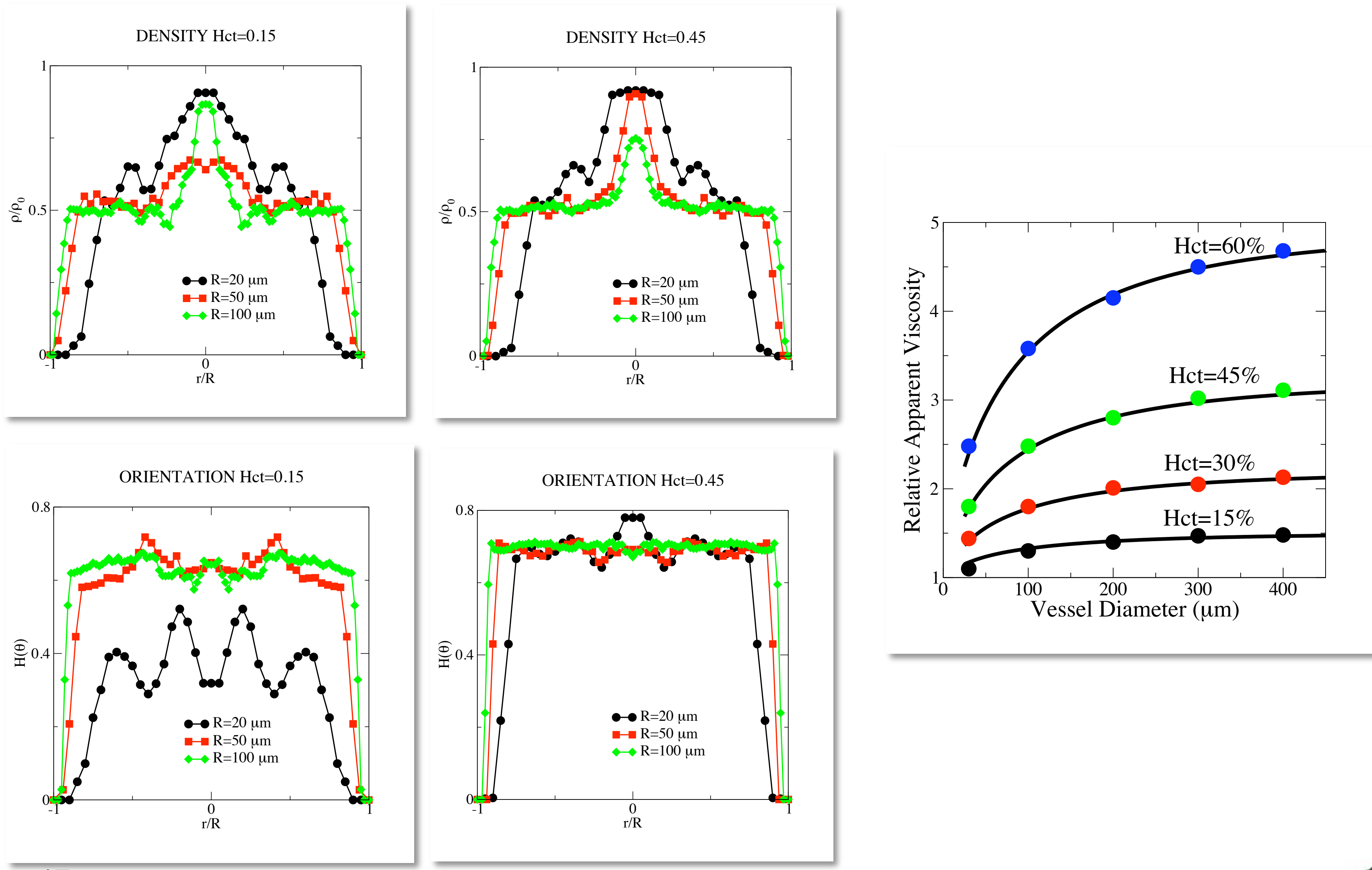




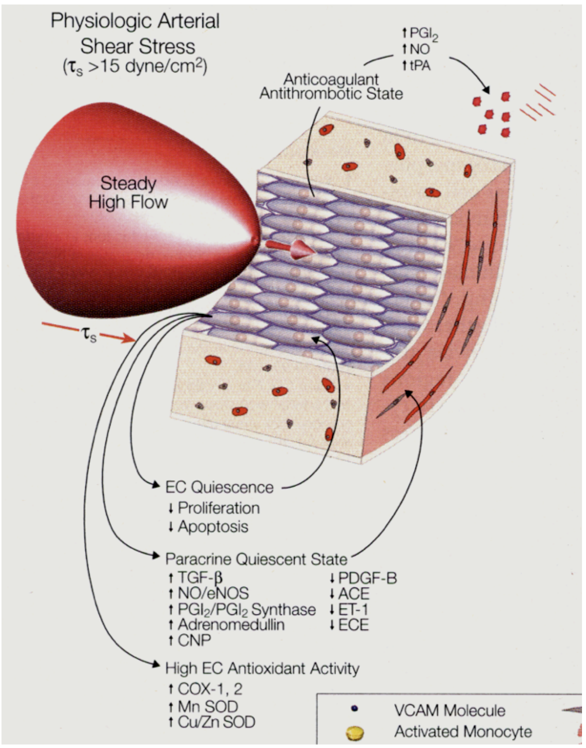
Red Blood Cell in Motion



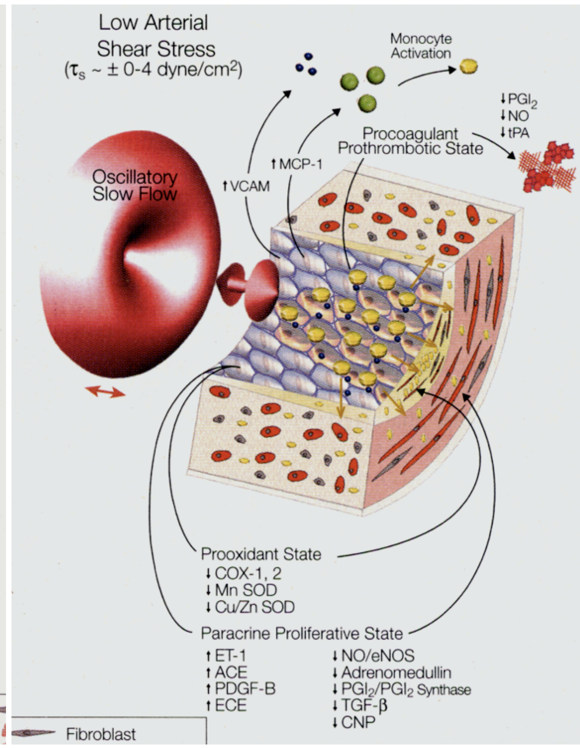
Fahraeus-Lindqvist effect



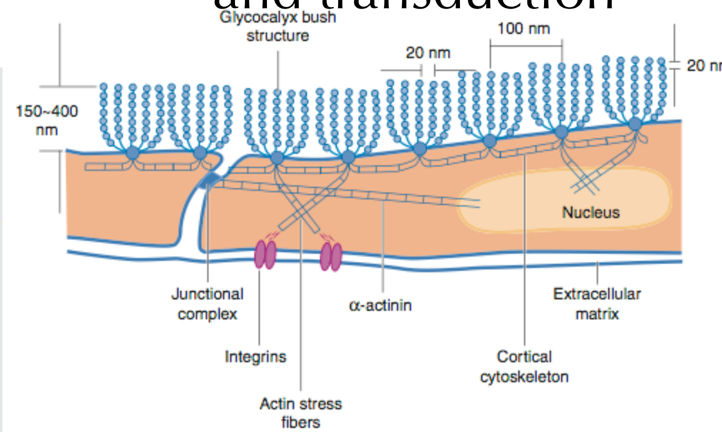
Mechanosensing and transduction

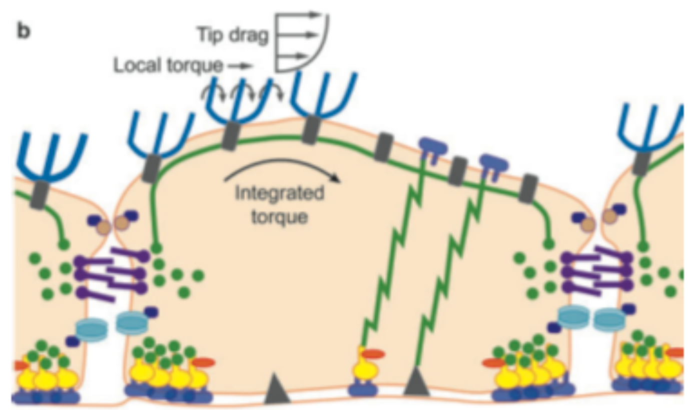


Vasculoprotective



Vascular adhesion of lipoproteins & inflammatory cells

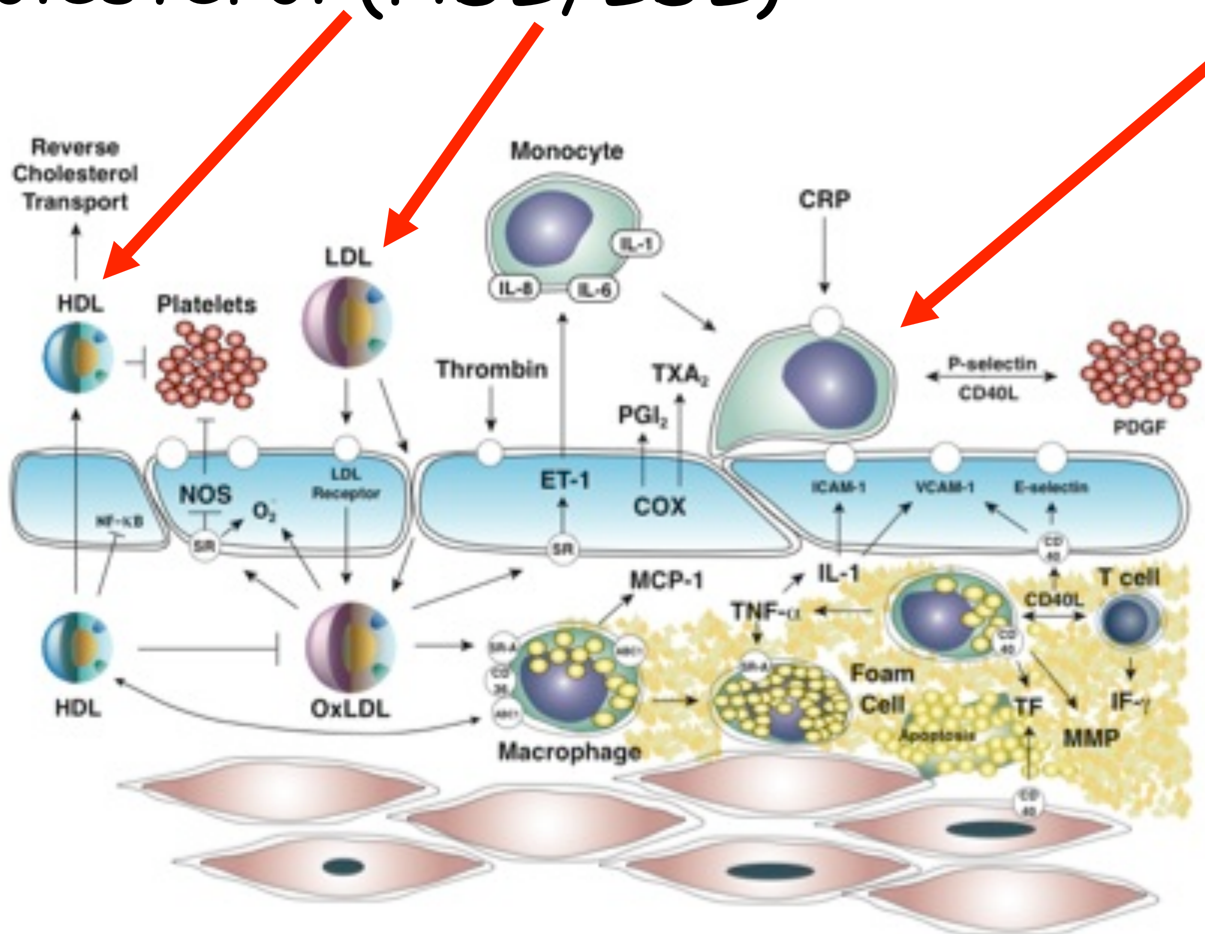




Inflammatory response & Feedback

Cholesterol (HDL, LDL)

White blood cell

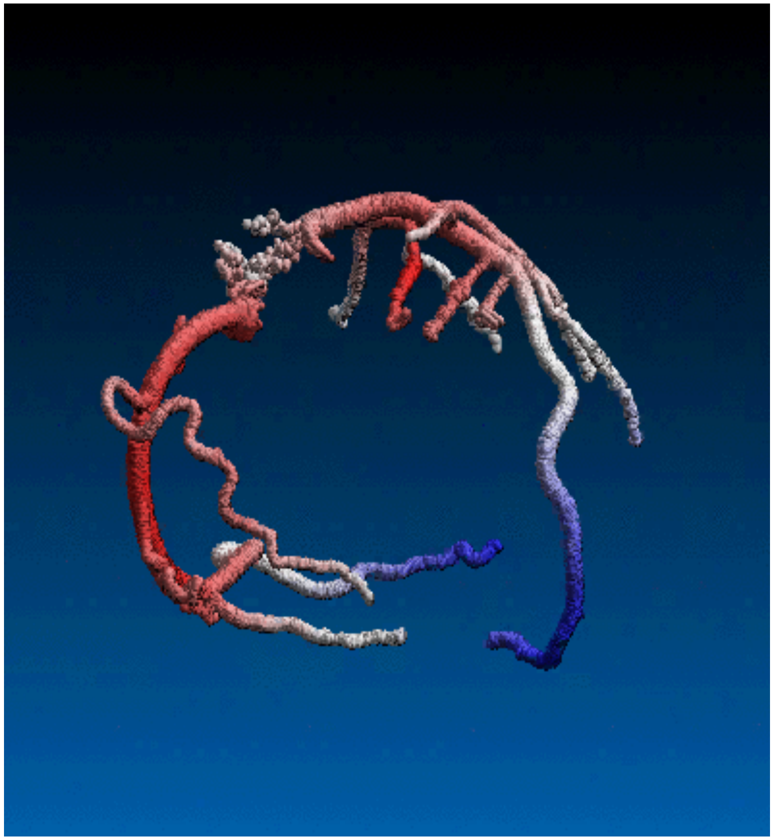


Endotheliu

Muscle tiss

Challenge: realistic artery geometries

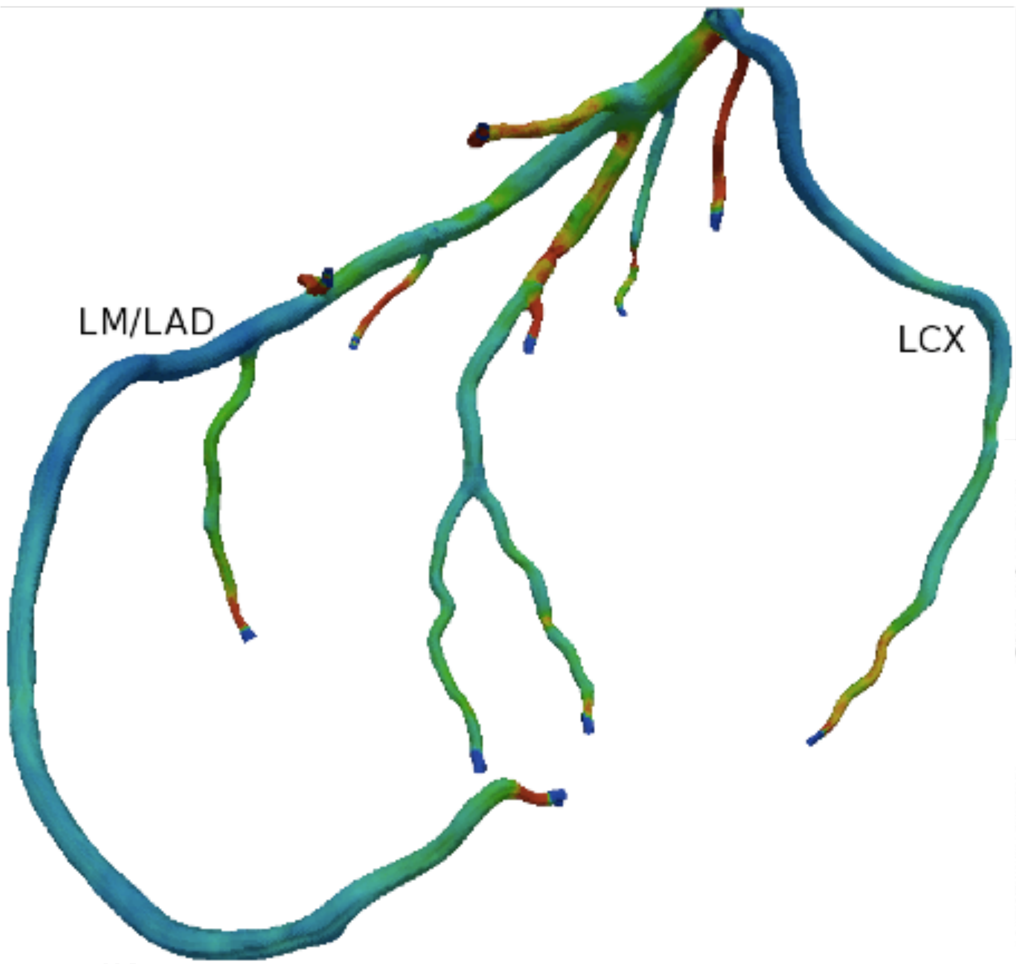
CT scan data



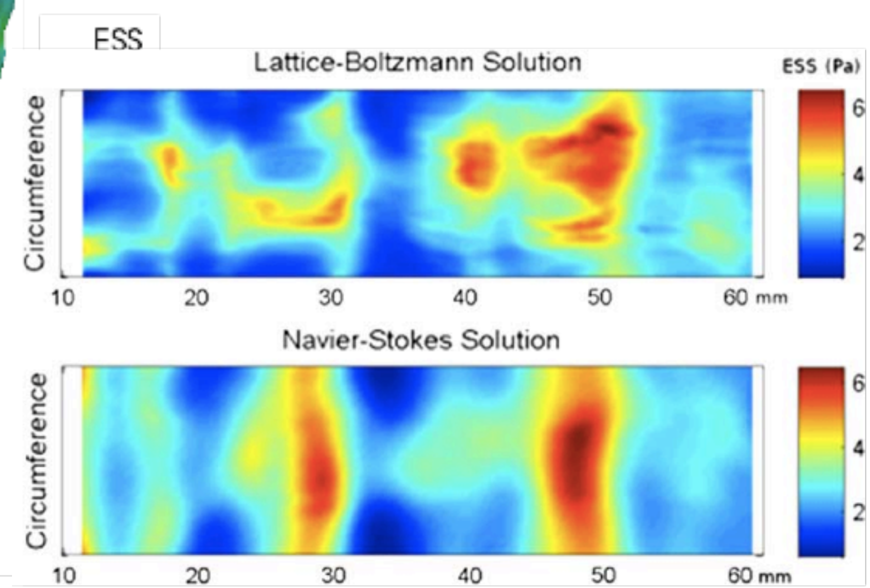
smoothing

(with F. Rybicki, C. Feldman, HMS)
International Journal of Cardiovascular Imaging
(2009)

ESS calculation in patient-specific arterial tree



Validation



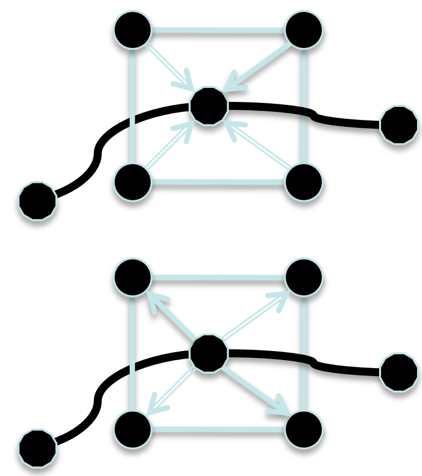
Coupling of particle and fluid (continuum) scales

$$(\partial_t + v \cdot \partial_x) f = -\omega(f - f^{eq}) - \frac{1}{M}\sum_R F^H \cdot \partial_v f$$

$$\frac{d}{dt}V = \frac{1}{M}(F + F^H)$$

$$F^H = -\gamma\left[V - u(x,\{R,V\})\right]\delta(x - R)$$

Momentum exchange (Newton's law)

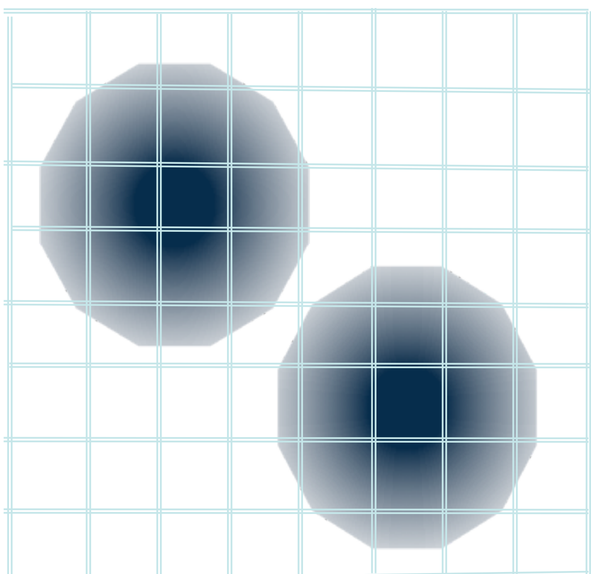


Definition of particles (cells, proteins, …)

$$\tilde{\delta}_\xi(x-R) = \prod_{\alpha=x,y,z} \tilde{\delta}_\xi(x_\alpha - R_\alpha)$$

$$\tilde{\delta}_\xi(a) = \begin{cases} \frac{1}{2\xi}\left(1+\cos\left(\frac{\pi|a|}{\xi}\right)\right) & 0 \le |a| \le \xi \\ 0 & \xi \le |a| \end{cases}$$

$$\sum_x \tilde{\delta}_\xi(x-R) = 1$$



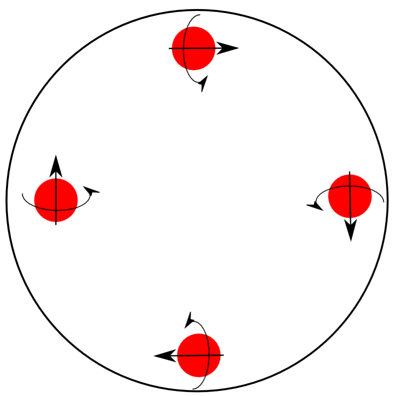
$$\varphi(x,R) = -\gamma\left(V - u(x)\right)\tilde{\delta}_\xi(x-R)$$

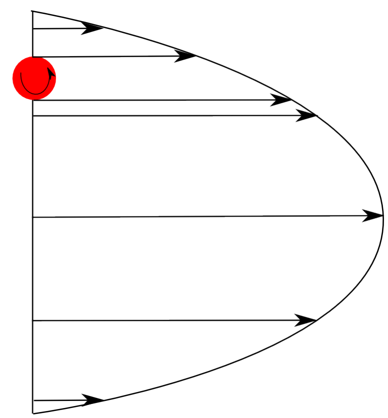
$$F^H = \sum_x \varphi = -\gamma\left(V - \tilde{u}\right)$$

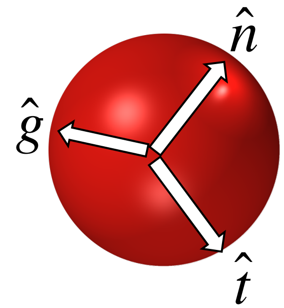
$$\tilde{u} = u * \tilde{\delta}_\xi$$

$$\Delta f_p = -\frac{w_p}{c^2} c_p \cdot \sum_R \varphi$$

Rotating particles







$$Q = \begin{pmatrix} n_x & t_x & g_x \\ n_y & t_y & g_y \\ n_z & t_z & g_z \end{pmatrix}$$

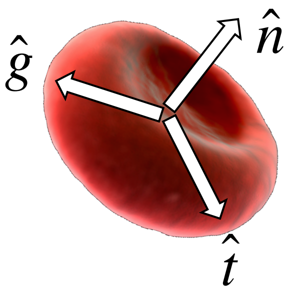
$$\tau(x,R) = -\gamma_R\left(\Omega - \omega(x)\right)\tilde{\delta}_\xi(x-R)$$

$$T^H = \sum_x \tau = -\gamma_R\left(\Omega - \tilde{\omega}\right)$$

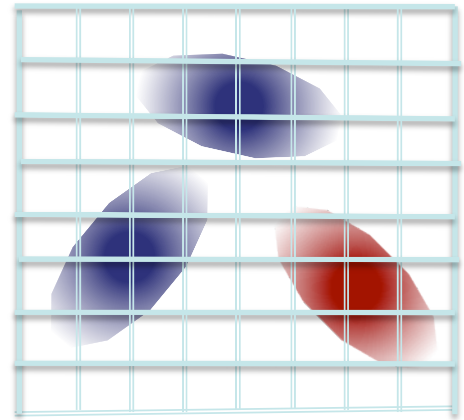
$$\tilde{\omega} = \omega * \tilde{\delta}_\xi$$

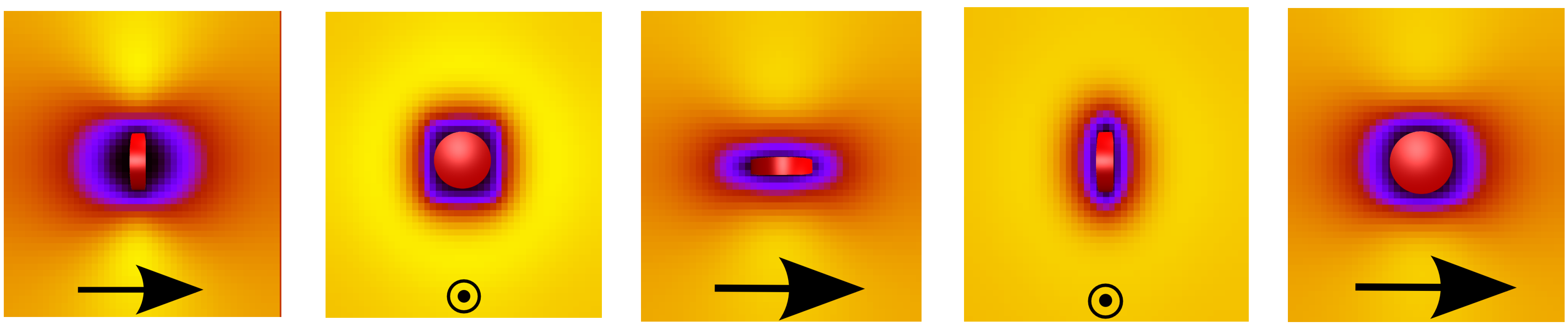
$$\Delta f_p = -\frac{w_p}{c^2} c_p \cdot \sum_R \left(\varphi - \partial\tilde{\delta}_\xi \times \tau\right)$$

Shape



$$\tilde{\delta}_{\xi_\parallel \xi_\perp}(x) = \prod_{\alpha=x,y,z} \tilde{\delta}_{\xi_\alpha}((Qx)_\alpha)$$





$$\gamma_\parallel = \frac{2}{3R} \frac{(1-R^2)^{3/2}}{\arctan\sqrt{R^{-2}-1} - R\sqrt{1-R^2}} \xrightarrow{R>>1} \frac{2}{3}$$

$$\gamma_\perp = \frac{2}{3R} \frac{(1-R^2)^{3/2}}{(1-2R^2)\arctan\sqrt{R^{-2}-1} + R\sqrt{1-R^2}} \xrightarrow{R>>1} \frac{2R}{3\ln(2R)}$$

Perrin ‘34

Particle dynamics:

$$\Xi \frac{d\Psi}{dt} \equiv \begin{pmatrix} M \dfrac{dV}{dt} \\ I \dfrac{d\Omega}{dt} \end{pmatrix} = \begin{pmatrix} F + F^H \\ T + T^H \end{pmatrix} \equiv \Phi + \Phi^H$$

$$\Phi^H_{6\times1} = \Gamma_{6\times6}\Psi^*_{6\times1} + \Delta_{6\times3\times3} : E_{3\times3}$$

$$\Psi^* \equiv \begin{pmatrix} V - u \\ \Omega - \omega \end{pmatrix}$$

Brenner et al '72

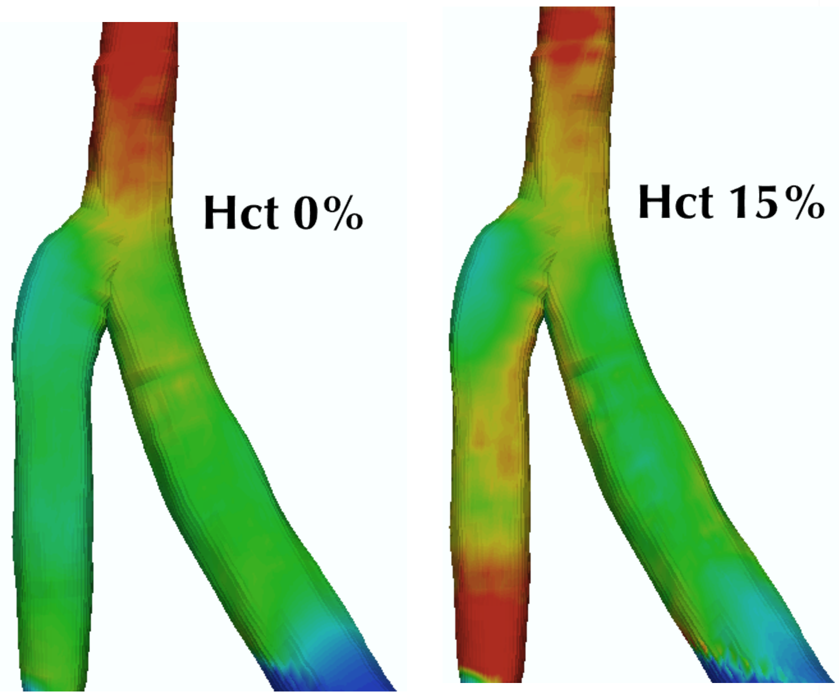
Γ	Grand Resistance matrix
Δ	Shear Resistance matrix
E	Strain tensor
u	Fluid velocity
$\omega = \frac{1}{2}\partial \times u$	Fluid vorticity

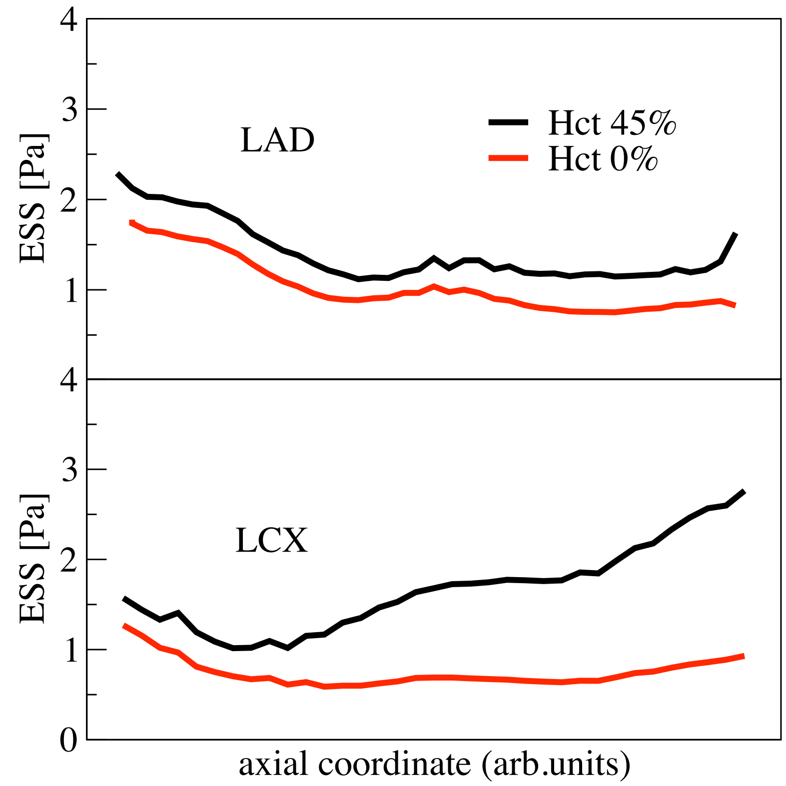
Γ and Δ depend on the whole configuration

Pair-wise superposition $O(N^3)$ complexity!

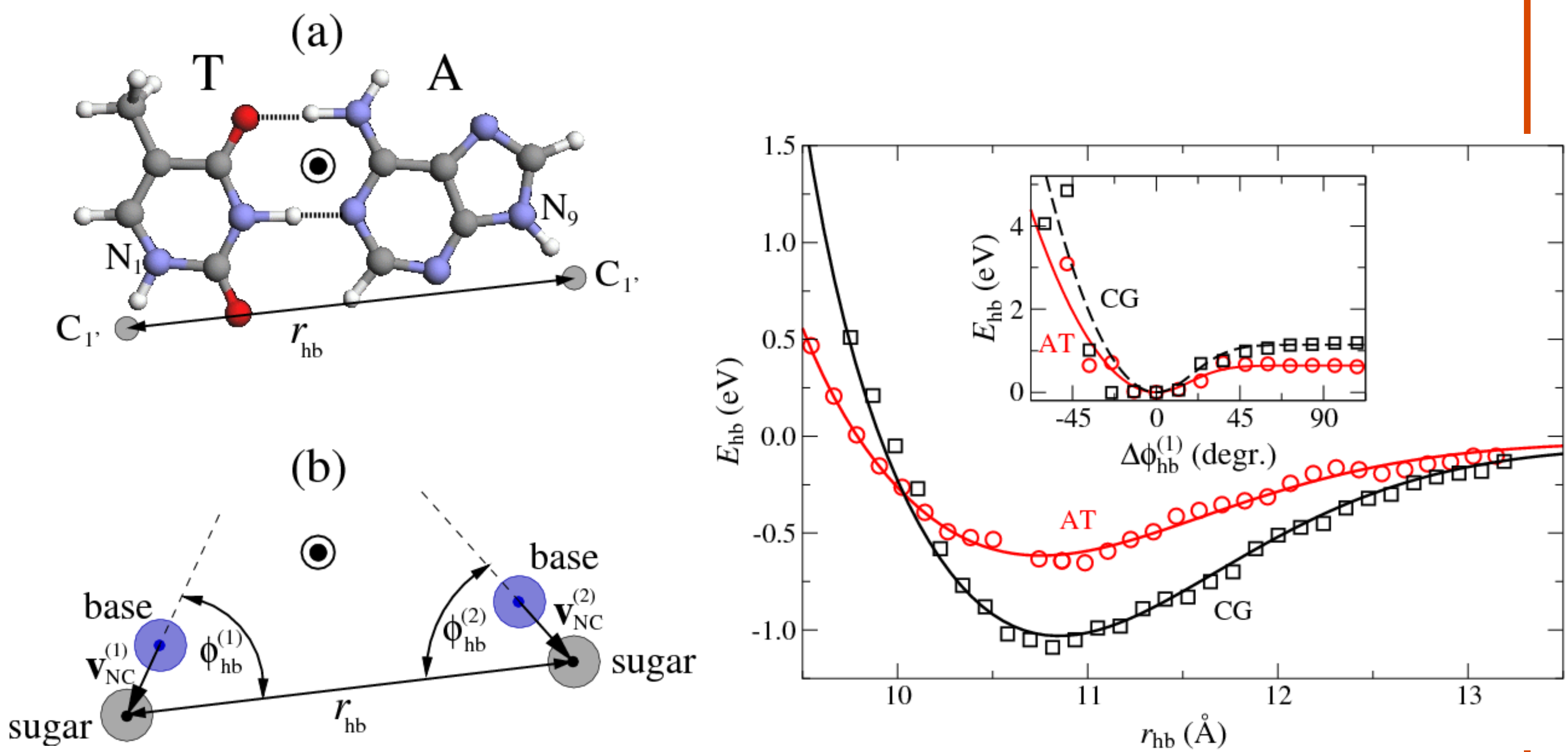
Brady & Bossis '89

Effect of particle motion on ESS:

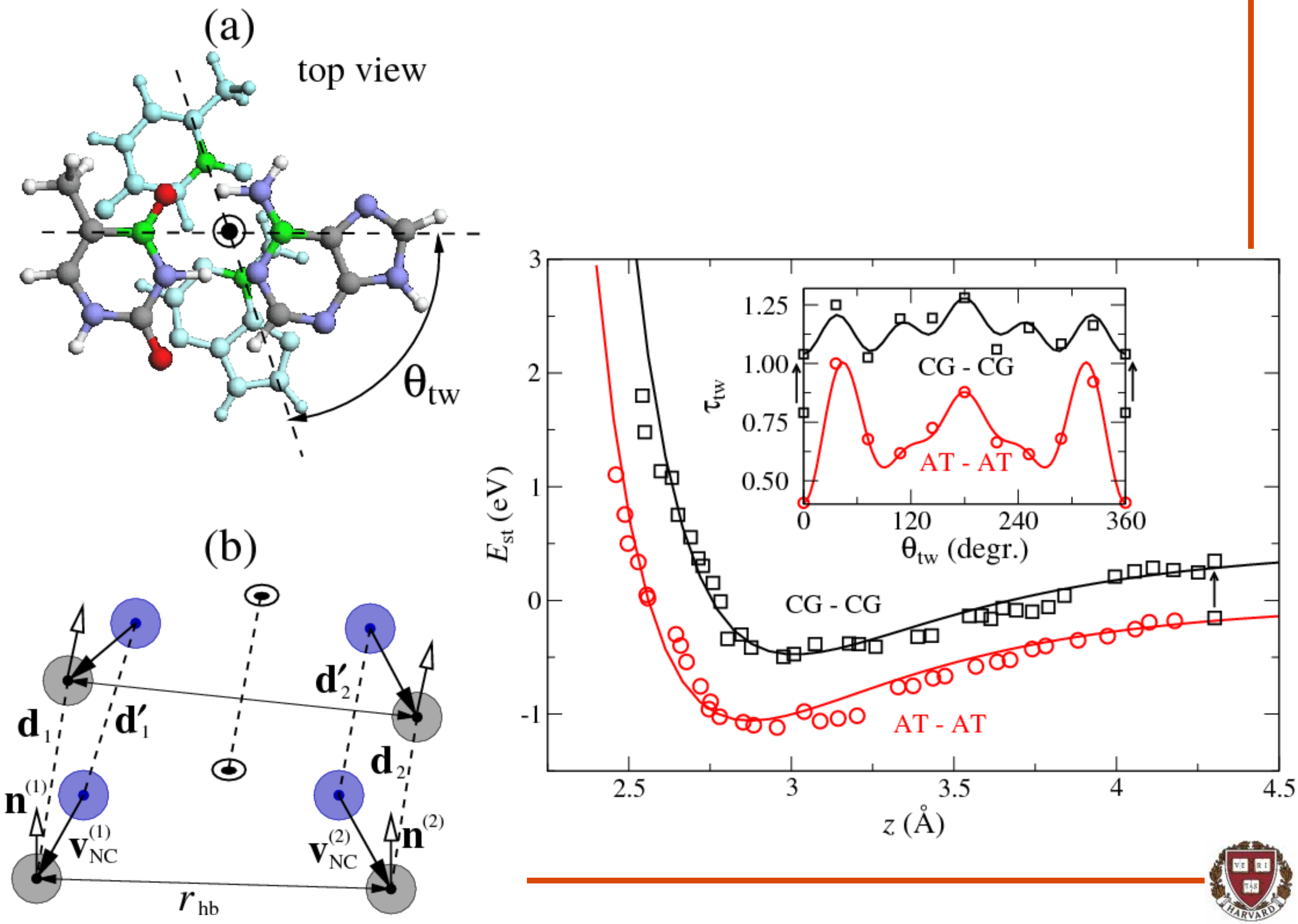




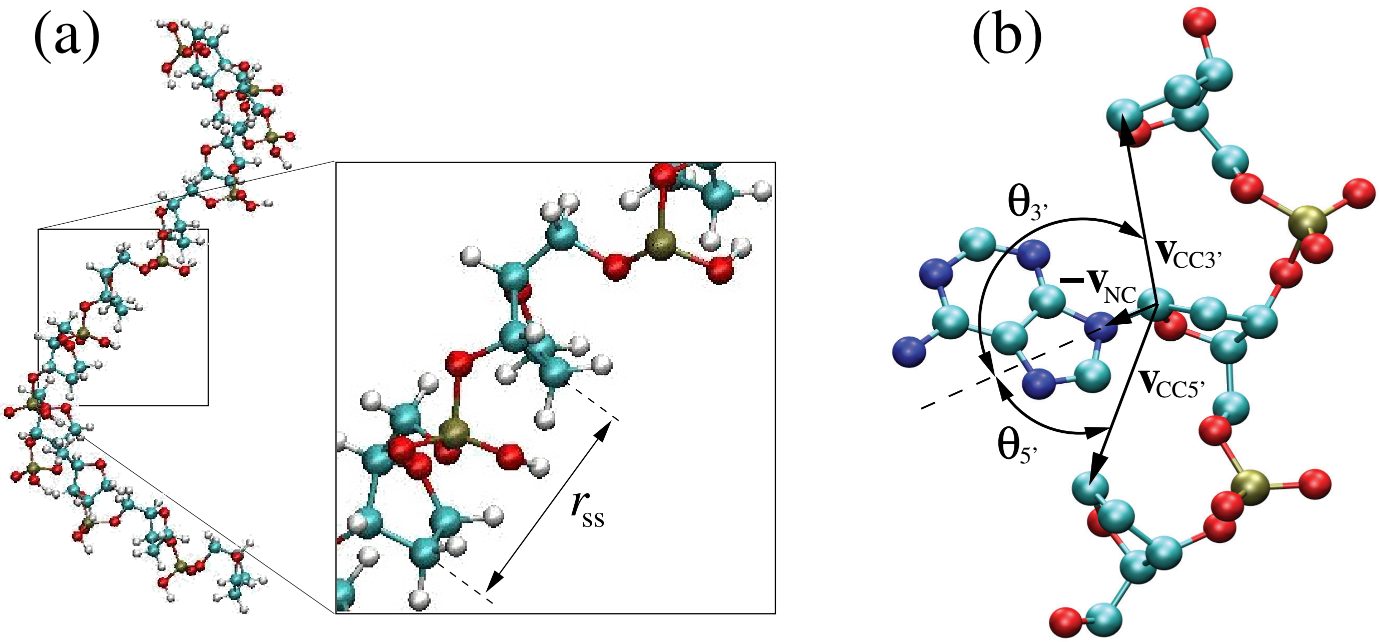
Coarse-grained potential – hydrogen bonding



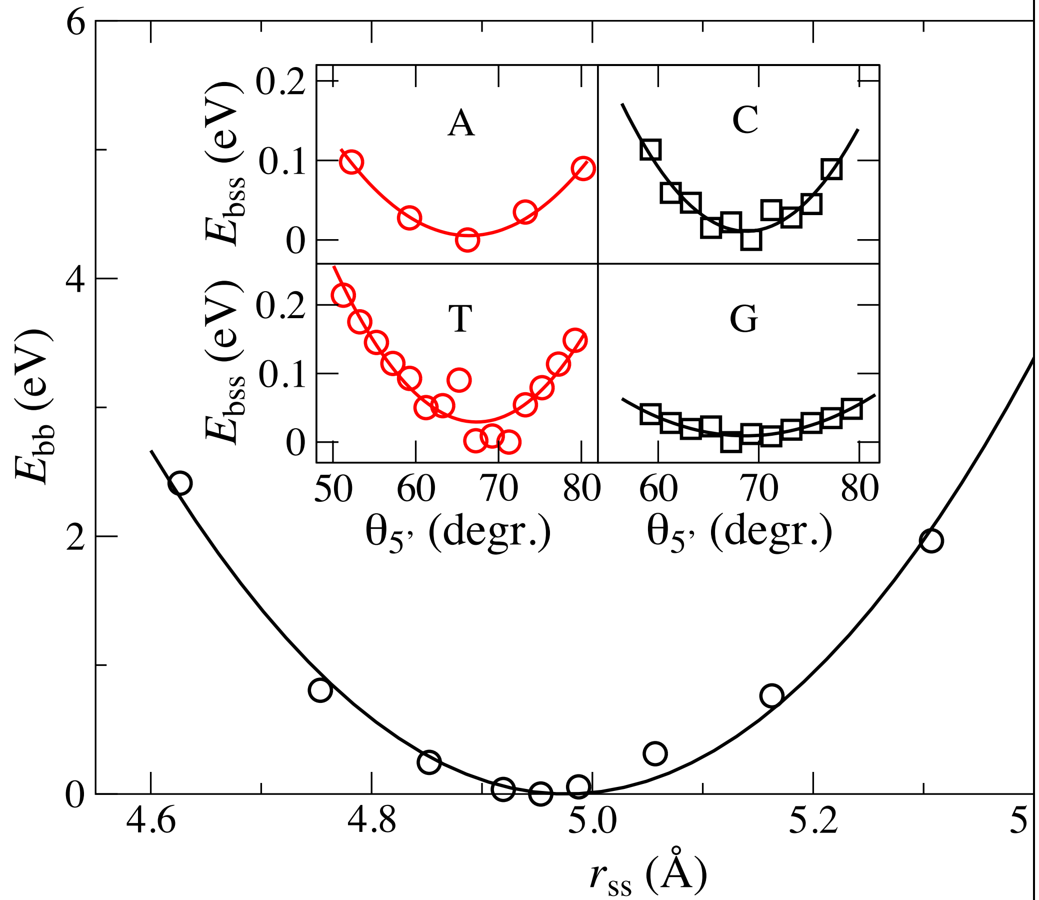
Coarse-grained potential – stacking interactions



Coarse-grained potential – backbone interactions



Coarse-grained potential – backbone interactions



$$E = \frac{1}{4\pi\varepsilon_0\varepsilon(r)}\frac{e^2}{r}$$

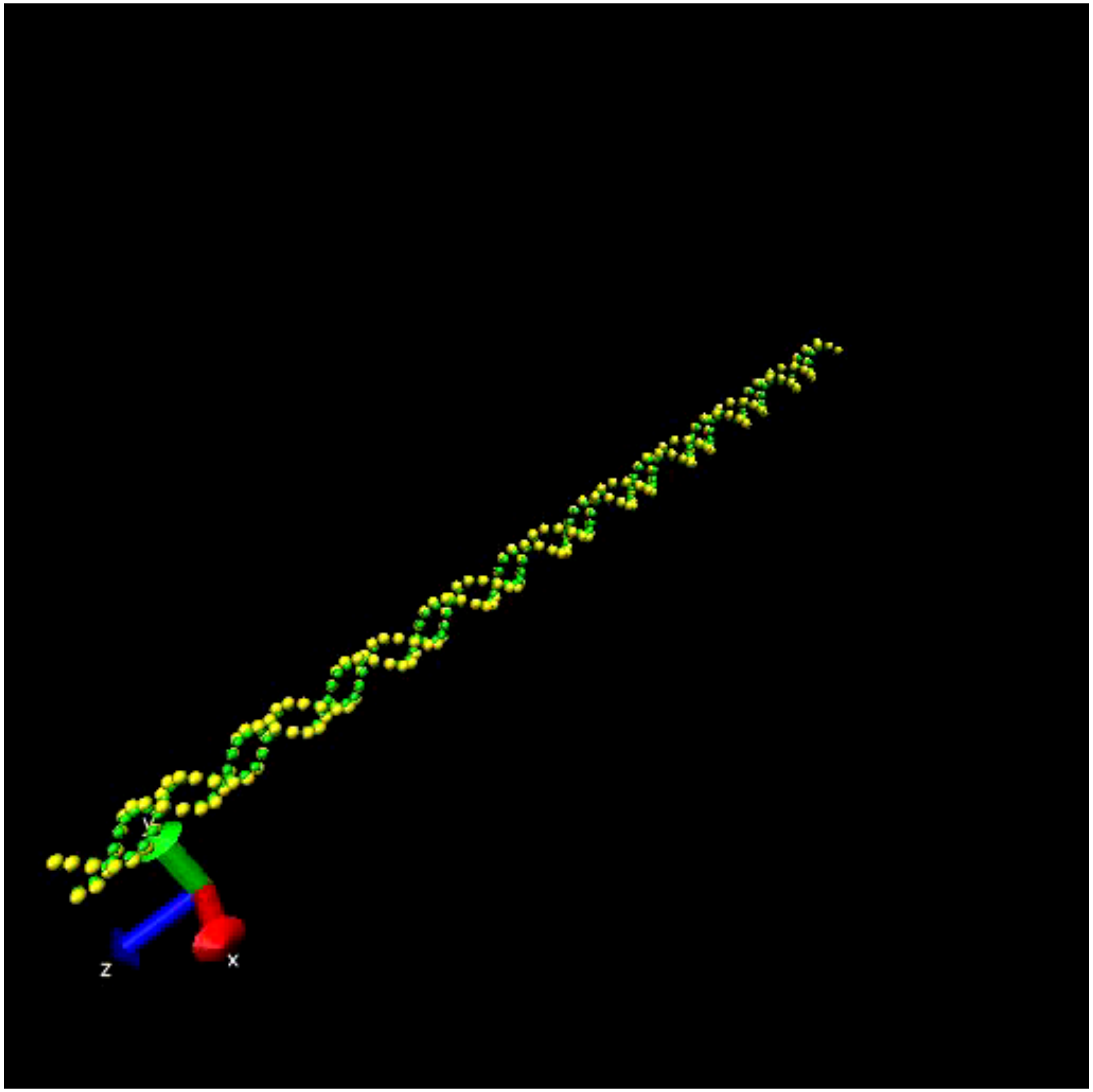
$$\varepsilon(r) = \varepsilon_{in} \qquad r < r_0$$

$$\varepsilon(r) = \varepsilon_{in}e^{\alpha(r-r_0)} \qquad r_0 < r < r_1$$

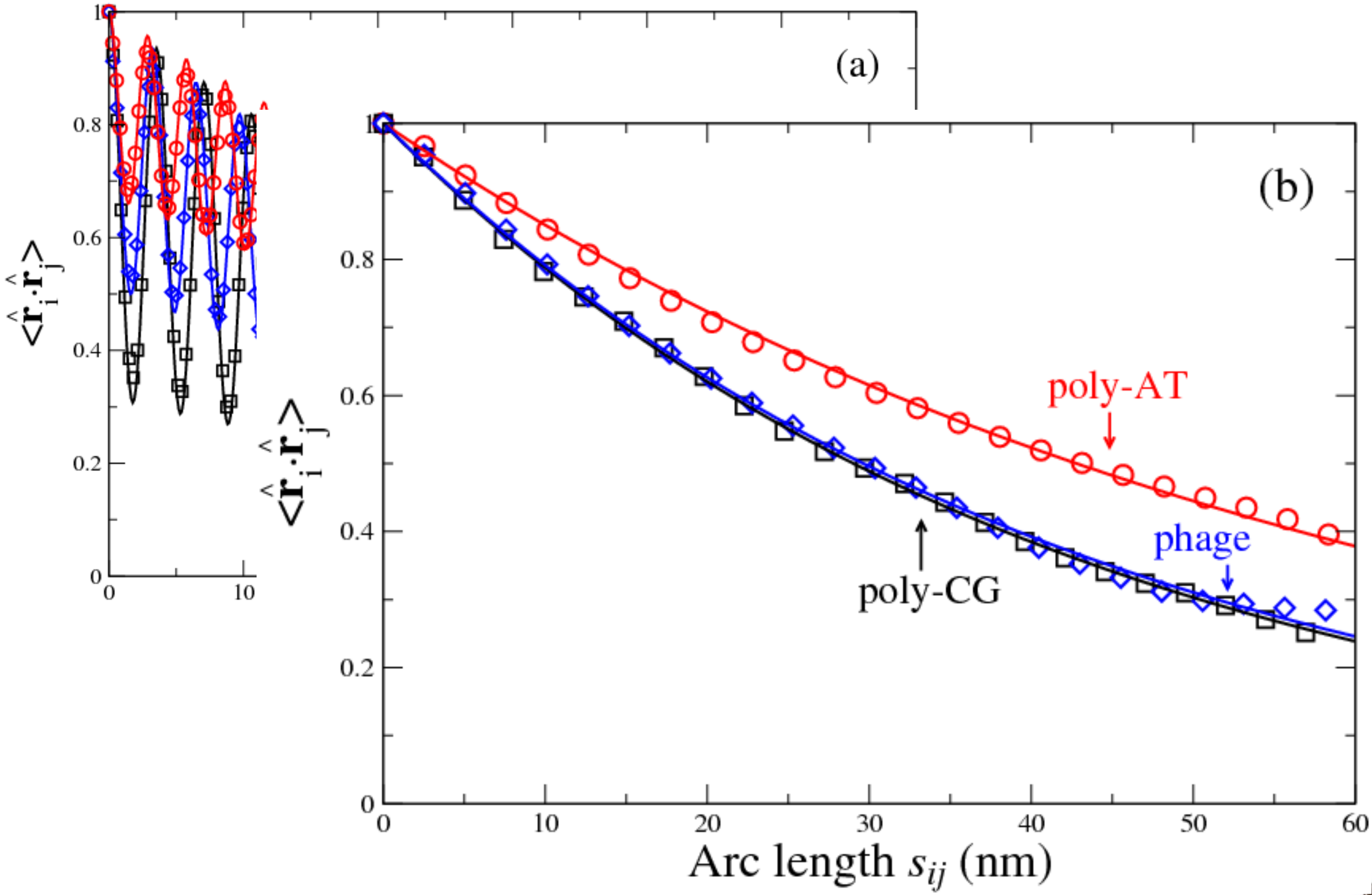
$$\varepsilon(r) = \varepsilon_{\infty}e^{-\kappa r} \qquad r > r_1$$

$$\kappa = \sqrt{\frac{\varepsilon_0\varepsilon_\infty k_B T}{2N_A e^2 I}}$$

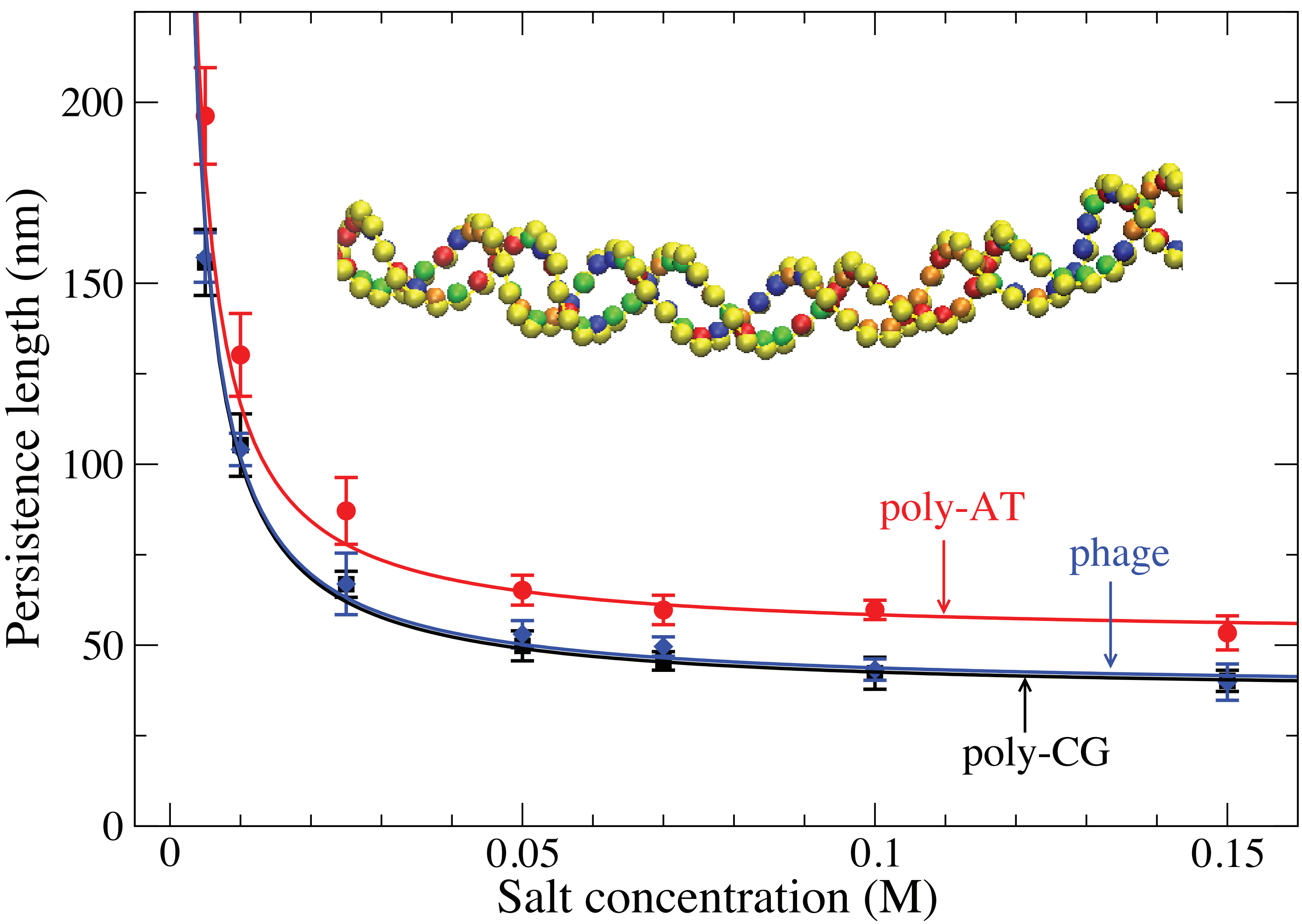
Coarse-grained potential – simulations



Coarse-grained potential – validation



Coarse-grained potential – validation



Force-extension simulations