SIBERIAN FEDERAL UNIVERSITY

Institute of fundamental biology and biotechnology

molpit International open laboratory for advanced science and technology

3rd International Conference
NANOBIOPHYSICS:
Fundamental and Applied Aspects
7-10 October 2013, Kharkov, Ukraine

Multi-level collective self-organization of biological particles

(Blot-droplet interaction of biological particles)

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Nobel Prizes 2013

- Physics. Organisation of elementary particles.
- Biology. Organisation of intracellular transport.
- Chemistry. Multi-scale organisation of biomolecules.

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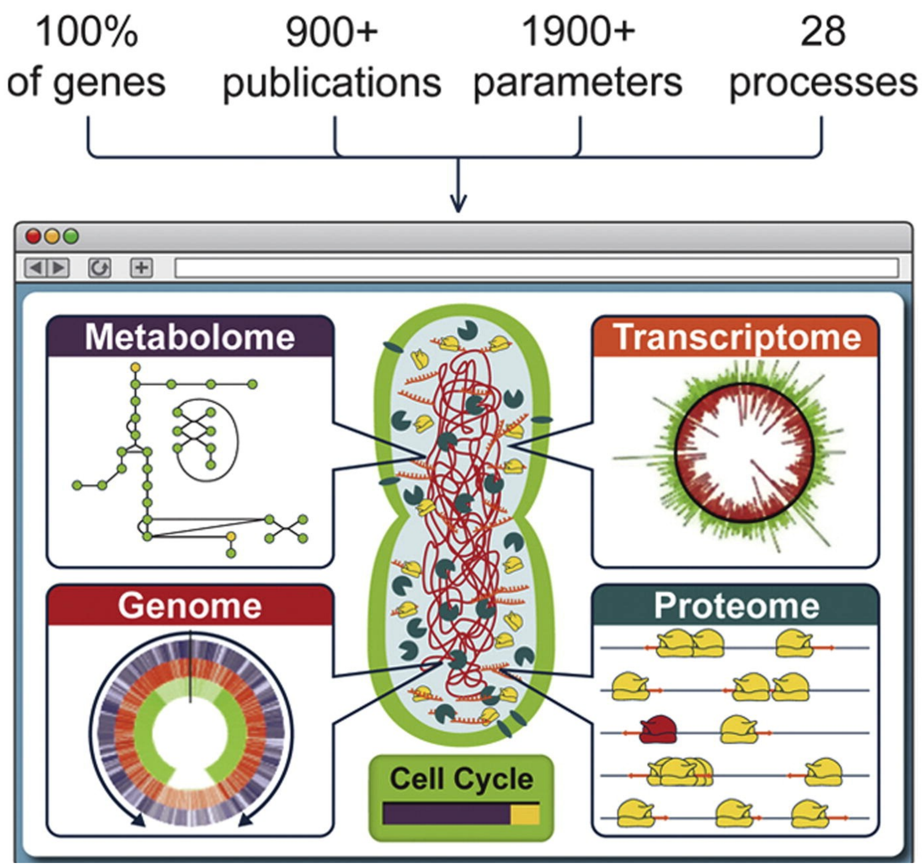
The Whole-Cell Computational Model



- To check novel biological hypotheses
- Theoretical computational experiments with new drugs
- Rational design of new biological experiments

J. R. Karr, J. C. Sanghvi, D. N. Macklin, M. V. Gutschow, J. M. Jacobs, B. Bolival, N. Assad-Garcia, J. I. Glass, and M. W. Covert, “A whole-cell computational model predicts phenotype from genotype,” Cell, vol. 150, no. 2, pp. 389–401, Jul. 2012.

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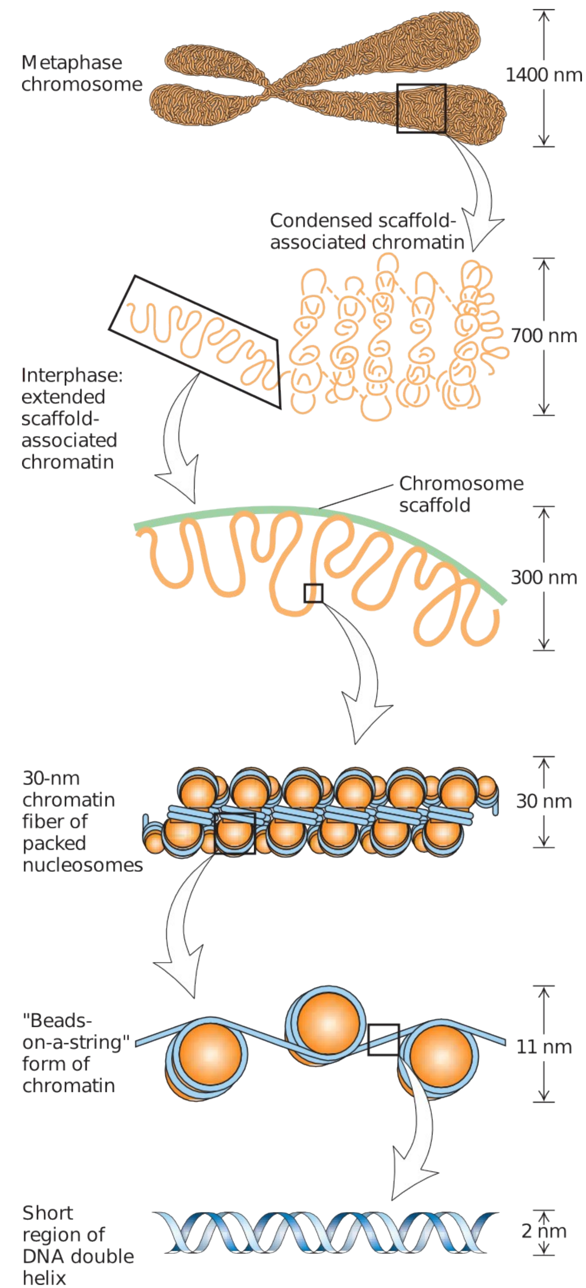
Multi-level problem in biology

Physics: Quarks, Elementary particles, Atoms, Molecules, Large molecules
Chemistry: Elementary particles, Atoms, Molecules, Large molecules, Complexes, Organells
Biology: Elementary particles … Planets
Physics: Biosphere, Planets, Stars, Solar systems, Galaxies, Universe

- Quarks
- Elementary particles
- Atoms
- Molecules
- Large molecules
- Complexes
- Organells
- Cells
- Tissues
- Organs
- Organisms
- Populations
- Ecosystems
- Biosphere
- Planets
- Stars
- Solar systems
- Galaxies
- Universe

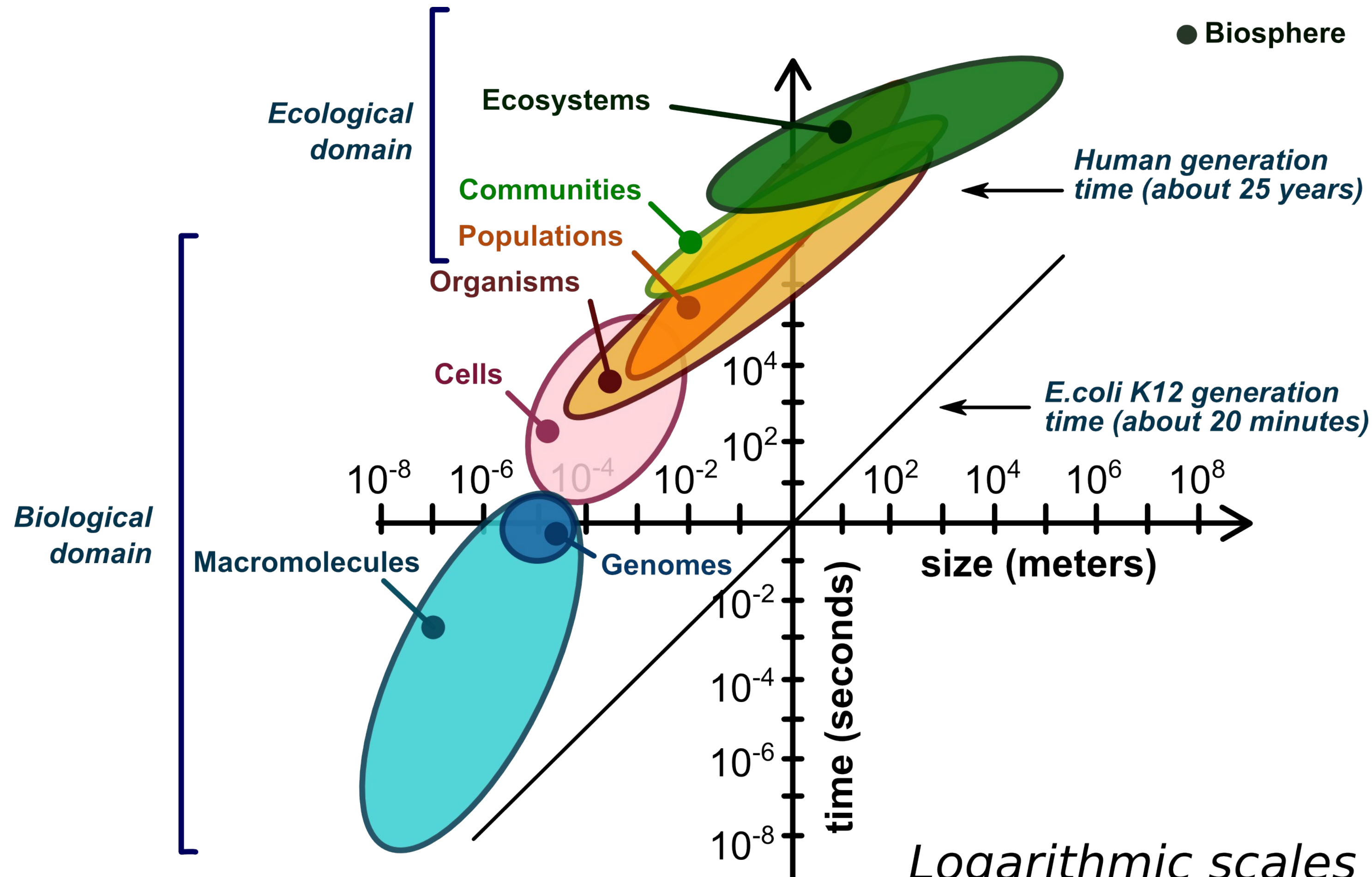
Modern research style in biology and medicine is multi-level — from genome to population (...omics).

It needs new math to link all the data in integral models.



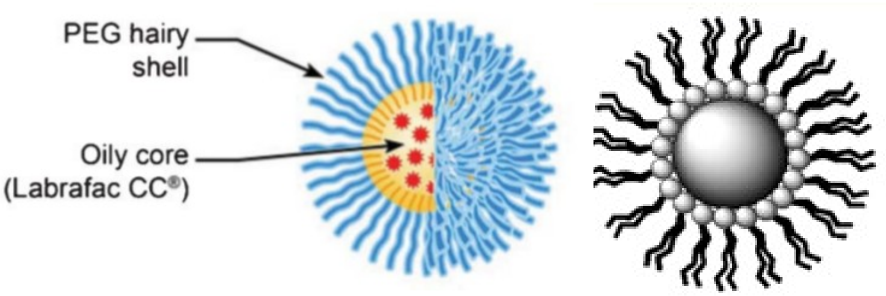
Idea was taken from F.A. Kondrashov lecture
http://elementy.ru/video?pubid=431332

How to model biological hierarchy?

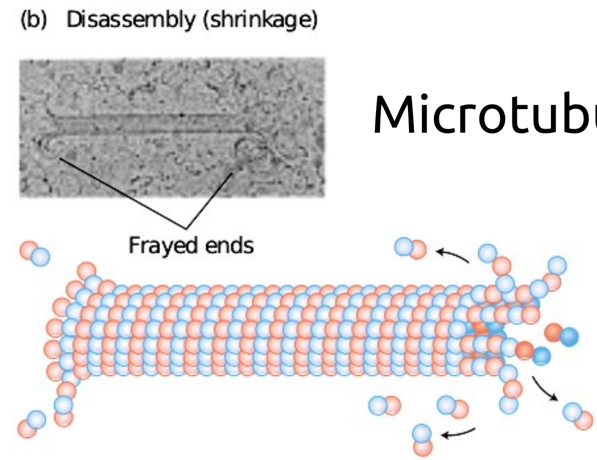


A. Pavé, "Biological and Ecological Systems Hierarchical Organisation," in Hierarchy in Natural and Social Sciences, vol. 3, D. Pumain, Ed. Berlin/Heidelberg: Springer-Verlag, 2006, pp. 39–70.

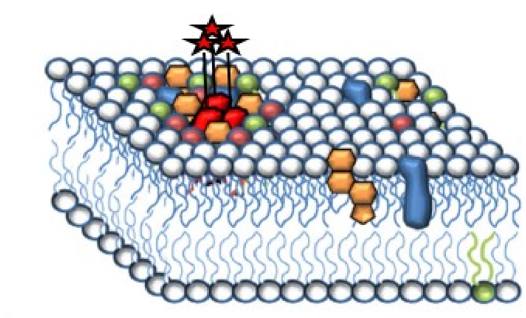
Each level is controlled by self-assembly



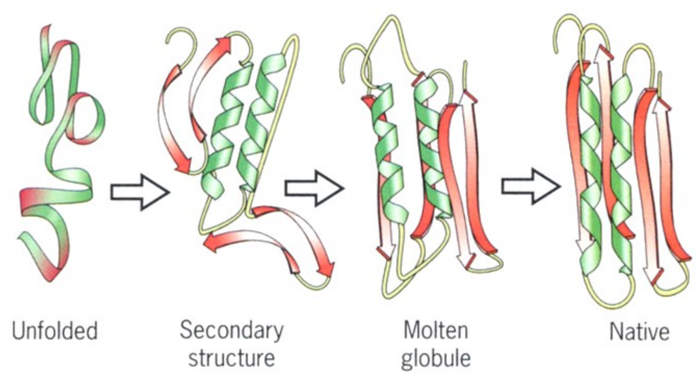
Micelles and liposomes



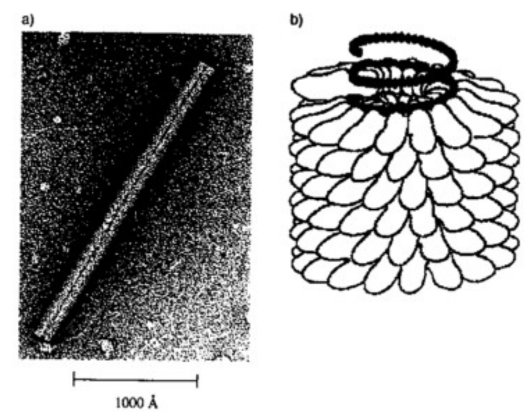
Microtubules



Lipid rafts



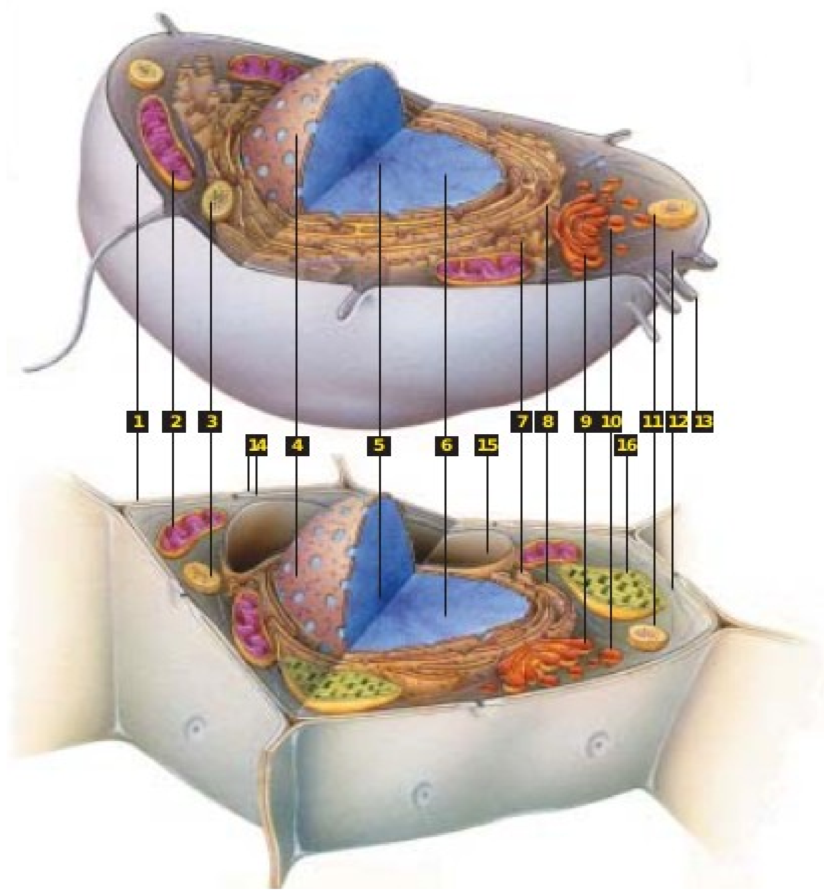
Protein folding



Viruses envelopes

George K.S., Wu S. Lipid raft: A floating island of death or survival. // Toxicology and applied pharmacology. Elsevier B.V., 2012. Vol. 259, № 3. P. 311–319.

Self-assembly in multi-level system of cell



For the whole-cell models we need:

1. Describe the interaction between bioparticles with known properties in several organization

2. Find the bioparticles properties in each level from character lows of physics, chemistry and biology for each level

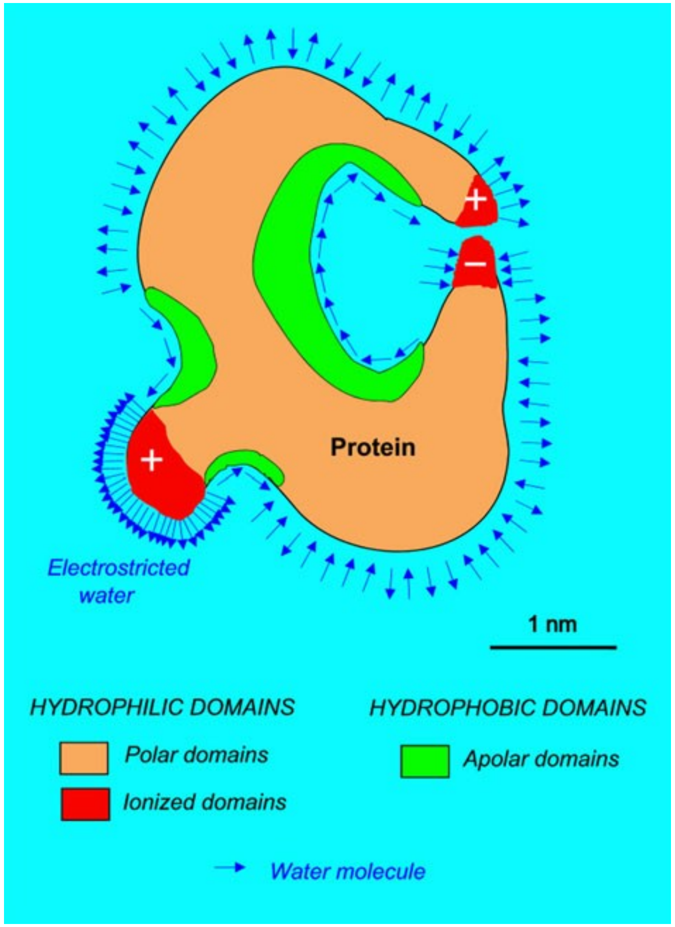
Lodish, 2003

Outlook

1. What is biological particle for the cell?
2. The multi-level model of bioparticles organization
3. Nanodiamond and cytoskeleton examples of multi-level self-organization.

1. What is biological particle for the cell?

Bioparticles and cell-sized water droplets



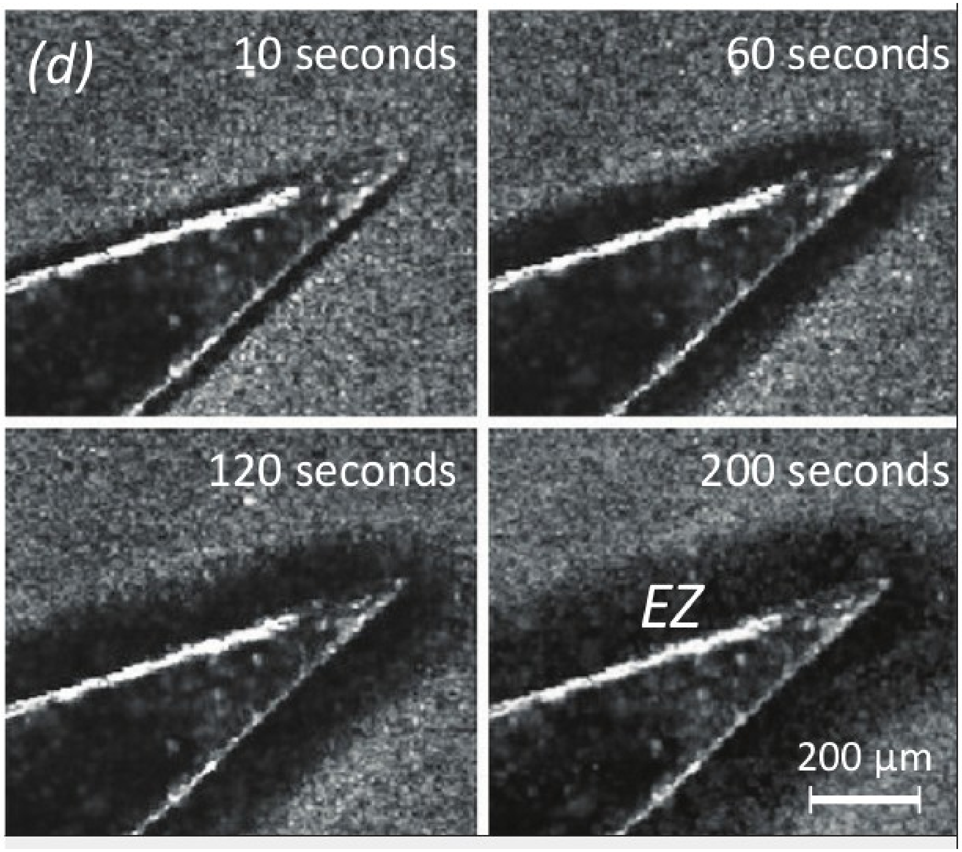
Hydrophilic surfaces changes surrounding water.

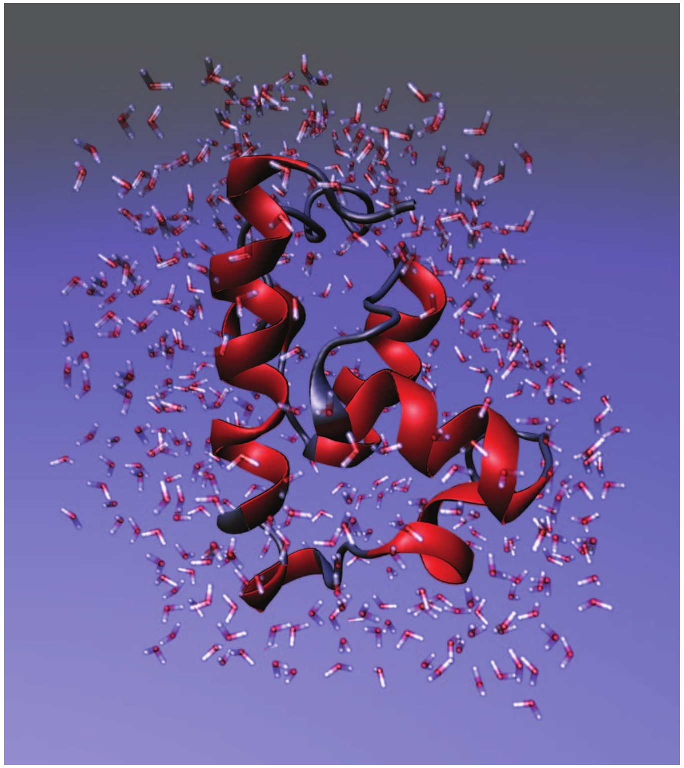
"physical properties of water could play a key role in the orchestration of the cell machinery"

Mechano-electrical collective properties of biomolecules.

Mentré P. Water in the orchestration of the cell machinery. Some misunderstandings: a short review // Journal of Biological Physics. 2011. Vol. 38, № 1. P. 13–26.

Exclusion zone





Leitner D.M., Gruebele M., Havenith M. Solvation dynamics of biomolecules: modeling and terahertz experiments // HFSP journal. 2008. Vol. 2, № 6. P. 314–323.

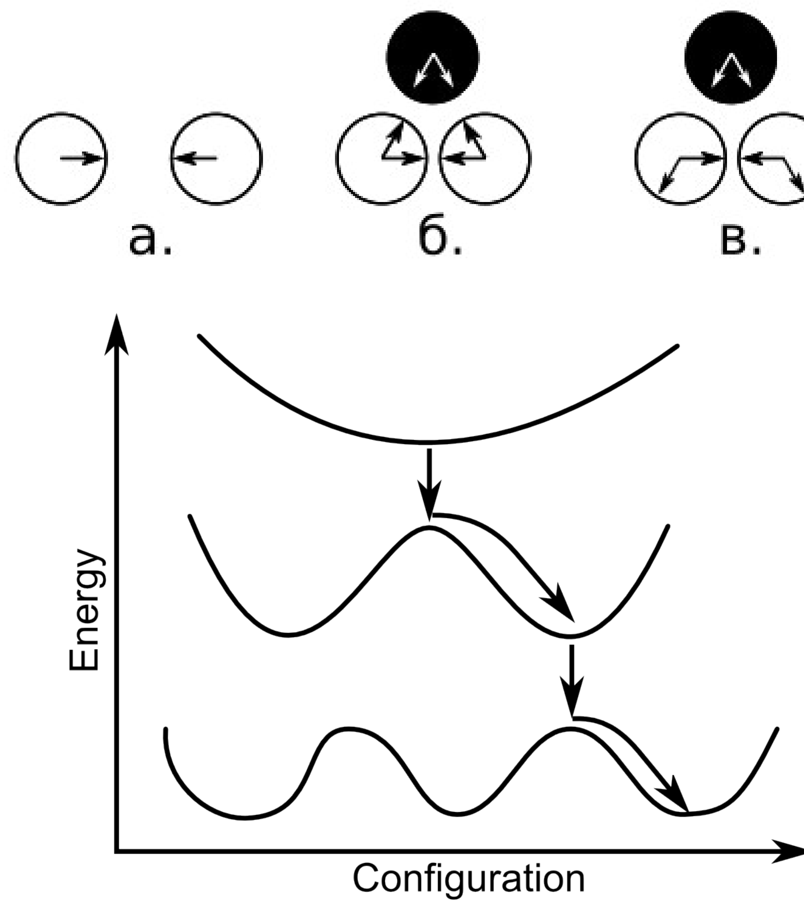
Pollack G.H. The fourth phase of water: beyond solid, liquid, and vapor. Seattle, WA: Ebner and Sons, 2013.

Biological particle is the structure defined in space and stable in a characteristic time of it's organisation level and having a biological function, that means direct or through levels of organisation formation of a living organism.

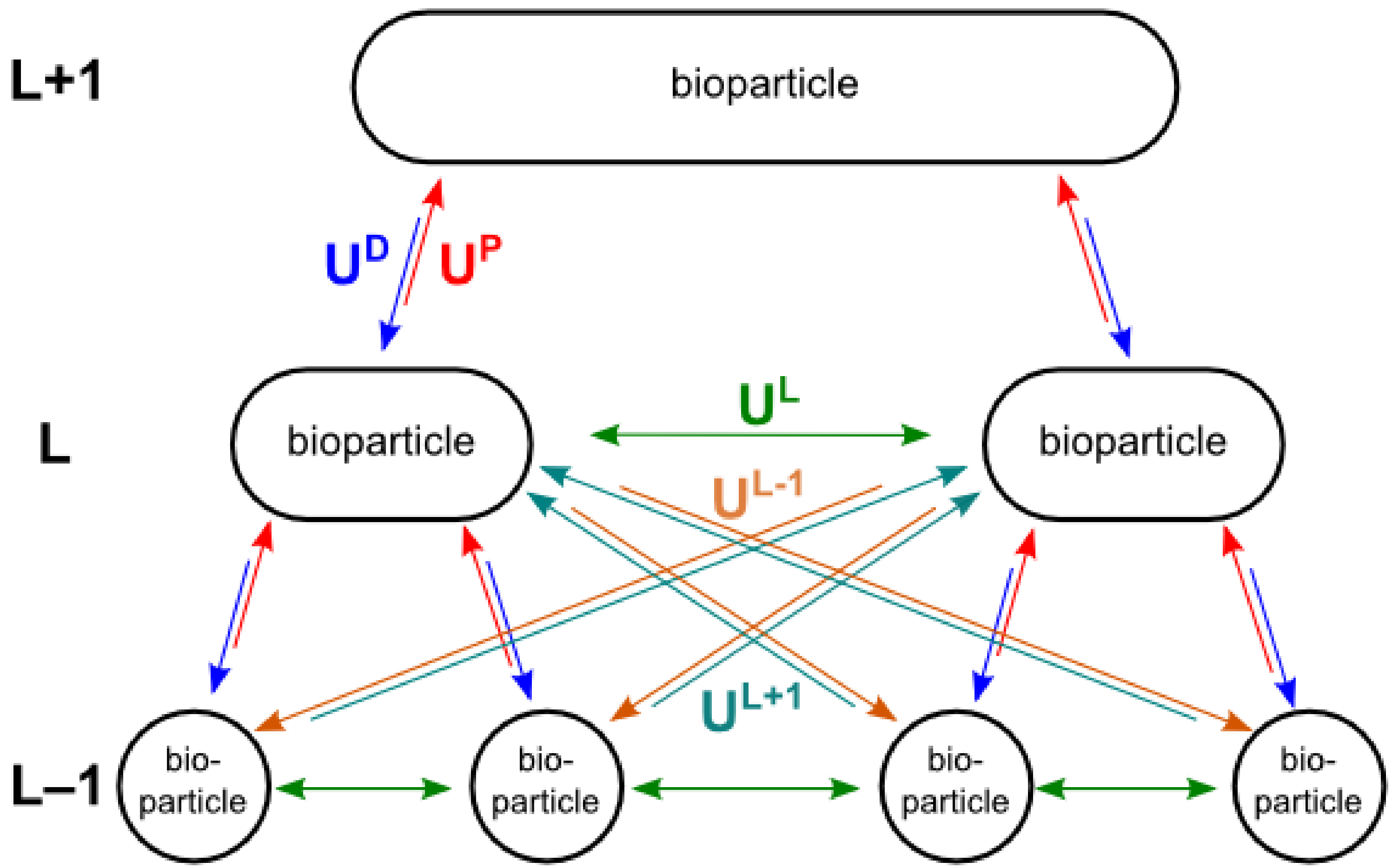
2. The multi-level model of bioparticles self-organisation

Bioparticles ≈ Object of organization

- Quasi-particle approach commonly used in physics for solving of many body problems.
- We are suggesting to use the object of organization for modeling of the energy landscape change.



Standard model for multilevel self-organized systems

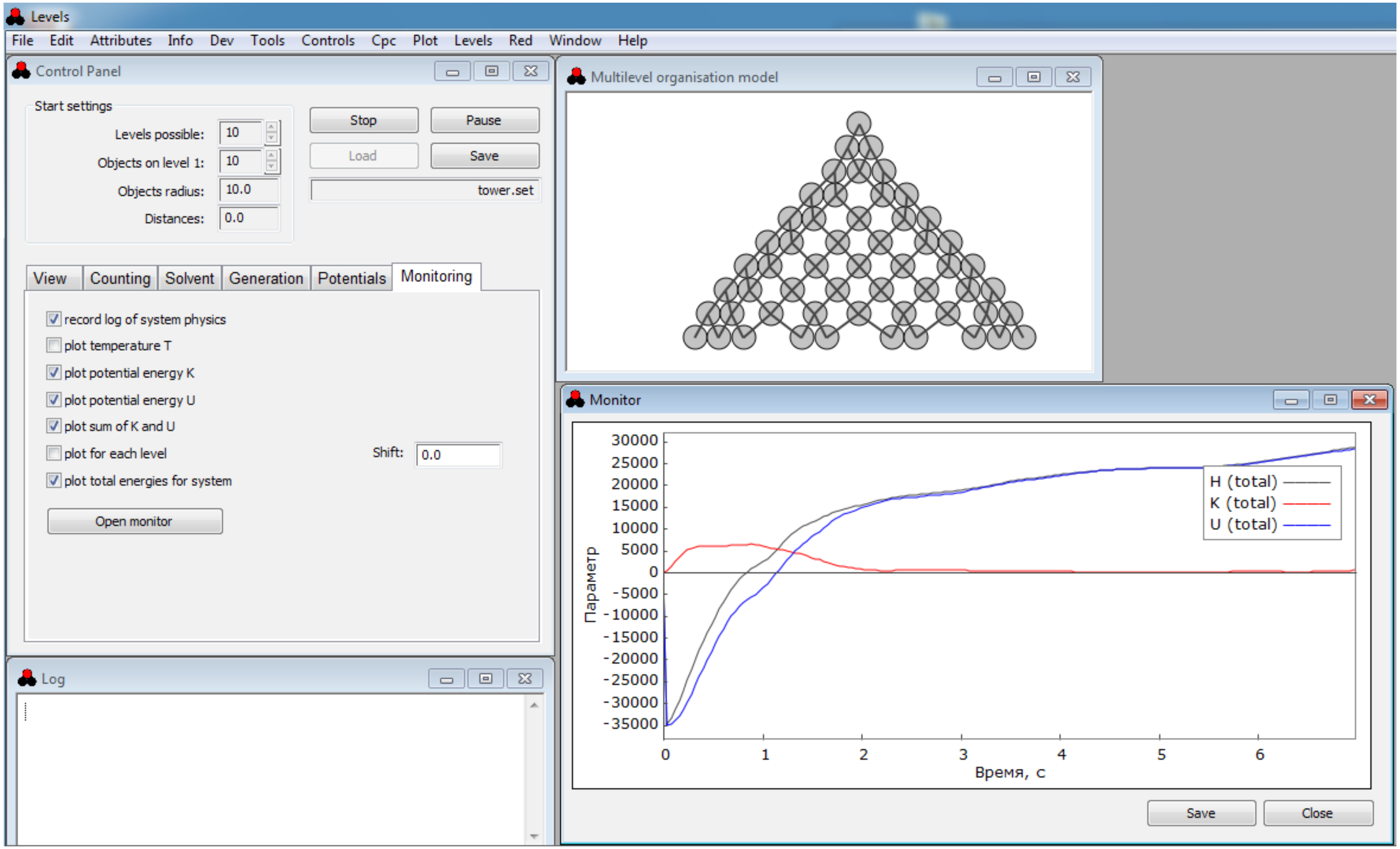


Classical mechanics and algorithms

$$
\left\{
\begin{aligned}
H = \sum_{i,j} \mathcal{T}_j^i \Bigg(& \frac{(p_j^i)^2}{2m_j^i} + \sum_{k\neq i} \mathcal{T}_j^k U_j^L(q_j^i, q_j^k) + \\
& + \sum_{k\notin D_j^i} \mathcal{T}_{j+1}^k U_j^{L+1}(q_j^i, q_{j+1}^k) + \sum_{k\notin P_j^i} \mathcal{T}_{j-1}^k U_j^{L-1}(q_j^i, q_{j-1}^k) + \\
& + \sum_{k\in P_j^i} \mathcal{T}_{j-1}^k U_j^P(q_j^i, q_{j-1}^k) + \sum_{k\in D_j^i} \mathcal{T}_{j+1}^k U_j^D(q_j^i, q_{j+1}^k) \Bigg),
\end{aligned}
\right.
$$

Algorithmic functions — *trigger function* and *successor functions*.

Application for exploring of multi-level systems



BlackBox Component Builder

Energy dynamics during the system evolution

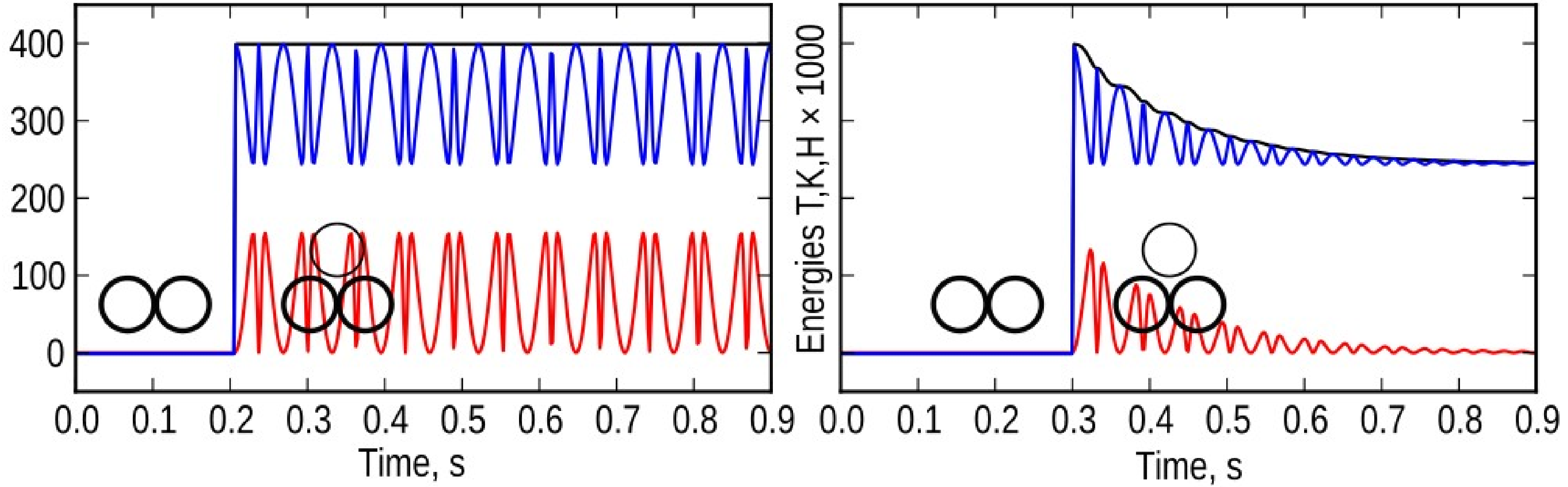
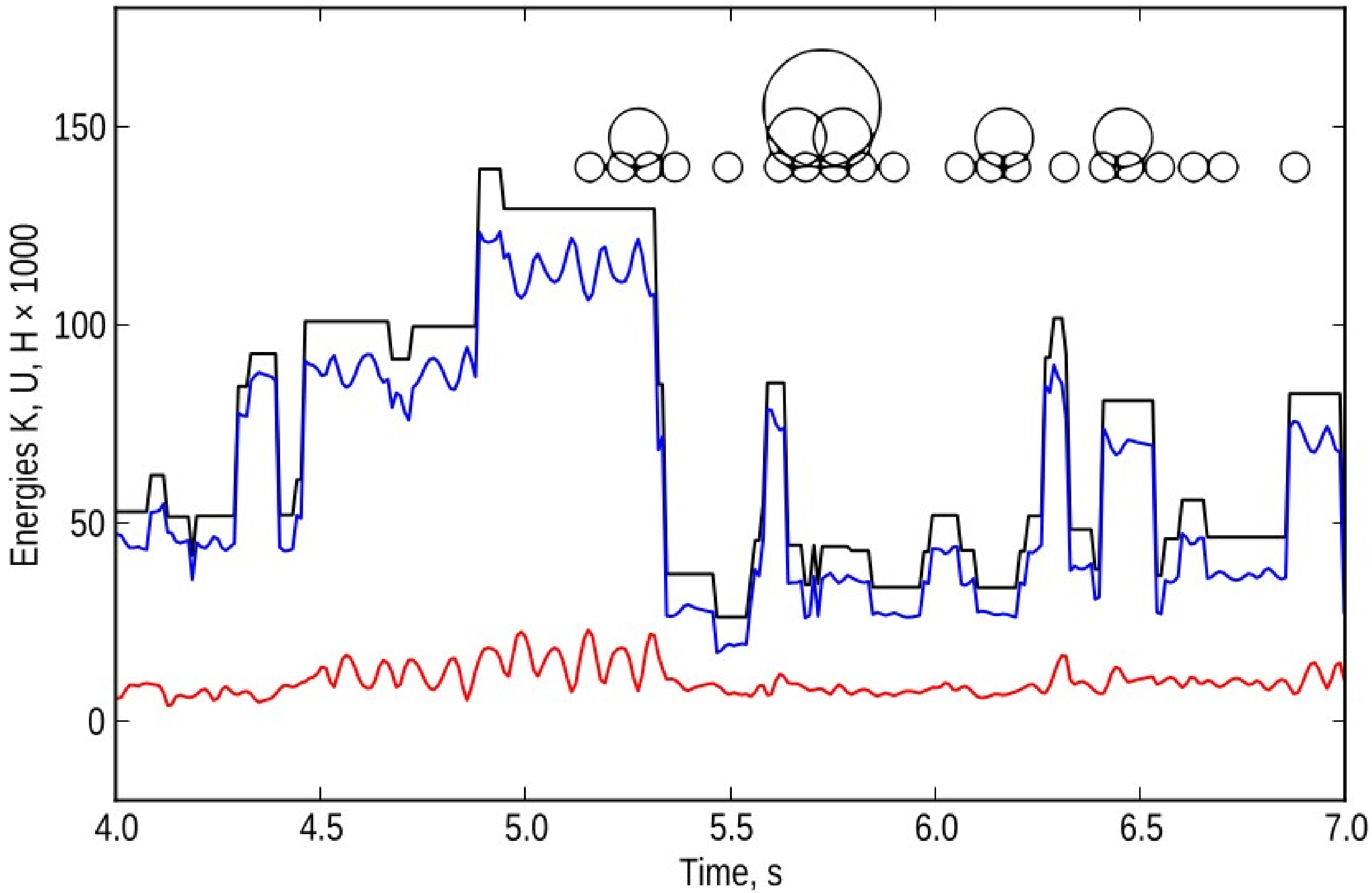


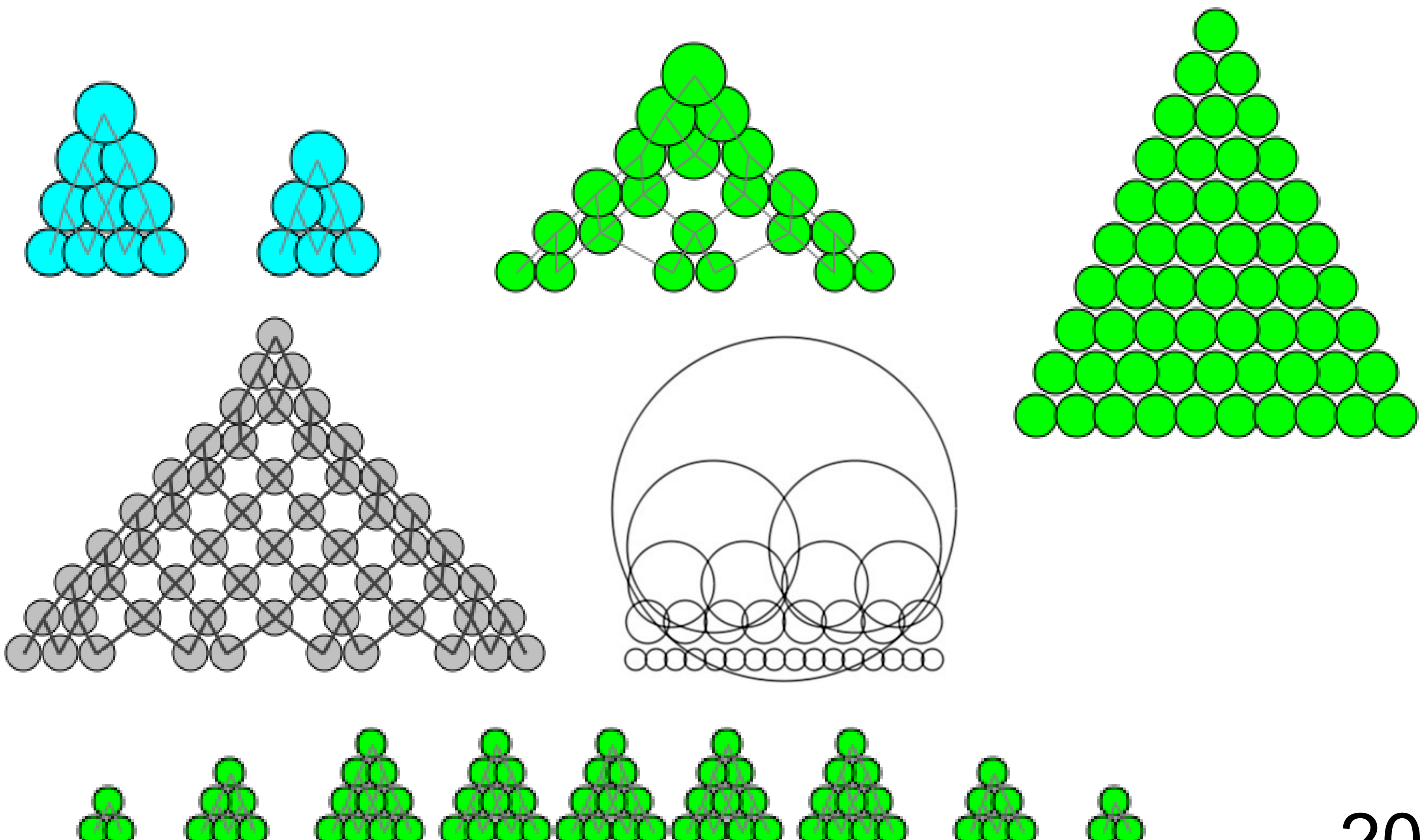
Fig. 9. The energy is skipping with appearing of new object and oscillate or decay in the case of dissipation

Energy dynamics during the system evolution



The total energy dynamics in the case of multi-level self-assembly

Organization patterns

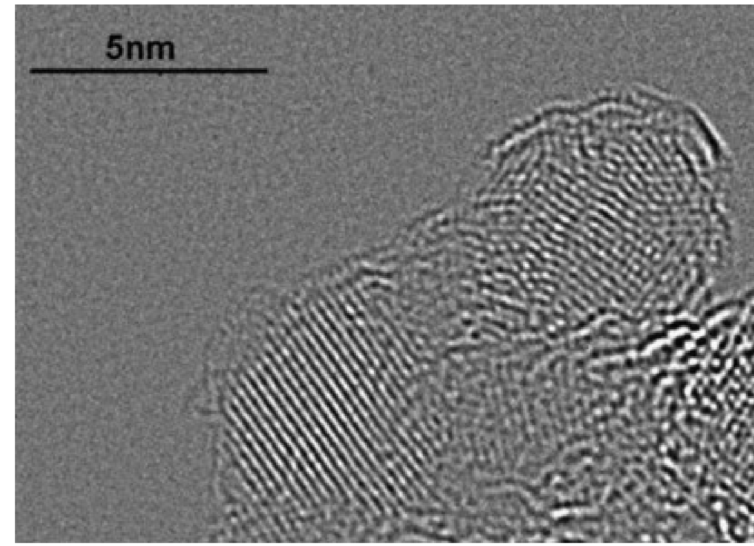


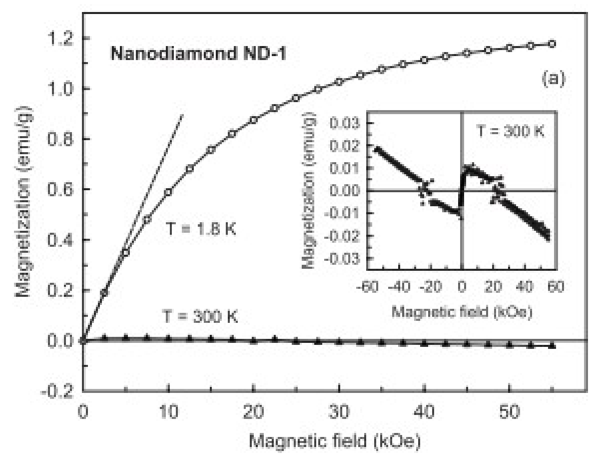
3. Nanodiamond and cytosceleton examples of multi-level self-organization

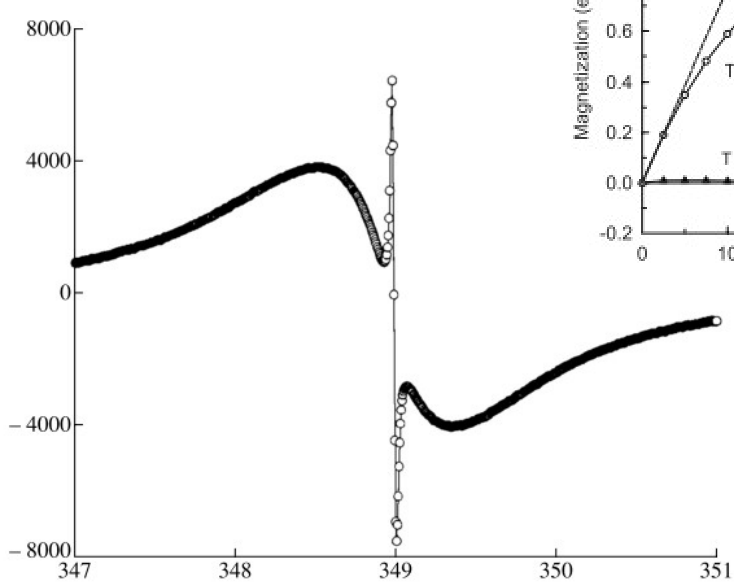
Nanodiamond

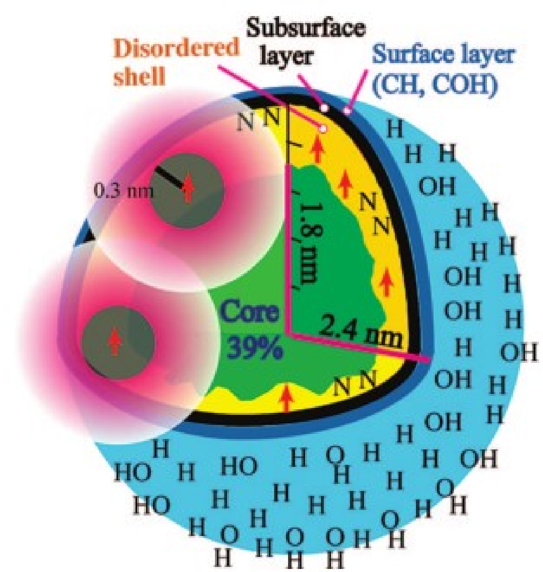
Collective states in nanodiamond: theoretical explanation of experiment.

Atomic orbitals → collective molecular orbitals → collective supramolecular orbitals → biopolimers

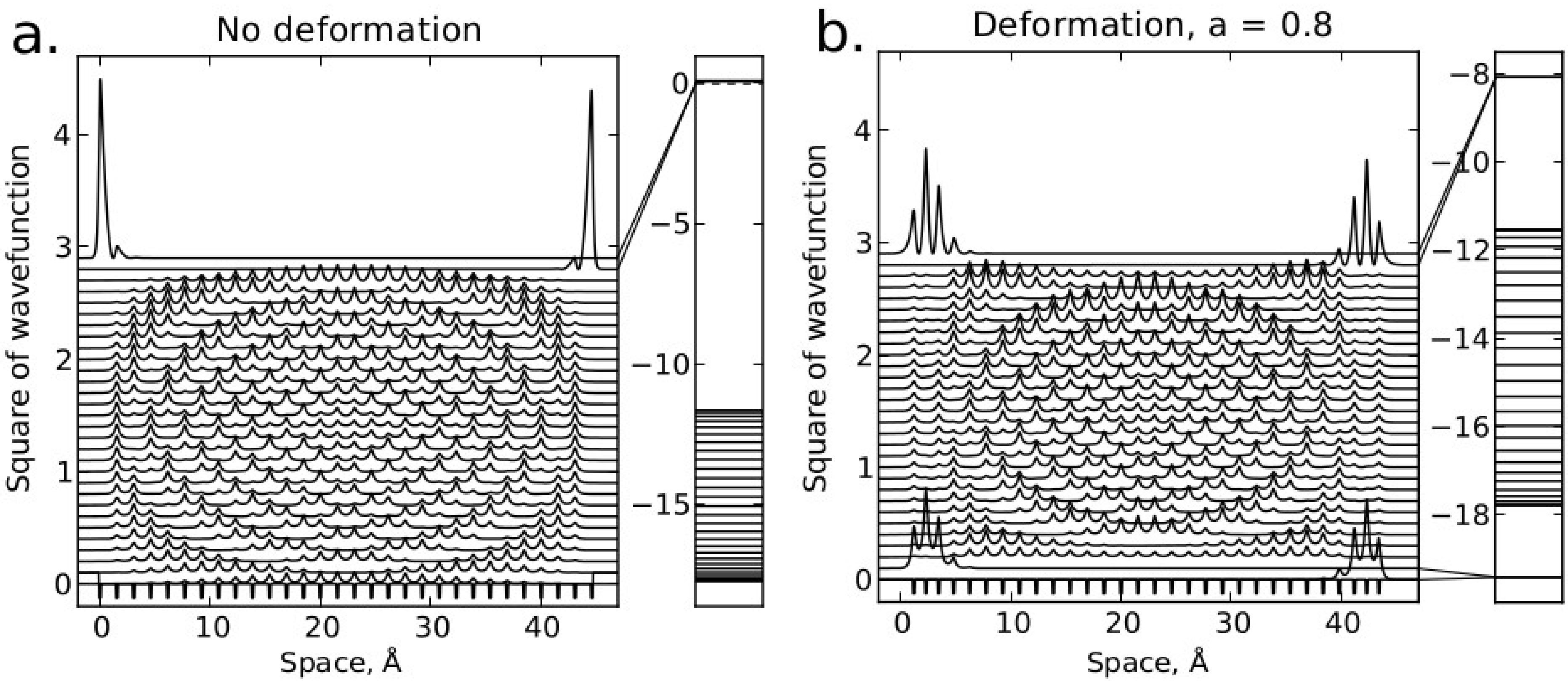








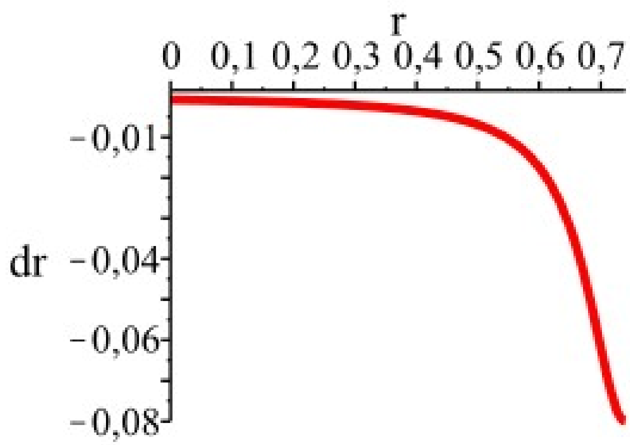
Tamm surface states & subsurface states of Phariseau



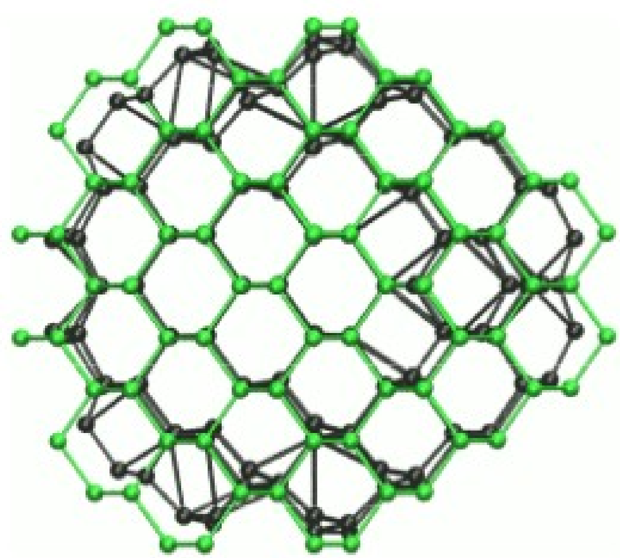
Compression of the diamond ball surface

$$dr(r) = \frac{-a}{\left(s - \frac{rs}{R}\right)^2 + 1},$$

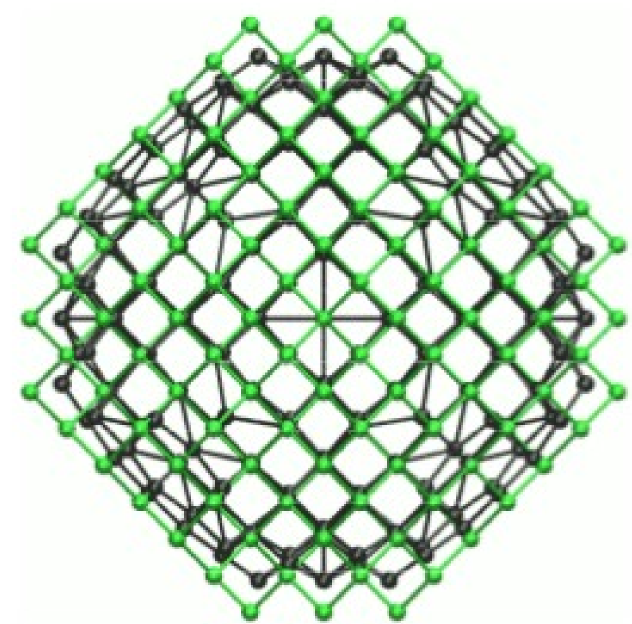
a



b



c



The demonstration of the deformation method (a) Atom position shift to the origin vs. coordinate (fitted to function (1) with parameters s = 10, a = 0.08). (b, c) Deformation of diamond ball carbon lattice C_{302} accordingto function (1) in two projection: initial molecule shown by green, deformed by black.

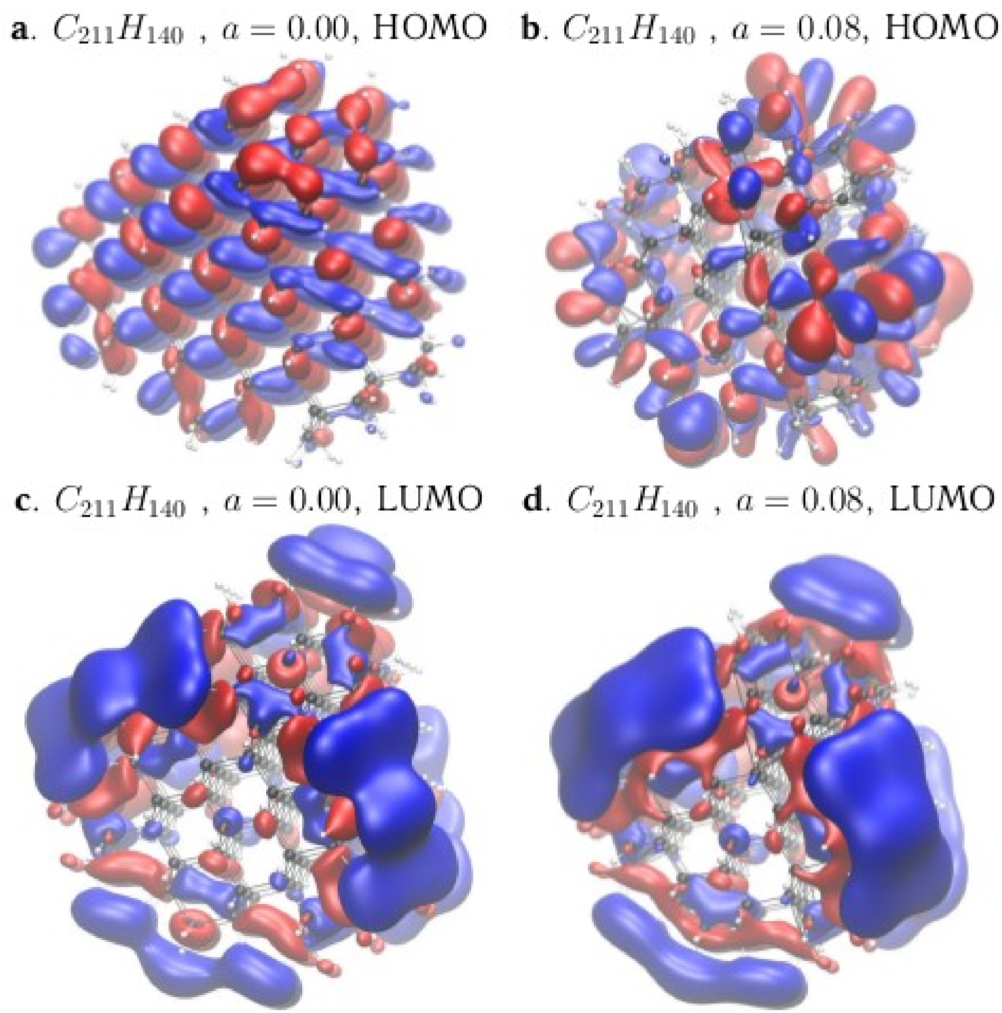
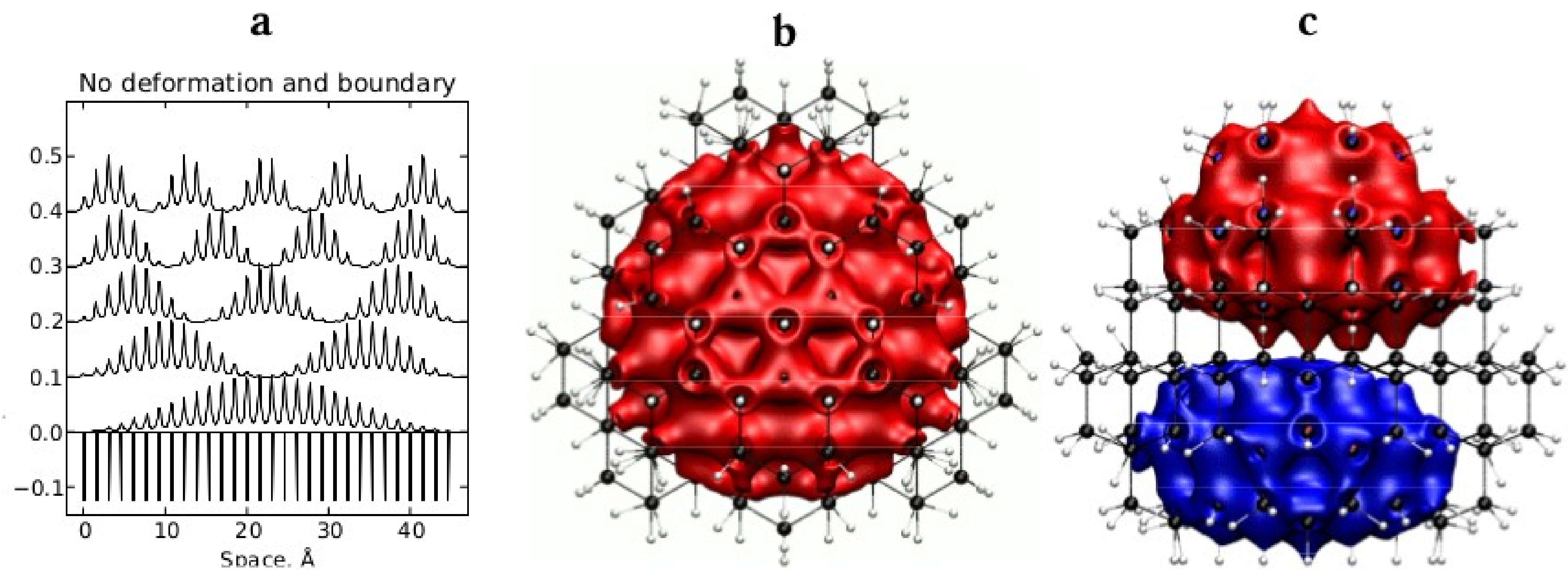
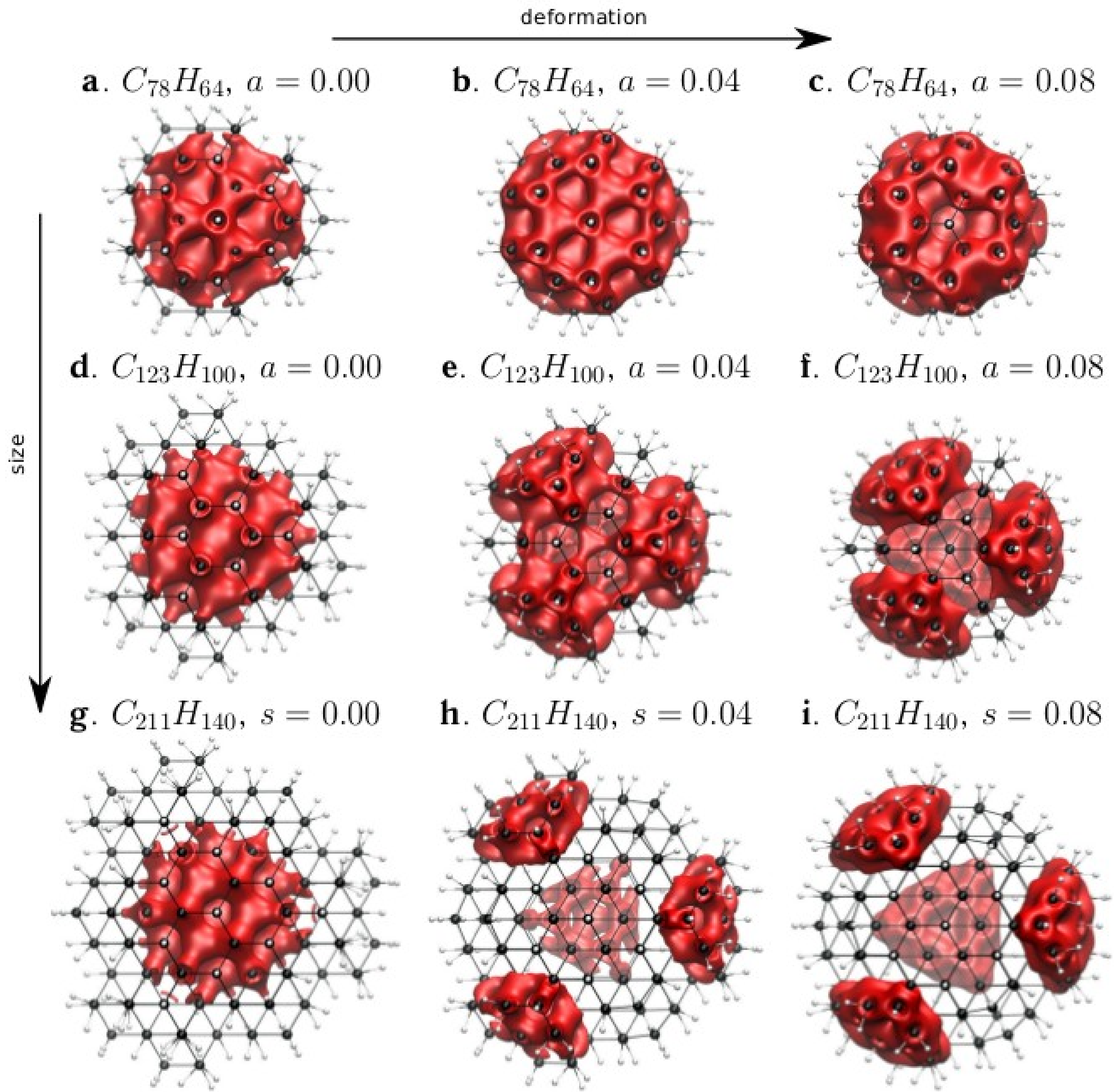


Рис. 3.6. Изоповерхности волновых функций алмазоида 1.34 нм в диаметре $C_{211}H_{140}$ (красным 0.01 a.u., синим −0.01 a.u.): (**a**) HOMO, $a = 0.00$, (**b**) HOMO, $a = 0.08$, (**c**) LUMO, $a = 0.00$, (**d**) LUMO, $a = 0.08$.

New spherical system resemble hydrogenic wavefunctions

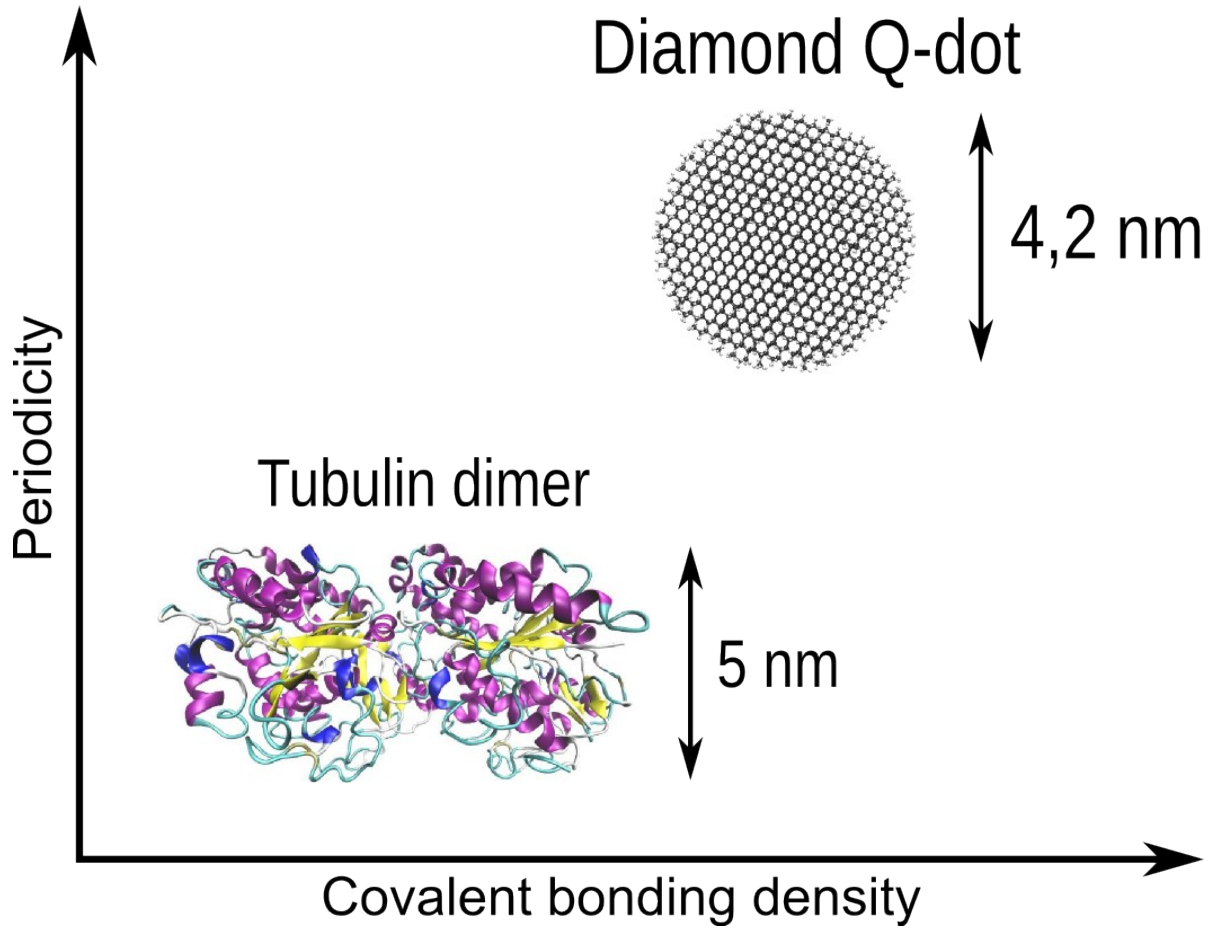


(a) First five bonding molecular orbitals for 1D case are resembling modulated particle-in-a-box solutions. (b, c) Isosurface of the first two bonding molecular orbitals #212 and #213 of $C_{211}H_{140}$ molecule resemble typical shapes and nodal structure of atomic s- and p-orbitals. Visualization is made in the VMD software package using PovRay



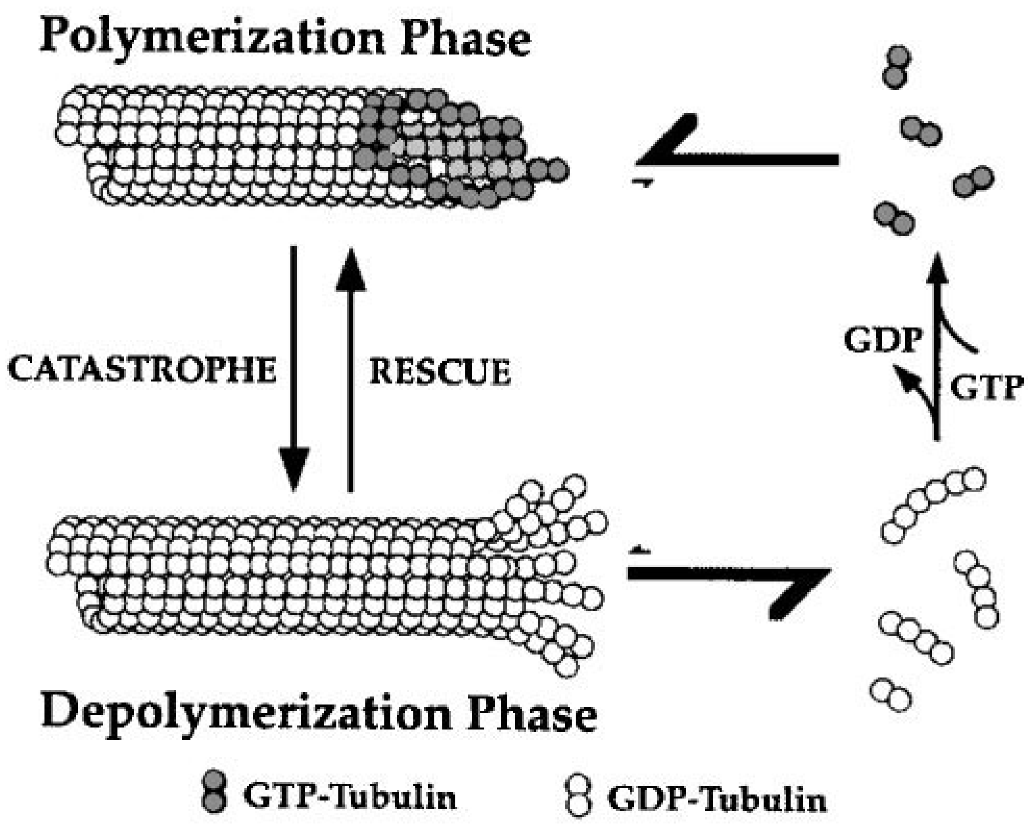
Subsurface collective electronic states in nanodiamond

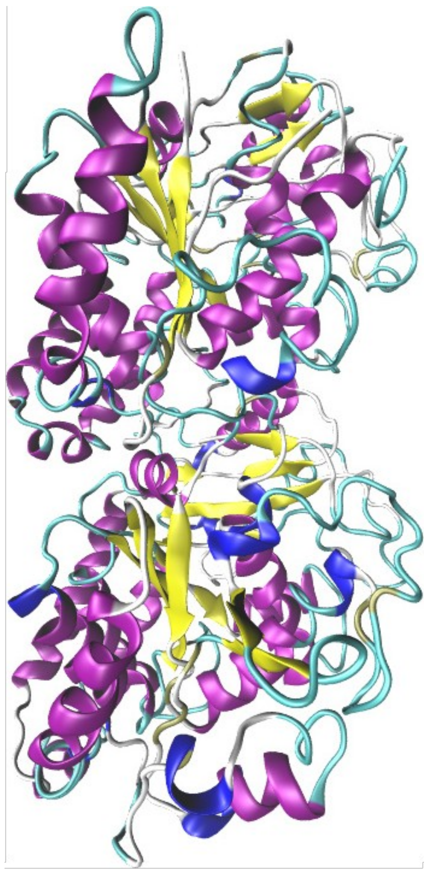
Nanodiamond as bioparticle model




Microtubules multi-level self-assembly

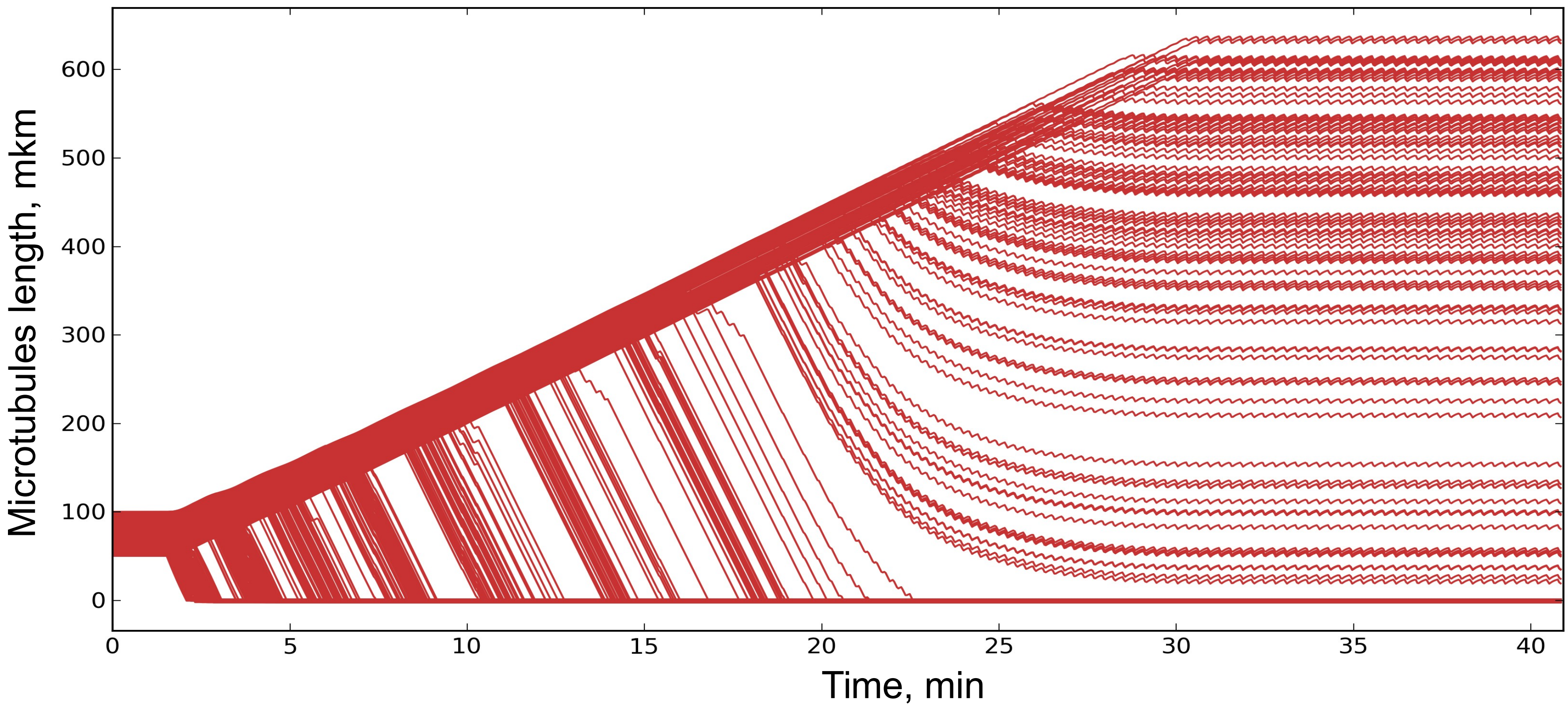
Microtubules multi-level self-assembly



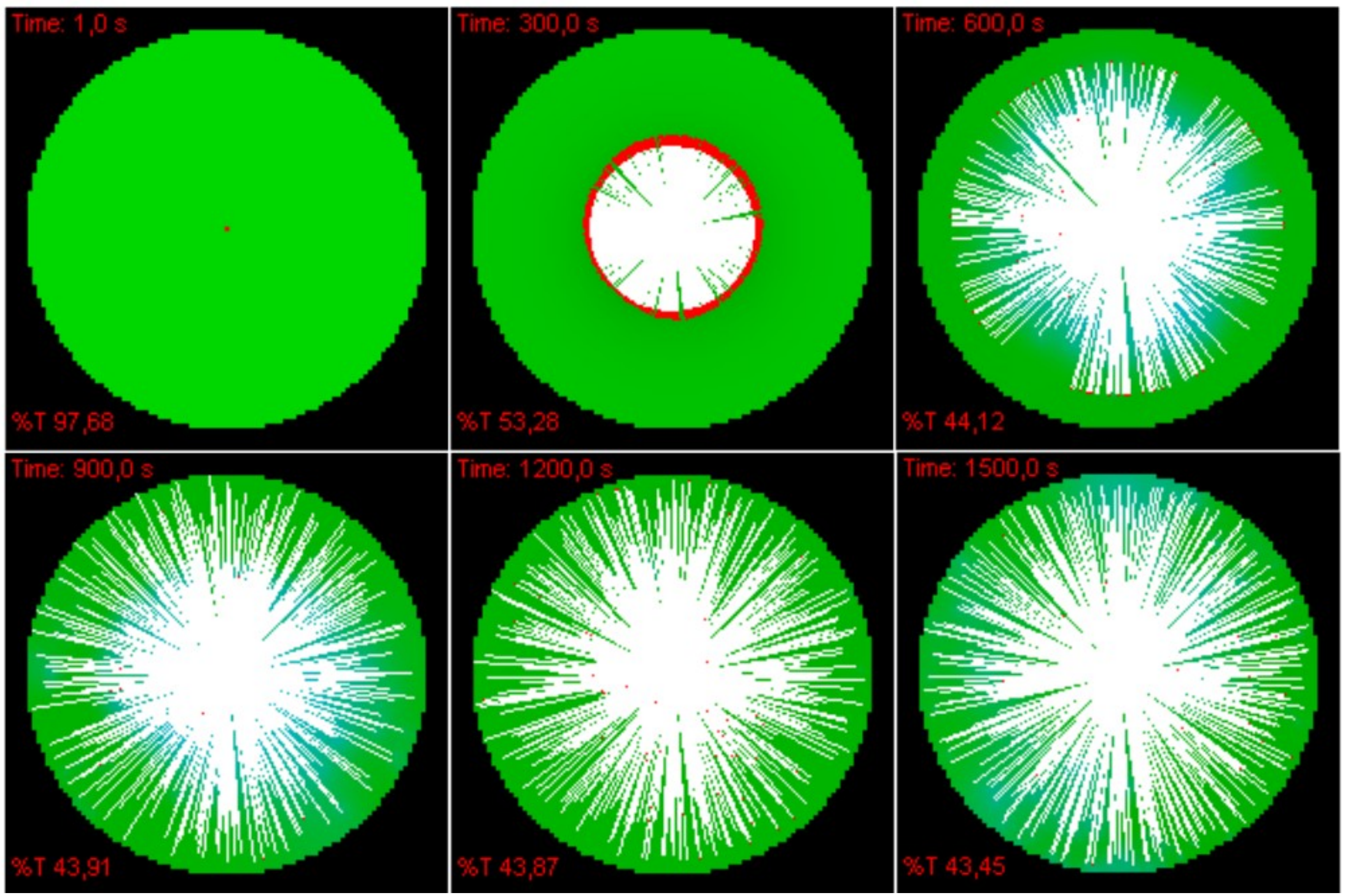


Desai A., Mitchison T.J. Microtubule polymerization dynamics // Annual review of cell and developmental biology. 1997. Vol. 13, № 1. P. 83–117.

500 microtubules competition without tubulin diffusion

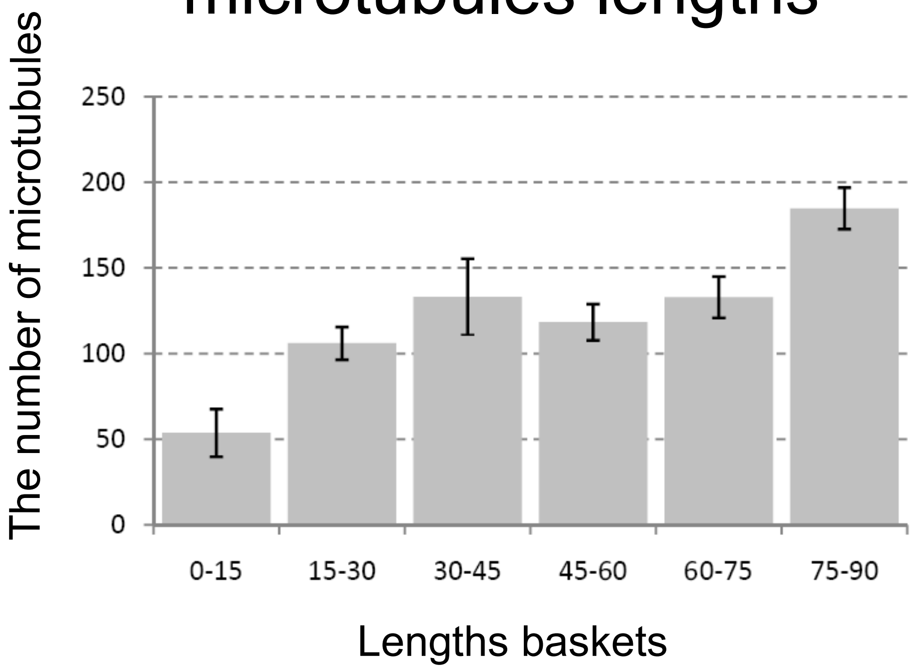


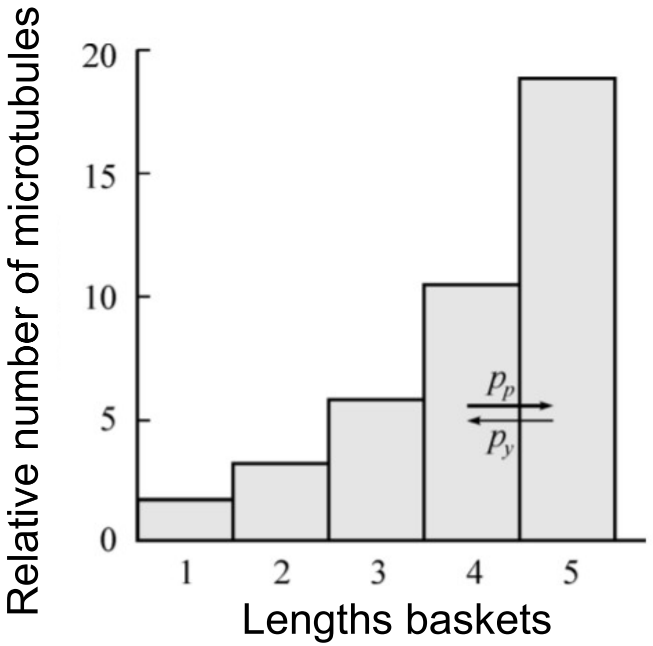
900 microtubules with diffusion of tubulins



Comparison

Bimodal distribution of microtubules lengths





Воробьев И.А., Малый И.В. Об отношении длины и динамики микротрубочек: краевой эффект и свойства протяженной радиальной сети // Цитология. 2008. т. 50, № 6. С. 477–486.

Conclusion

1. Suggested multi-level approach for modeling can be used to study the biological systems with several organization levels

2. The subsurface localization of collective orbitals can explain physical properties of nanodiamond

3. Three-level model of microtubules is describing experimental effects better than two-level model

Acknowledgement

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Sergey I. Barcev, Renat R. Sibgatulin

Final look

1. The problem of biological hierarchy.
2. What is biological particle?
3. The multi-level theory of bioparticles organization
4. Model for theoretical computational experiments.
5. Nanodiamond and cytoskeleton examples of multi-level self-organization.

Genotype→Phenotype mapping