



The physical chemistry of the photostability of life



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in collaboration
with

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1. Elementary building blocks of life

2. Problem of photostability

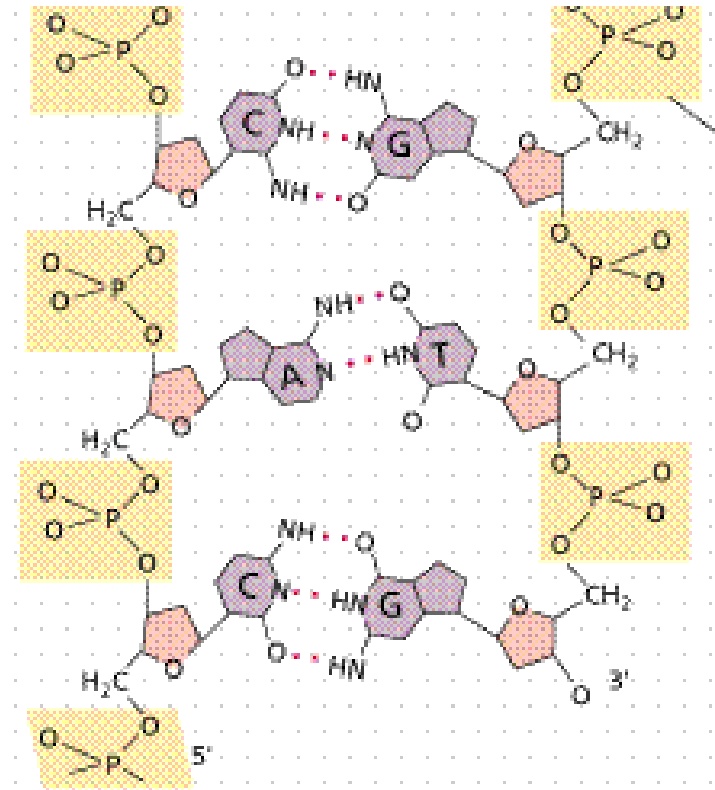
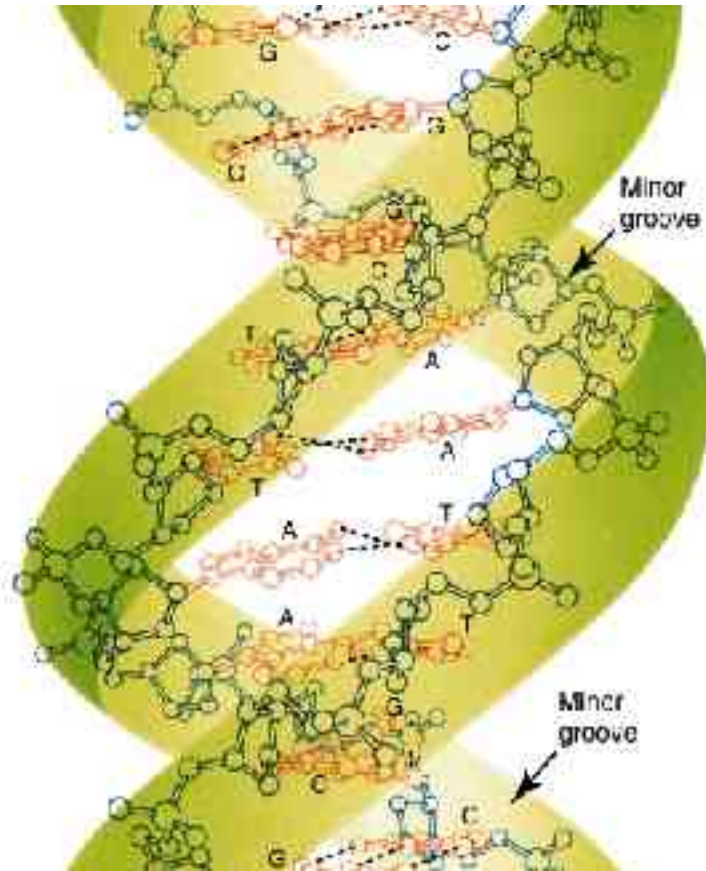
3. Photophysics of selected bio-molecules

4. Conclusions

1. Elementary building blocks of life

Life is an incredibly complex biochemical process which involves numerous molecular and macromolecular structures. On the molecular level one can notice, however, that the basic structures of living matter are constructed from relatively few molecular „bricks”.

Building blocks of life: DNA

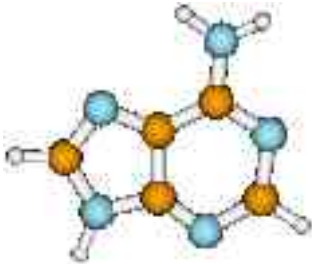


Almost all genetic information of creatures living on the Earth is encoded in DNA, the double helix form of which is determined by hydrogen bonds between the pair of molecules called DNA bases.

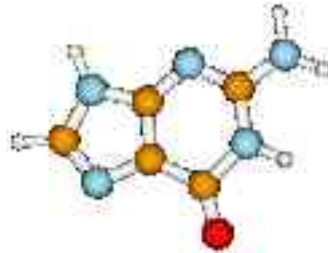
Building blocks of life: DNA bases

Among the variety of the so-called heteroaromatic molecules, Nature has „selected” only four for encoding of genetic information in DNA. These are:

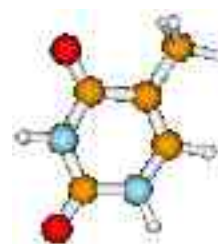
adenine



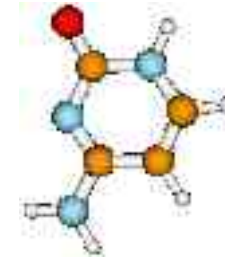
guanine



thymine

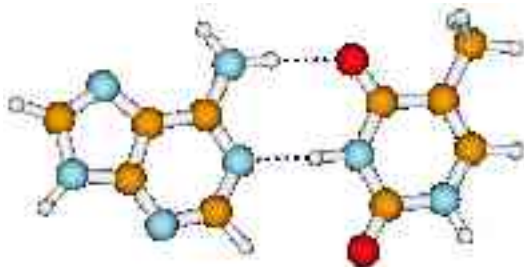


cytosine

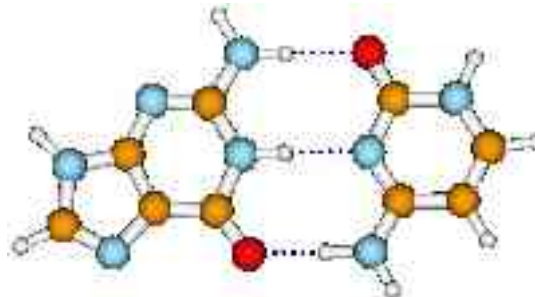


Only two pairs of the bases, called as the complementary Watson-Crick pairs, encode the genetic information in DNA

Adenine-Thymine



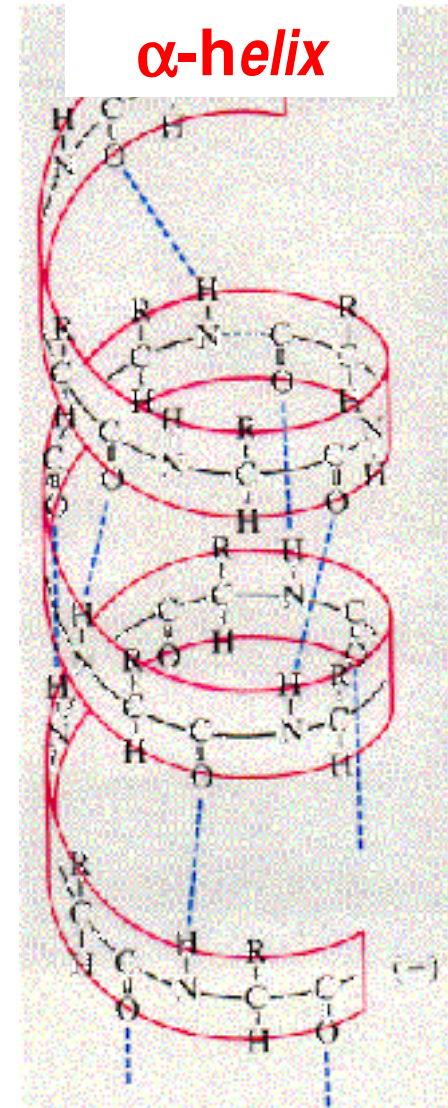
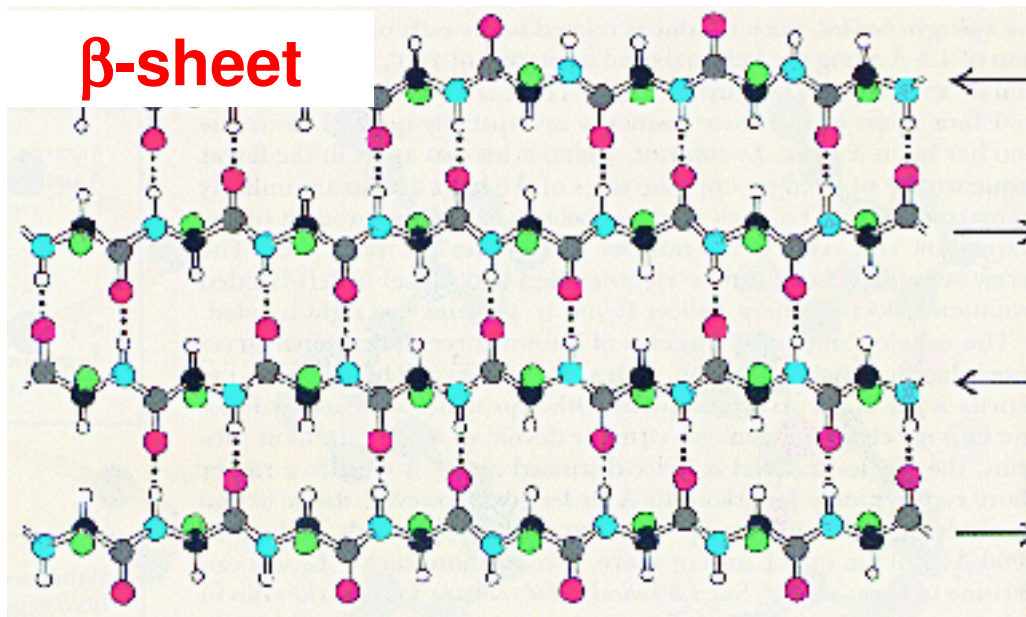
Guanine-Cytosine



- carbon
- nitrogen
- oxygen
- hydrogen

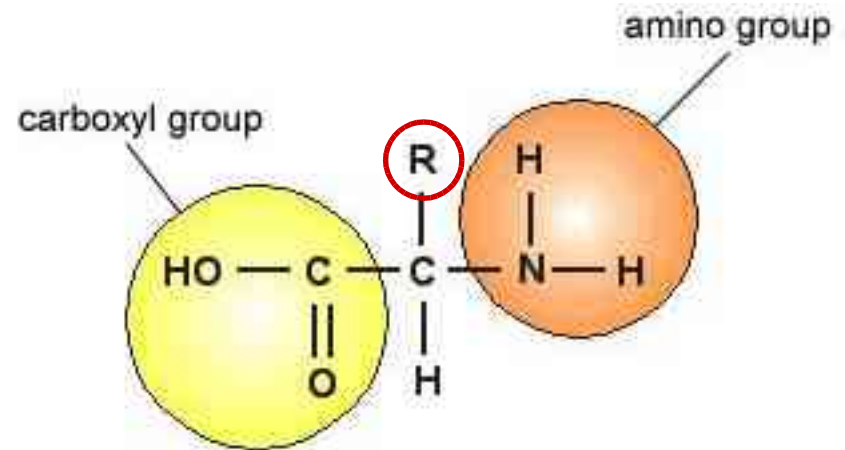
Building blocks of life: proteins

Construction of the living cell and its biochemical machinery base on proteins. The so-called primary structure of these is determined by the sequence of aminoacids forming the peptide bone, while their secondary structure is determined by hydrogen bonds within the peptide chain. There are two basic secondary forms of proteins:

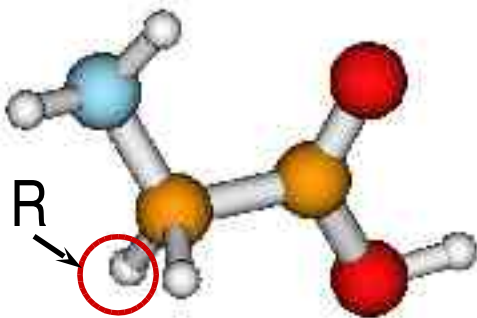


Building blocks of life: aminoacids

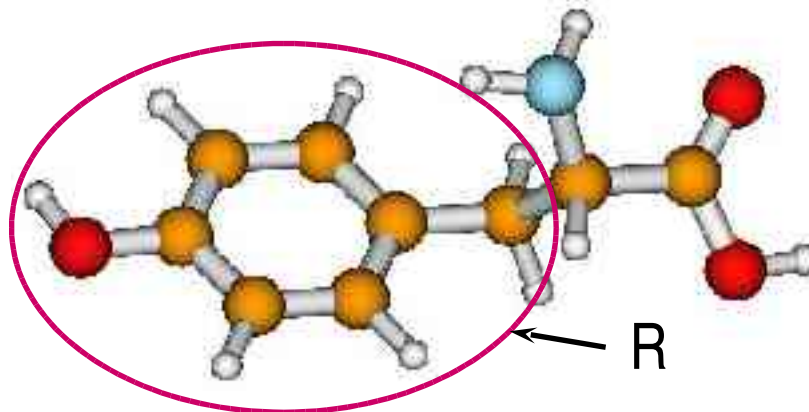
Almost all proteins are constructed from only 20 aminoacids. The common motif of these compounds are the carboxy (COOH) and amino (NH₂) groups. They differ from each other by only the side chain R. Thus the simplest aminoacid – glycine, has R=H, and one of the three aromatic aminoacids – tyrosine, contains phenyl residuee in this position.



glycine



tyrosine



- carbon
- nitrogen
- oxygen
- hydrogen

2. Problem of photostability

Why the living matter has to be photostable?

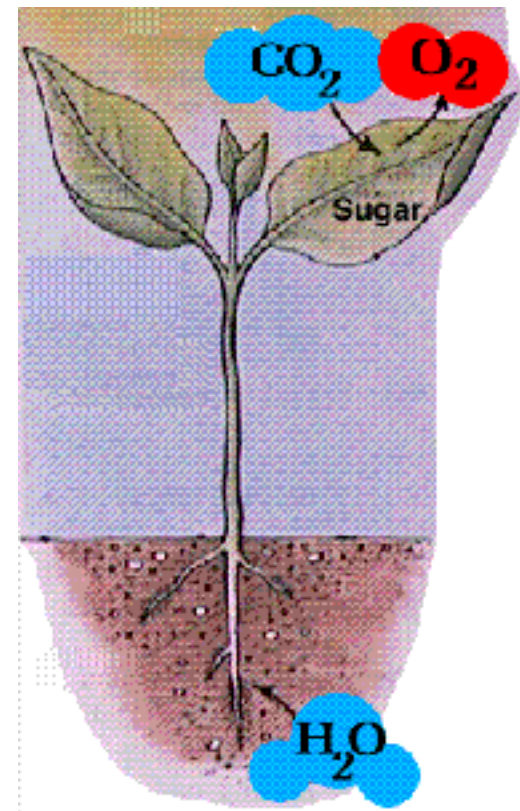
Photoreaction of life

Almost all energy utilized by life on the Earth arrives from the sun in the form of electromagnetic radiation in the visible (VIS) and in the ultraviolet (UV) spectral domain.

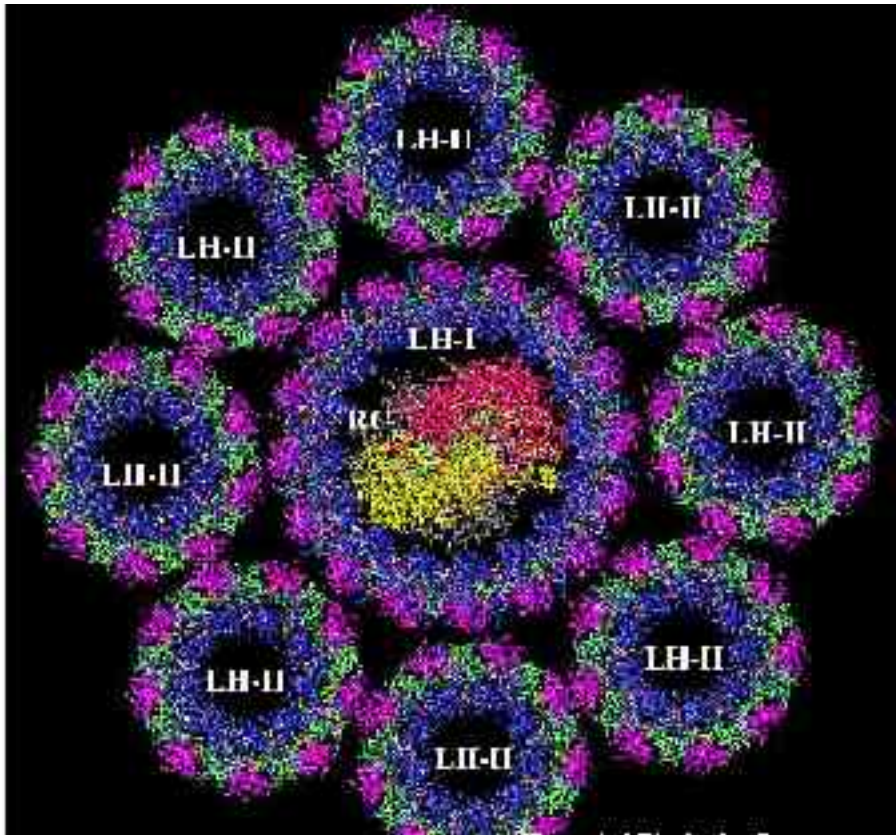
This primary form of energy is transformed into chemical energy in the course of the photosynthesis process in plants and some bacteria.

Life on the Earth thus depends essentially on harvesting the solar radiation and cannot escape from this. In that sense the basic structures of living matter have to be photo-proof (photostable).

UV/VIS



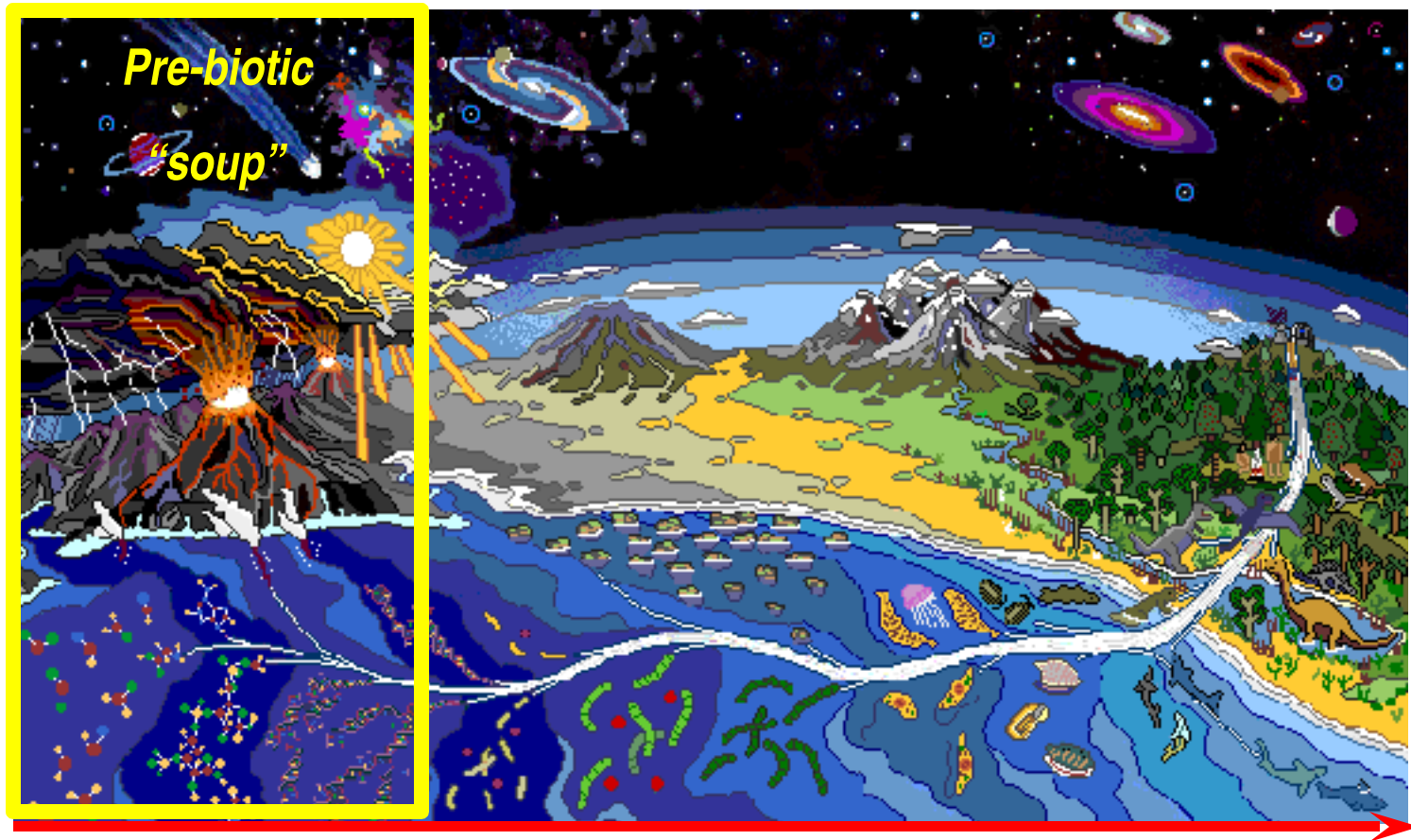
Light-harvesting molecular complex



Molecular structures responsible for harvesting of solar radiation and for its transformation into chemical energy are very specialized and possess complex mechanisms for protection against the harmful radiation and for reparation of radiation-induced damage. These processes do not subject to interpretation in terms of simple physical mechanisms.

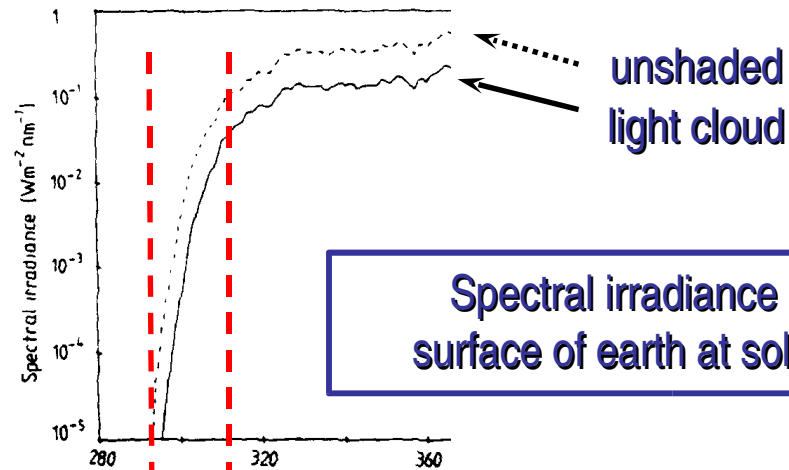
But not always was like that...

Evolution of life on the Earth

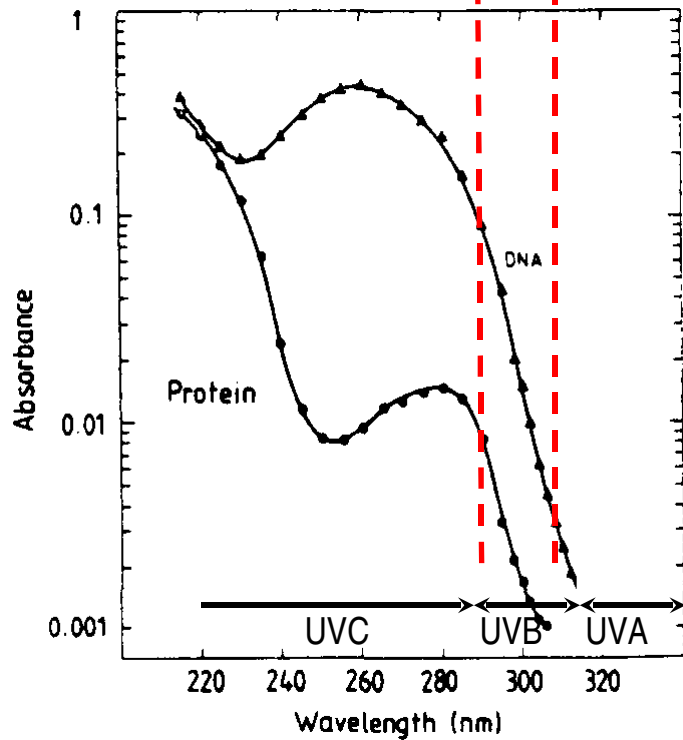


the time

Selection of molecular „bricks” used for construction of the first forms of life on the Earth has occurred under the pressure of strong UV radiation (lack of protecting ozone layer, and even of atmosphere).



Spectral irradiance at the surface of earth at solar noon

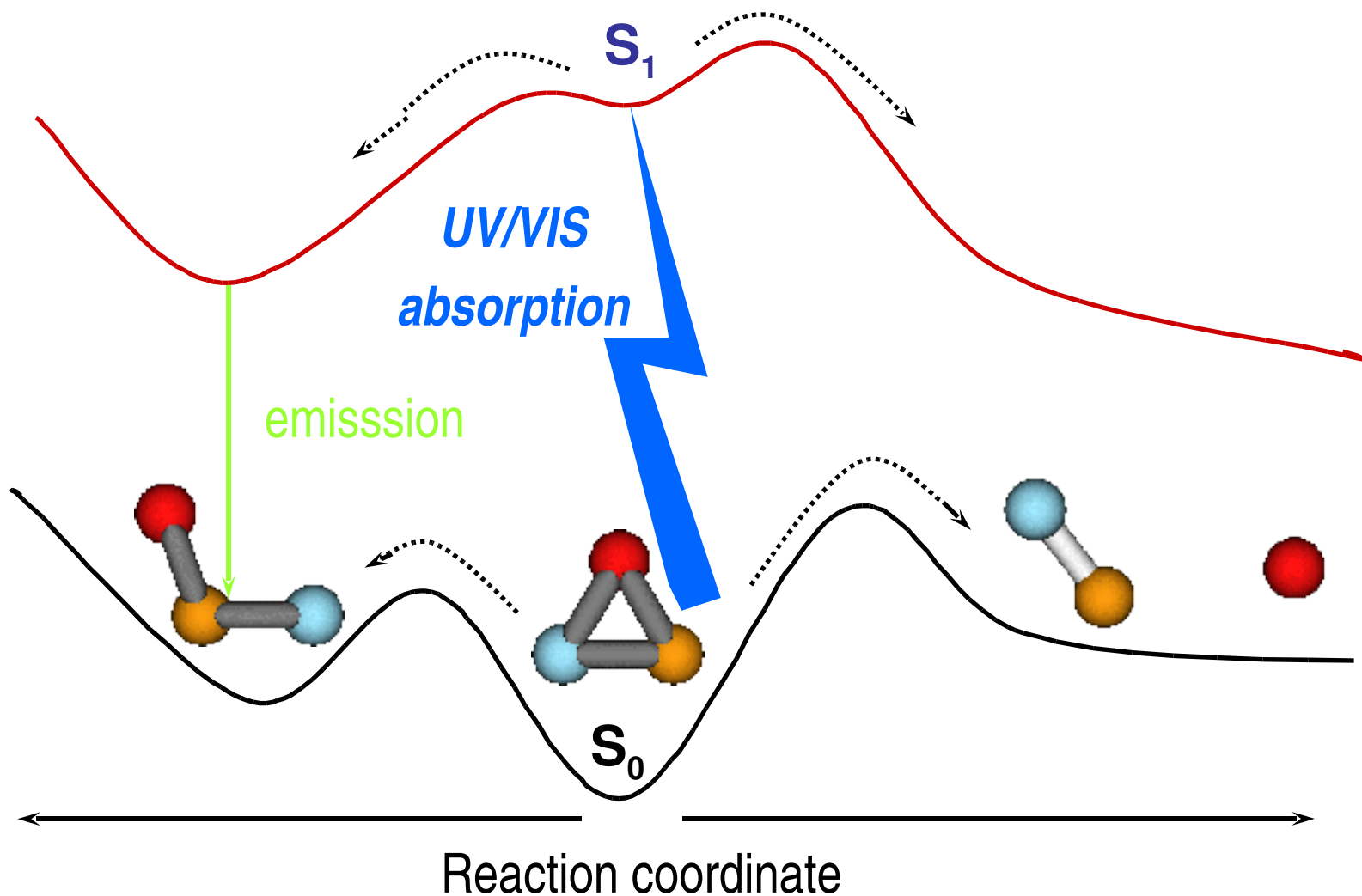


Molecular structures, proteins and DNA, which are most essential for construction and encoding of life on the Earth, are well „fitted” with respect to solar spectrum.

Could it be a result of photoselection on the early stage of development of life?

Molecular (photo)stability

Organic molecules are not generally resistant with respect to UV/VIS radiation and may be subject to photo-induced chemical changes

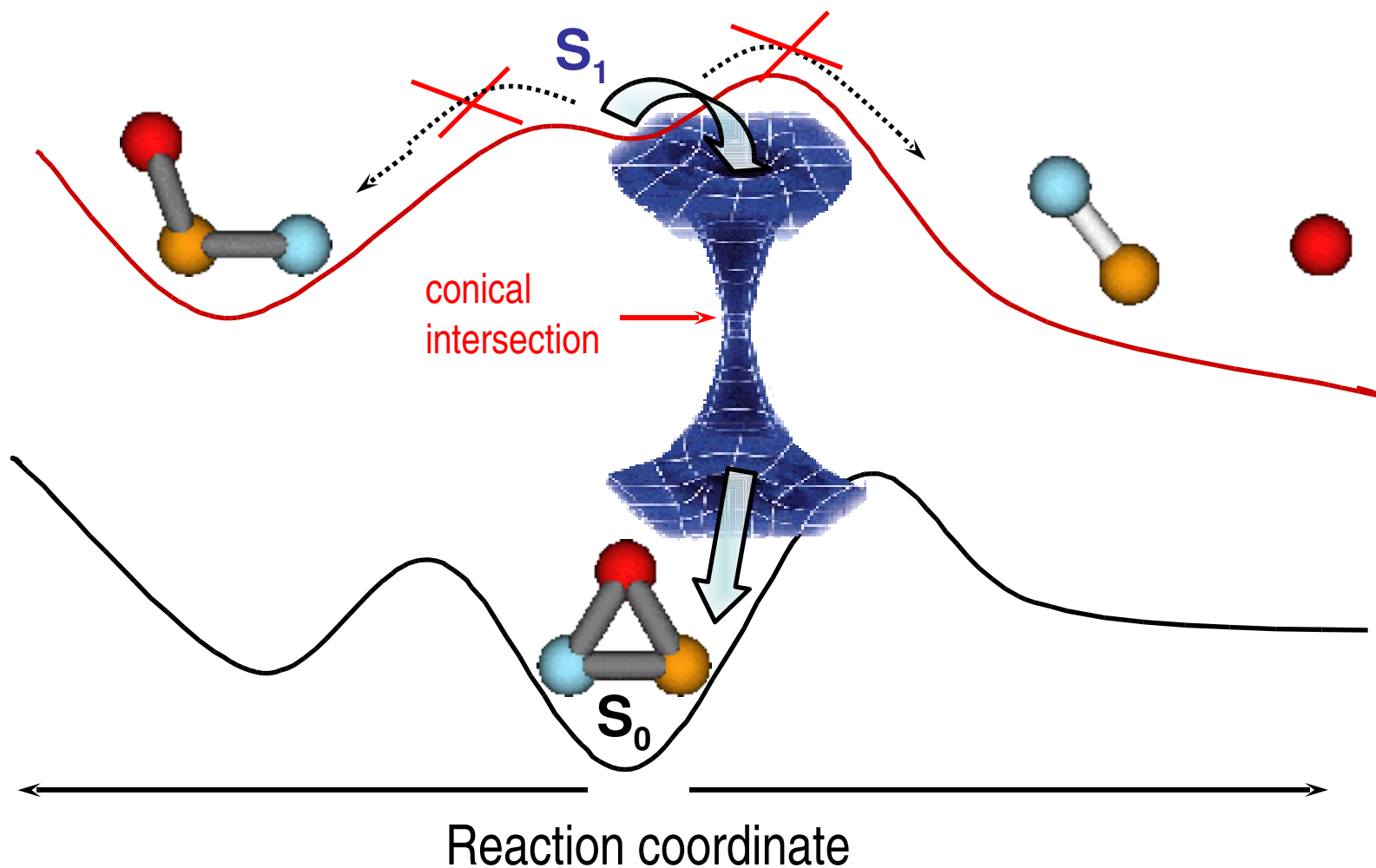


Molecular photostability

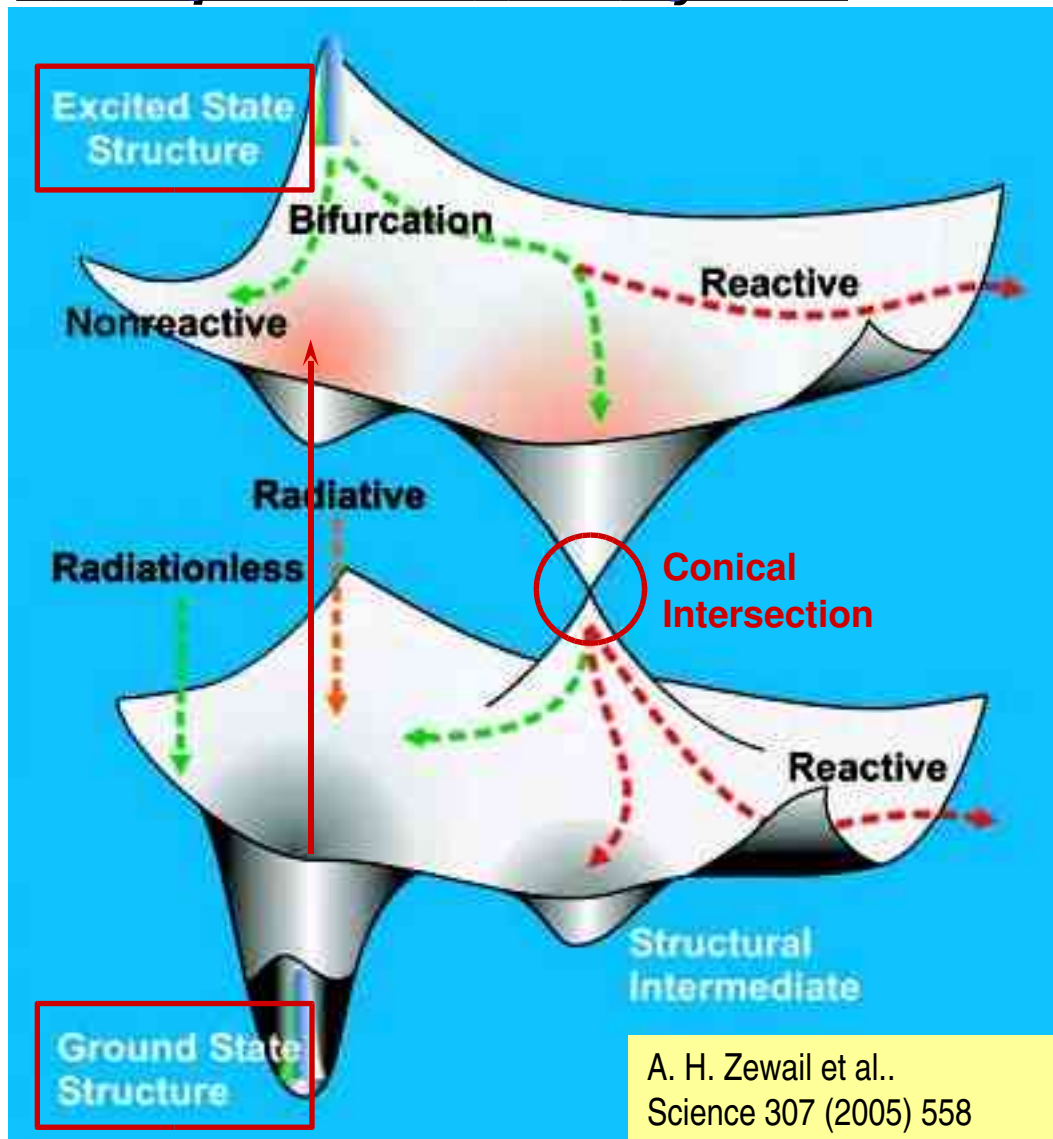
Photostable molecule must possess very efficient and fast channel of radiationless deactivation of optical excitation, which transforms electronic energy into the heat of vibrations in the ground state in order to avoid photo-reactive channels

Molecular photostability

There is a common agreement that such channel is provided by special features of the potential-energy surfaces called **conical intersections**

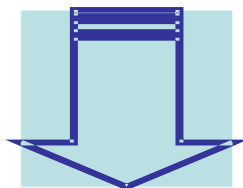


Potential energy surfaces of a complex molecular system



The question:

What is the mechanism of internal conversion of an optical excitation in biomolecular systems?



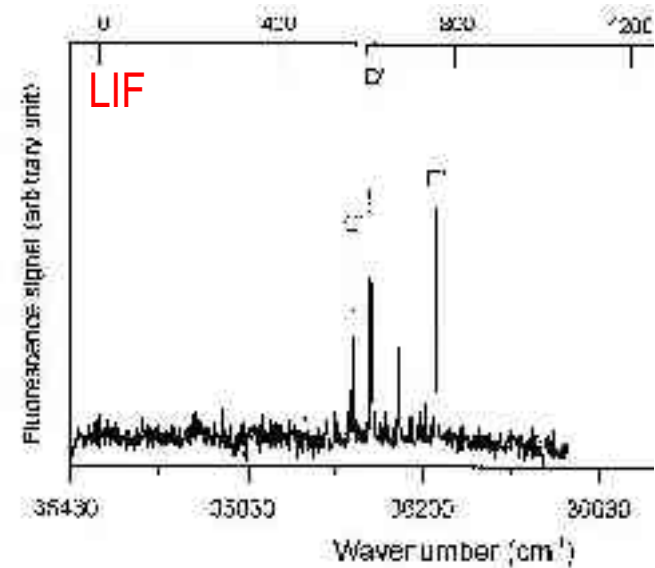
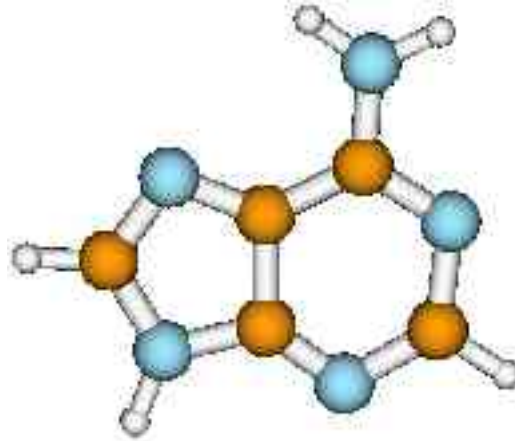
*What is the intramolecular transformation (**stretching, bending, twisting, etc.**) which leads to intersection of excited-state potential-energy surface with the ground state?*

Theoretical search for conical intersections:

Ab initio explorations of $3N-6$ -dimensional excited-state potential-energy surfaces

3. Photophysics of selected bio-molecules: adenine

- carbon
- nitrogen
- oxygen
- hydrogen



Adenine excited within the lowest singlet manifold (S_n) returns to the ground state on the sub-picosecond time scale ($<10^{-12}$ s). Observation of only few discrete lines in the fluorescence excitation spectrum (LIF) indicates the presence of low-lying S_1 - S_0 conical intersection and of the $S_1 \rightarrow S_0$ radiationless deactivation channel related to this.

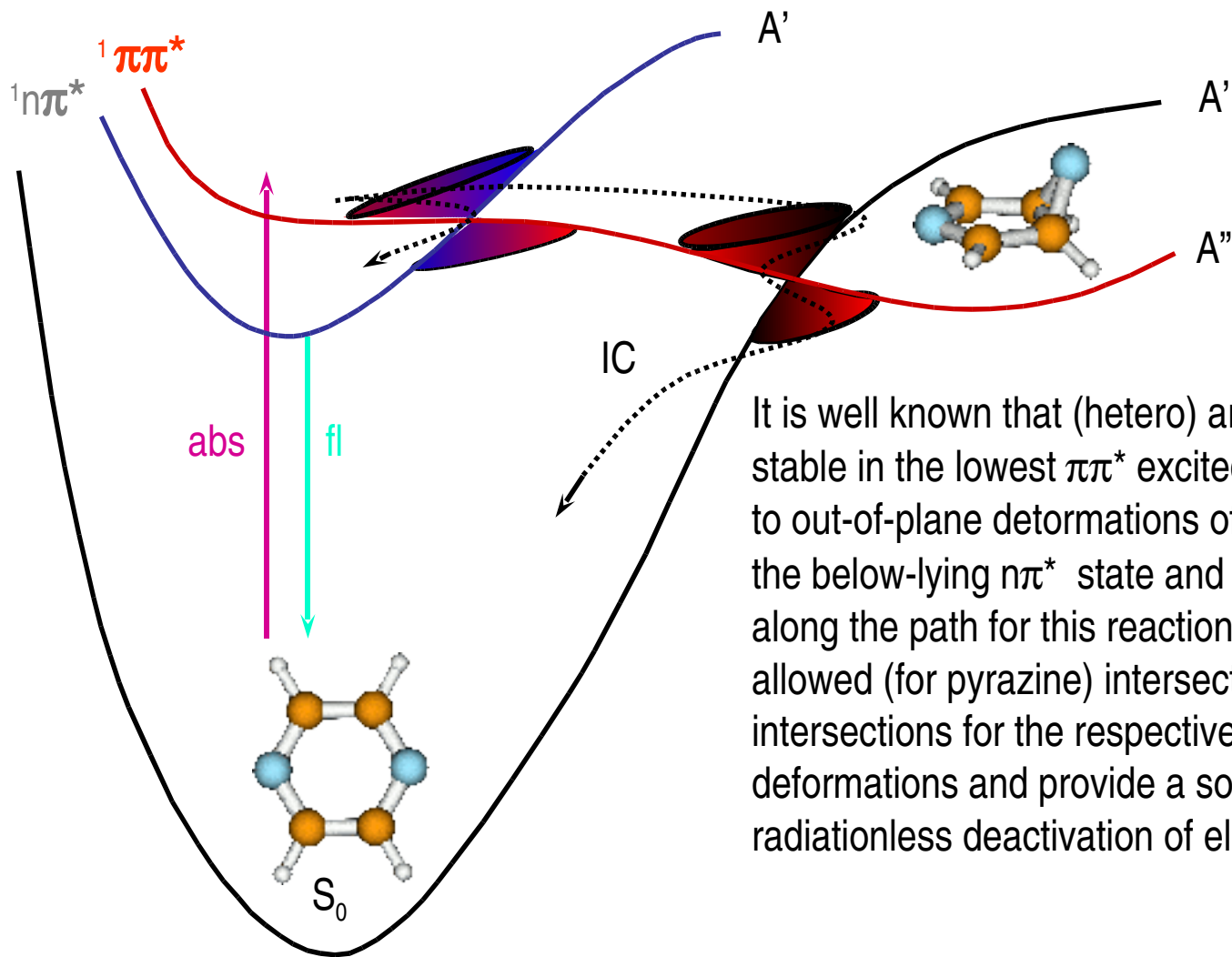
Photophysics of adenine

The question:

which of the 39 intramolecular coordinates of adenine are the most relevant with respect to access to the low-lying conical intersection with the ground state?

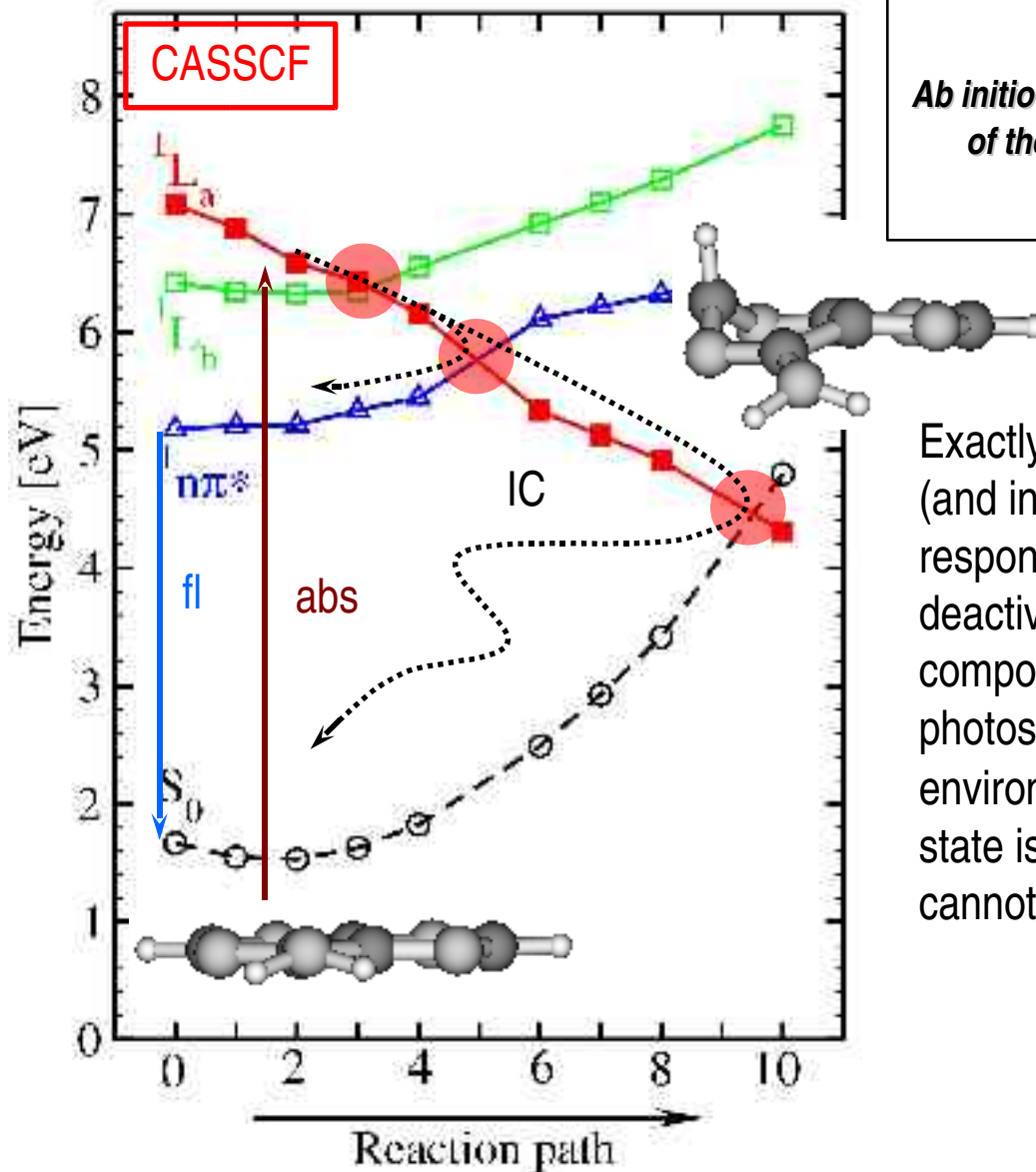
Photophysics of pyrazine

Domcke, Sobolewski & Woywod
Internal conversion funnel in benzene and pyrazine: adiabatic and diabatic representation
Chem. Phys. Lett. **203** (1993) 220



It is well known that (hetero) aromatic rings are not stable in the lowest $\pi\pi^*$ excited states with respect to out-of-plane deformations of the ring and cross the below-lying $n\pi^*$ state and the ground state along the path for this reaction. These symmetry-allowed (for pyrazine) intersections develop conical intersections for the respective out-of-plane deformations and provide a source of efficient radiationless deactivation of electronic excitation.

Photophysics of adenine

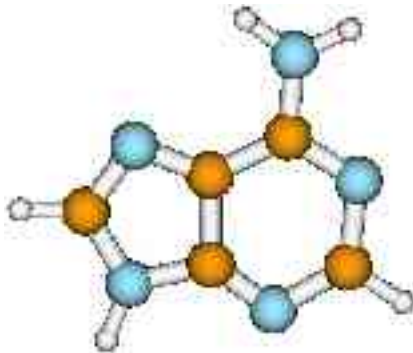


Perun, Sobolewski & Domcke,
*Ab initio studies on the radiationless decay mechanisms
of the lowest excited singlet states of 9H-adenine*
J. Am. Chem. Soc., **127** (2005) 6257

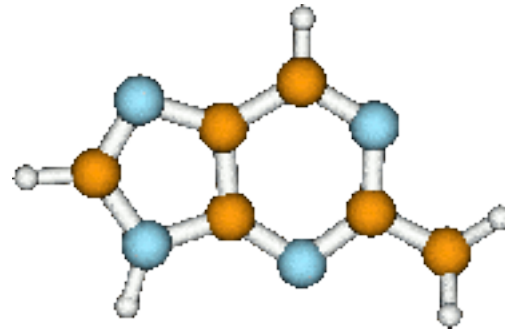
Exactly the same effect occurs in adenine (and in remaining DNA bases), and is responsible for ultra-fast radiationless deactivation of electronic excitation in these compounds and in the resulting photostability. Moreover, in aqueous environment, the potentially „reactive” $n\pi^*$ state is „pushed up” to higher energy and cannot „trap” the excitation.

Adenine vs. 2-aminopurine

Even a minimal modification of chemical structure of „selected” by nature DNA bases results in loss of the channel of ultra-fast radiationless deactivation and resulting photostability. A standard example is 2-aminopurine – isomer of adenine, which has quantum yield of fluorescence close to unity in the gas phase, as compared to 10^{-3} of adenine.



adenine

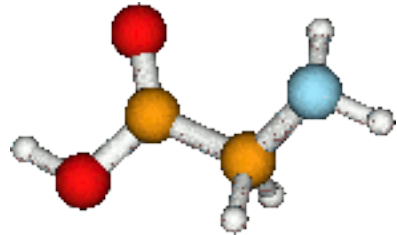


2-aminopurine

Theoretical investigations (Perun, Sobolewski, Domcke, Mol. Phys. **104** (2006) 1113) show that for this spectacular effect is responsible a lack of low-lying S_1 - S_0 conical intersection in 2-aminopurine.

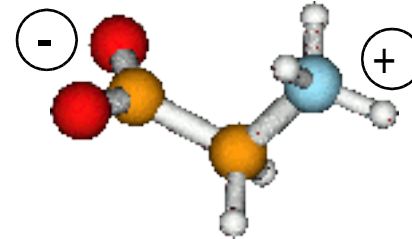
Aminoacids: glycine

neutral form

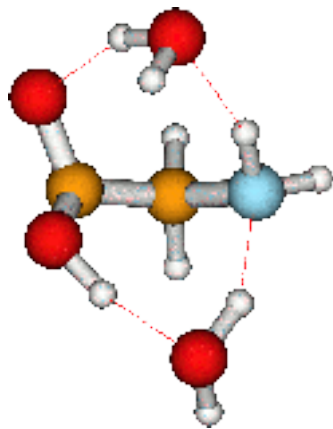


in aqueous environment

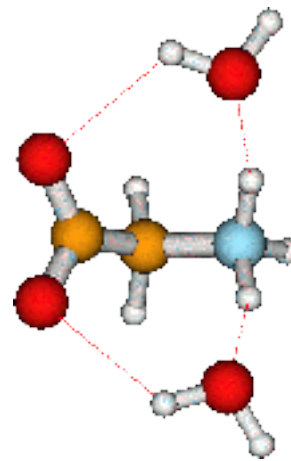
zwitterionic form



The zwitterion form (unstable in the gas phase) can be theoretically modeled by investigation of complexes of aminoacids with a cluster of water molecules. For instance: two water molecules are enough for stabilization of glycine in the zwitterionic form.



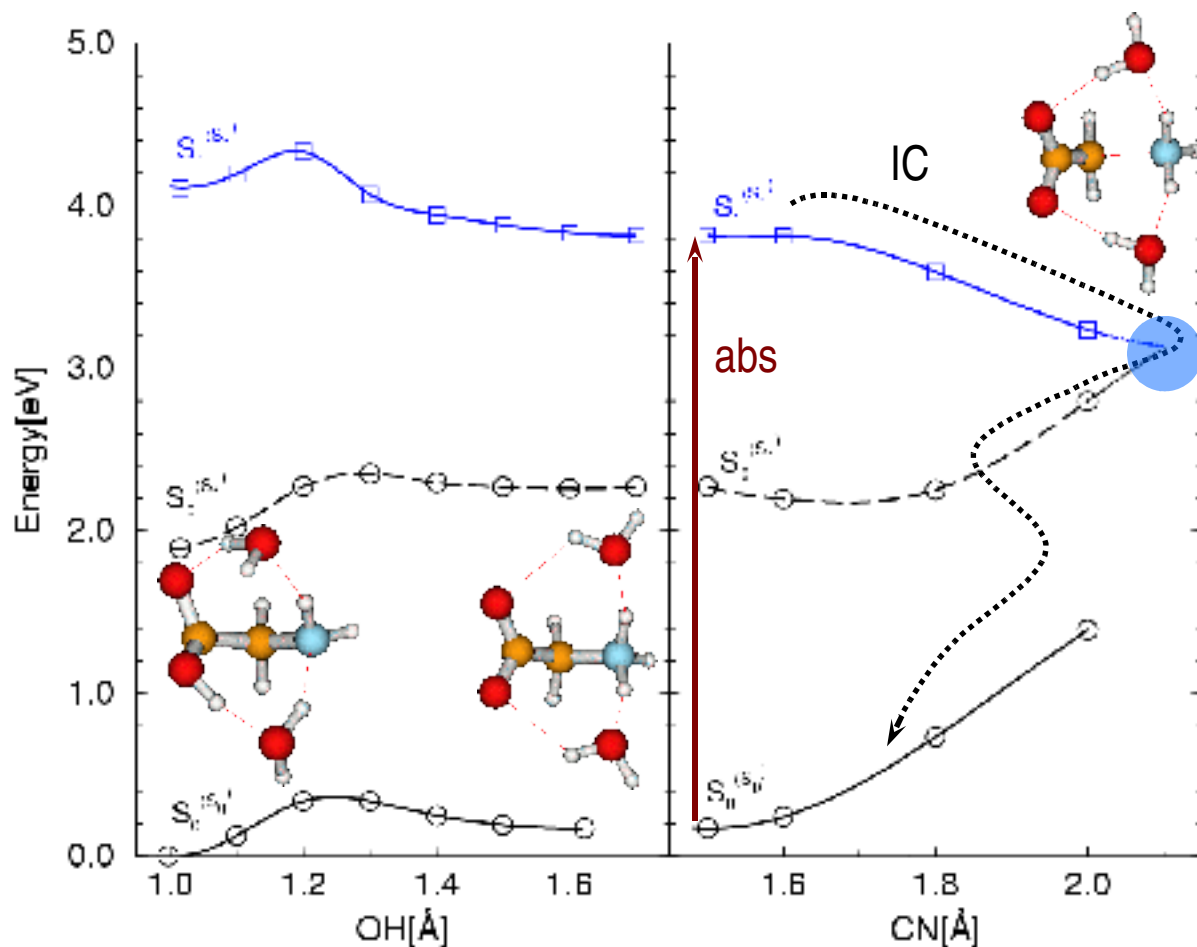
Gly⁽⁰⁾-(H₂O)₂



Gly^(z)-(H₂O)₂

- carbon
- nitrogen
- oxygen
- hydrogen

Photophysics of Gly-(H₂O)₂

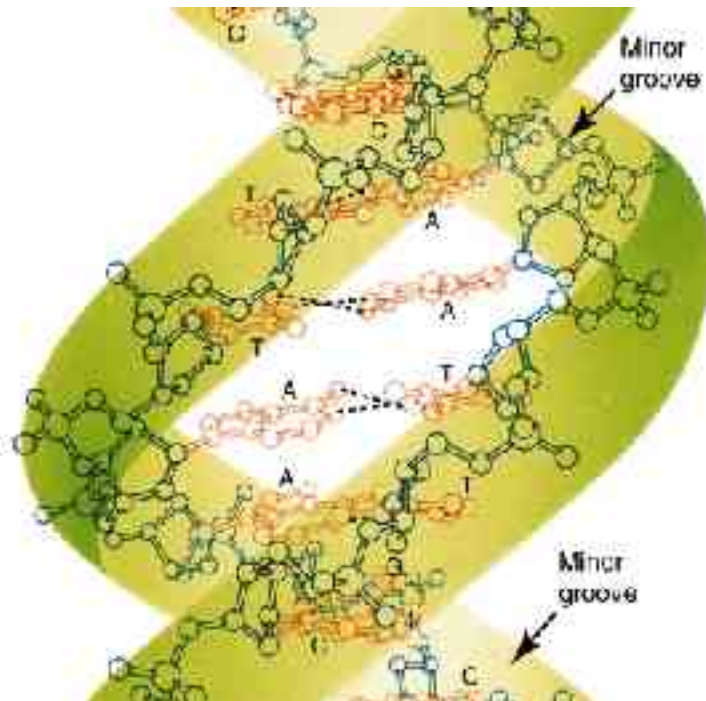


The zwitterionic form of glycine possesses a barrierless access to the S₁-S₀ conical intersection (the blue circle in the figure) along the reaction path for reaction of „abandoned” detachment of the NH₃ group. This mechanism is universal for all aminoacids since it constitutes an intrinsic property of the aminoacidic moiety and do not depend on the side moiety R.

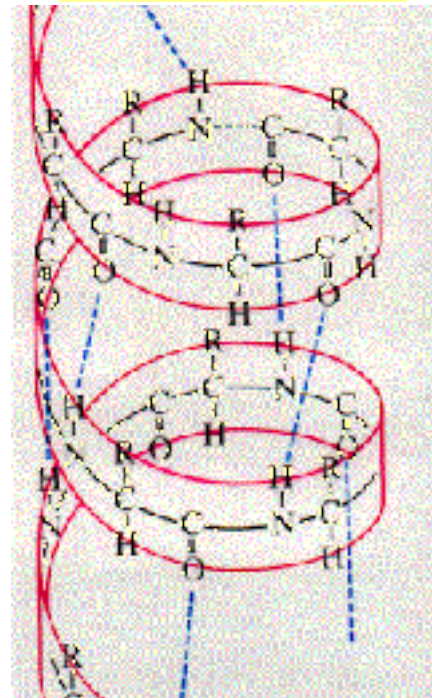
The first conclusion:

The basic molecular building blocks of life (**DNA bases and aminoacids**) possess specific intramolecular mechanisms that provide them with a unique photostability.

The double helix of DNA



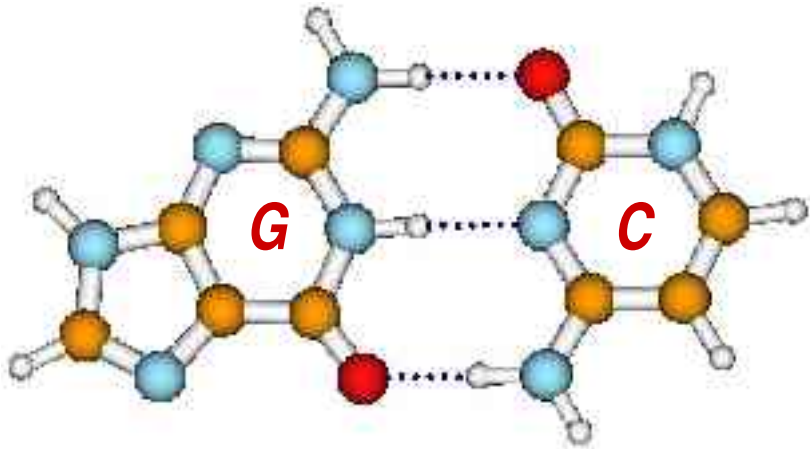
α helix of a protein



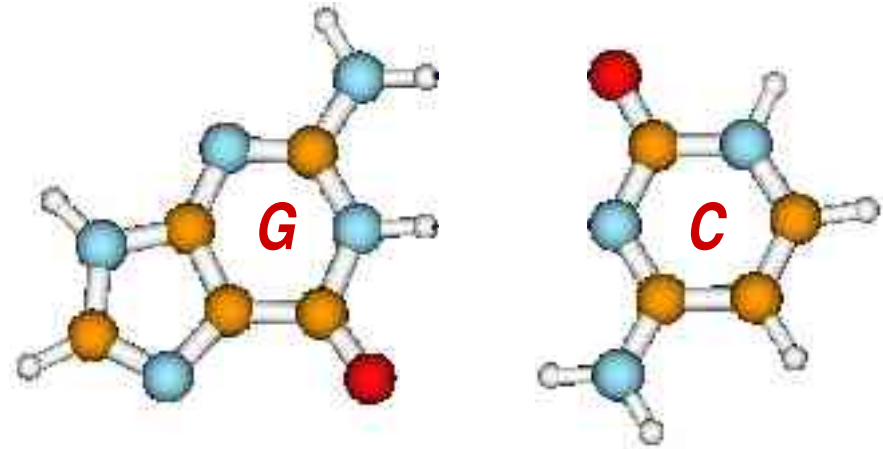
There is a natural question: does the inclusion of these photostable molecular blocks into the structure of DNA and protein not destroy their photophysical properties? One can expect that hydrogen bonds and stacking interactions in DNA handicaps the out-of-plane distortions of bases, and formation of the peptide chain of protein deprives aminoacids of their amine and carboxy ends.

An important property of hydrogen bonds:

GC dimer



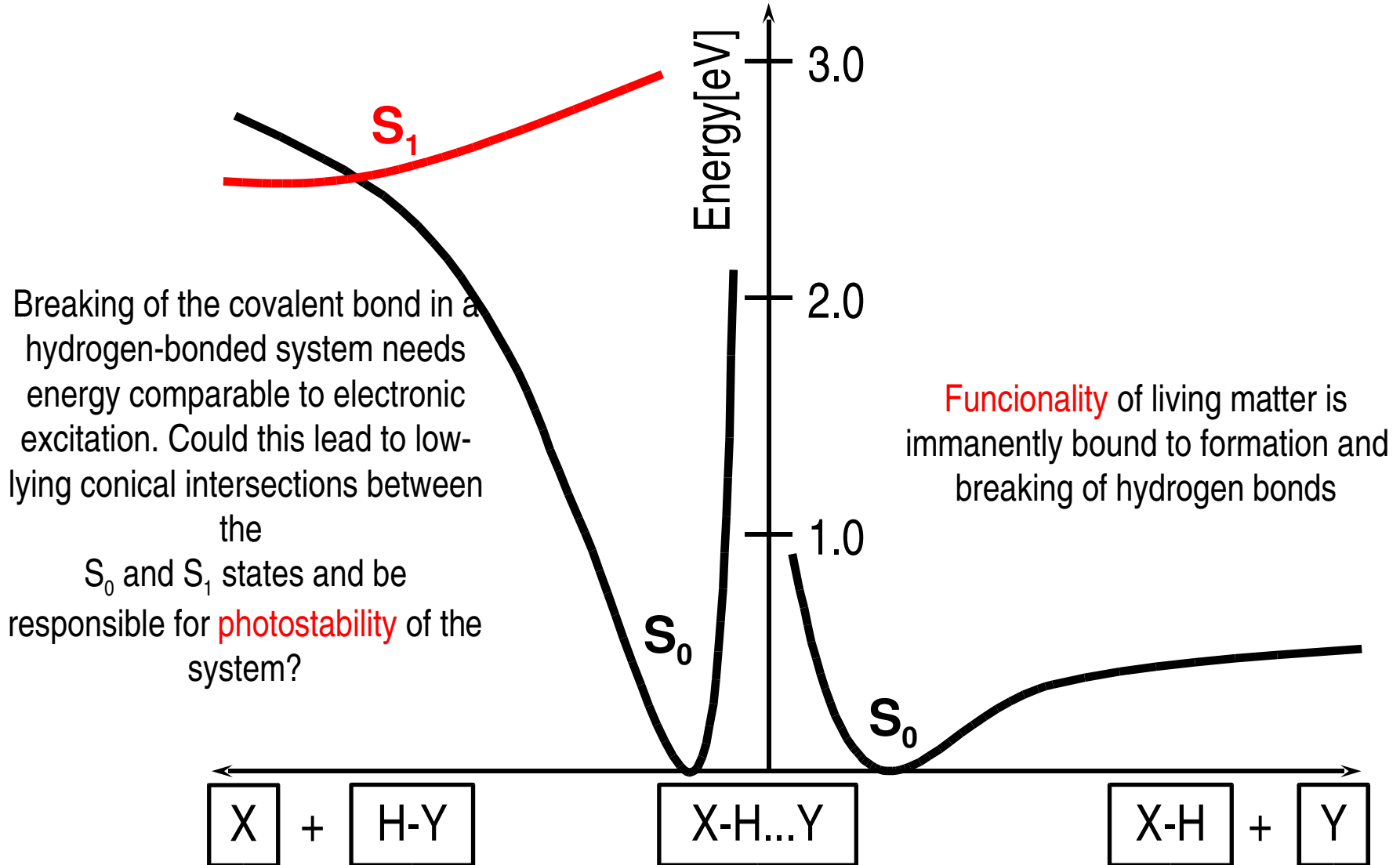
G and C monomers



Hydrogen bond possesses a peculiar property: it is relatively stable at room temperature, but when it is broken, the participating molecules recover their chemical identity.

Hydrogen bond – a **post-it-type** glue

Hydrogen bond vs. covalent bond

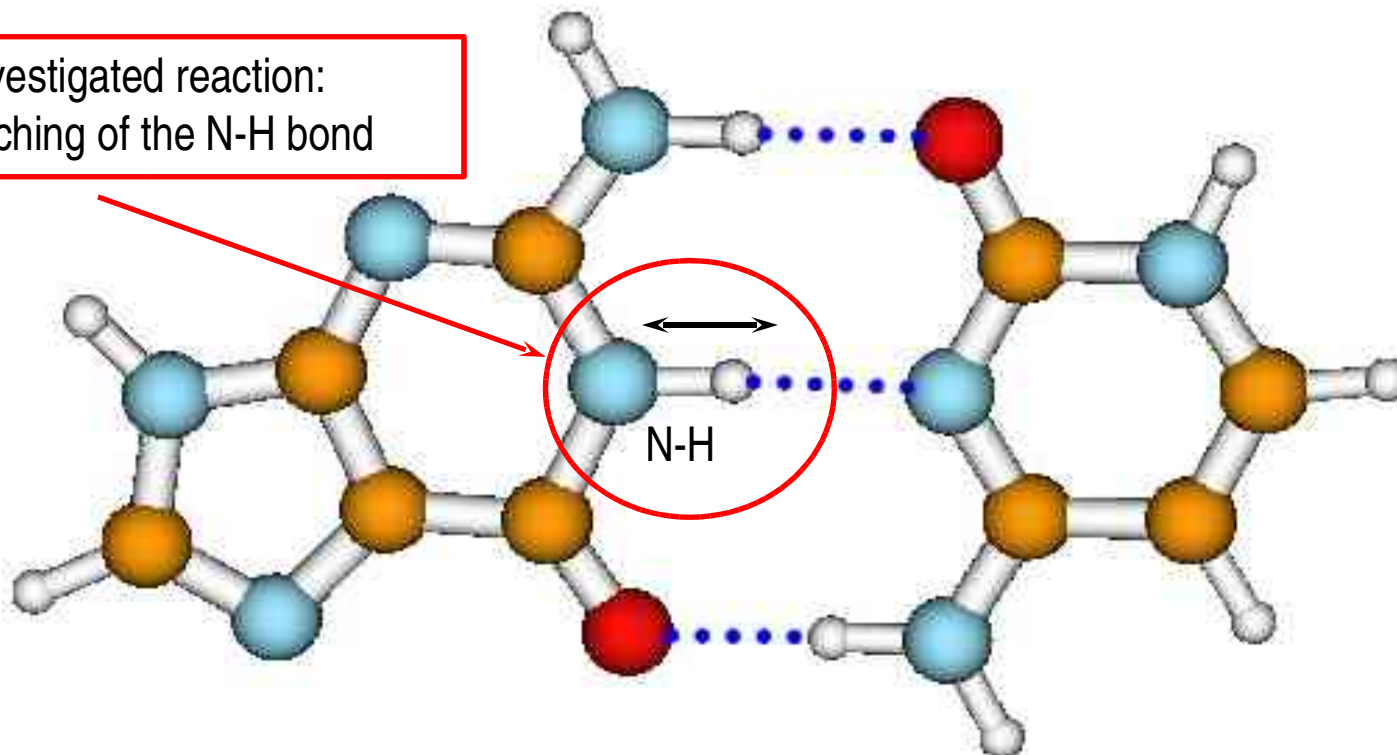


Photophysics of **guanine-cytosine** base pair

guanine

cytosine

Investigated reaction:
stretching of the N-H bond

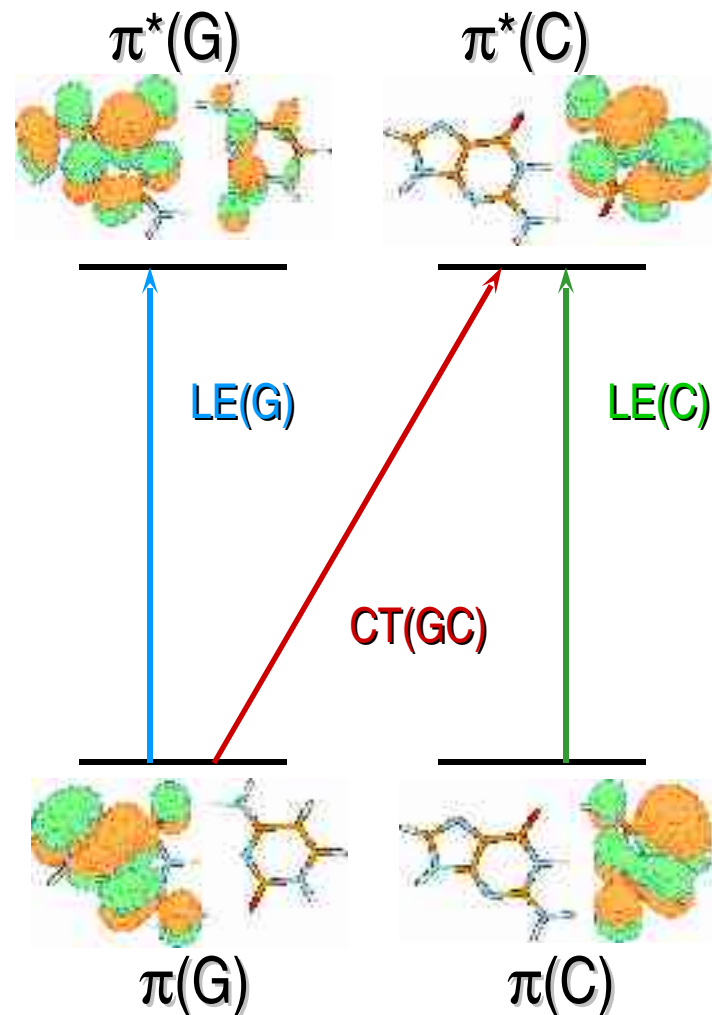
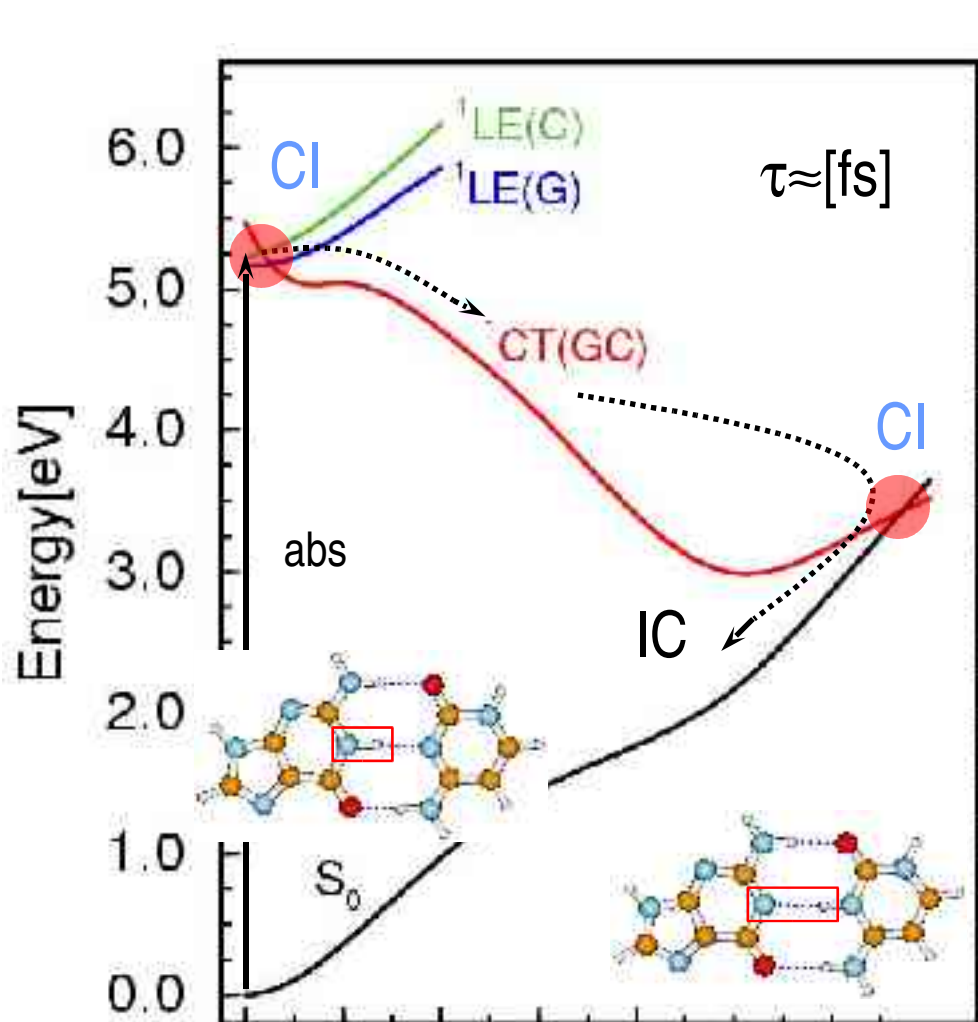


Sobolewski & Domcke

Ab initio studies on the photophysics of the guanine-cytosine base pair

Phys. Chem. Chem. Phys. 6 (2004) 2763

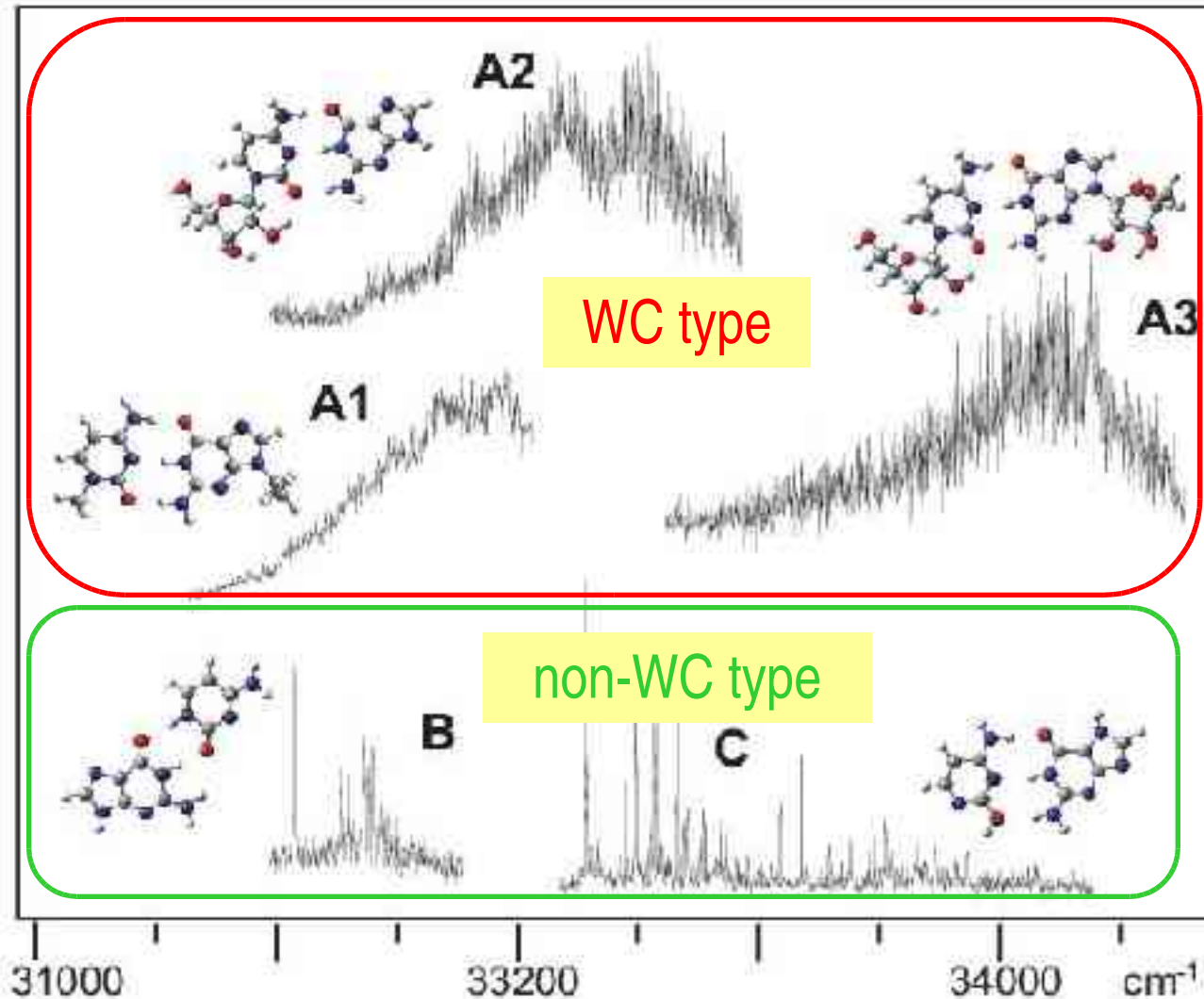
Photophysics of **guanine-cytosine** base pair



Conclusion: electronic excitation of the GC base pair leads in a barrierless manner to the S_1 - S_0 conical intersection along the coordinate for hydrogen-atom transfer

Sobolewski & Domcke
Ab initio studies on the photophysics of the
guanine-cytosine base pair
Phys. Chem. Chem. Phys. 6 (2004) 2763

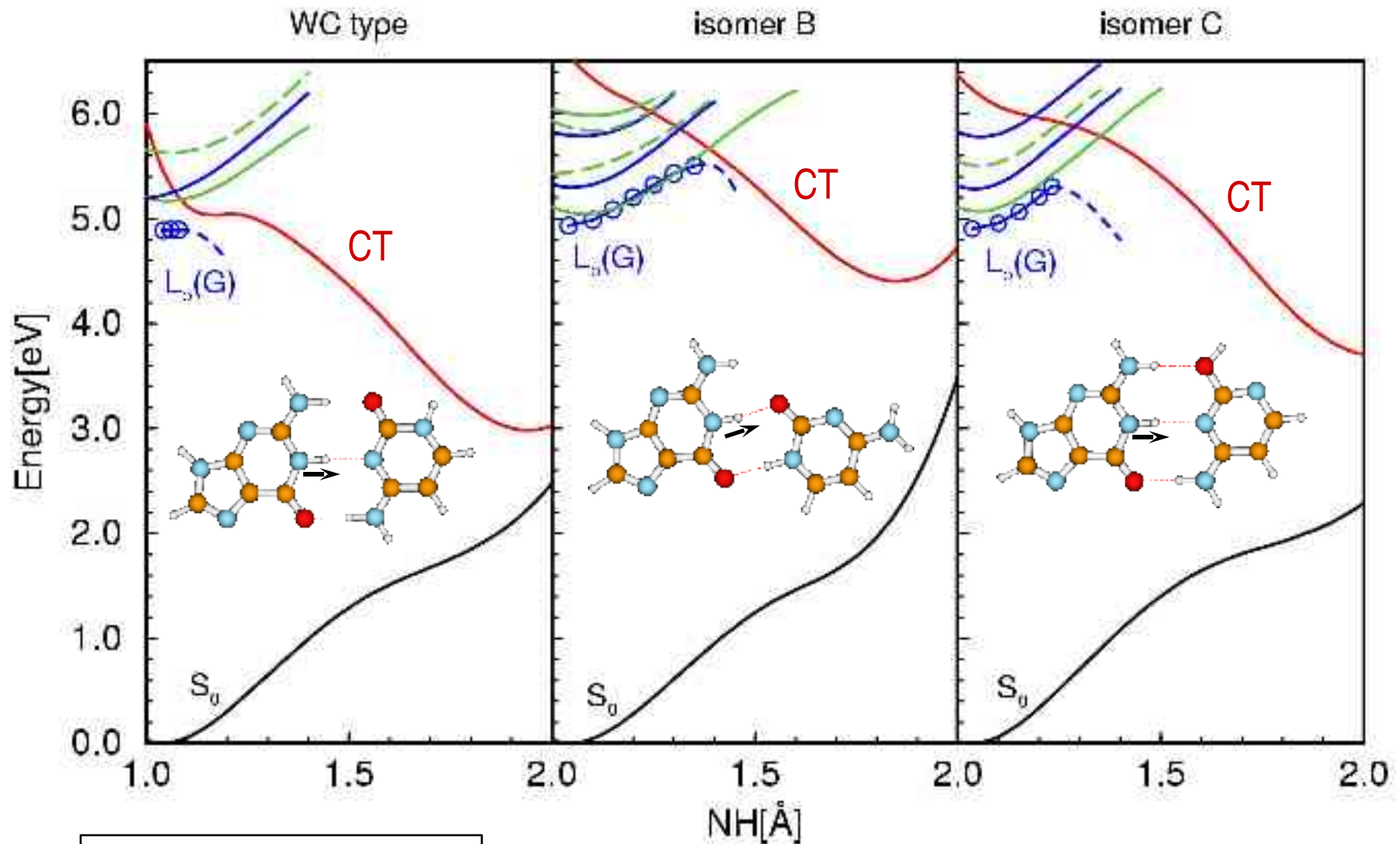
Photophysics of **guanine-cytosine** base pair



Theoretical prediction of an ultra-fast radiationless deactivation of the GC base pair discussed on the previous slide was one year later confirmed experimentally. Moreover, it was shown, that this is the only case of the Watson-Crick-type base pair, selected by the nature. Other experimentally observed isomers and conformers of this pair does not show such property.

A. Abo-Riziq, L. Grace, E. Nir, M. Kabelec, P. Hobza, M. S. De Vries
Photochemical selectivity in guanine-cytosine base-pair structures
Proc. Nat. Acad. Sci., 102 (2005) 20

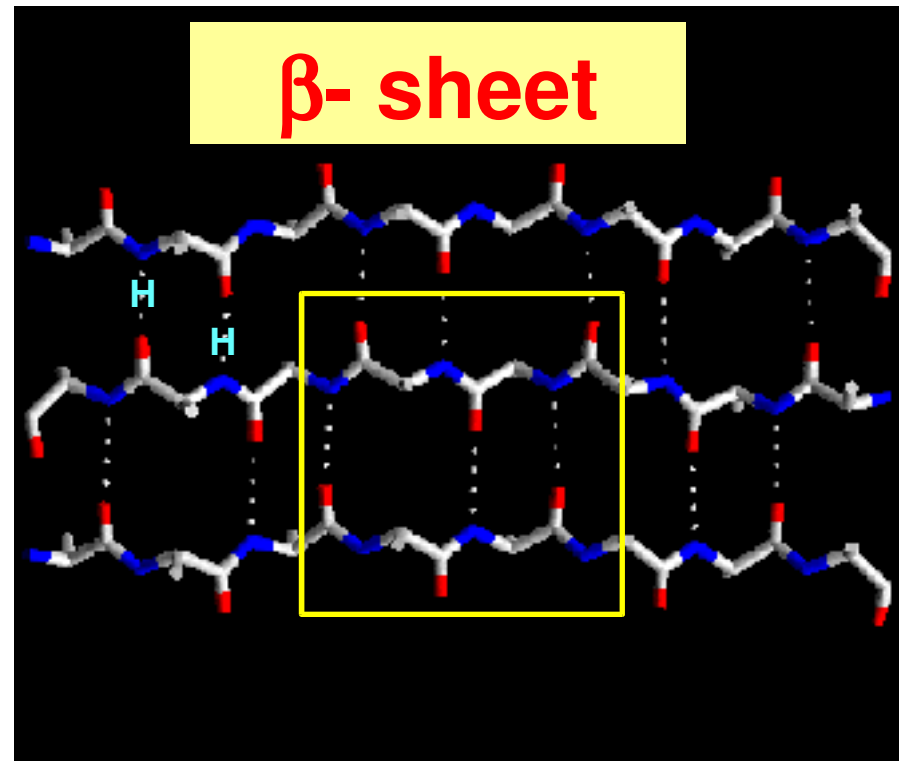
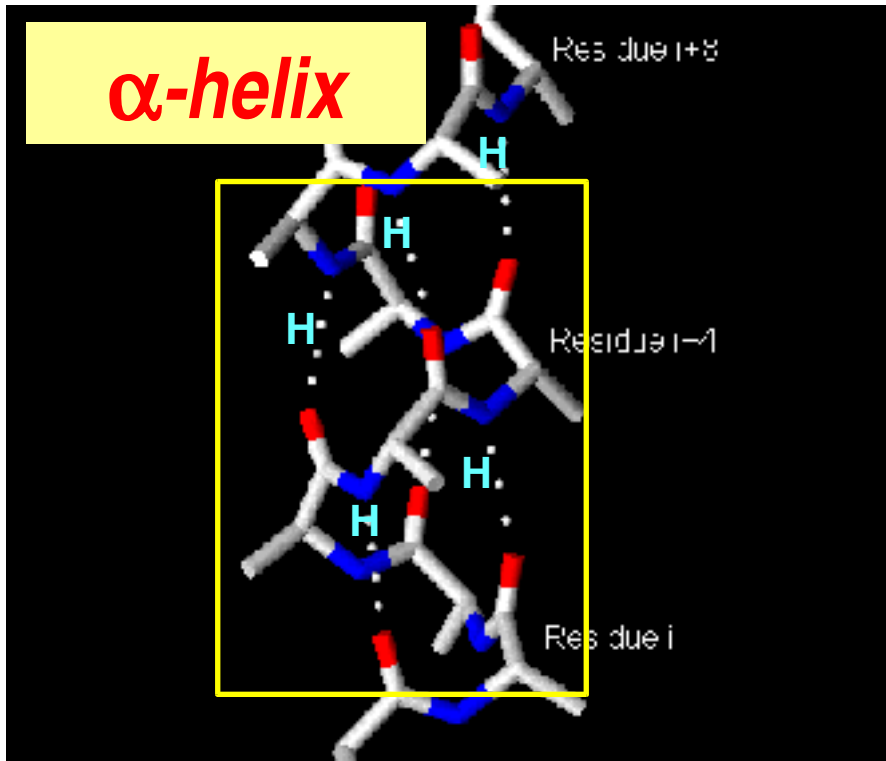
Photophysics of *guanine-cytosine* base pair



Sobolewski, Domcke & Hättig
Proc. Nat. Acad. Sci.
102 (2005) 17903

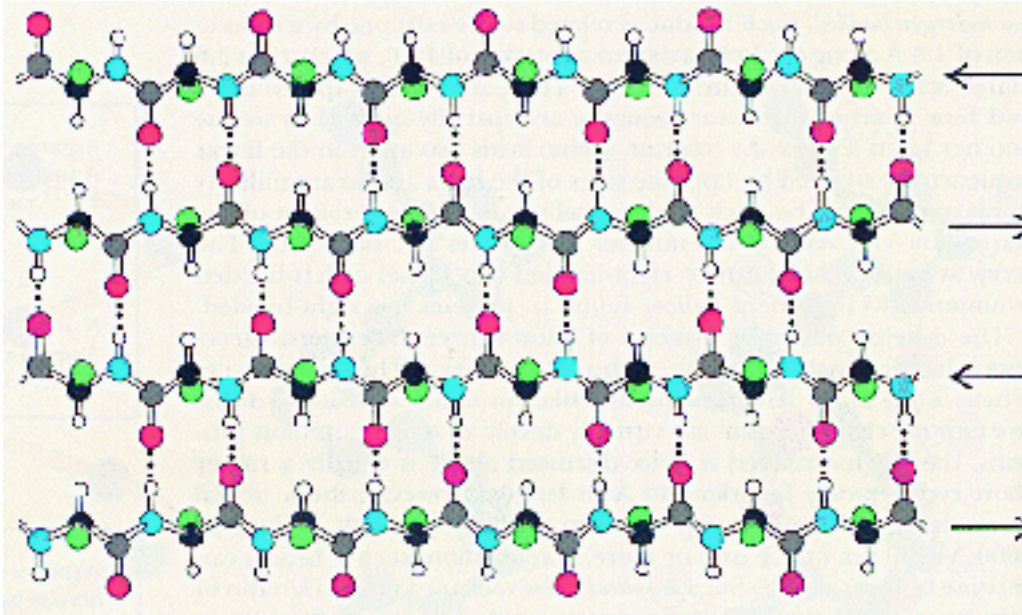
In this theoretical work we have „confirmed” the experimental observation by correlating observed properties of the GC base pairs with the location of the „reactive” charge-transfer state.

The secondary structure of proteins

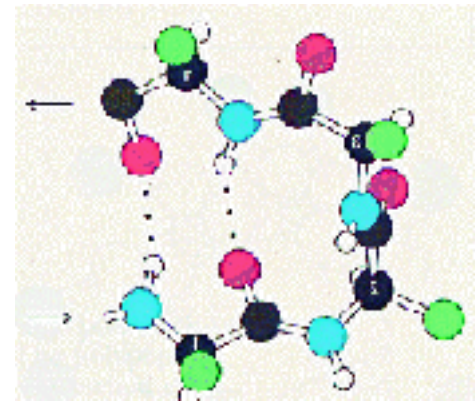


Theoretical modelling of the photophysical properties of protein is more complex task. A small truncated parts of the peptide chain are not stable in the native form, but quantumchemical calculations performed for large systems are not credible enough.

β -sheet



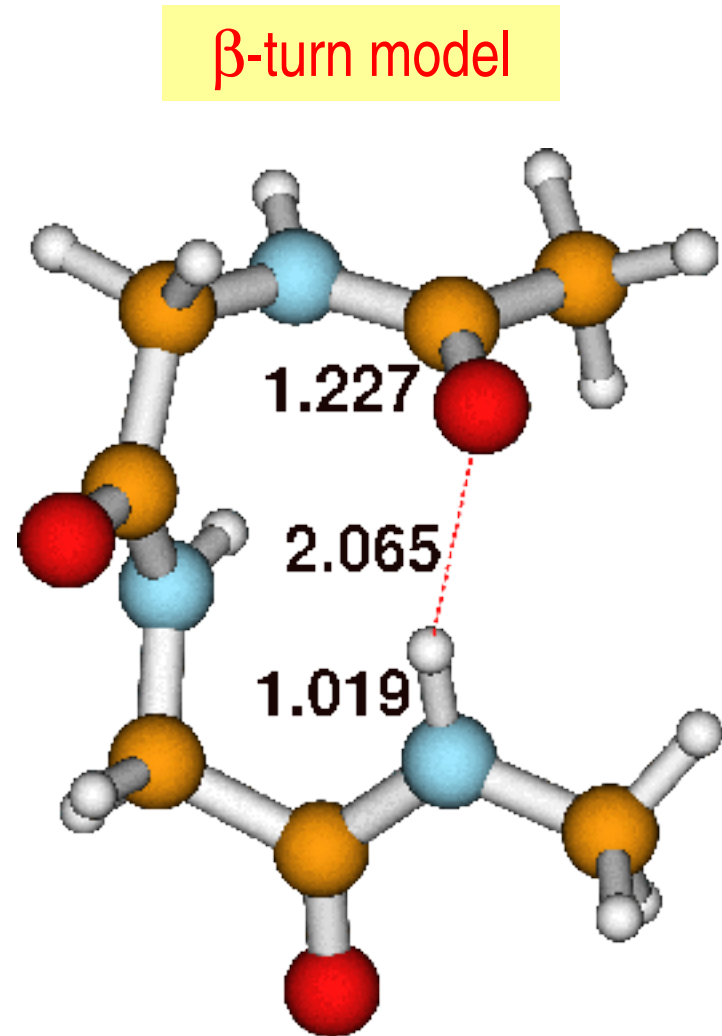
β -turn



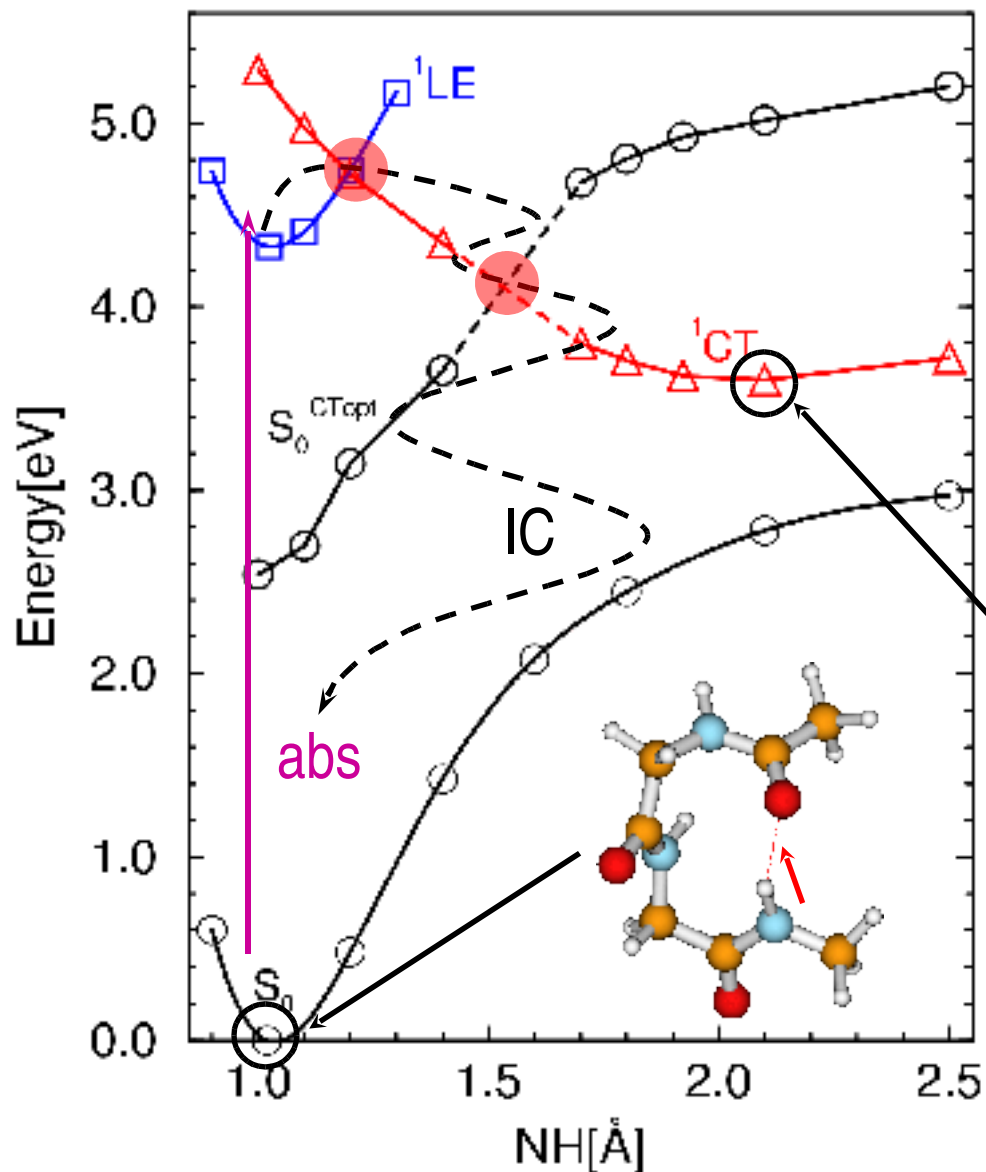
A kind of solution to the problem is provided by modelling a molecular fragment present in the β -sheet, the so-called „ β -turn”.

3Gly: a model of β -turn

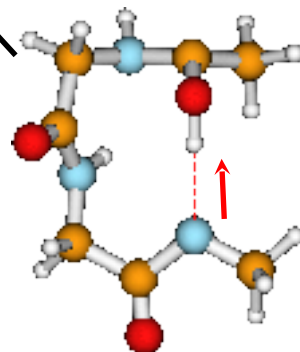
Tri-peptide of glycine (3Gly) capped with methyl groups is a minimal molecular system which can model β -turn



Photophysics of 3Gly:



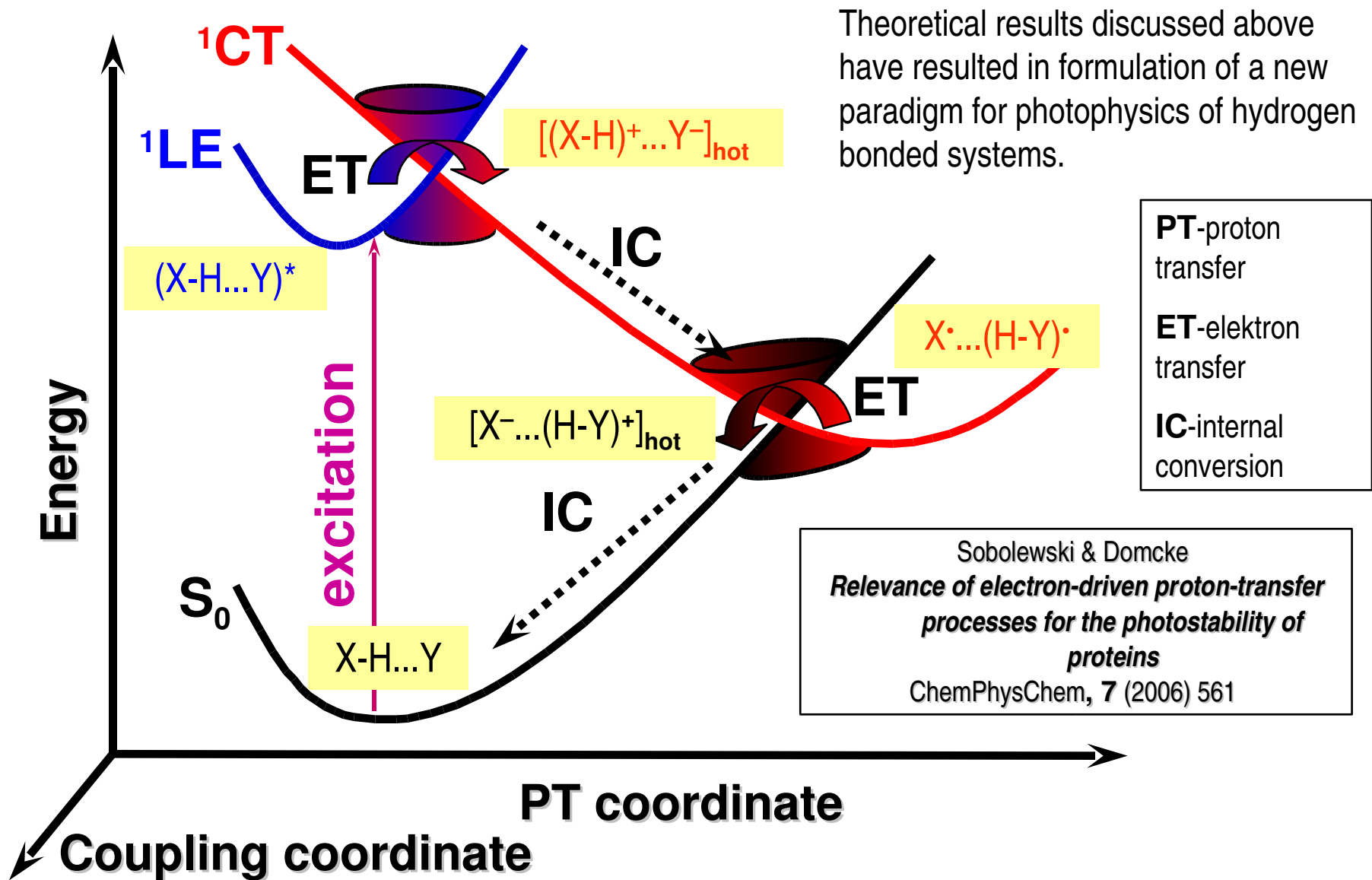
Quantumchemical calculations performed for this system have resulted in the scheme of deactivation of an electronic excitation which is qualitatively similar to that of the GC base pair. A radiationless deactivation of the system occurs along the path for transfer of the proton from the N-H group to the C=O moiety along the hydrogen bond.



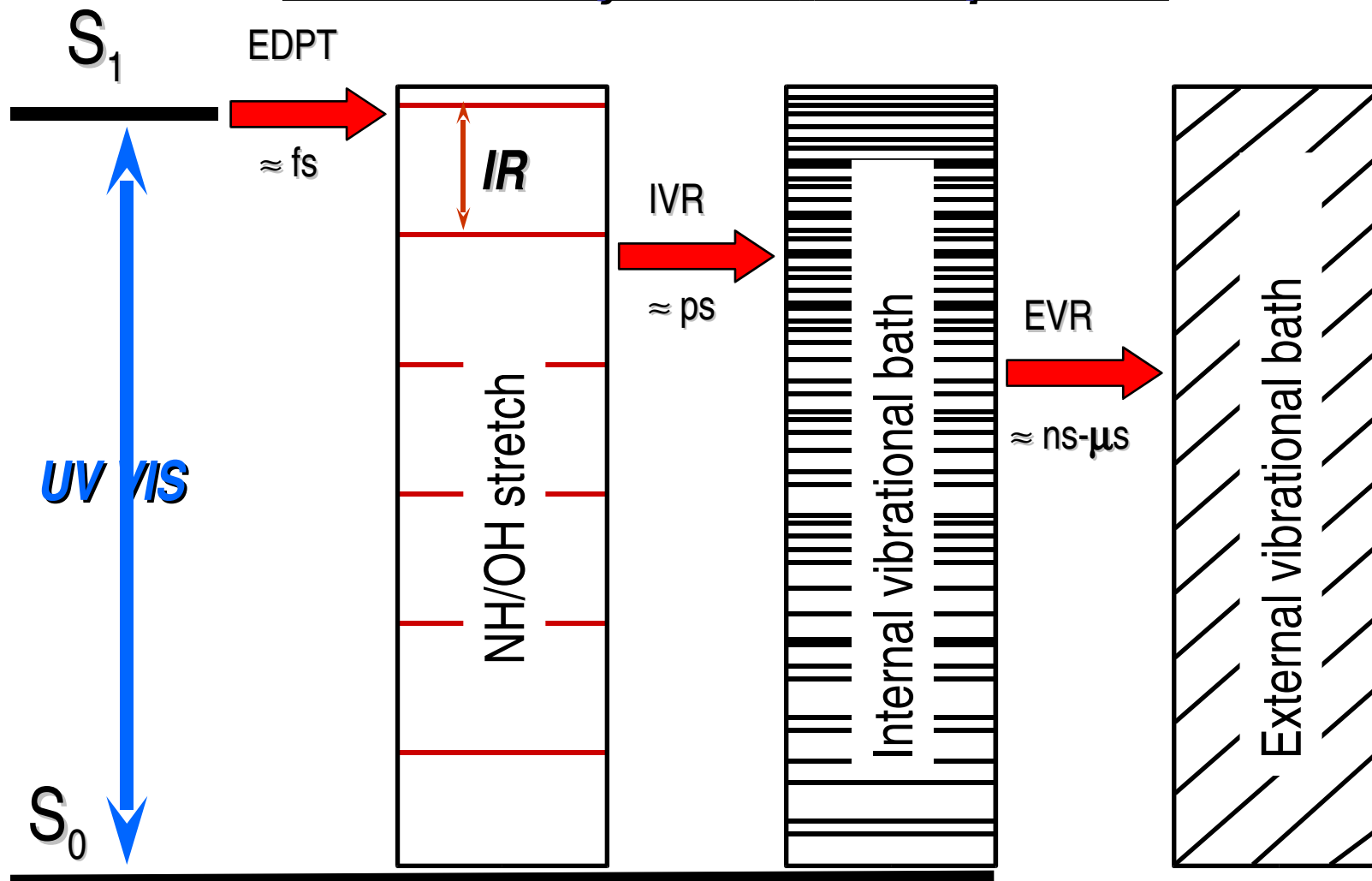
Sobolewski & Domcke
Relevance of electron-driven proton-transfer processes for the photostability of proteins

ChemPhysChem, **7** (2006) 561

Electron-Driven Proton-Transfer proces EDPT

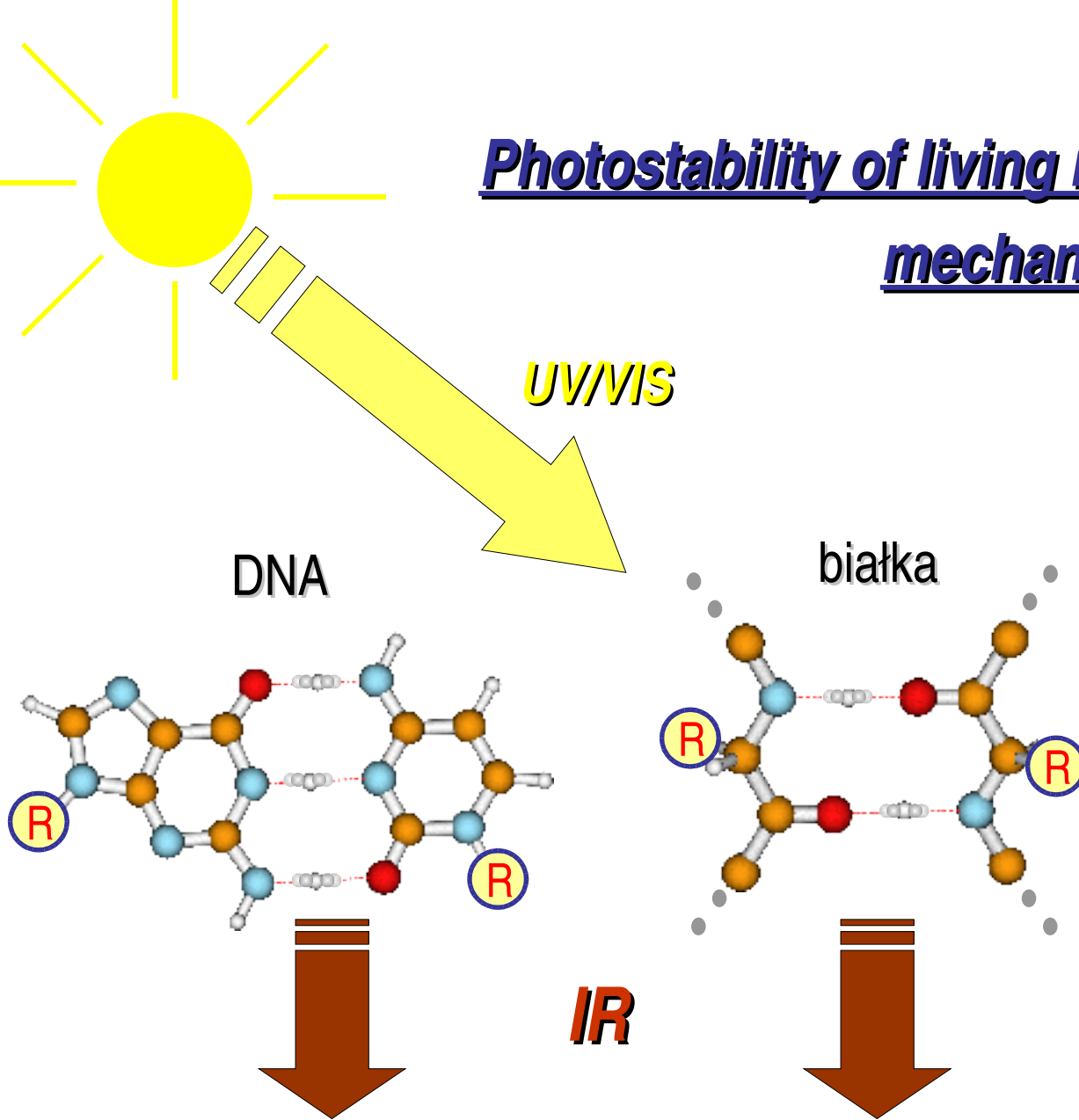


Photostability due to **EDPT** process



Energy of optical excitation is very fast (on the scale of 10^{-15} s) converted into the vibrational quanta of a proton, and is successively transferred in the form of heat (vibrations) to other intra- and inter-molecular degrees of freedom and eventually is transferred to environment.

Photostability of living matter via the **EDPT** mechanism



A „ping-pong”-like motion of protons along the hydrogen bridges provides the key for photostability of living matter.

The second conclusion:

Hydrogen bond is an ingenious „invention” of the nature and provides a key not only for **functionality** of the living matter, but also for its **photostability**.