CENTRO RICERCHE
ENRICO FERMI

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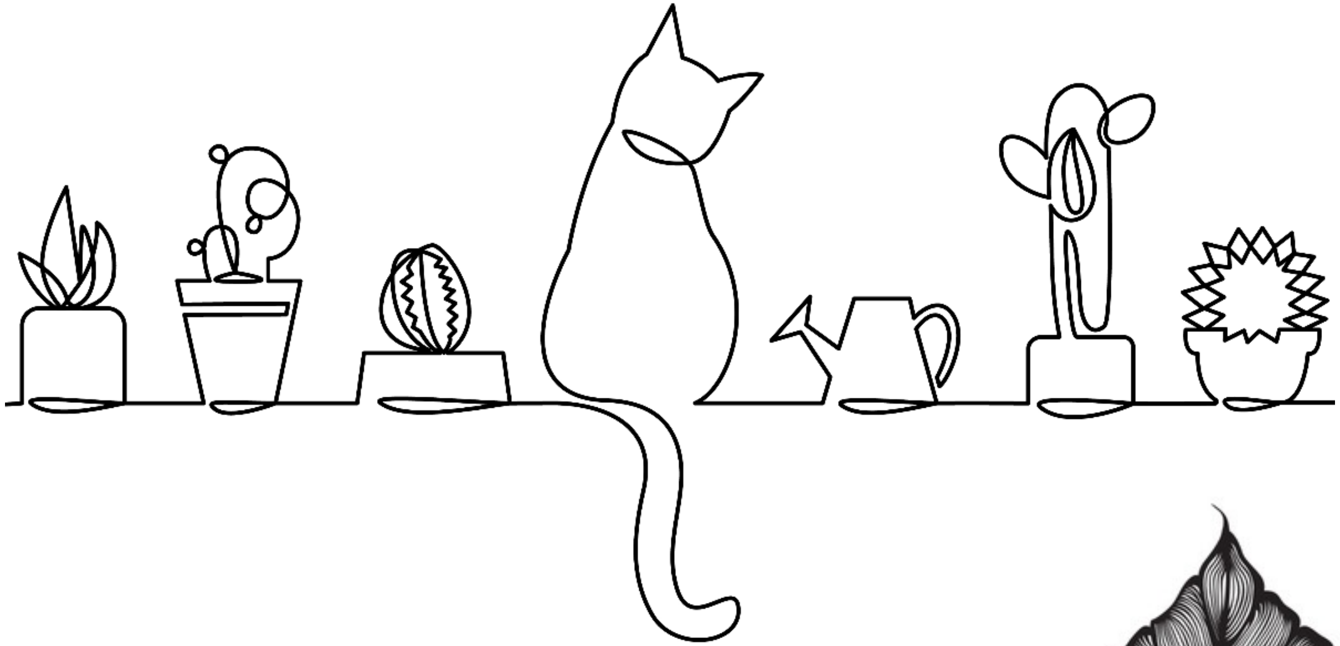

Quantum Biology

May Quantum Mechanics
affect the «life» of living systems?

Silvia Pisano

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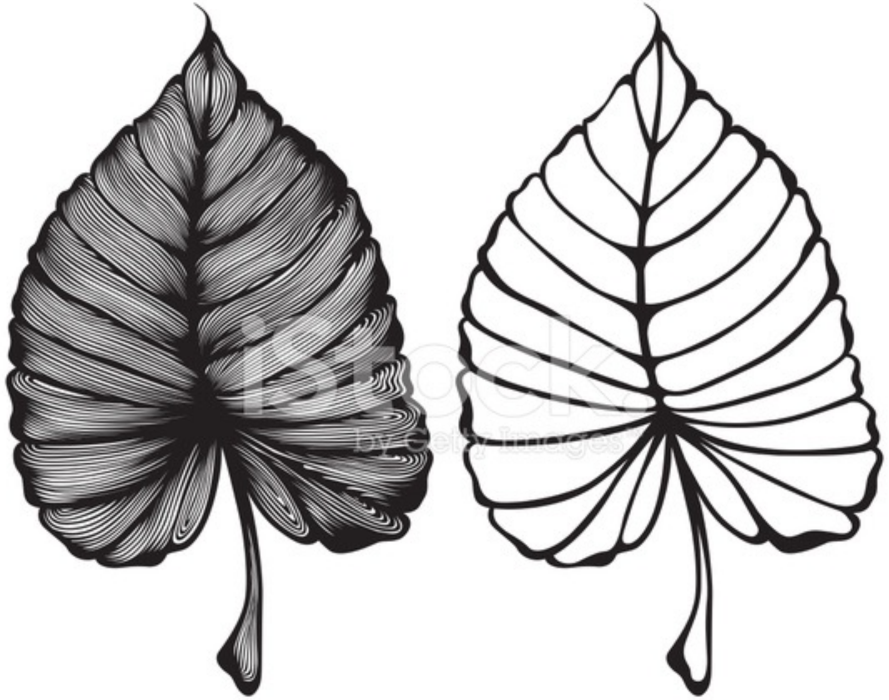
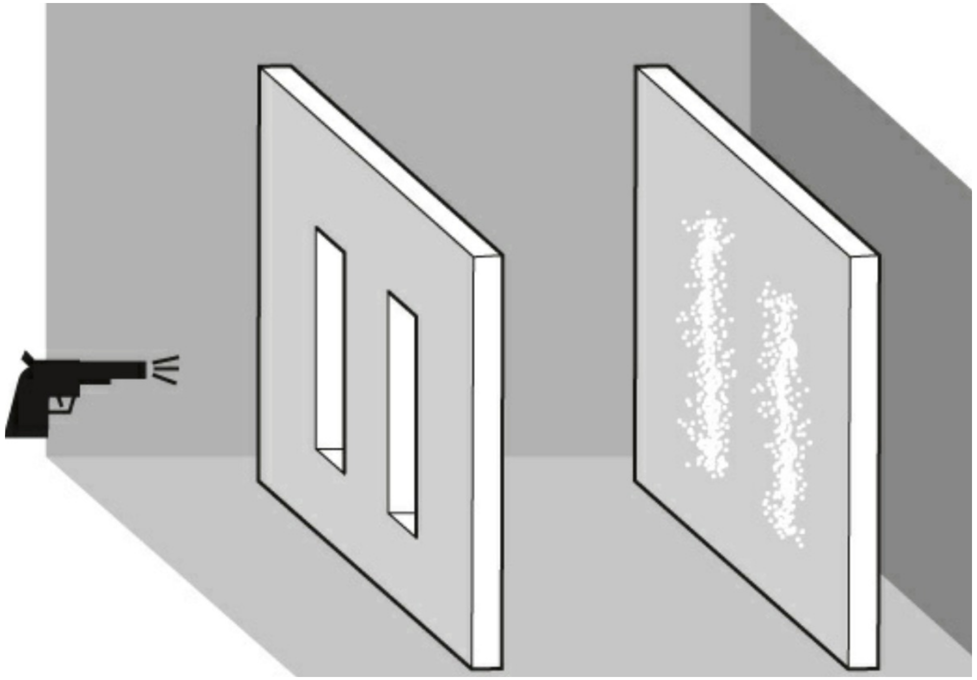
Laboratori Nazionali di Frascati - INFN

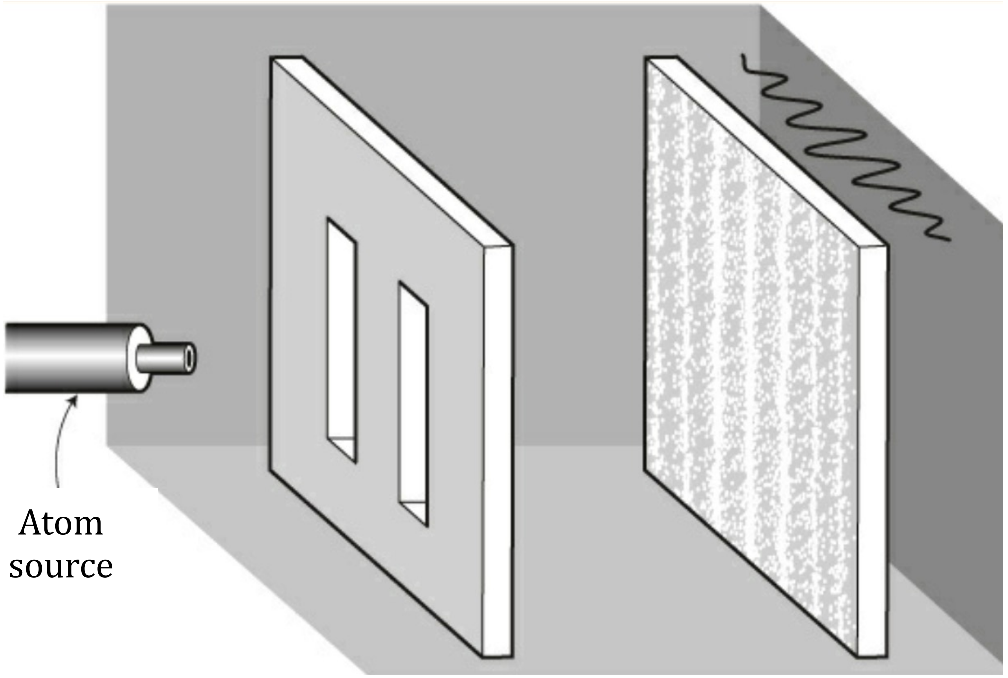
Museo Storico della Fisica e Centro Studi e Ricerche «Enrico Fermi»



Quantum *vs.* classic



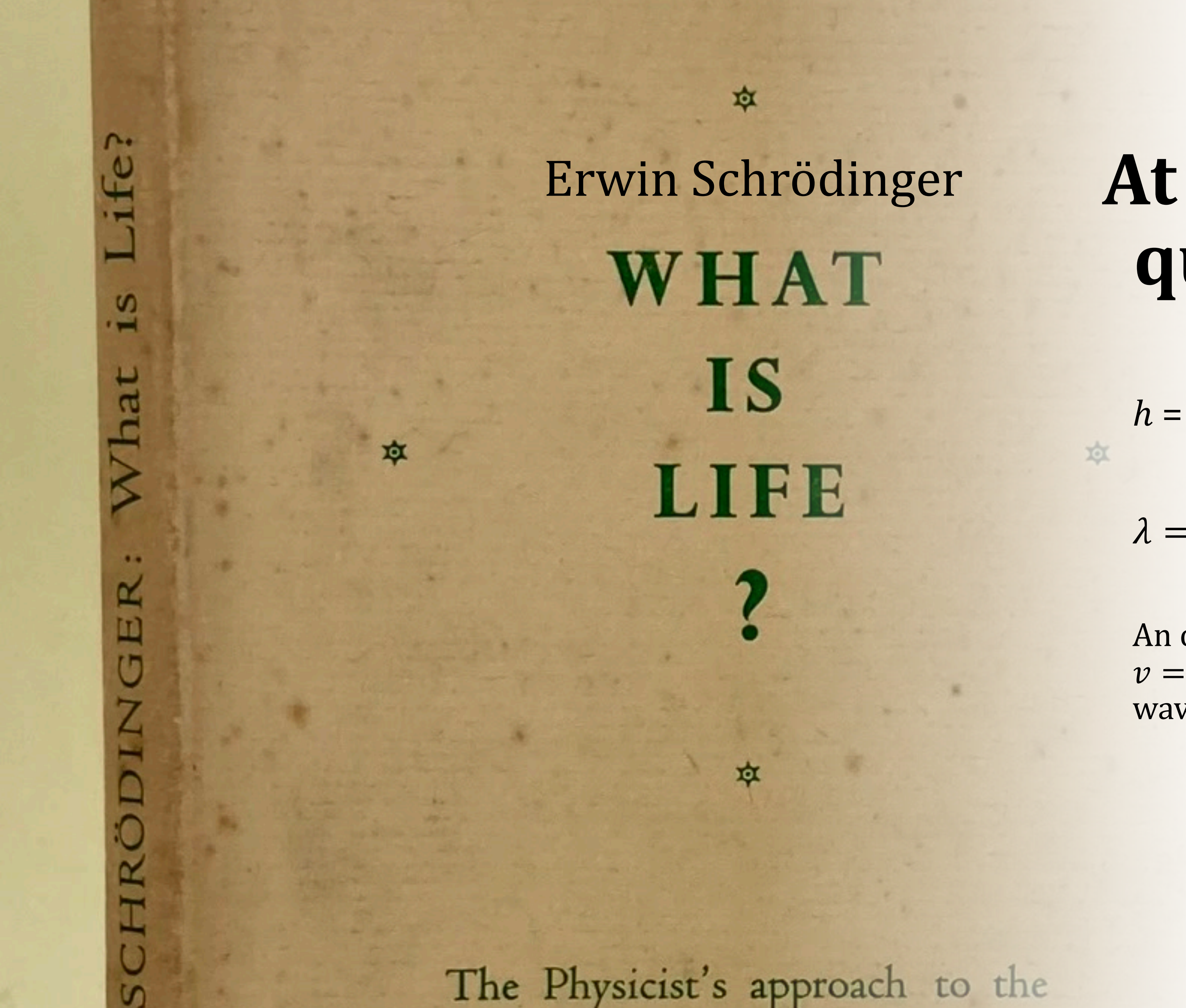
Classical behaviour



Mechanical behaviour

Al-Khalili, Jim; McFadden, Johnjoe. La fisica della vita: La nuova scienza della biologia quantistica (Italian Edition), Bollati Boringhieri.

Erwin Schrödinger



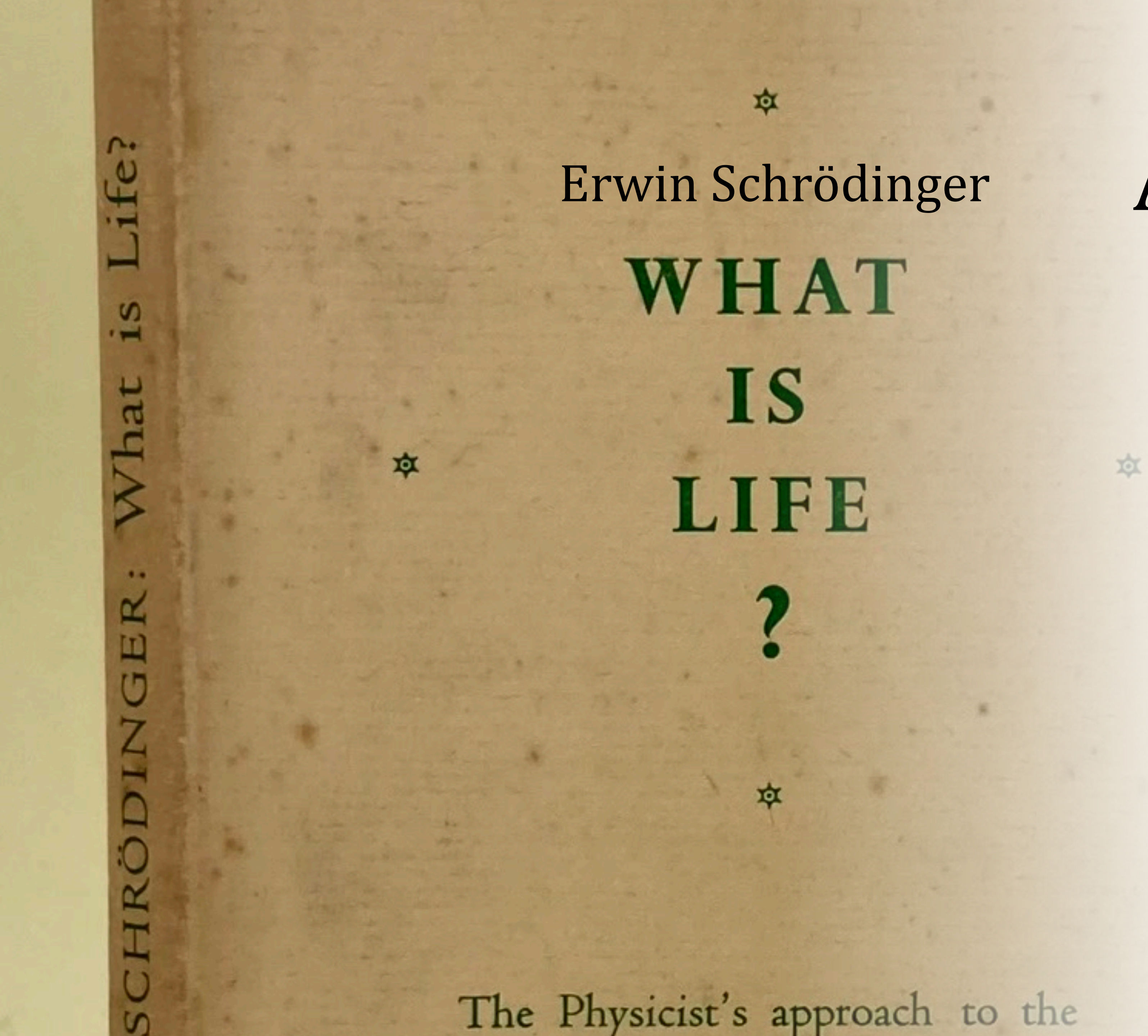
At the edge of the quantum world

h = 6.62607015 × 10^{-34} m^2kg/s

$\lambda = h/p = h/mv$

An object with a mass $m = 10^{-6}$ kg and $v = 10$ m/s will have a De Broglie wavelength

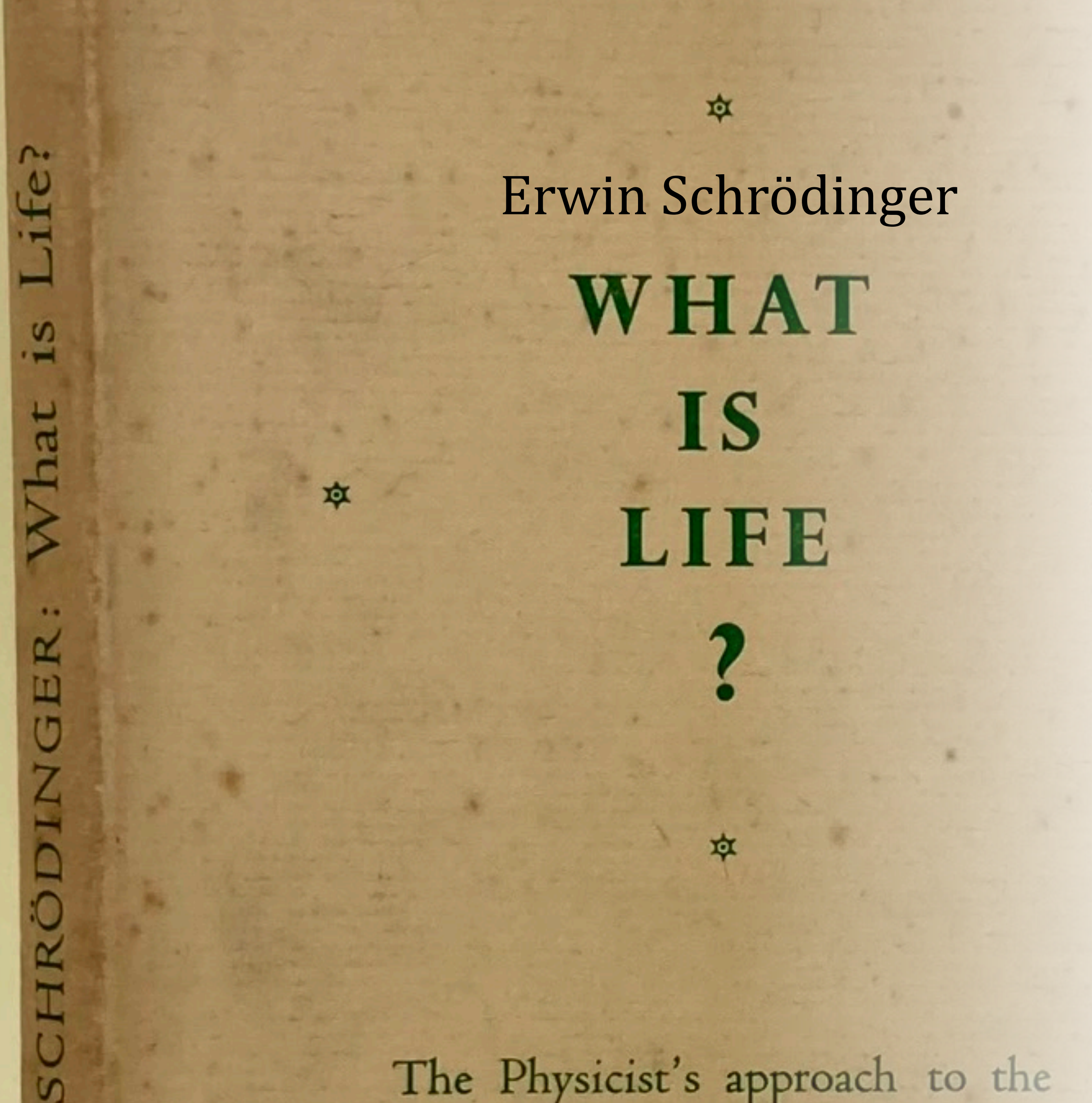
$$\lambda \sim 10^{-28} m$$



At the edge of the quantum world

Living Matter Evades the Decay to Equilibrium

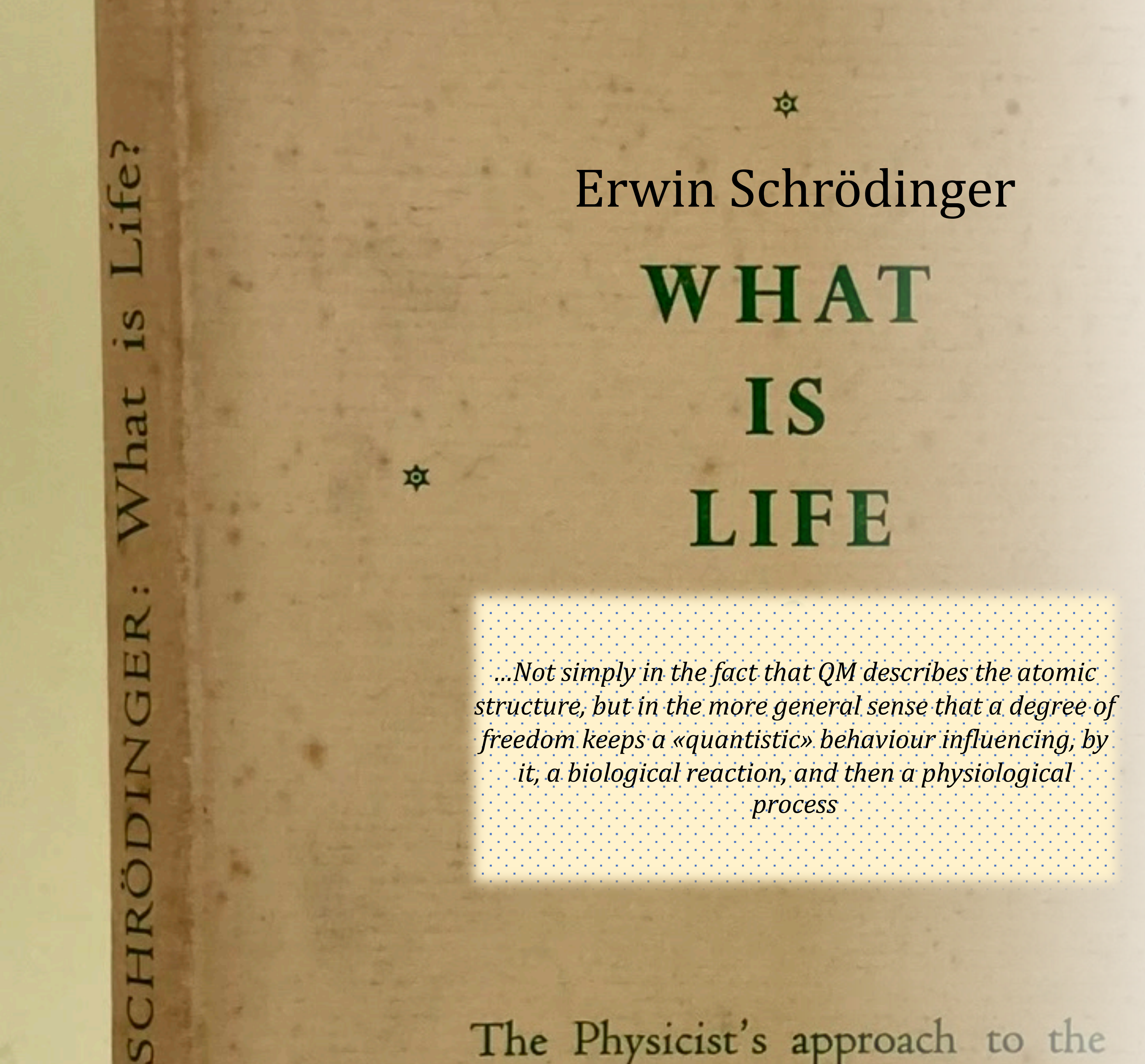
"What is the characteristic feature of life? When a system that is not alive is isolated or placed in a uniform environment, all motion usually comes to a standstill very soon as a result of various kinds of friction; differences of electric or chemical potential are equalized, substances which tend to form a chemical compound do so, temperature becomes uniform by heat conduction. After that the whole system fades away into a dead, inert lump of matter. A permanent state is reached, in which no observable events occur. The physicist calls this the state of thermodynamical equilibrium, or of 'maximum entropy'."



Erwin Schrödinger

At the edge of the quantum world

- Sensorial perception is a «classical» phenomenon → we detect collapsed, averaged quantities
- Are there biological systems that use quantum mechanics to perform a task that either cannot be done classically, or can do that task more efficiently than even the best classical equivalent?
- A variety of organism may harness some of the unique feature of the quantum mechanics to gain a biological advantage
- Is it possible to harnessing quantum coherence on physiologically important timescales?
- **Can Quantum Mechanics play a role in biology?**



Erwin Schrödinger

...Not simply in the fact that QM describes the atomic structure, but in the more general sense that a degree of freedom keeps a «quantistic» behaviour influencing, by it, a biological reaction, and then a physiological process

At the edge of the quantum world

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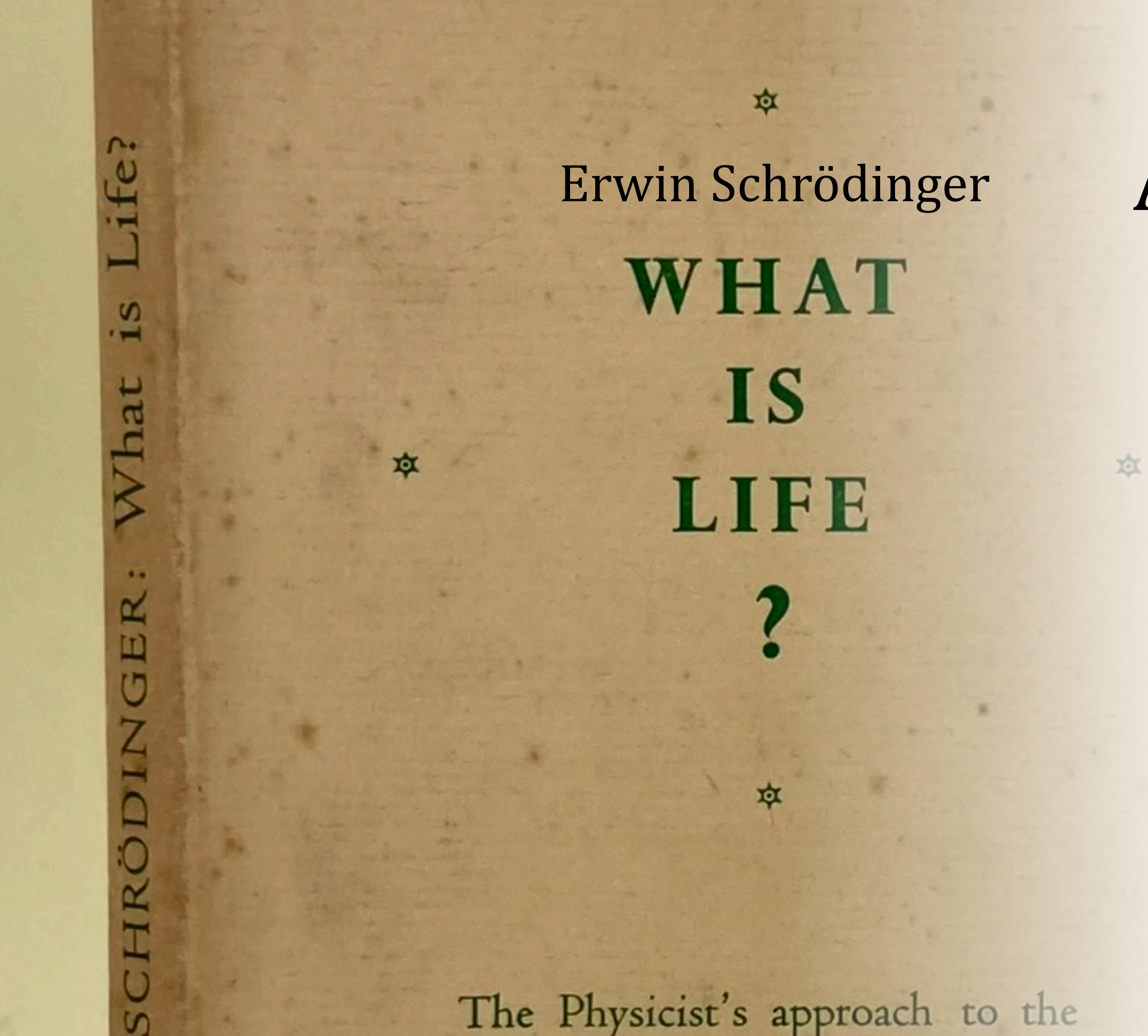

At the edge of the quantum world

All living systems are made up of molecules, and fundamentally all molecules are described by QM.

Traditionally, however, due to the vast separation of scales between systems described by QM and those studied in biology, as well as the seemingly deifferent properties of inanimate and animate matter, has maintained some separation between the two realm of knowledge.

In some biological phenomena, however, the classical approach seems to fail.

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Photosynthesis

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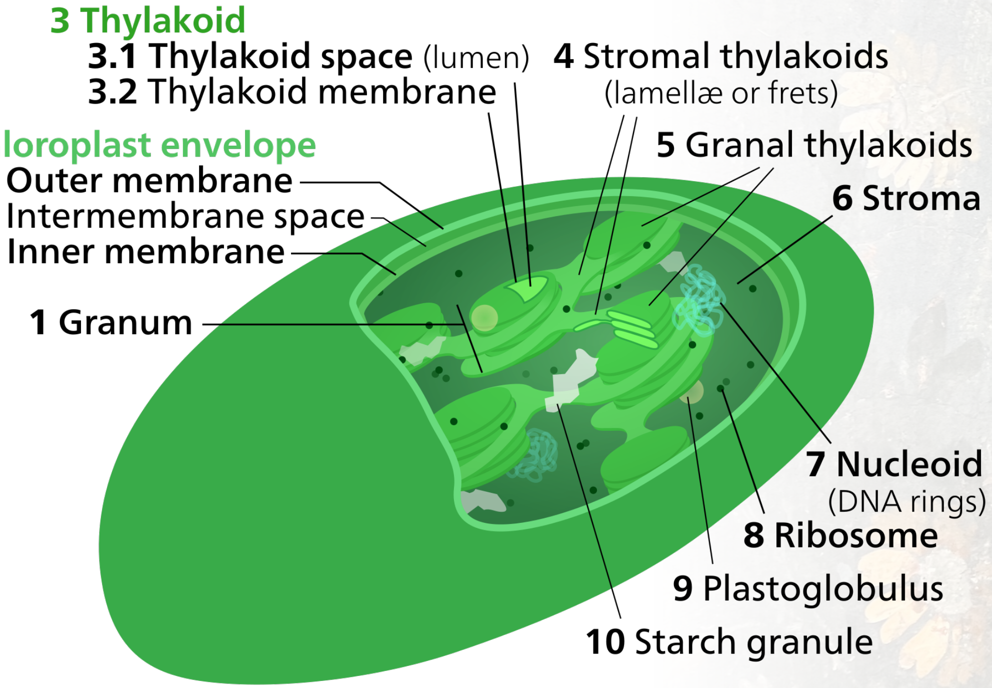
Photosynthesis

Chloroplast: membrane-bound organelle where photosynthesis takes place. In it, thylakoid containing chlorofyll molecules – *i.e.* the pigments capturing solar light - are contained.



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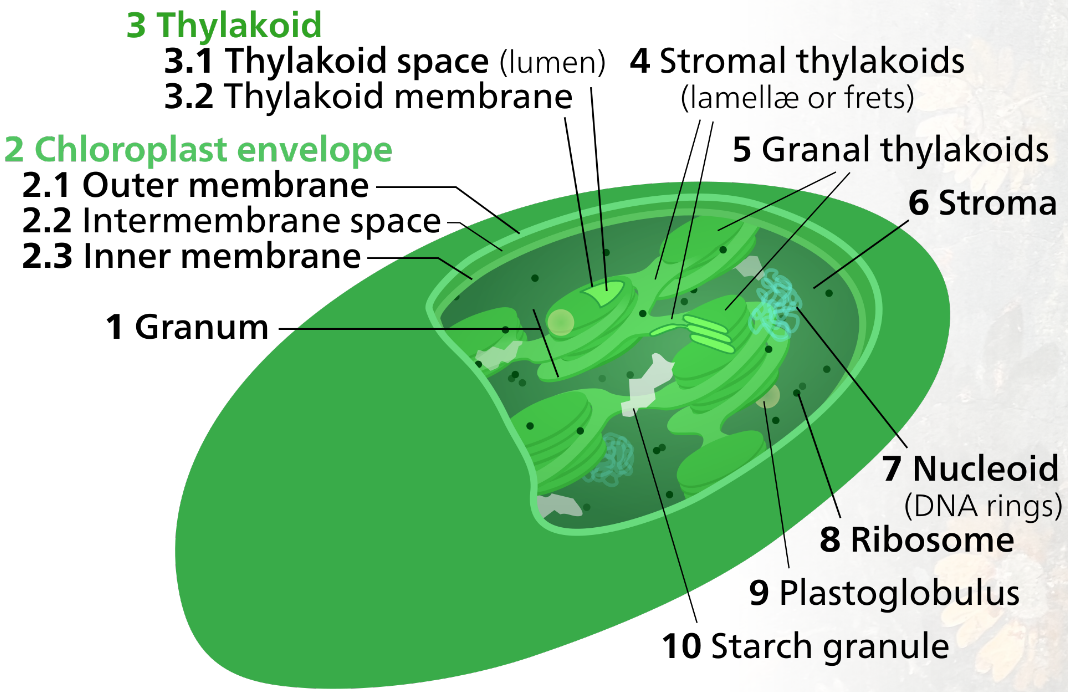

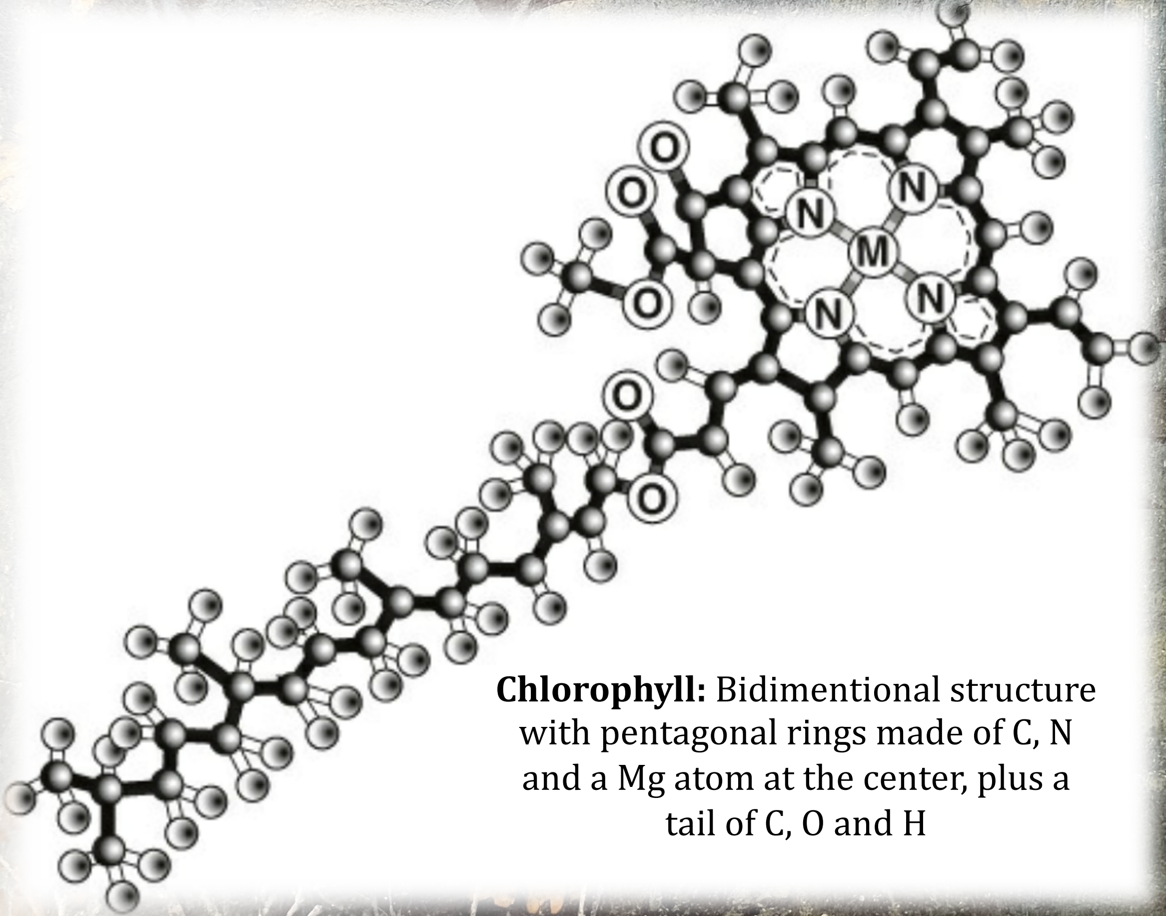

Chlorophyll: Bidimentional structure with pentagonal rings made of C, N and a Mg atom at the center, plus a tail of C, O and H

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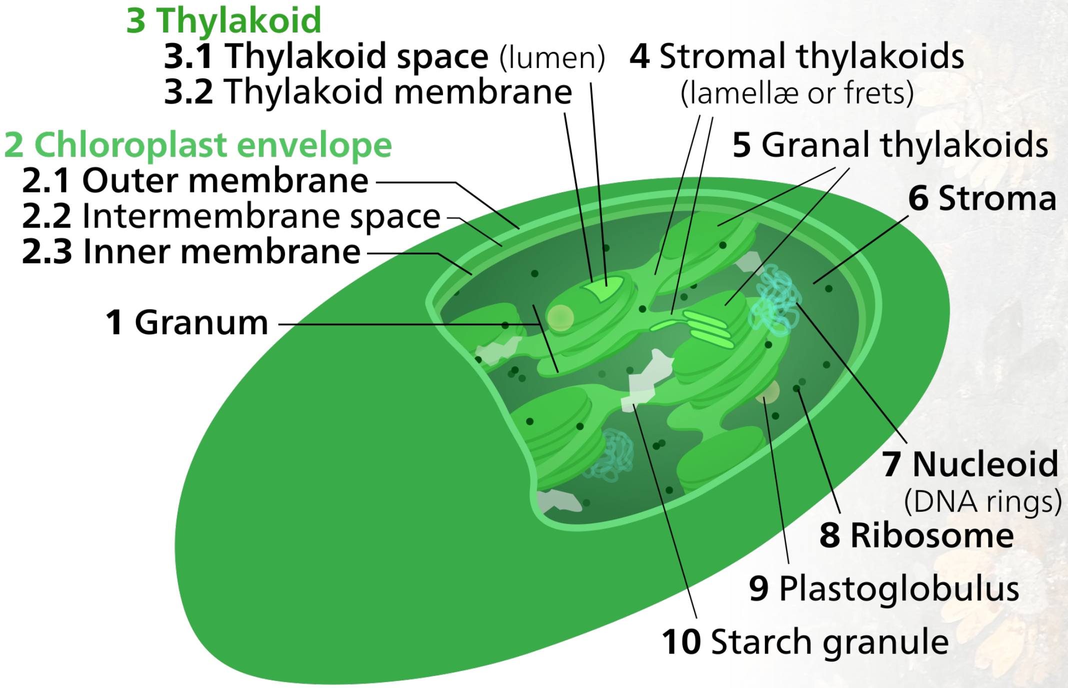

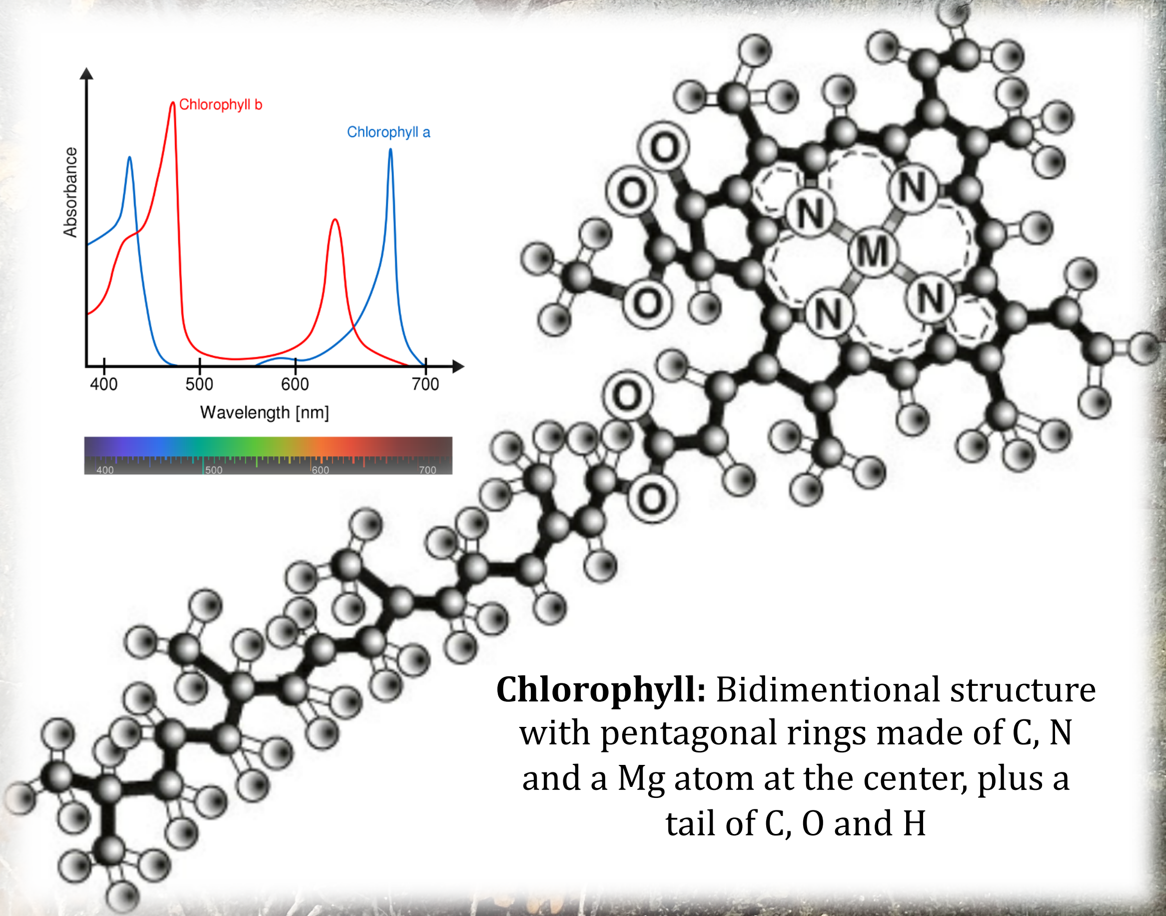

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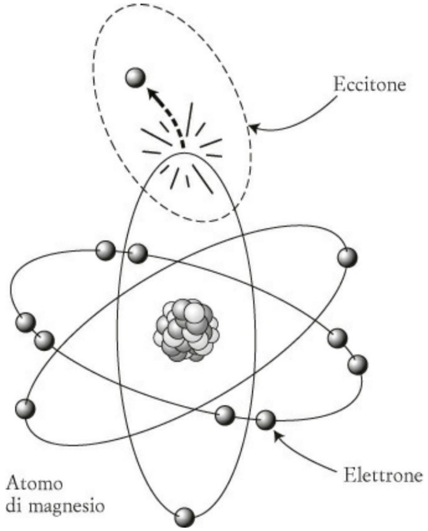
Photosynthesis

An **exciton** is a bound state of an electron and an electron hole which are attracted to each other by the electrostatic Coulomb force → electrically neutral quasiparticle, that can transport energy without transporting net electric charge.



Frenkel exciton: small size exciton, almost completely localized within the molecule (typical binding energy of 0.1÷ 1 eV)

Franck and Teller, https://doi.org/10.1063/1.1750182

Photosynthesis

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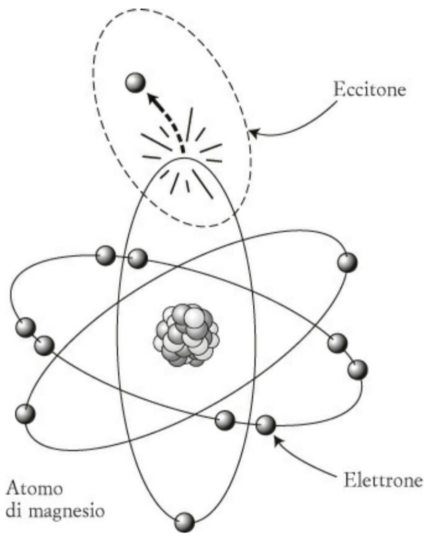

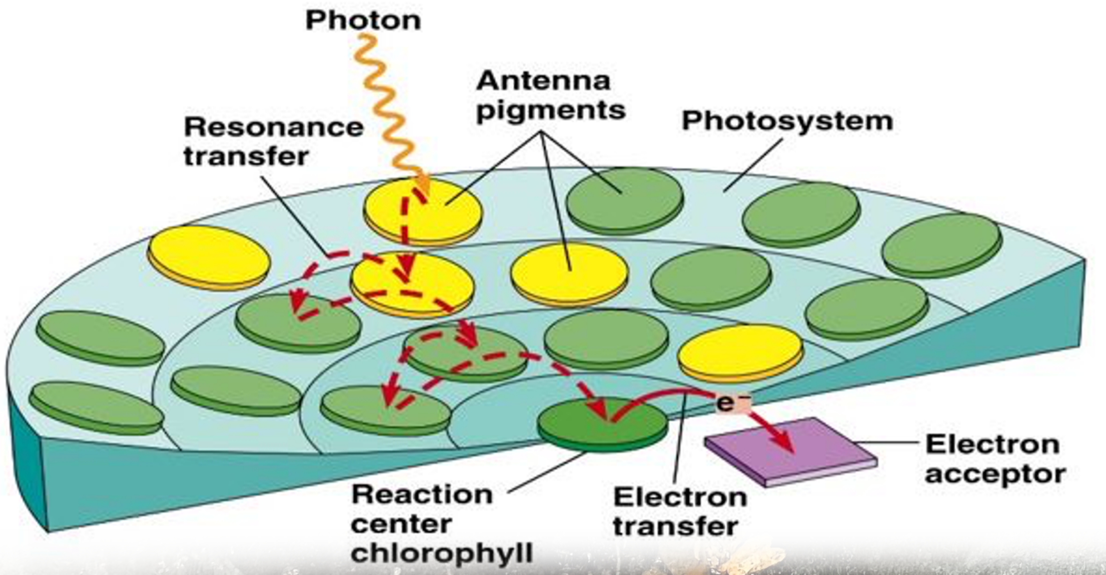

Tend to recombination → needs to be transported to a reaction center where the actual «charge separation» takes place. **The transfer proceeds through the different chlorophyll molecules.**

Photosynthesis

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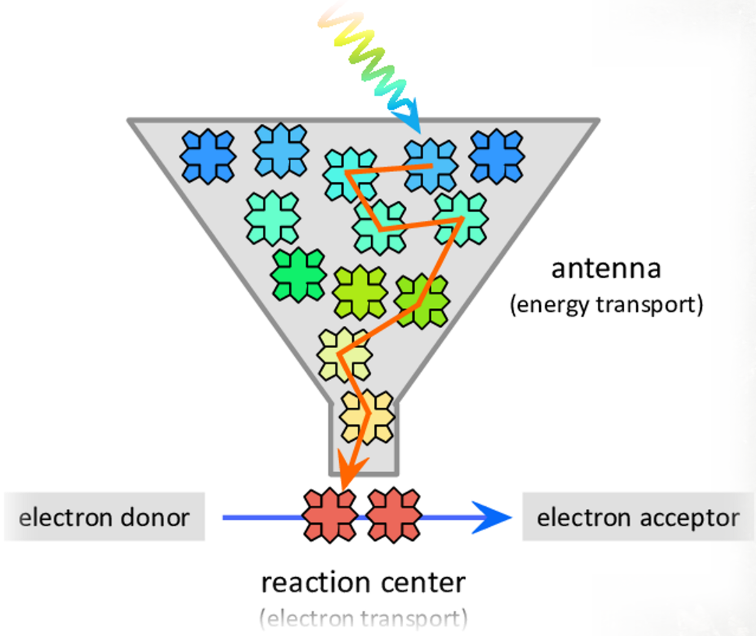
Chlorofyll is highly concentrated → the exciton is transferred by the different molecules up to the reaction center.

Final step: **charge separation** ⇒ it will be operated in a dedicated structure that eventually will convert the energy absorbed by a pigment through a solar photon to *biochemical energy.*



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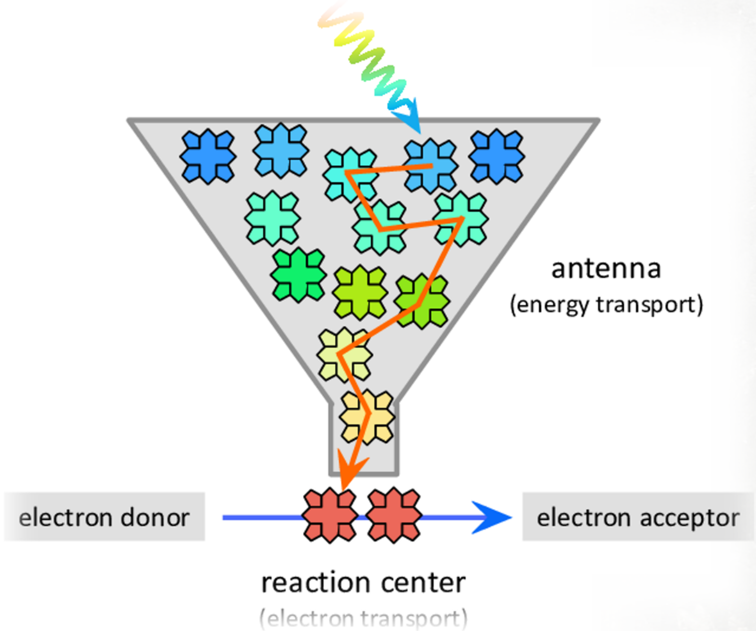
Photosynthesis

Absorption time-scale $\sim 10^{-15}$ s $\Rightarrow$ large absorption coefficients, high density of pigments

Transfer time-scale $\sim 10^{-9}$ s $\Rightarrow$ then the excitation will be lost

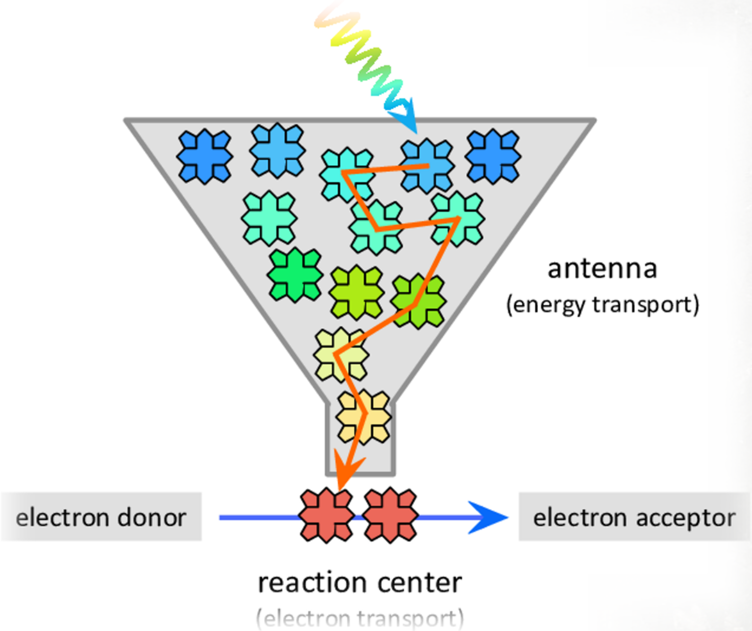
Global process time-scale $\sim 10^{-10}$ s $\Rightarrow$ to reach a high efficiency



Photosynthesis

Charge separation ⇒ must take place before the exciton will «decay» and the recombination takes place.

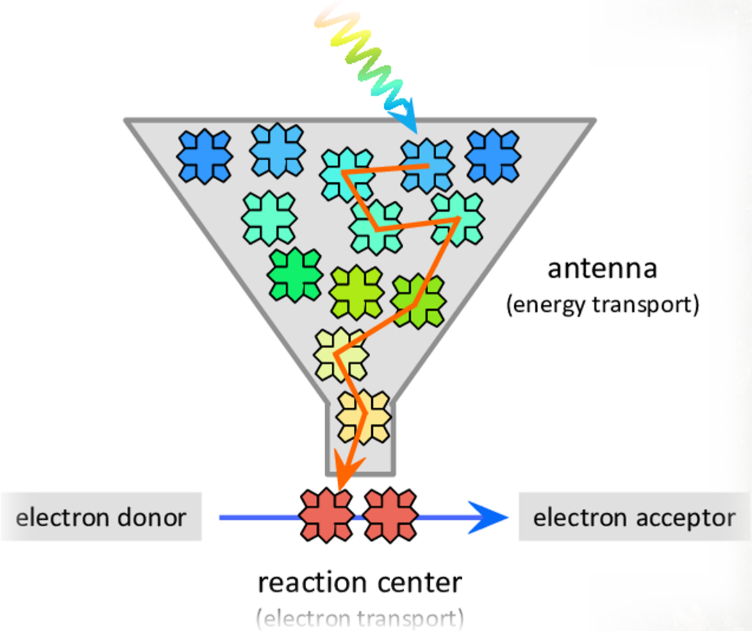
A classical «space-exploration», i.e. *classical random-walk*, would take too long, and part of the excitation will be lost before reaching the reaction center.

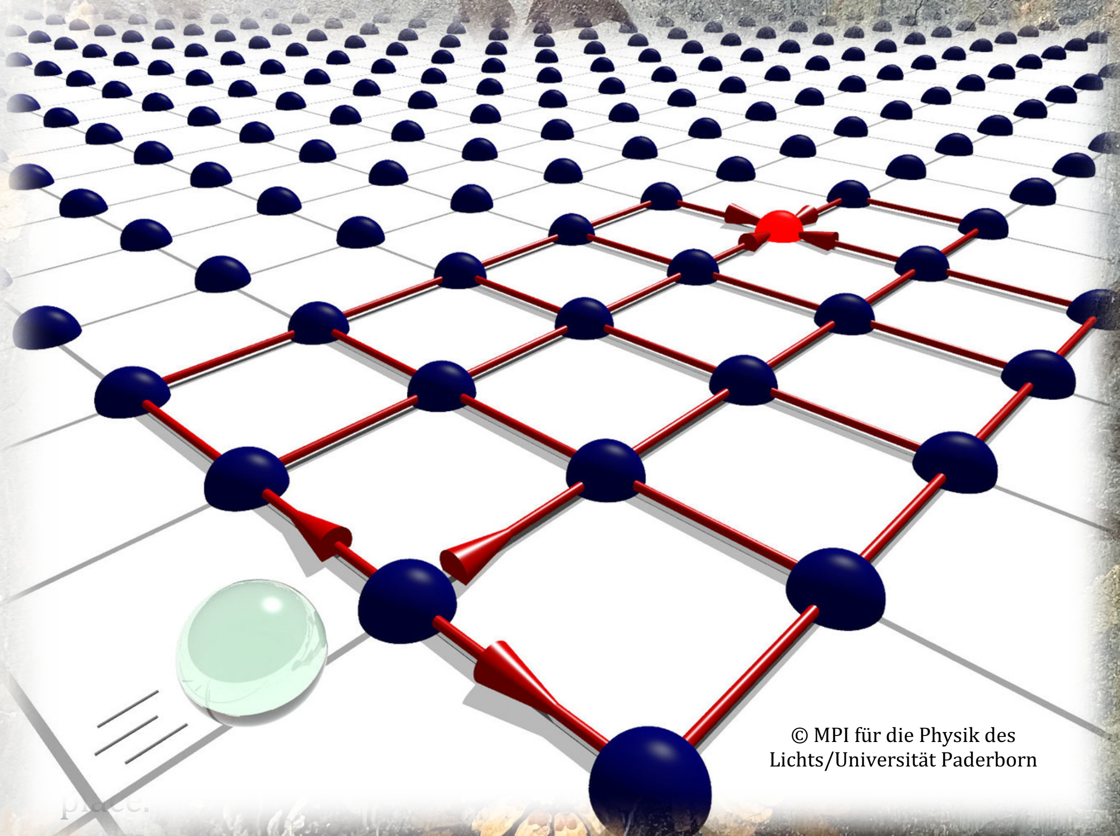


Photosynthesis

Charge separation ⇒ must take place before the exciton will «decay» and the recombination takes place.

Quantum-walk ⇒ provide a speedup (exponential, polynomial etc) over any classical algorithm.





How to investigate quantum-walk in photosynthetic complexes

- It proceeds through the excitation of the molecular dynamics through a suitable source

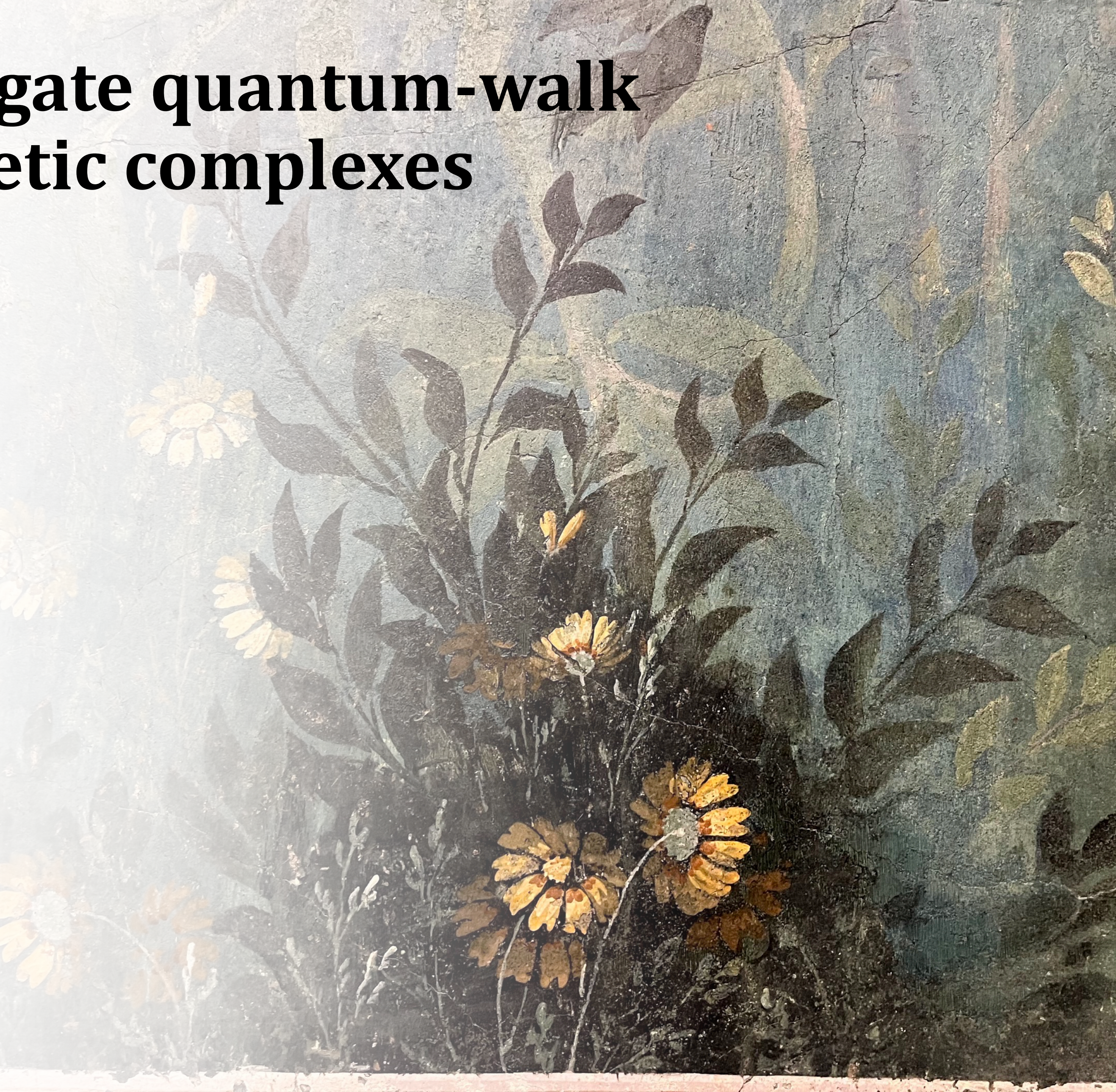
- Depending on the photosynthetic complex to be analyzed, different sources may be used

- One of the main technique is based on *femtosecond lasers*

- The idea is to extend the concept beyond the NMR, that investigates spins, to the analysis of the electron dynamics and possible interplay with the molecular dynamics (*e.g.,* vibrational spectra)

- Molecules are frozen on the femtosecond timescale

- Femtosecond 2DFT experiments might reveal the fastest motions in chemical reactions with the highest possible time and frequency resolution



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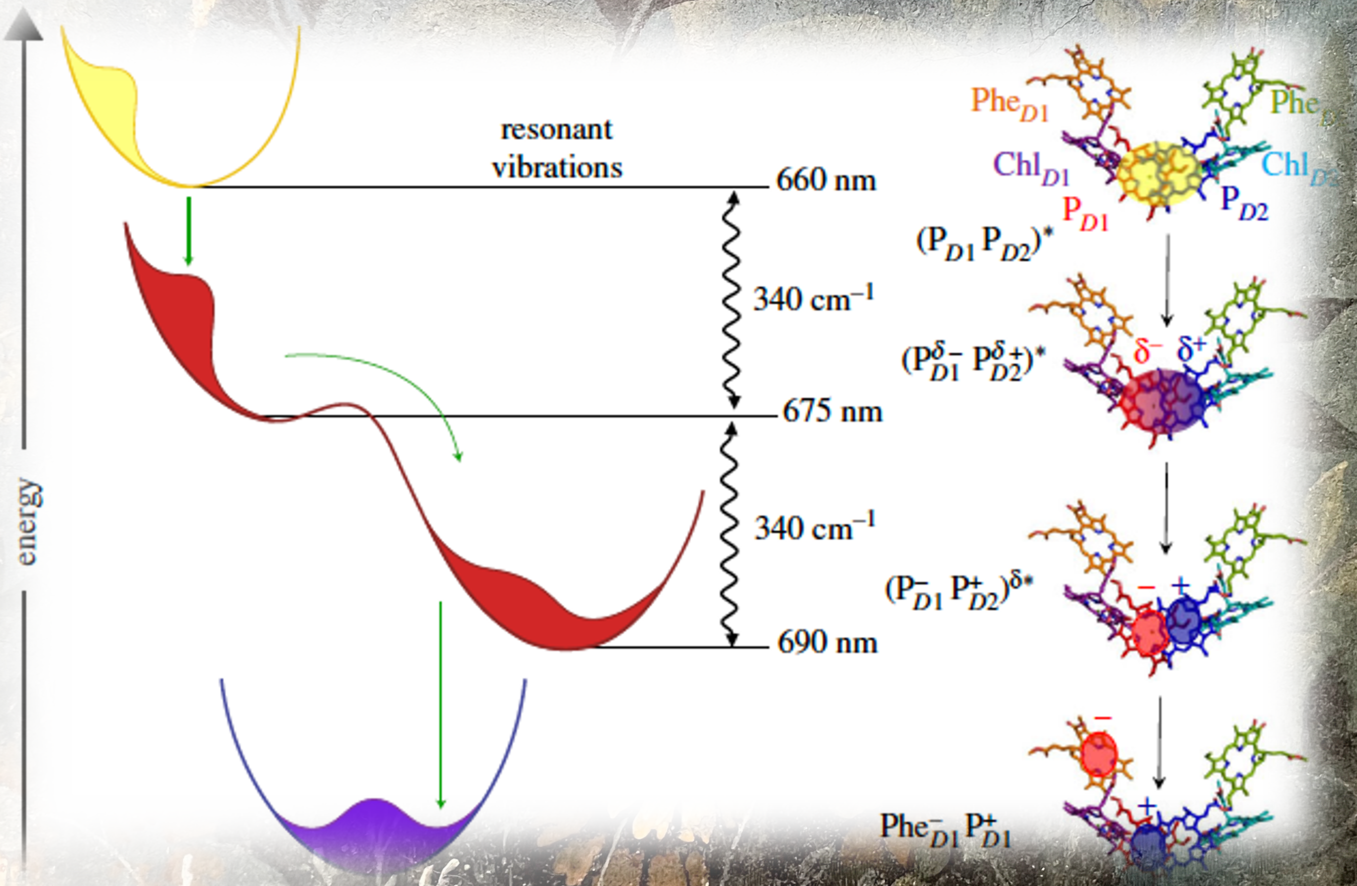

10.1146/annurev.physchem.54.011002.103907, 10.1063/1.1776112, https://doi.org/10.1146/annurev.physchem.54.011002.103907

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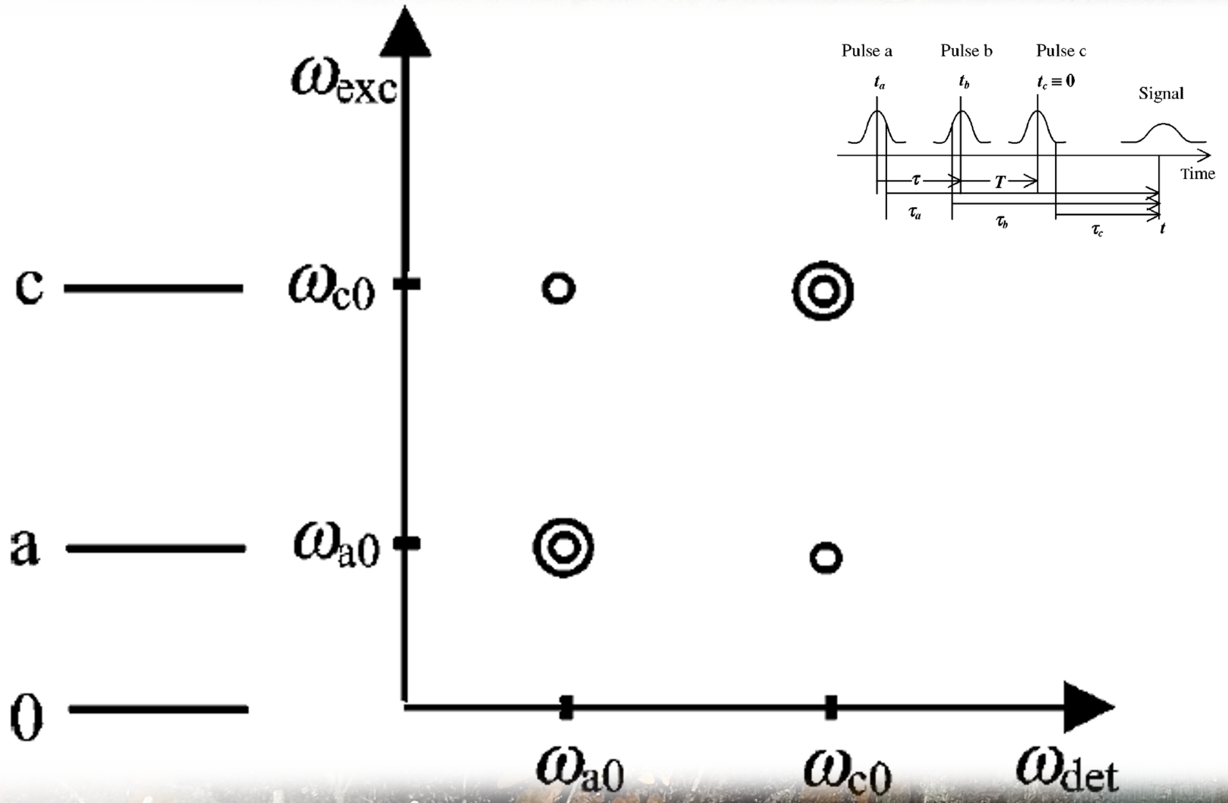

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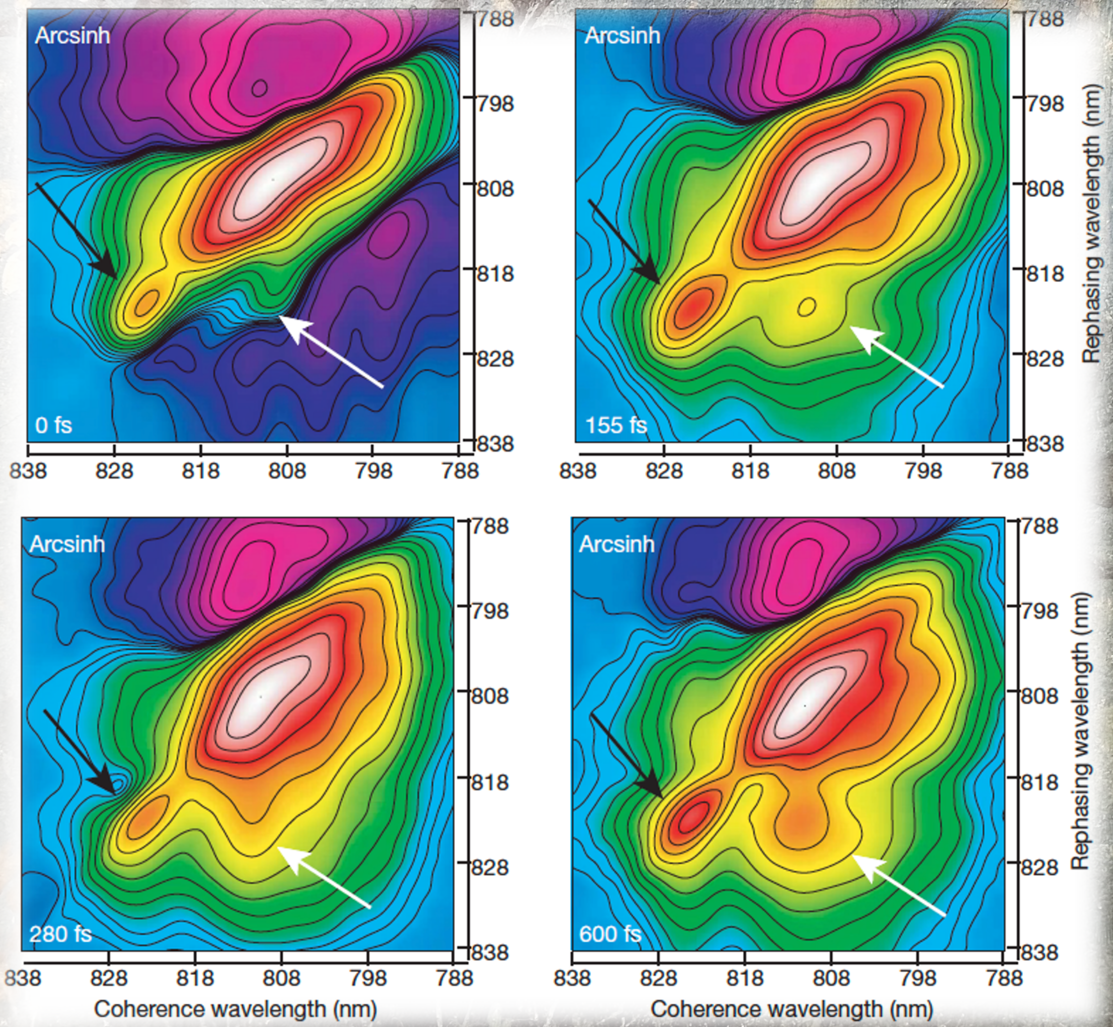

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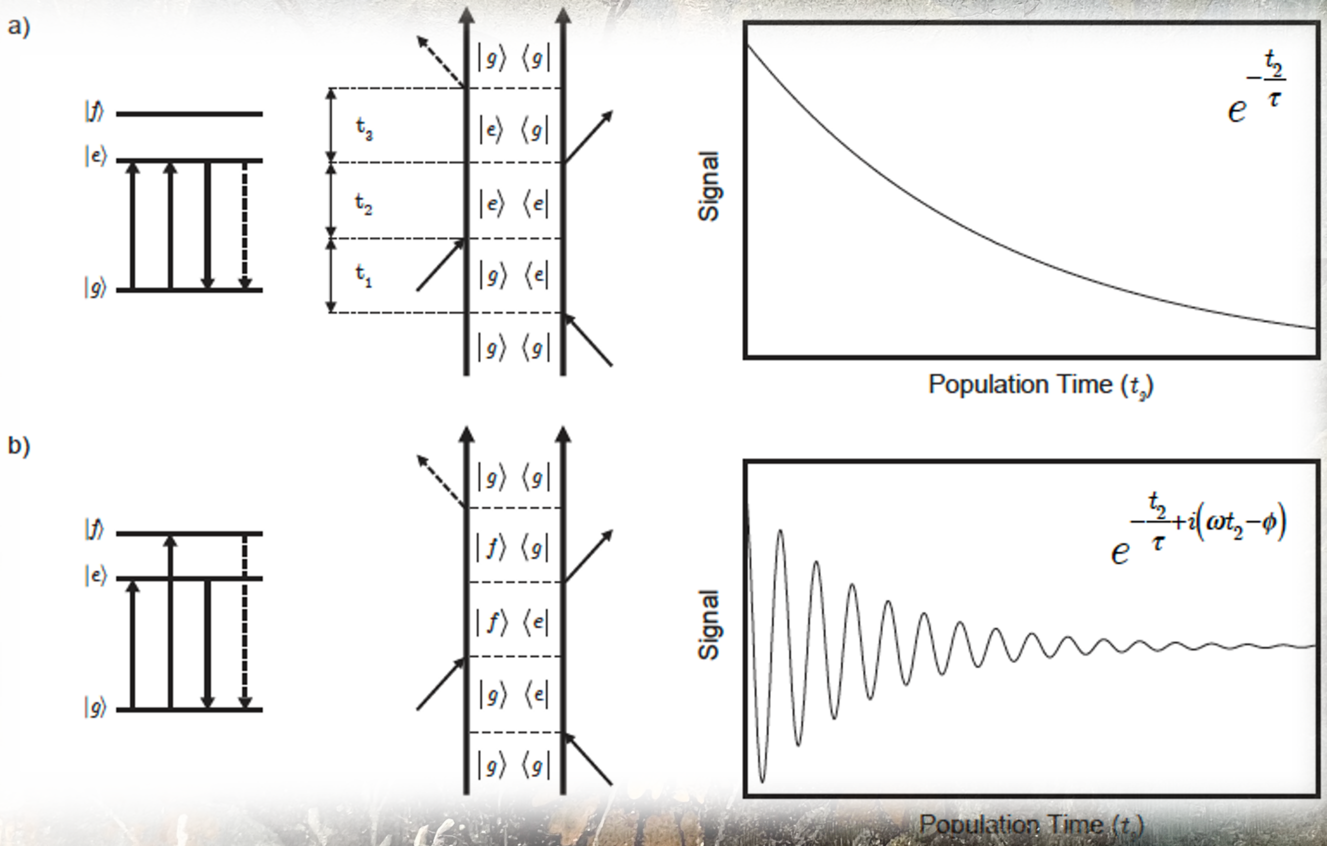

http://dx.doi.org/10.1364/OE.24.024773

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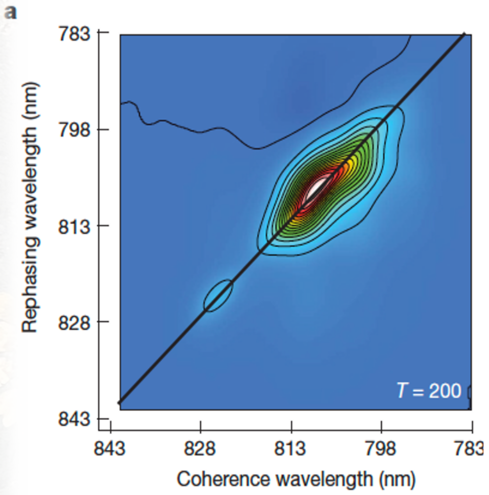
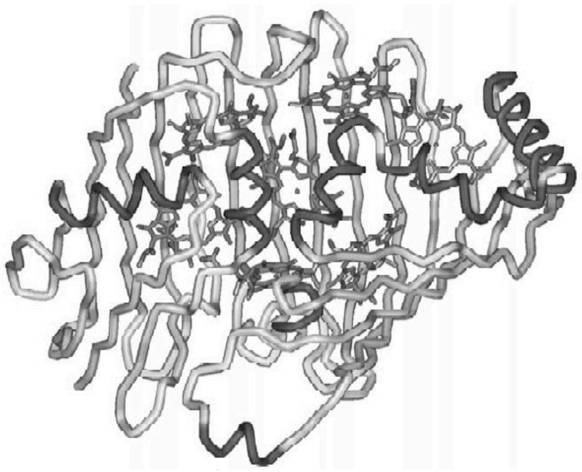
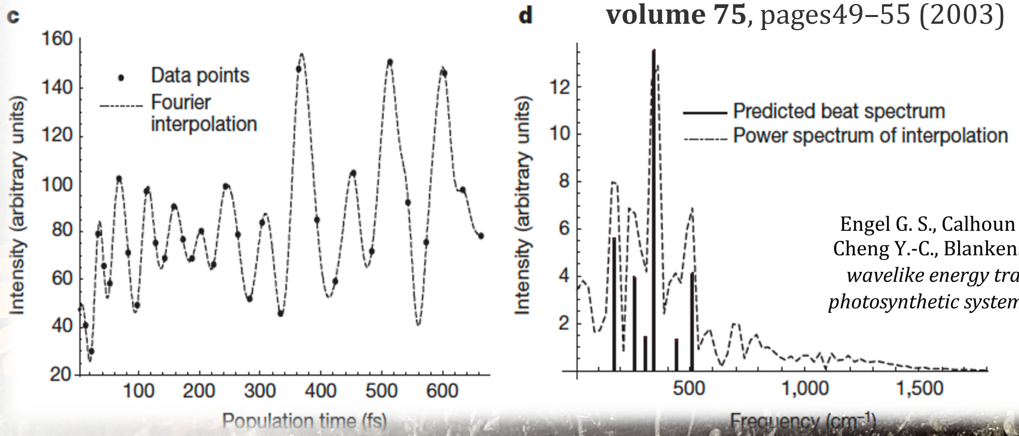




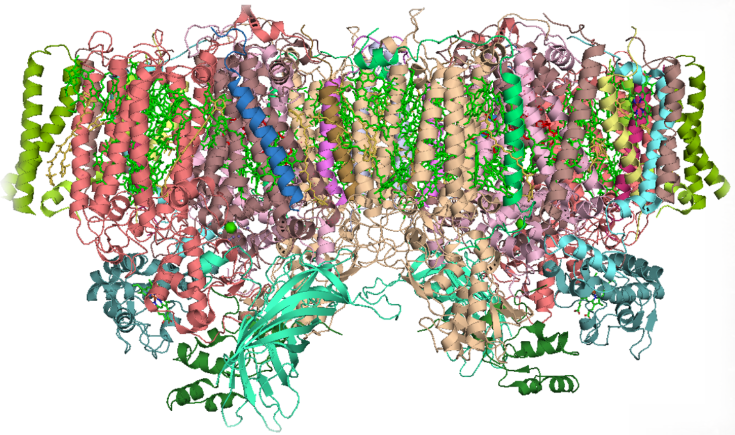
[Photosynthesis Research](#) **volume 75**, pages49–55 (2003)

«The quantum coherence manifests itself in characteristic, directly observable quantum beating signals among the excitons within the ***Chlorobium tepidum FMO complex at 77 K*****»**.

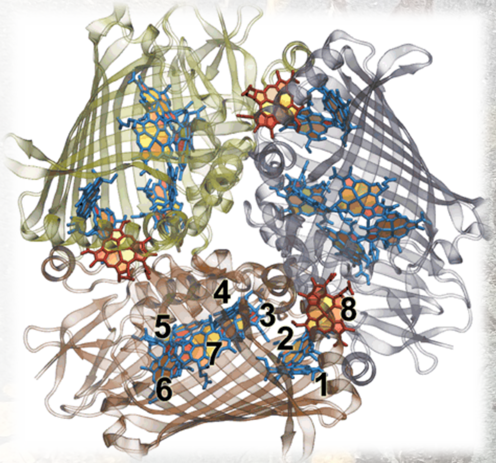


Engel G. S., Calhoun T. R., Read E. L., Ahn T-K., Manč al T., Cheng Y.-C., Blankenship R. E. e Fleming G. R., *Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems*, «**Nature**», vol. 446 (2007), pp. 782-86.

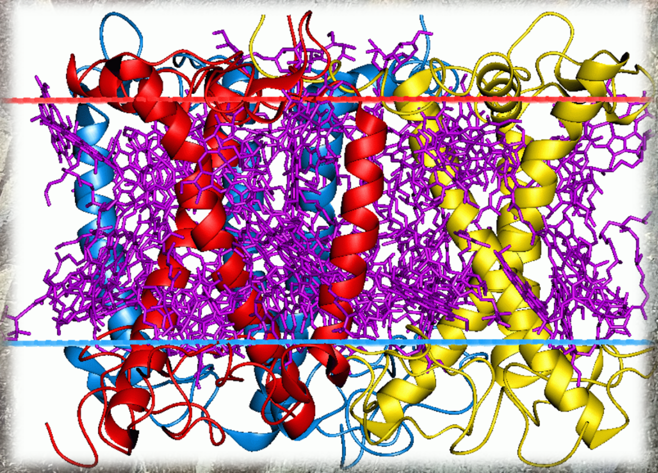
Where these photosynthetic complexes appear?



Cyanobacteria photosystem II, Dimer, PDB 2AXT



FMO homo-trimer from Chlorobaculum tepidem. Each monomer sandwiches 7 bacteriochlorophyll molecules for light harvesting.



Chlorophyll A-B binding protein - Light-Harvesting Complex II (LHCB)

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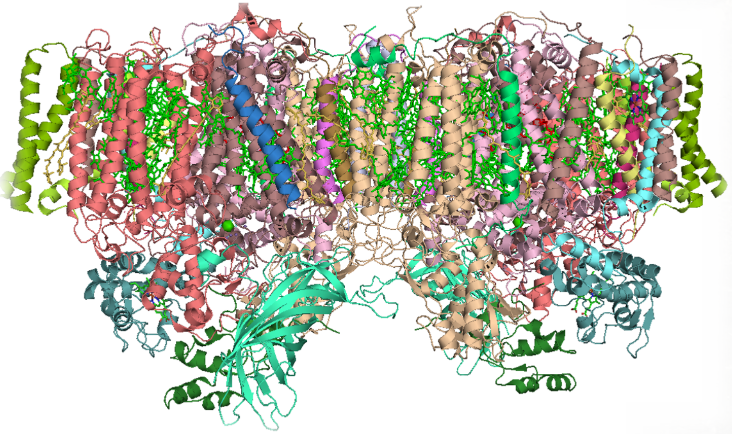

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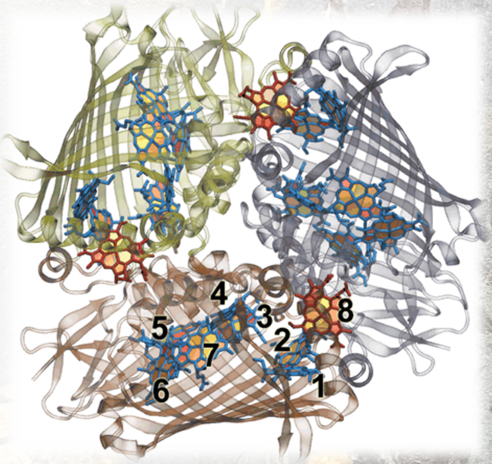

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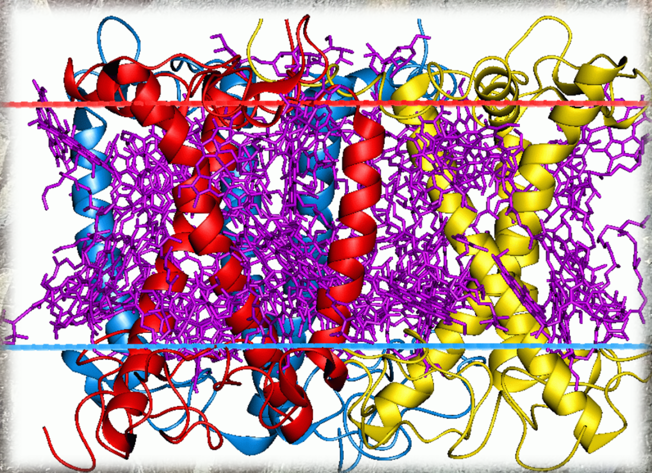
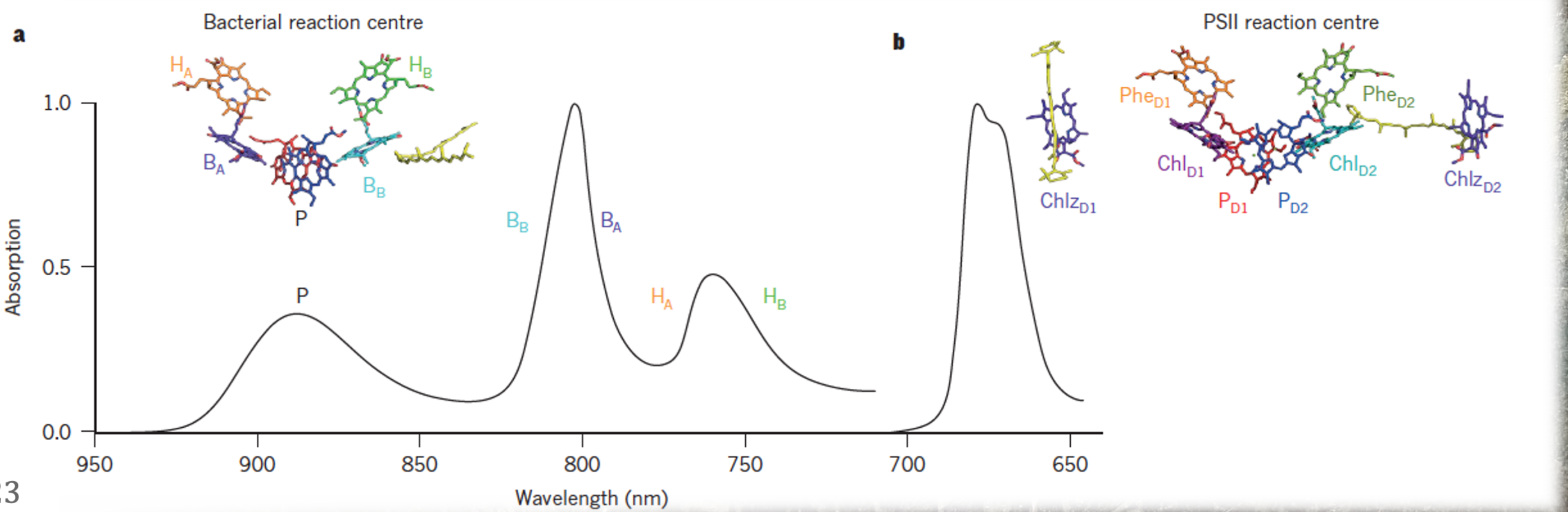


Chlorophyll A-B binding protein - Light-Harvesting Complex II (LHCB)

Absorption spectra and X-ray structure of the bacterial reaction centre and the PSII reaction centre. a) The absorption spectrum of the bacterial reaction centre of Rhodobacter sphaeroides at 77 K is shown with the X-ray crystal structure of the complex. b) The 77 K absorption spectrum of the PSII reaction centre of spinach (Spinacia oleracea) is displayed with the X-ray crystal structure of the complex .



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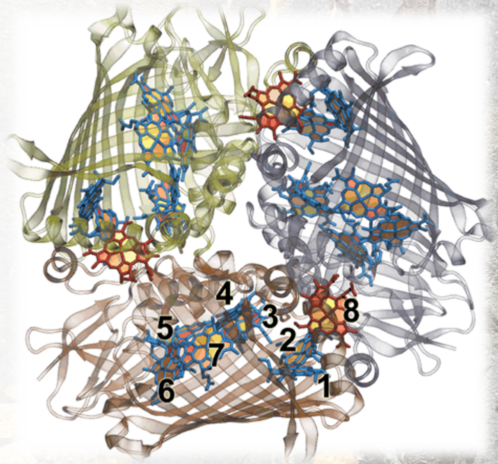
Where these photosynthetic complexes appear?

The most suitable experimental methods are spectroscopic techniques

1. absorption spectroscopy ⇒ *energy of the absorbing states*
2. fluorescence spectroscopy ⇒ *energy of the lowest energy-emitting state*
3. linear dichroism and circular dichroism ⇒ *pigment interactions and orientations*
4. triplet-minus-singlet spectroscopy ⇒ *energetic position of the triplet state and of the singlet state on which the triplet is formed*
5. Stark spectroscopy ⇒ *charge-transfer character of excited states*
6. Time-resolved spectroscopic techniques ⇒ **two-dimensional electronic spectroscopy**



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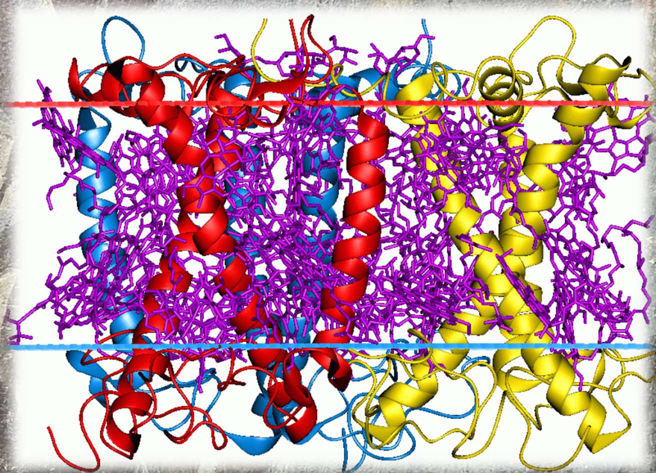

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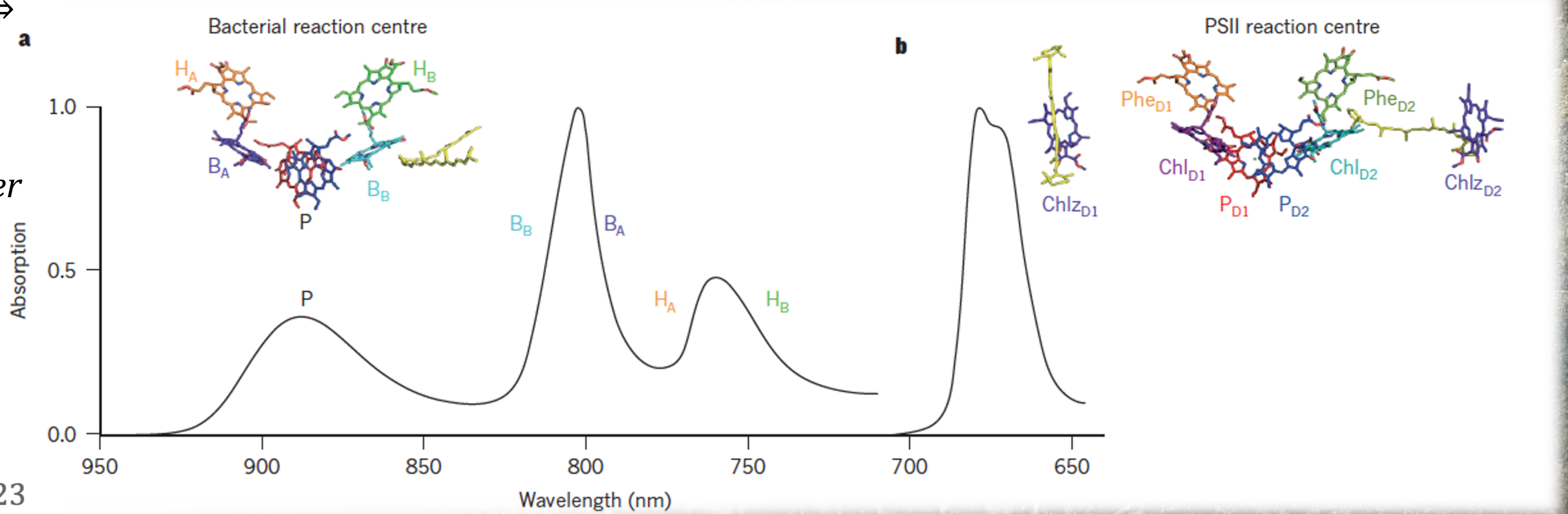
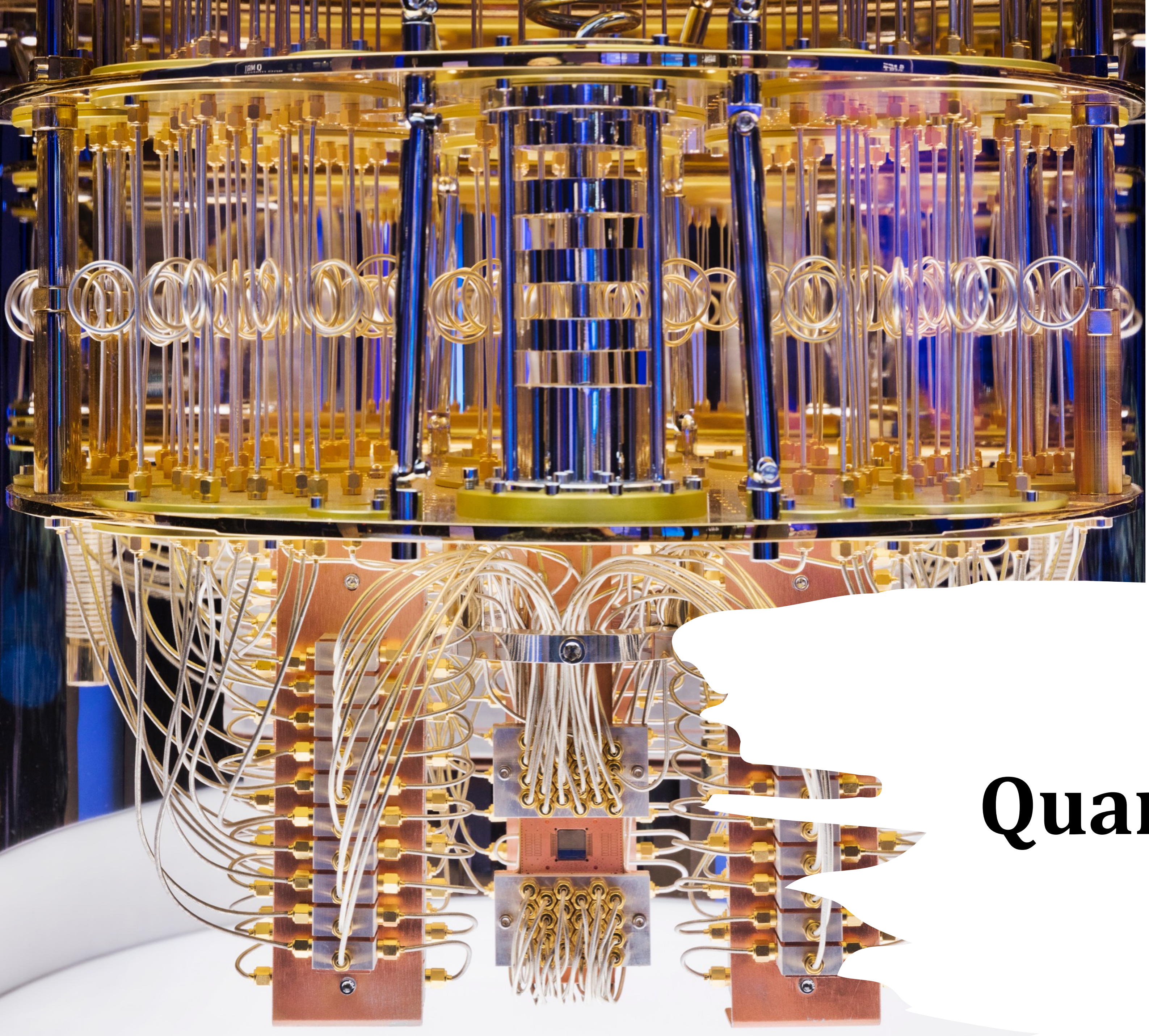
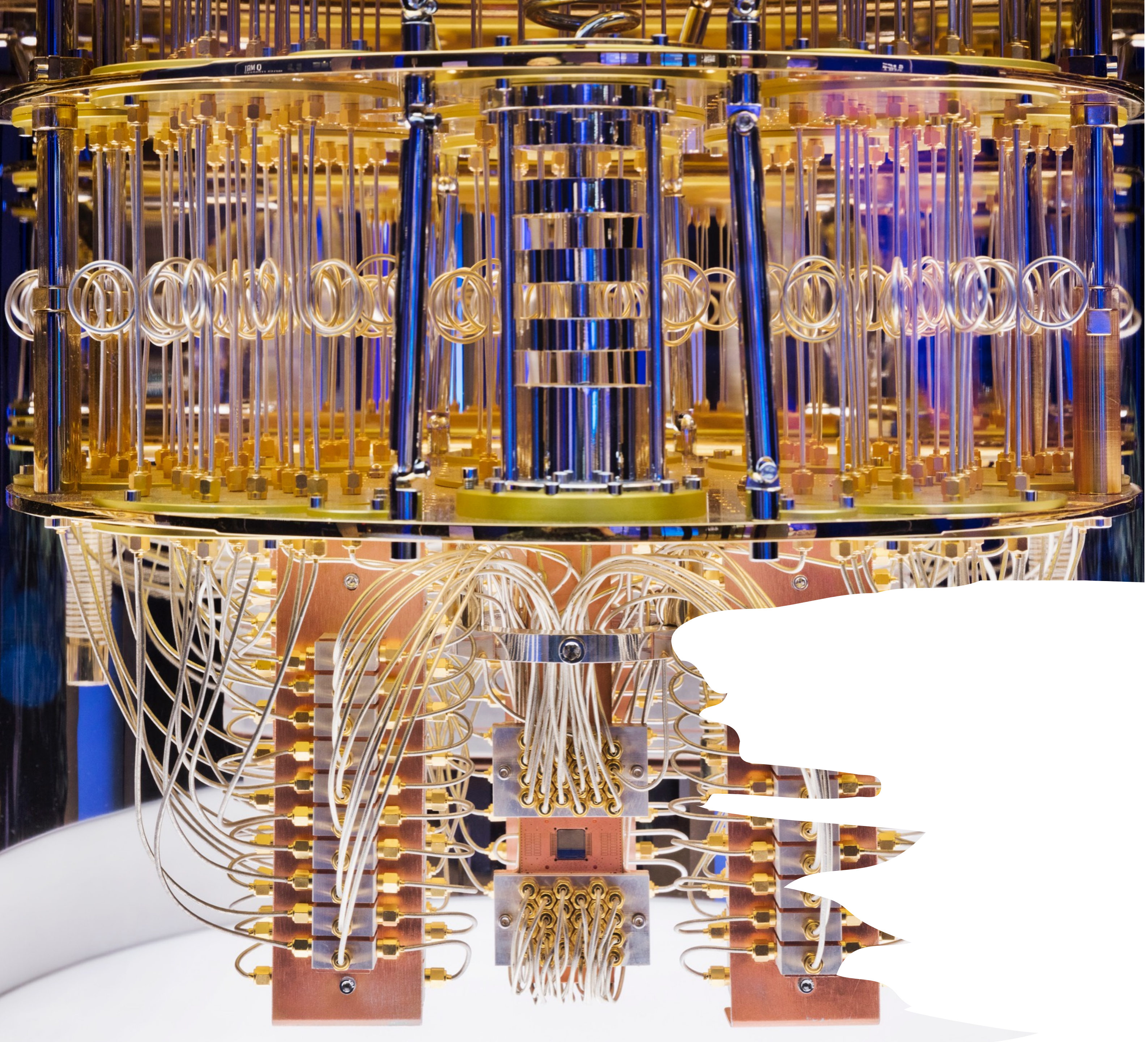
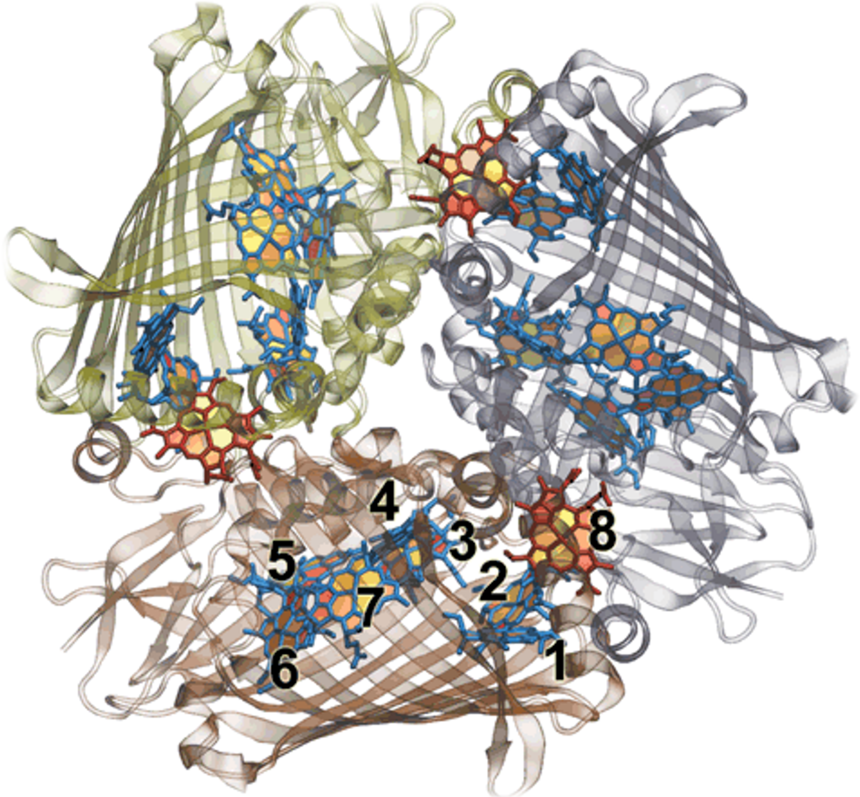




Quantum computing

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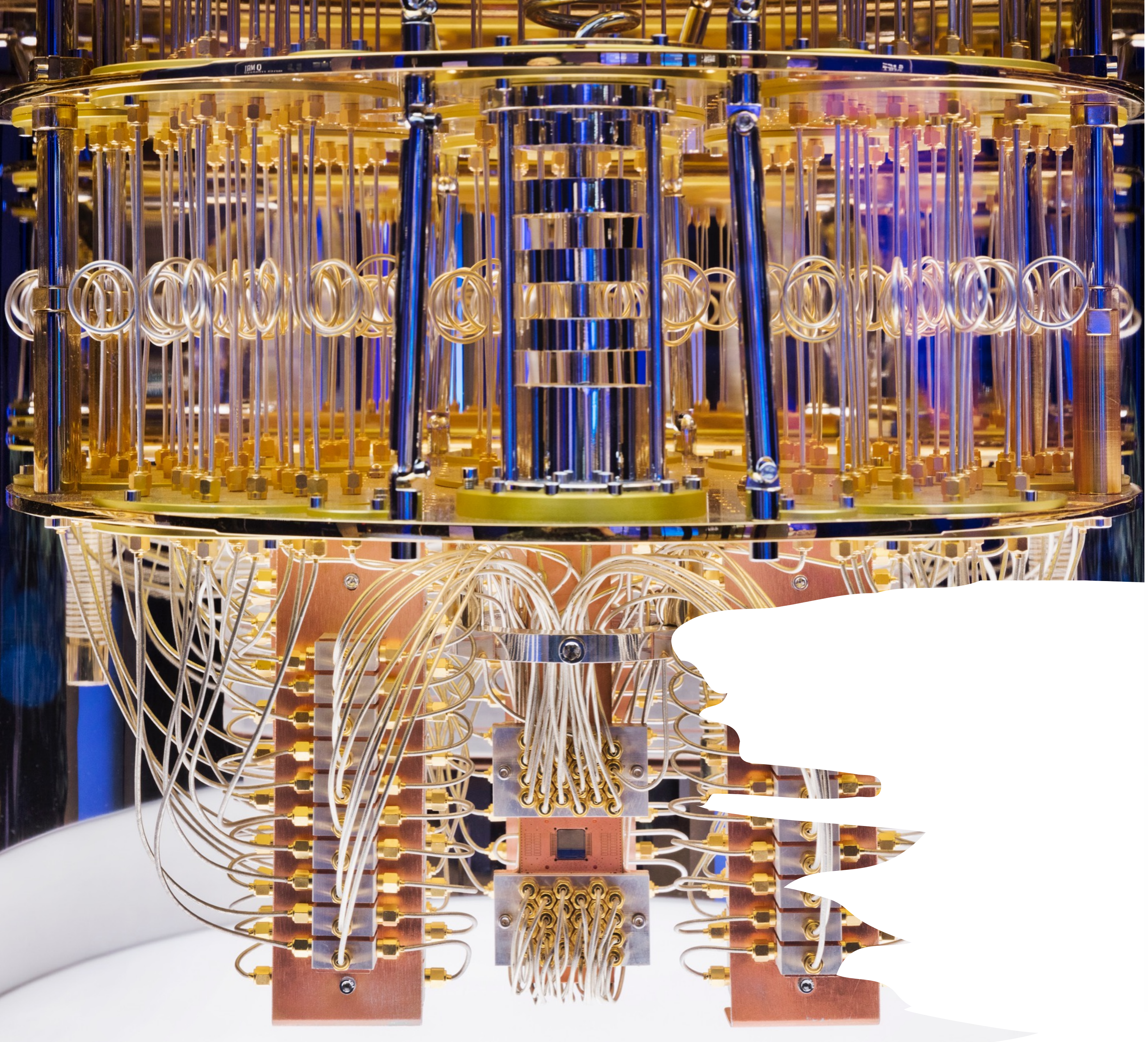

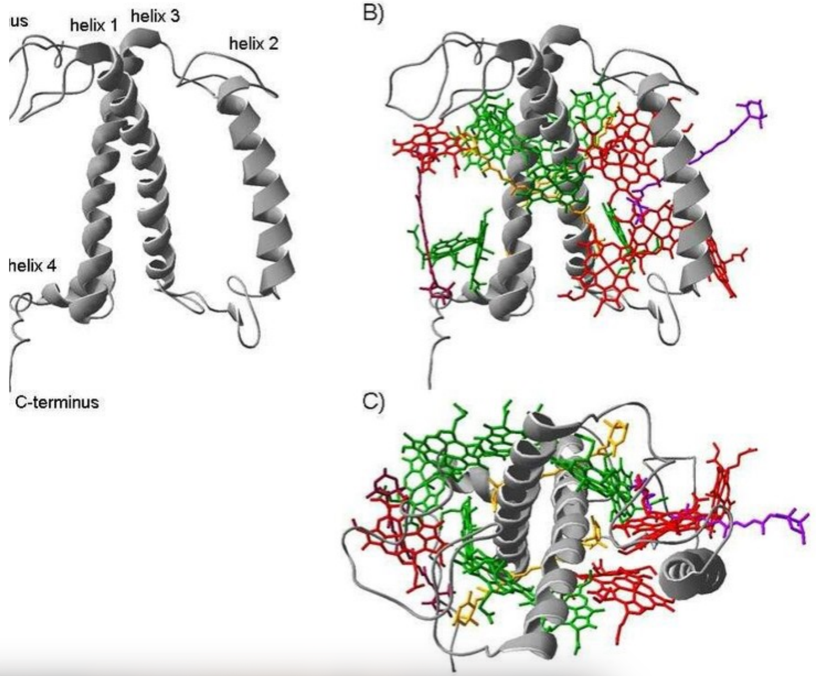
us
helix 1
helix 3
helix 2
helix 4
C-terminus
B)
C)

The European Sparrow

The (quantum) robin

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Magnetoreception

Quantum Biology - LNL, June 15th, 2023

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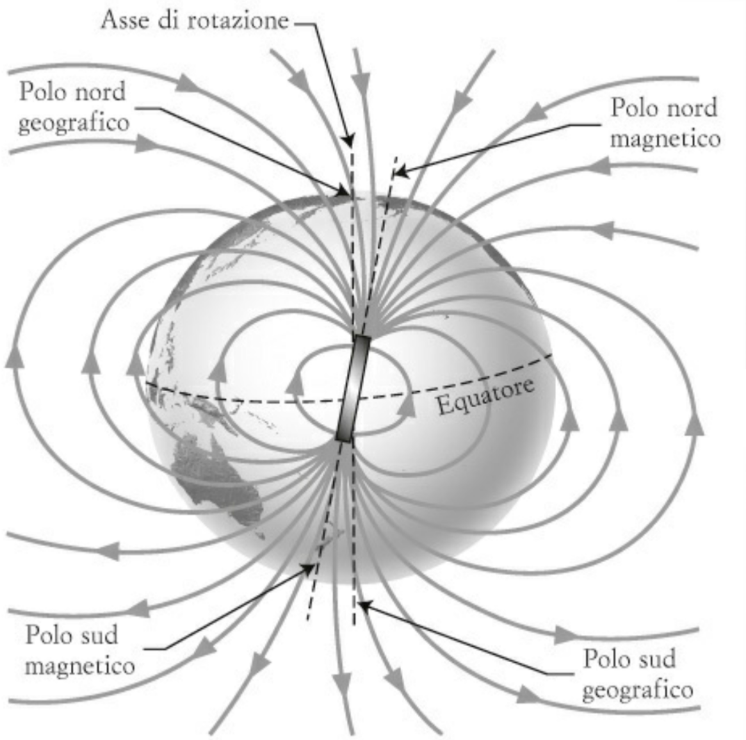
Magnetoreception

Earth's magnetic field is very low: 20÷70 μT. The corresponding photon vehicles an energy less than 10^9 the one needed to break a chemical bond and activate, then, a physiological response



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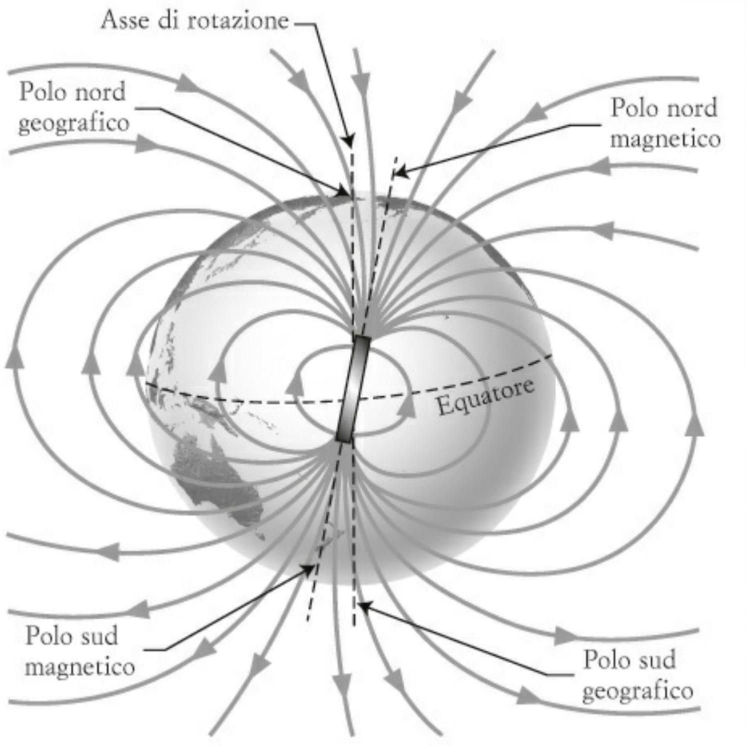
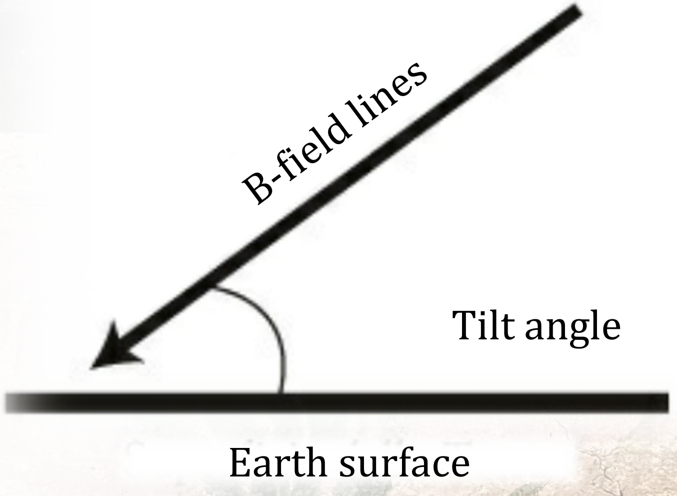
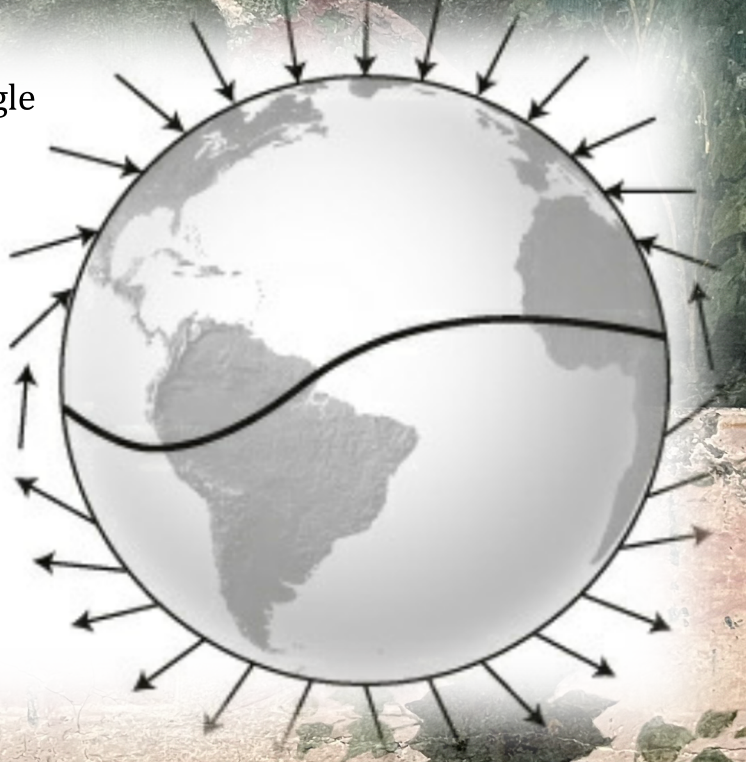


Avian compass ⇒ tilt compass: it measures the angle between the field lines and the Earth surface, distinguishing poles from the Equator (but not the two poles)





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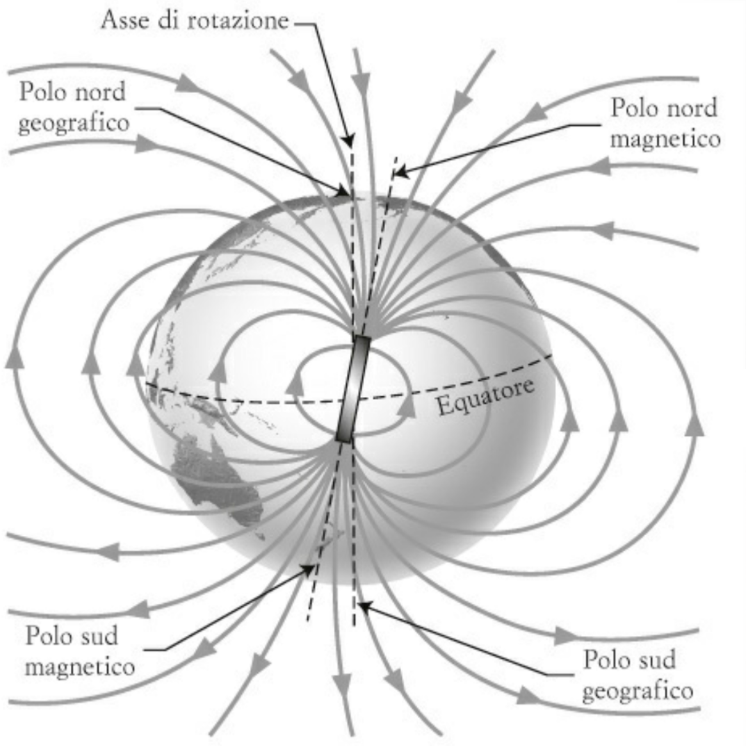
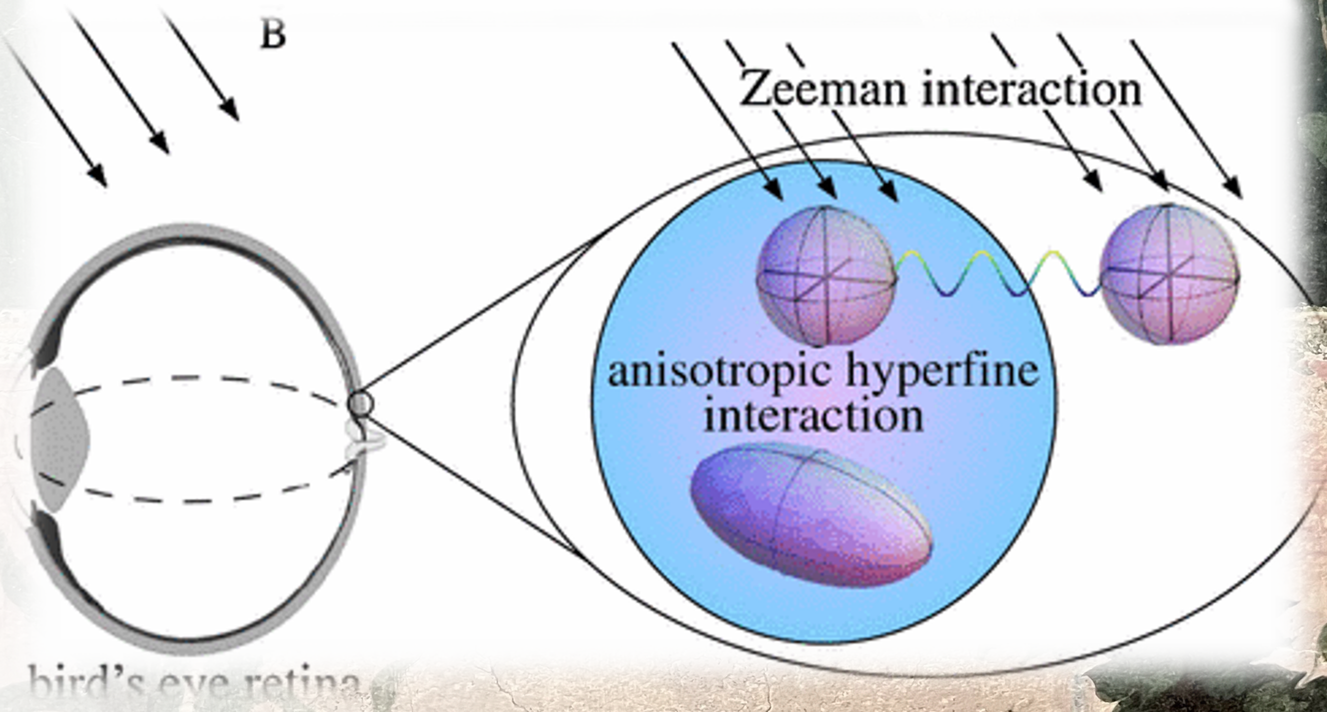


Emlen S., Wiltschko W., Demong N. e Wiltschko R., *Magnetic direction finding: evidence for its use in migratory indigo buntings*, «Science», vol. 193 (1976), pp. 505-08.



The European Sparrow

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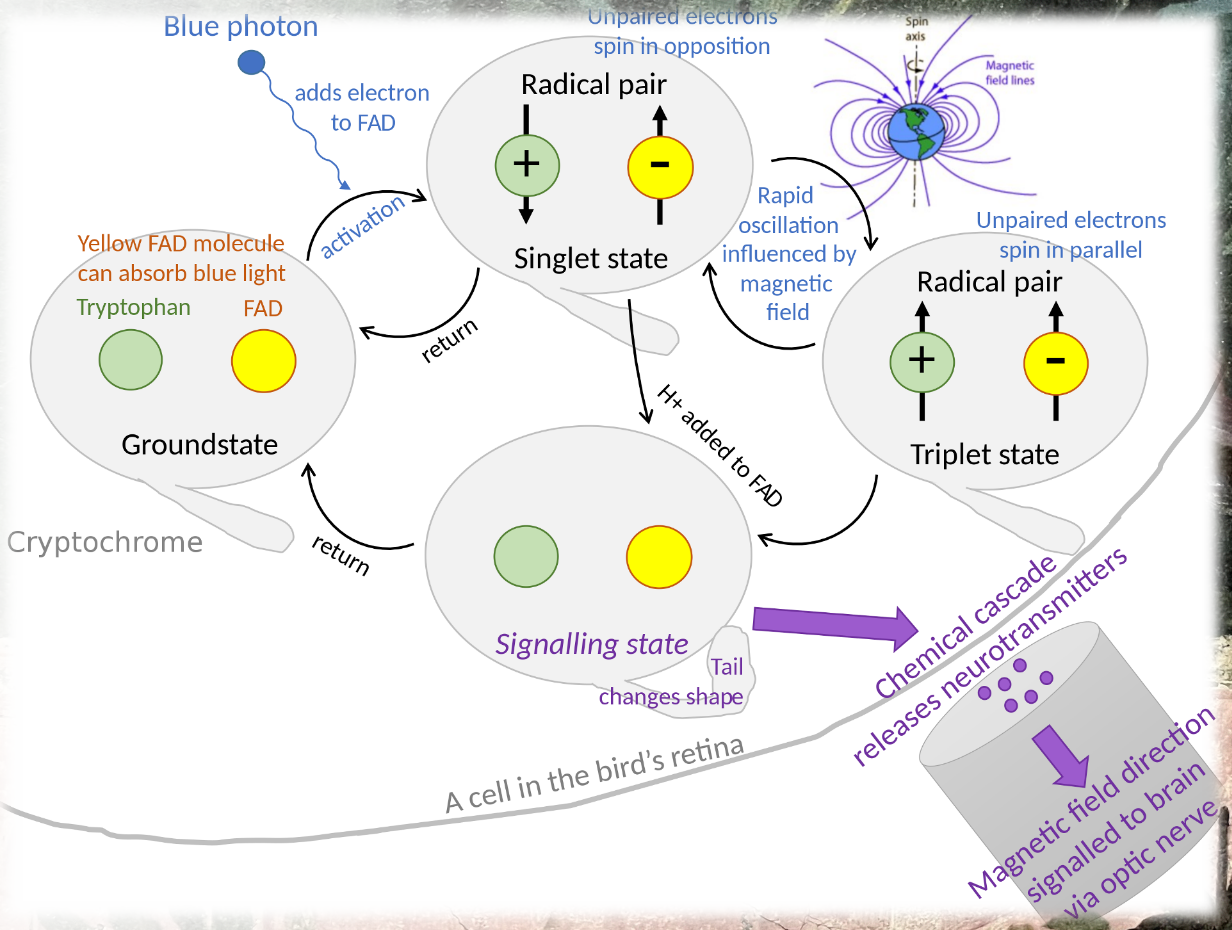
- Atoms are bound by sharing e^-
- If the molecules breaks, two free radicals are produced
- *Free radicals*: molecule with an unpaired e^- in the external orbitals → the non-zero spin gets sensitive to the magnetic field
- The two external e^- are normally in a *singlet* state
- However, the coupling with the Earth's magnetic field may produce a *triplet* component
- The different percentage of singlet and triplet states affect the final chemical products of the physiological reaction



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FAD: flavin adenine dinucleotide pigment

A Model for Photoreceptor-Based Magnetoreception in Birds
Volume 78, Issue 2, February 2000, Pages 707-718

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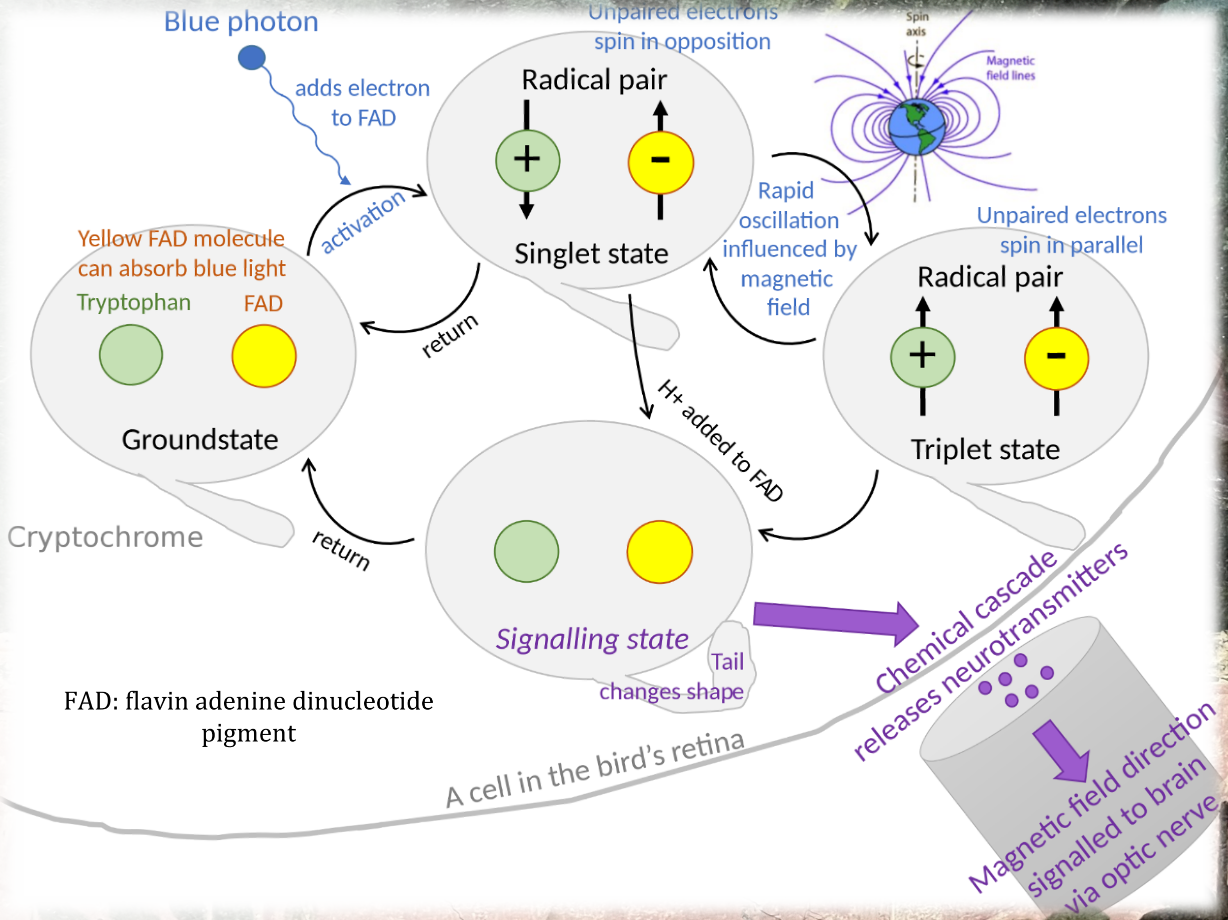
The initial break of the original molecule may be produced by a visible photon (in the blue-light region).



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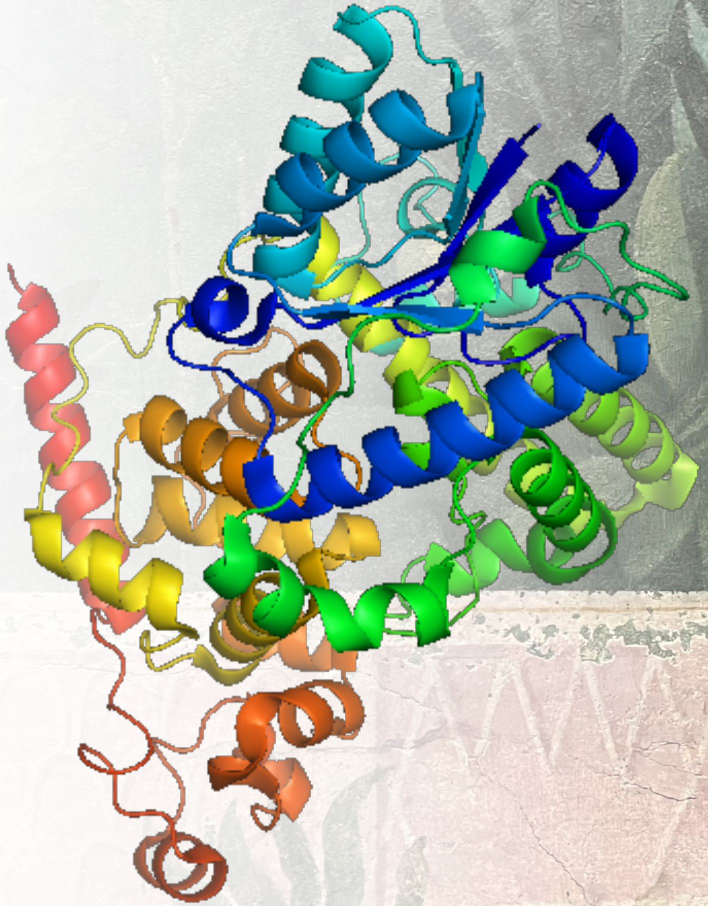

The candidate structure, observed in bird's eyes, is a cryptochrome, a flavoprotein excited by blue-green light (also involved in cicardian rhythms)

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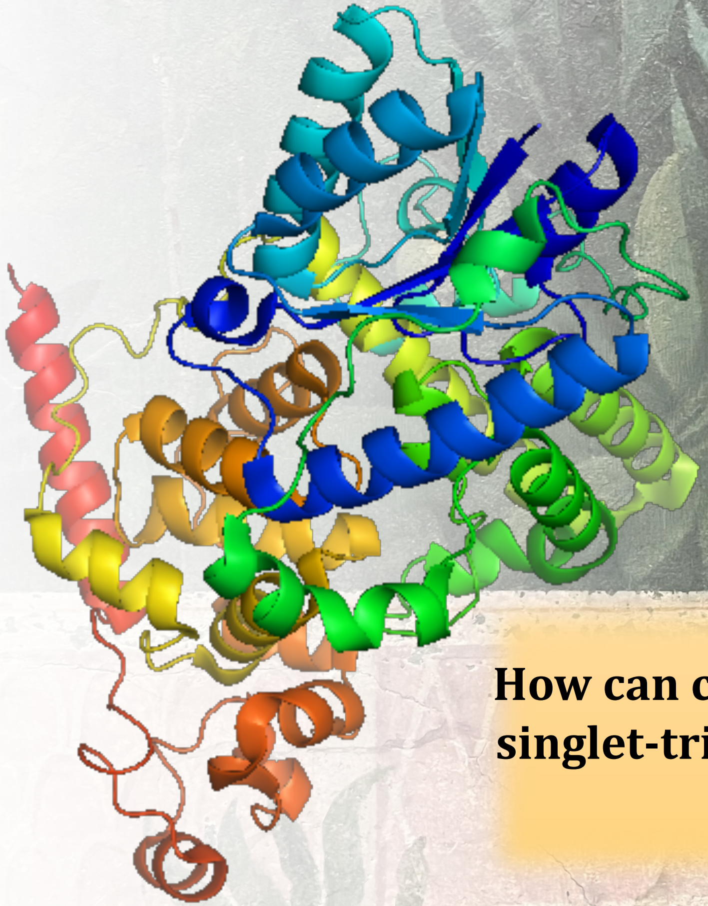

How can coherence be mantained in the time the singlet-triplet oscillation affects the biochemical reaction in the bird's eyes?

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Quantum biology for nuclear physicists

CENTRO RICERCHE ENRICO FERMI

Istituto Nazionale di Fisica Nucleare
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The most suitable experimental methods are spectroscopic techniques

1. absorption spectroscopy ⇒ *energy of the absorbing states*
2. fluorescence spectroscopy ⇒ *energy of the lowest energy-emitting state*
3. linear dichroism and circular dichroism ⇒ *pigment interactions and orientations*
4. triplet-minus-singlet spectroscopy ⇒ *energetic position of the triplet state and of the singlet state on which the triplet is formed*
5. Stark spectroscopy ⇒ *charge-transfer character of excited states*
6. Time-resolved spectroscopic techniques ⇒ **two-dimensional electronic spectroscopy**

Study of the decoherence process

1. QUPLAS (QUantum interferometry and gravitation with Positrons and LASers) ⇒ *quantum decoherence study*
2. Within the analysis of the decoherence studies in biological system, a reductionist approach is being attempted
3. Expertise of QUPLAS with positronium may be extended to other systems/environments

Characterization of the magnetic-field sensitive device: biological detectors?

1. Avian compass for low-energy magnetic field characterization
2. Cryptochrome as possible photo-detectors
3. The drastic change in the approach comes from an efficiency research not based on the signal-to-noise ratio but on the natural selection

CENTRO RICERCHE
ENRICO FERMI

Quantum biology for nuclear physicists: what we can *do*

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Natural selection as the new R&D approach

1. The drastic change in the approach comes from an efficiency research not based on the signal-to-noise ratio but *on the natural selection*

2. How to manage the noise is a crucial aspect in the development of quantum computers

3. Living systems have been exploring and characterizing the environmental noise for ages (*literally*) and may have learned how to exploit it for evolutionary purposes

4. May the noise be used for mantaining quantum coherence? **PRE 82, 021921 (2010): https://doi.org/10.1103/PhysRevE.82.021921**

5. Mapping of the different kind of noise: is there any type of noise mostly recurring in biological systems? May have the quantum selection learnt how to exploit them?

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4. Ringsmuth *et al.*, «Multiscale photosynthetic and biomimetic excitation energy transfer», doi: 10.1038/NPHYS2332

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3. Gauger *et al.*, *«Sustained Quantum Coherence and Entanglement in the Avian Compass»*, DOI: 10.1103/PhysRevLett.106.040503
4. Cai *et al.*, *«Dynamic entanglement in oscillating molecules and potential biological implications»*, DOI: 10.1103/PhysRevE.82.021921

Il Passero
Europeo
is the new
Gatto di
Schröedinger

backup

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Possible research lines

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https://agenda.infn.it/event/29631/contributions/160348/attachments/88436/118450/LEA_17Feb_2022_v1.pdf

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How to investigate quantum-walk in photosynthetic complexes

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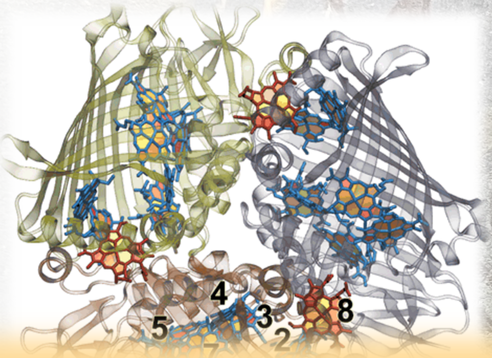
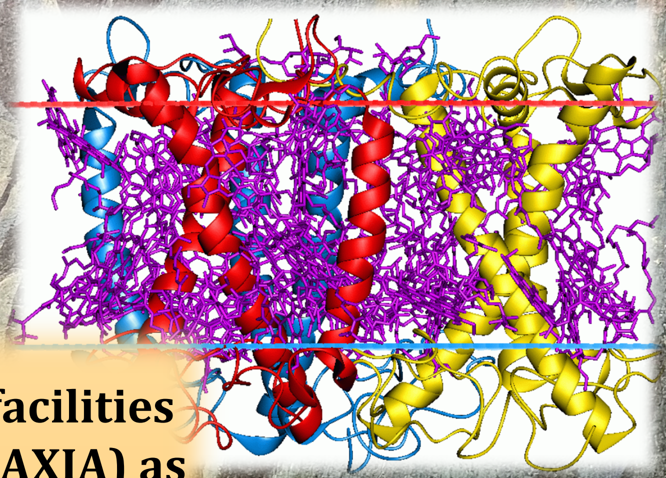
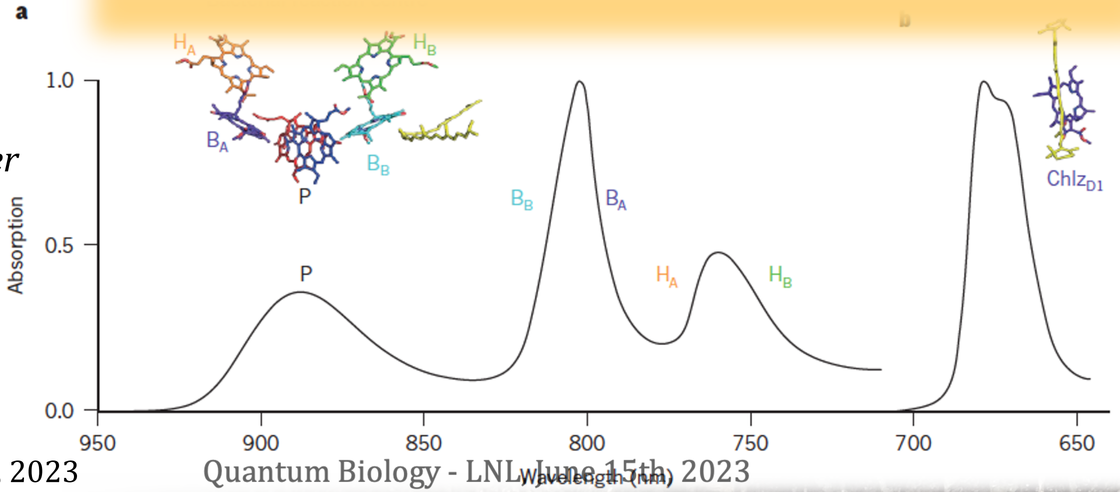
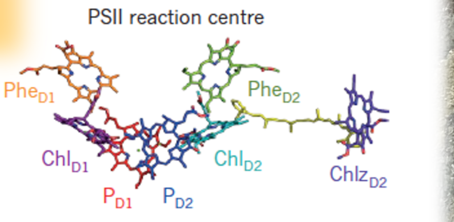




hyll A-B binding protein - Light-Harvesting Complex II (LHCB)

Possible approach with multi-source facilities being built in INFN laboratories (EuPRAXIA) as well as algorithm development for disentangling different contributions unders a single band





Absorption spectra and X-ray structure of the bacterial reaction centre and the PSII reaction centre. a) The absorption spectrum of the bacterial reaction centre of Rhodobacter sphaeroides at 77 K is shown with the X-ray crystal structure of the complex. b) The 77 K absorption spectrum of the PSII reaction centre of spinach (Spinacia oleracea) is displayed with the X-ray crystal structure of the complex .

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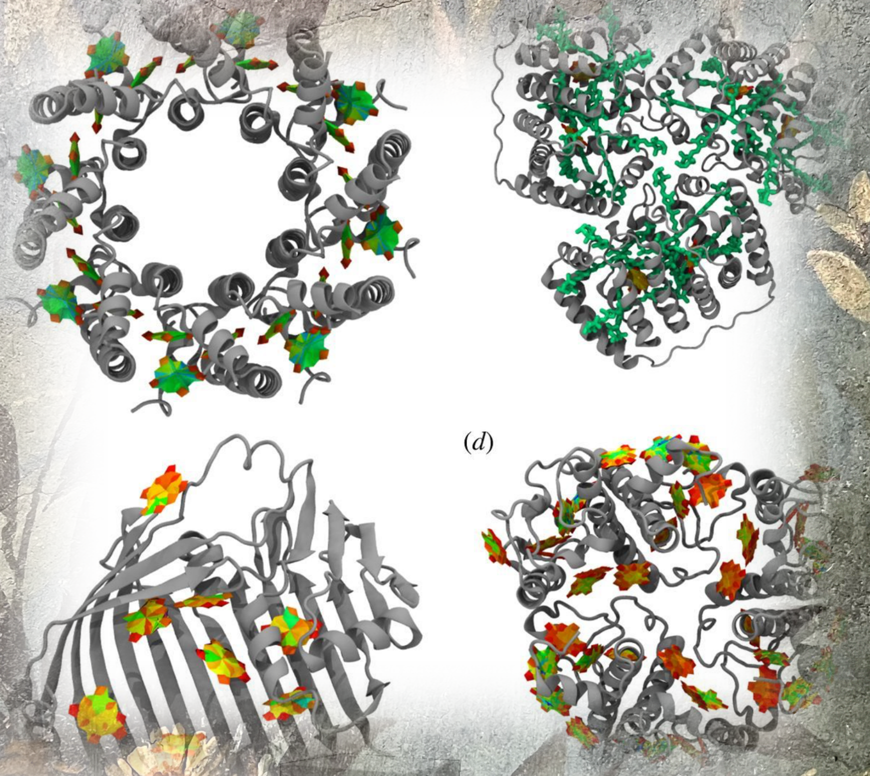
Possible research lines

Investigation of different photosyntetic complexes through laser, X-rays and multi-purpose facilities



1. Catalog the different photosynthetic complexes and the most suitable techniques to be adopted to test their *quantum-like* excitation patterns

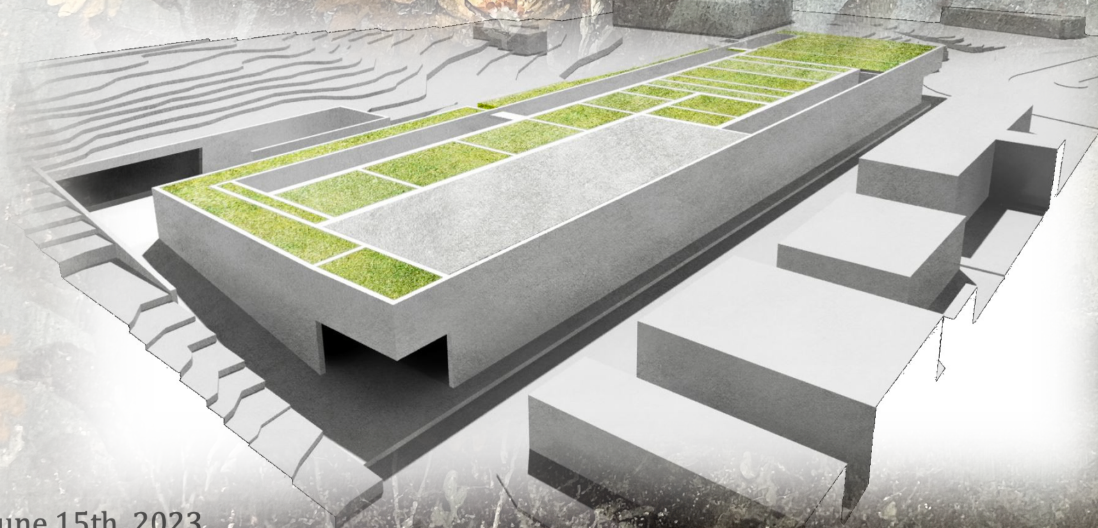
2. Identify the typologies and the energy/intensity range of the radiation to investigate the propagation of the exciton through the complex

https://doi.org/10.1021/jp710243t

3. Map the different radiation/intensity/energy intervals available at the present and future facilities at INFN laboratories

https://www.nature.com/articles/nphys1032
https://doi.org/10.1103/PhysRevLett.77.4728
https://doi.org/10.1103/PhysRevLett.101.090502
https://doi.org/10.1103/PhysRevLett.92.220402

4. Identify the equipment needed for a test facility



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Photosynthesis

nature Vol 446|12 April 2007|doi:10.1038/nature05678

LETTERS

Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems

Gregory S. Engel[1,2], Tessa R. Calhoun[1,2], Elizabeth L. Read[1,2], Tae-Kyu Ahn[1,2], Tomáš Mančal[1,2]†, Yuan-Chung Cheng[1,2], Robert E. Blankenship[3,4] & Graham R. Fleming[1,2]

Photosynthetic complexes are exquisitely tuned to capture solar light efficiently, and then transmit the excitation energy to reaction centres, where long term energy storage is initiated. The energy transfer mechanism is often described by semiclassical models that invoke 'hopping' of excited-state populations along discrete energy levels[1,2]. Two-dimensional Fourier transform elec-

The quantum coherence manifests itself in characteristic, directly observable quantum beating signals among the excitons within the *Chlorobium tepidum* FMO complex at 77 K. This wavelike characteristic of the energy transfer within the photosynthetic complex can explain its extreme efficiency, in that it allows the complexes to sample vast areas of phase space to find the most efficient path.

Different landscapes for different pathways to the reaction center

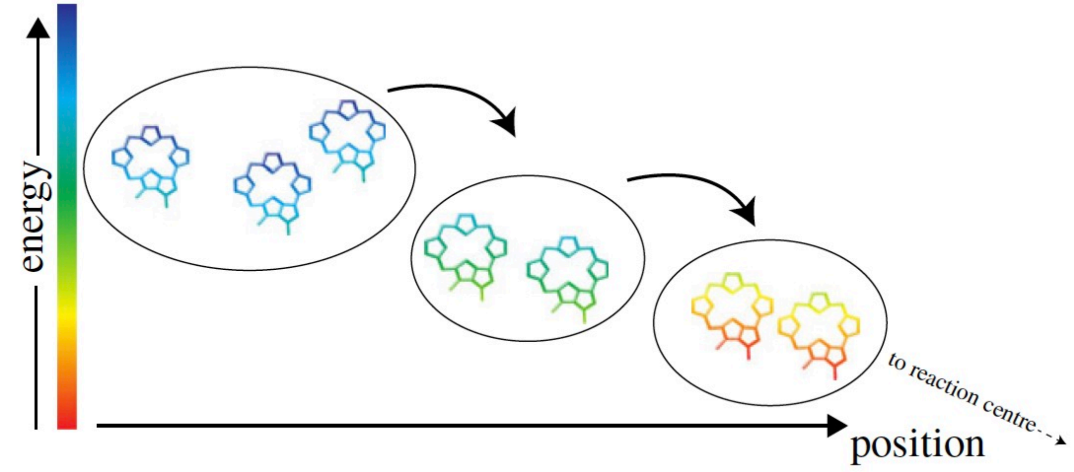


Figure 1. A schematic illustrating the concept of excitation energy transfer in photosynthetic light-harvesting complexes. The ovals depict pigment clusters in which strong excitonic coupling occurs while the arrows represent incoherent transfer of the energy amongst the clusters. Within each cluster, the energy is delocalized over all pigments and is transferred coherently.

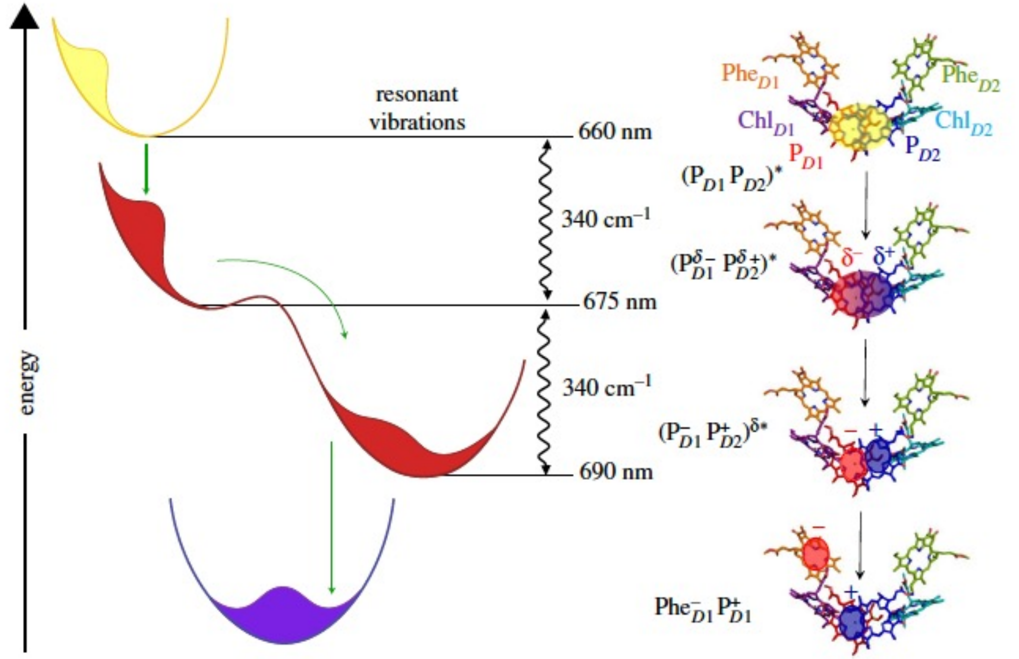
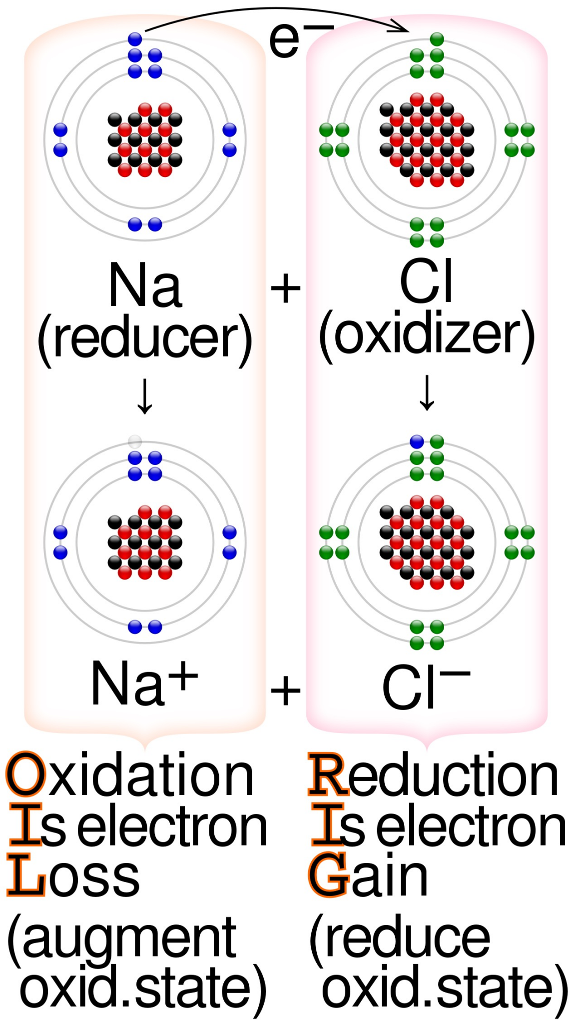


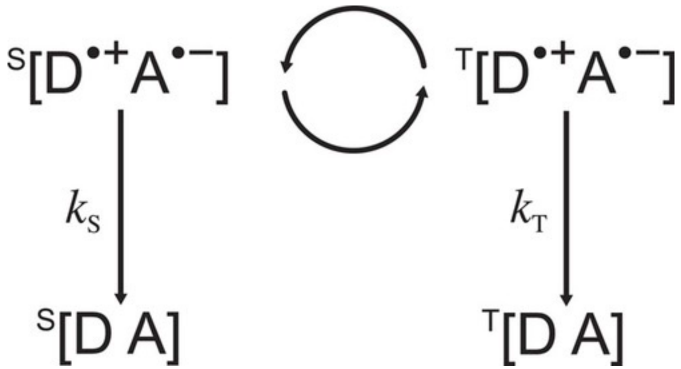
Figure 2. Schematic of quantum-coherent charge separation in the Photosystem II reaction centre of higher plants along one of at least two existing pathways, according to the model in [23]. On the left are four wavepackets on harmonic potentials, each corresponding to a different state along the charge separation pathway. For each state, the key pigments and approximate location and sign of the charge clouds are shown on the right. Horizontal lines depict absorption peaks at the specified wavelength of the corresponding state shown on the right, while the wavy arrows depict resonance interaction with the indicated vibrational mode. The symbols δ and * represent charge-transfer character and exciton character, respectively. The nature of the four states are $(P_{D1}P_{D2})^*$—a high exciton state, $(P^{\delta-}_{D1} P^{\delta+}_{D2})^*$—an exciton state with some charge-transfer character, $(P^{-}_{D1}P^{+}_{D2})^{\delta*}$—a charge-transfer state mixed with an exciton state, and $Phe^{-}_{D1}P^{+}_{D1}$—the final charge-separated state. Note that an intermediate between the last two states, involving Chl_{D1}, is omitted. The first three steps involve coherent relaxation due to coupling with a vibrational mode, while the last step involves incoherent transfer. Symbols: D1 and D2, two branches of the symmetric reaction centre structure; Chl, chlorophyll; P, primary electron donor/special-pair Chl; Phe, pheophytin. Adapted from Romero *et al.* [23].

Electron-transfer reaction



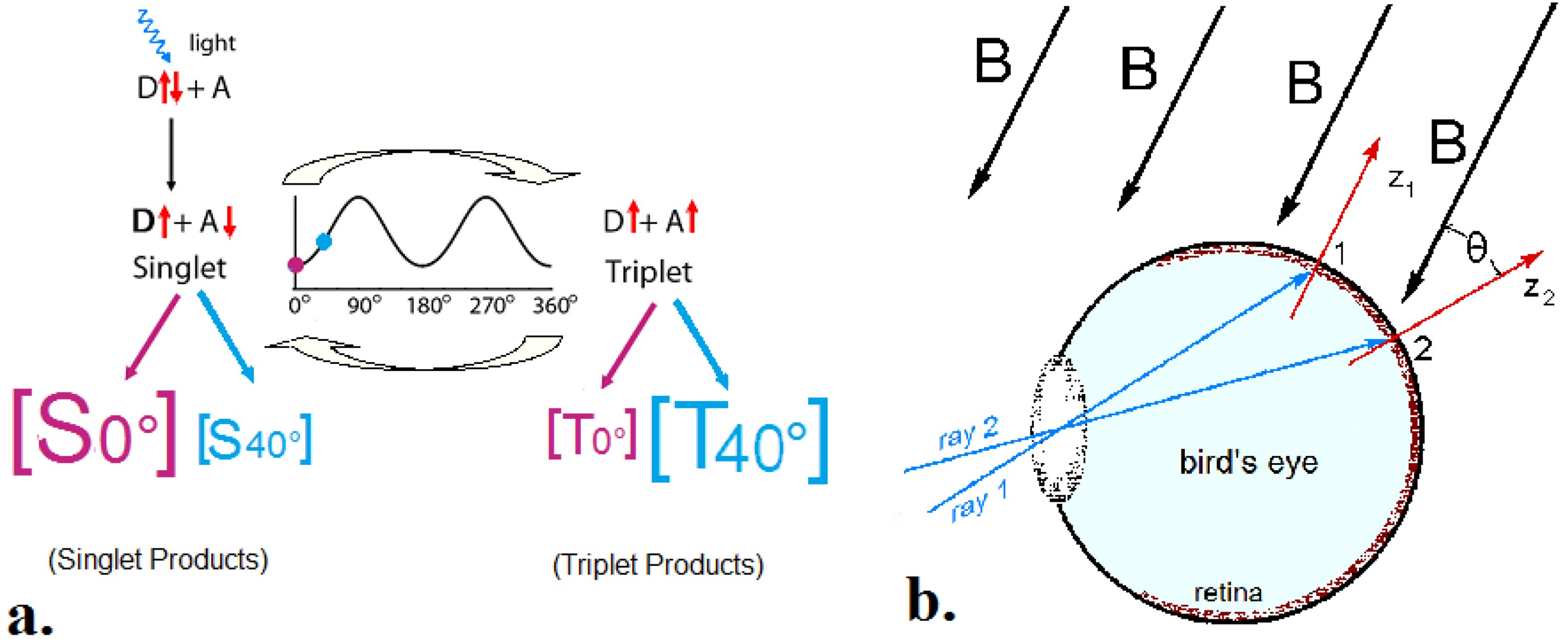
Occurs when an electron relocates from an atom or molecule to another atom or molecule.

It can eventually produce a pair of free radicals

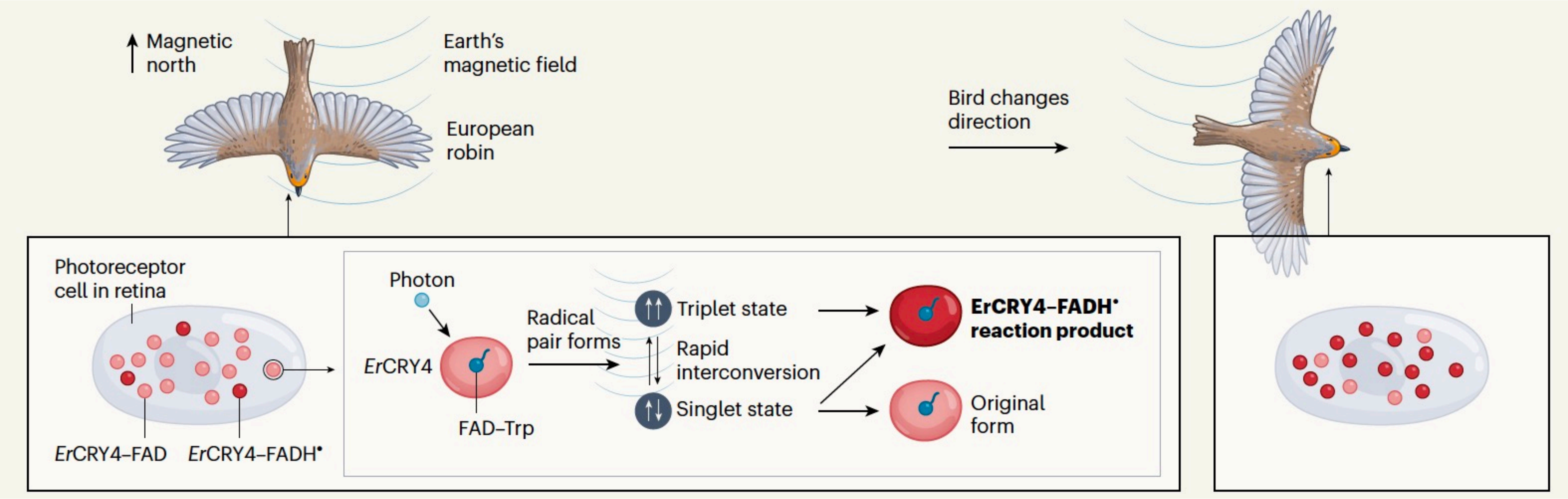


Cryptochrome Cry1a

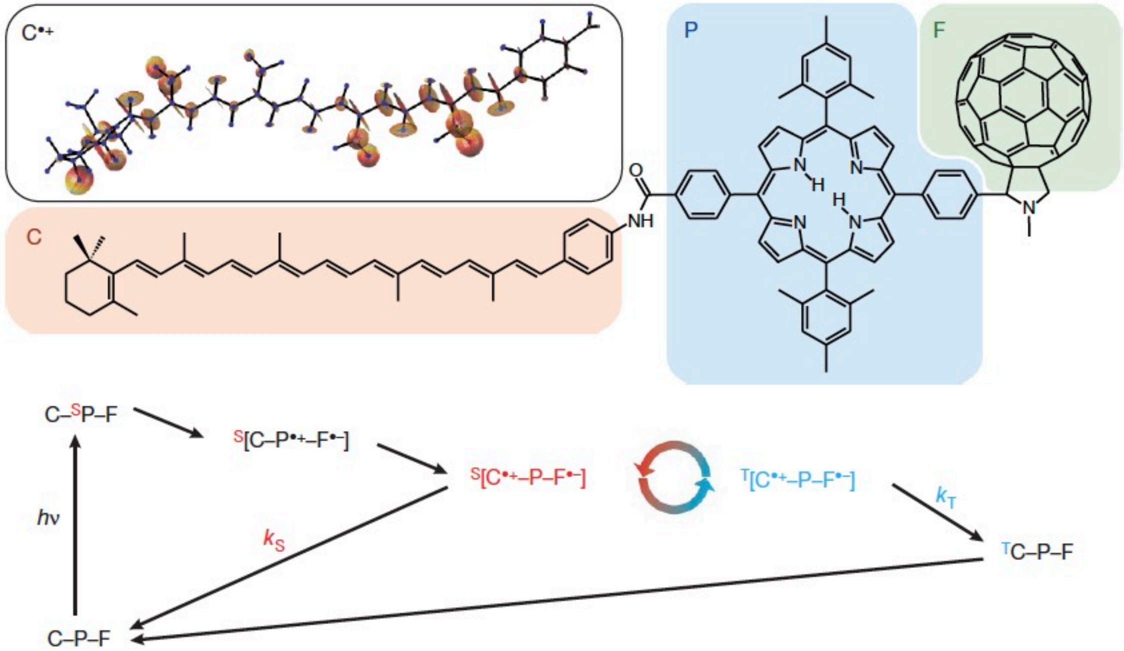
Photoreceptor proteins located in the retina and sensitive to the blue-green part of the spectrum

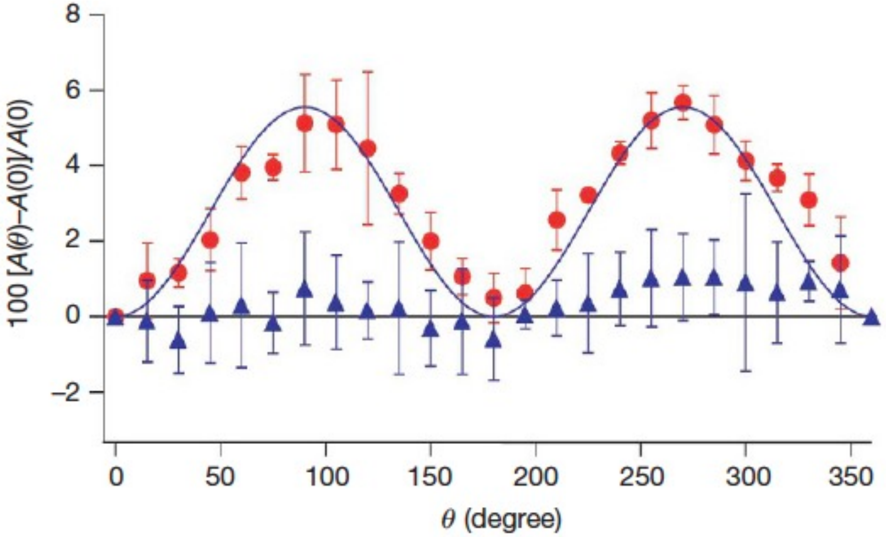


Principle of avian compass FAD-based



Feasibility of an avian compass based on a weak magnetic field





Polar plot of the anisotropy of the magnetic field effect, $[A(\theta)-A(0)]/A(0)$ (as a function of θ, in degrees), on the transient absorption of $[C^{\bullet+}–P–F^{\bullet-}]$ detected using an aligned sample (purple, 3.1 mT, 193 K) and by photoselection (red, 3.4 mT, 88 K). The maximum magnetic field effects in the two cases were ~1.5% and ~5%, respectively. The data for the aligned sample have been doubled for clarity. The anisotropy is smaller in the liquid crystal measurement than in the photoselection experiment mainly because of the faster spin relaxation at the higher temperature of the former. **c**, Data from the photoselection measurements. The red dots show the dependence of the $[C^{\bullet+}–P–F^{\bullet-}]$ absorption on the direction of the magnetic field, θ. The solid line is the best fit to a $\sin^2\theta$ form. Also shown (blue) are the signals detected when the polarization axis of the probe light was z (that is, vertical). No θ-dependence is expected or seen. Error bars, ±1 s.d.

Maeda *et al.*, Nature 2008, 453, 387; doi:10.1038/nature06834

Collasso nel mondo classico

"Was the world wave function waiting to jump for thousand of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer for some highly qualified measurer, – with a Ph.D.?”

John Stewart Bell

How to investigate quantum-walk in photosynthetic complexes

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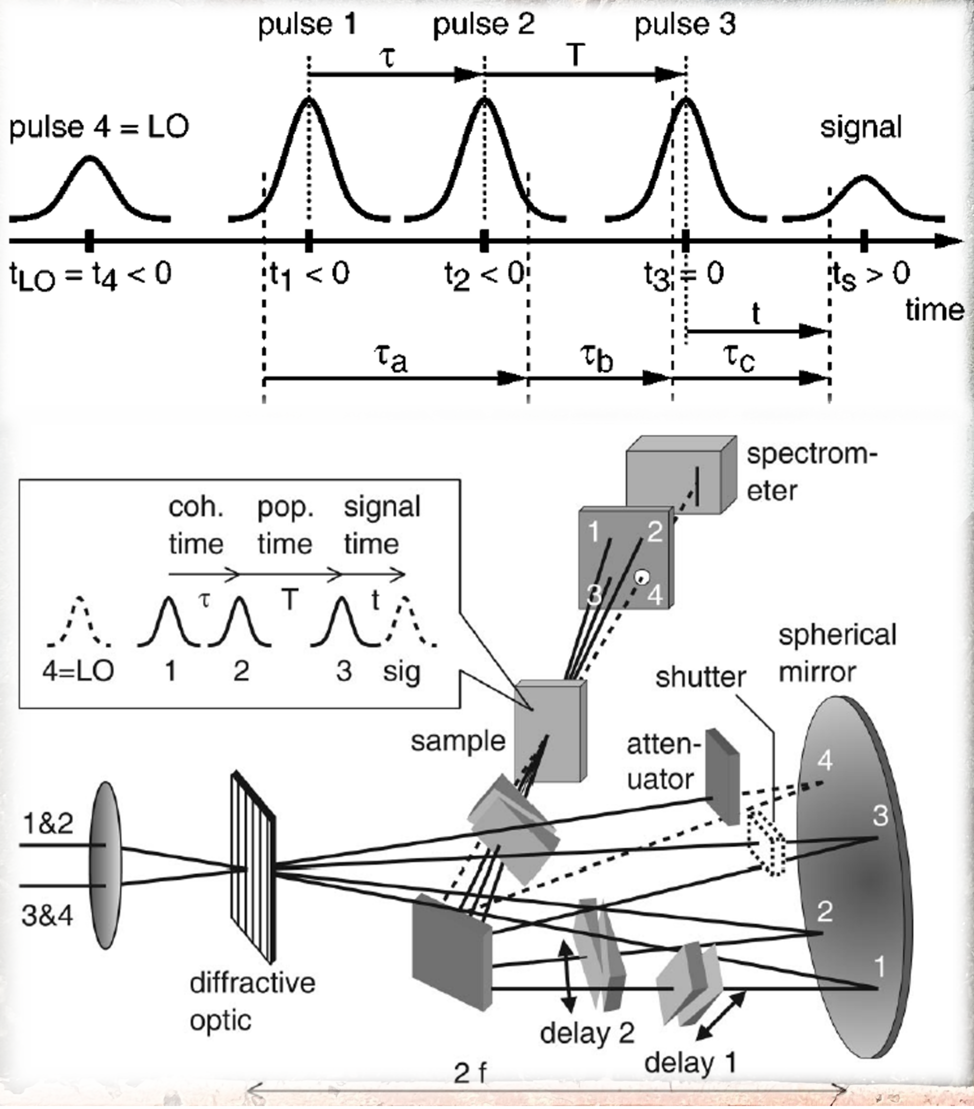
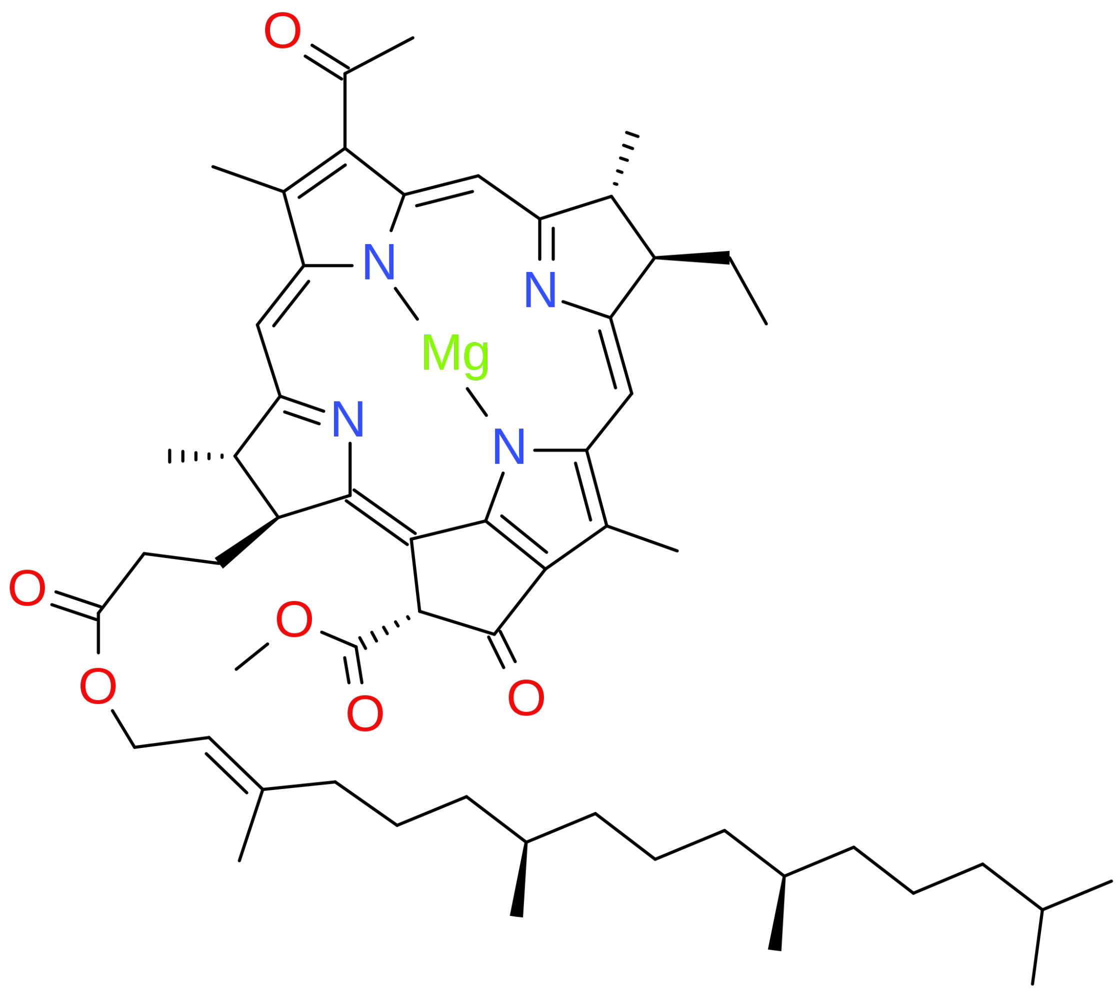
- It proceeds through the excitation of the molecular dynamics through a suitable source
- Depending on the photosynthetic complex to be analyzed, different sources may be used
- One of the main technique is based on *femtosecond lasers*
- The idea is to extend the concept beyond the NMR, that investigates spins, to the analysis of the electron dynamics and possible interplay with the molecular dynamics (*e.g.,* vibrational spectra)
- Molecules are frozen on the femtosecond timescale
- Femtosecond 2D FT experiments might reveal the fastest motions in chemical reactions with the highest possible time and frequency resolution



Bacteriochlorophyll a



Battimenti quantistici

Complesso fotosintetico «Fenna-Matthews-Olson» (FMO) → microbi fotosintetici chiamati chlorobi, che si trovano nelle profondità di bacini ricchi di zolfo, come il Mar Nero.

- Un laser deposita il segnale concentrato in picchi rapidi e perfettamente sincronizzati
- Si misura il segnale di luce prodotto dal campione
- *Questo permette di studiare come la luce si propaga nel sistema*

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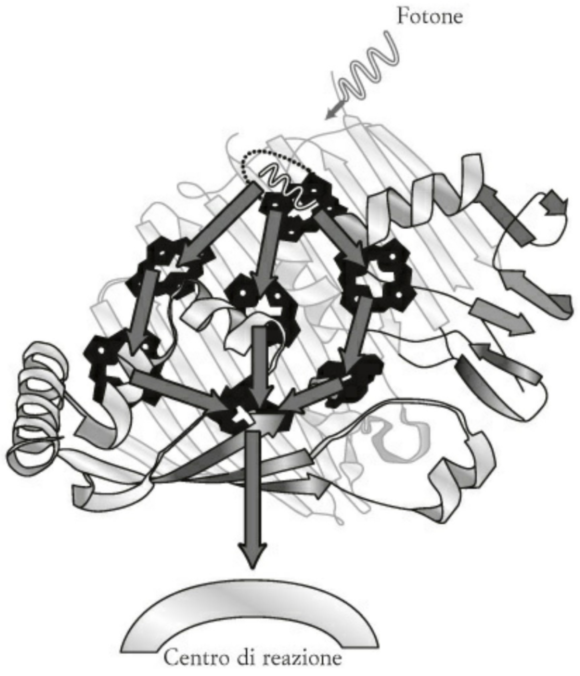
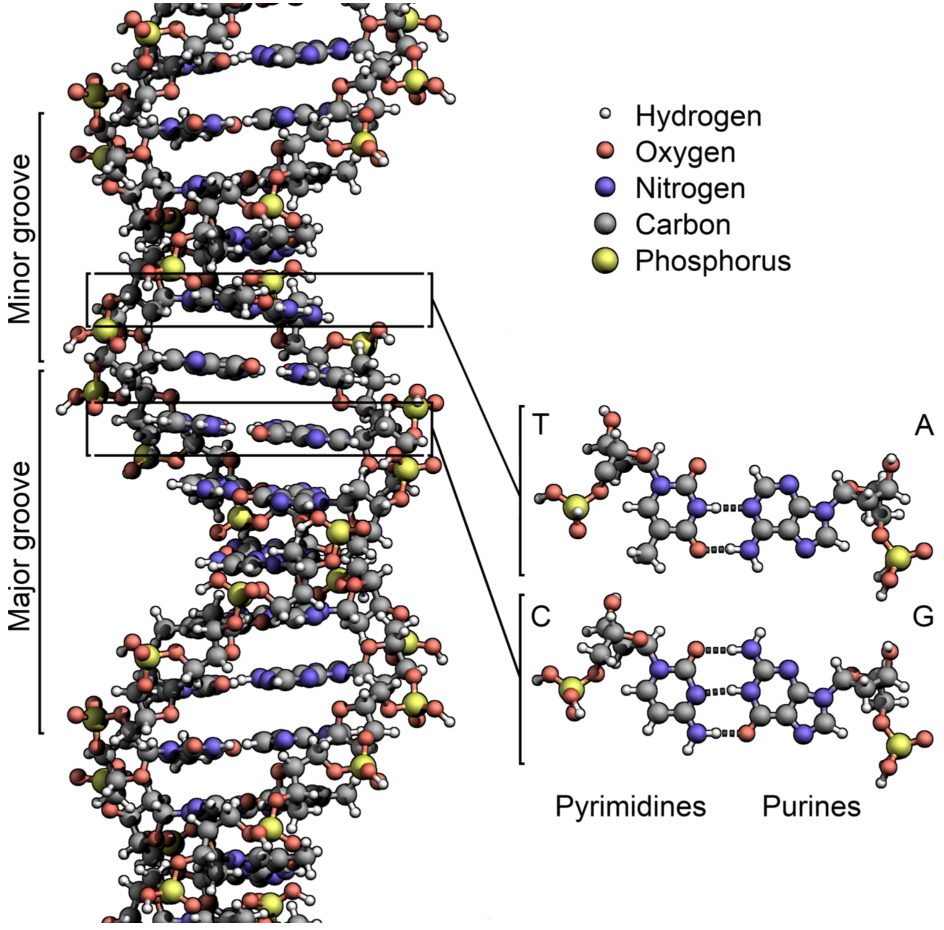


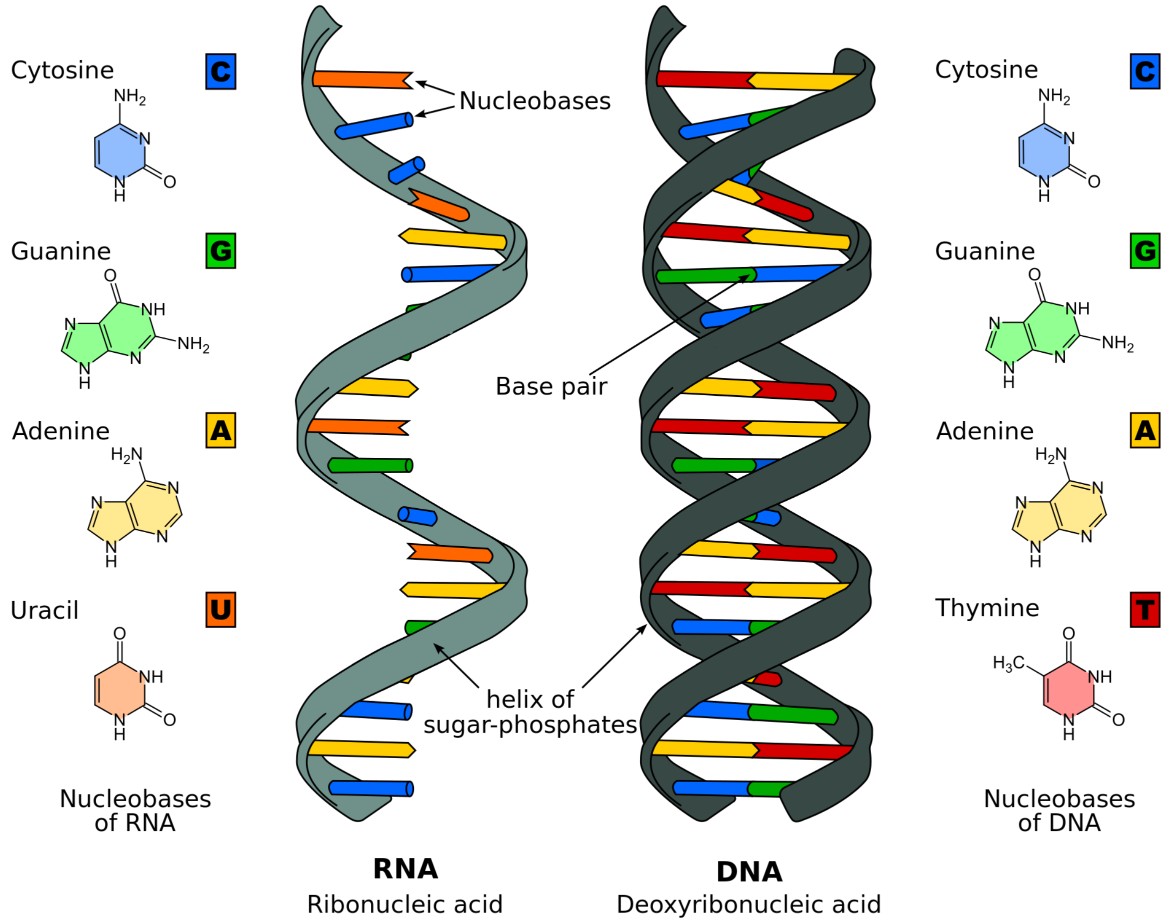
Engel G. S., Calhoun T. R., Read E. L., Ahn T-K., Manč al T., Cheng Y.-C., Blankenship R. E. e Fleming G. R., Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems, «Nature», vol. 446 (2007), pp. 782-86.

CENTRO RICERCHE ENRICO FERMI

Deoxyribonucleic acid

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati





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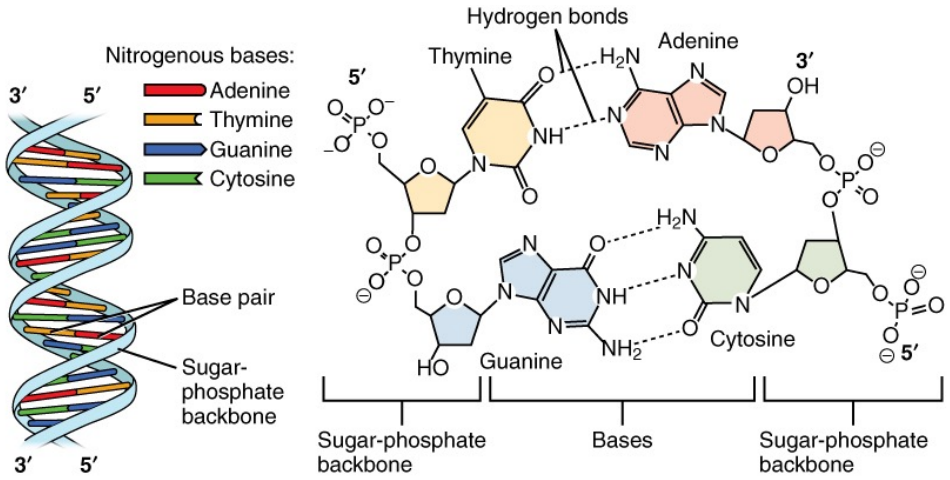
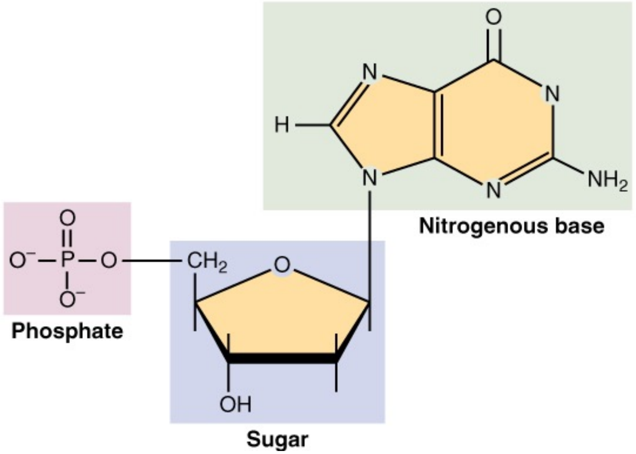
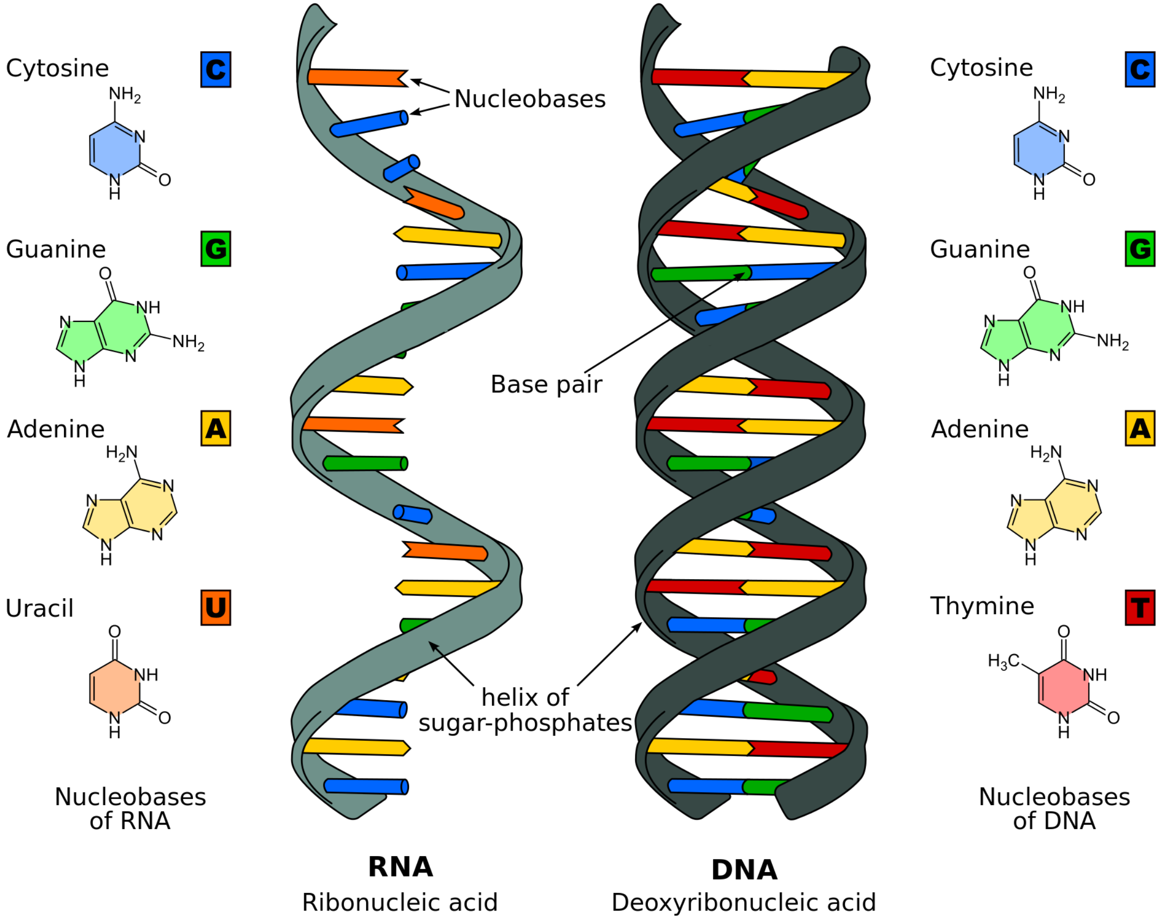




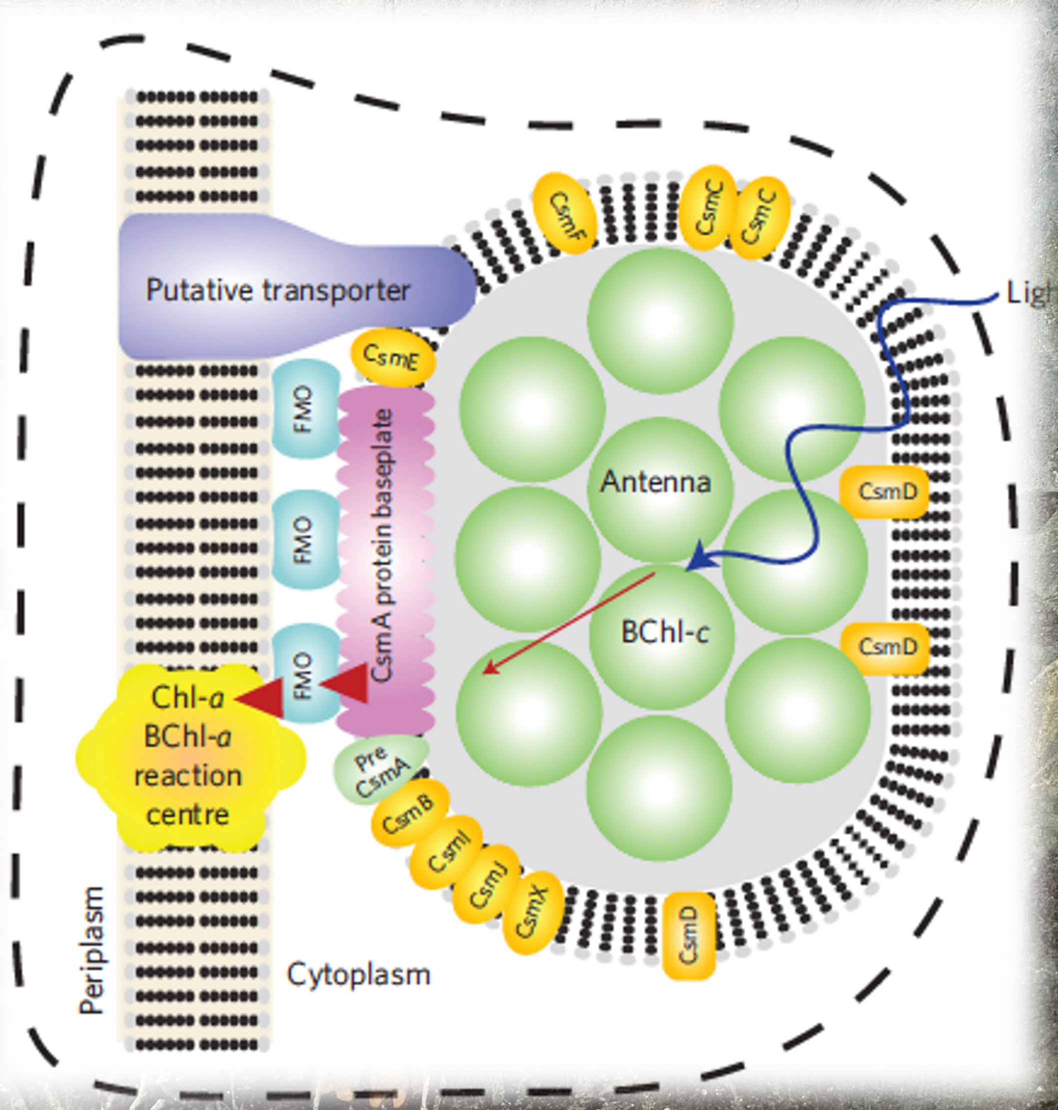


Nucleic acids are *naturally occurring chemical compounds* → primary information-carrying molecules in cells.

Photosynthesis

FMO-complex: the well-studied FMO complex in the light-harvesting apparatus of green-sulphur bacteria exhibits some signatures of quantum coherent energy transfer.

a. Diagram of the photosynthetic apparatus of green sulphur bacteria, including its antenna, energy-conducting baseplate and FMO complexes, and reaction centre. The chlorosome antenna (green discs) is composed of roughly 200,000 BChl-c molecules, and is an exceptionally large structure that is designed to capture as many photons as possible in the low-light conditions the bacteria thrive in. Sunlight creates an excitation in this antenna that is transferred (red arrows) to the reaction centre through one of several FMO complexes.
b. The BChl-a arrangements of one of the FMO pigment-protein complexes through X-ray diffraction. The FMO complex comprises eight (although only seven are shown here) bacteriochlorophyll-a (BChl-a) molecules that are encased in a protein scaffolding (not shown). The excitation arrives from the chlorosome at one of the sites, typically thought to be the site denoted as 1. This excitation is then transported from one BChl molecule to the next. Once it arrives at site 3 it can irreversibly enter the reaction centre and start a charge-separation process.



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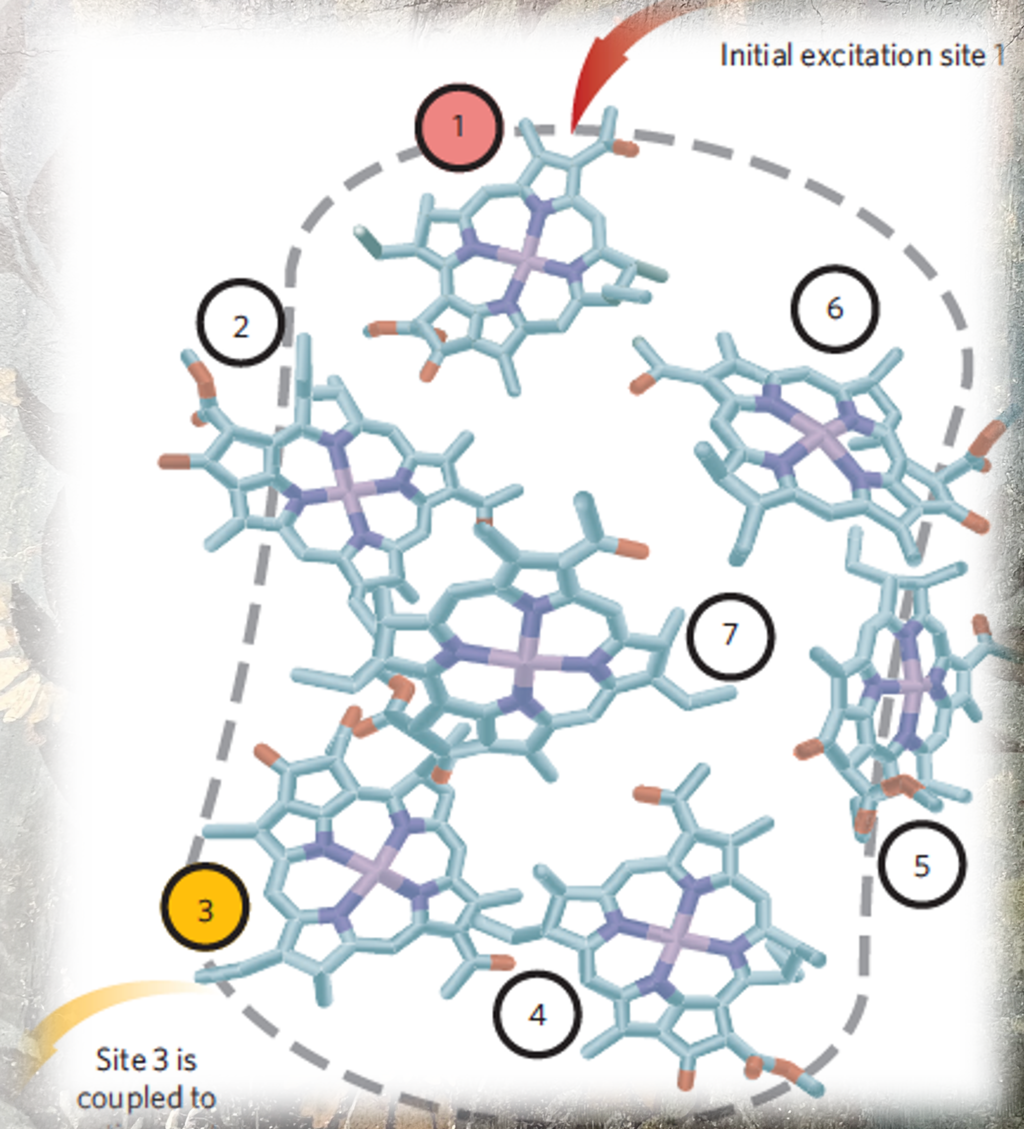

CENTRO RICERCHE
ENRICO FERMI

Engel et al. @77 K

The quantum coherence manifests itself in characteristic, directly observable quantum beating signals among the excitons within the *Chlorobium tepidum* FMO complex at 77 K. This wavelike characteristic of the energy transfer within the photosynthetic complex can explain its extreme efficiency, in that it allows the complexes to sample vast areas of phase space to find the most efficient path.

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LETTERS

Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems

Gregory S. Engel[1,2], Tessa R. Calhoun[1,2], Elizabeth L. Read[1,2], Tae-Kyu Ahn[1,2], Tomáš Mančal[1,2]†, Yuan-Chung Cheng[1,2], Robert E. Blankenship[3,4] & Graham R. Fleming[1,2]

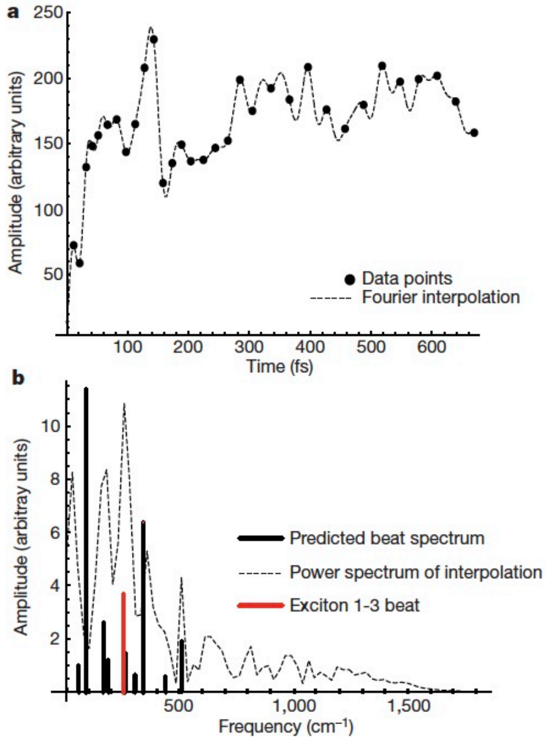
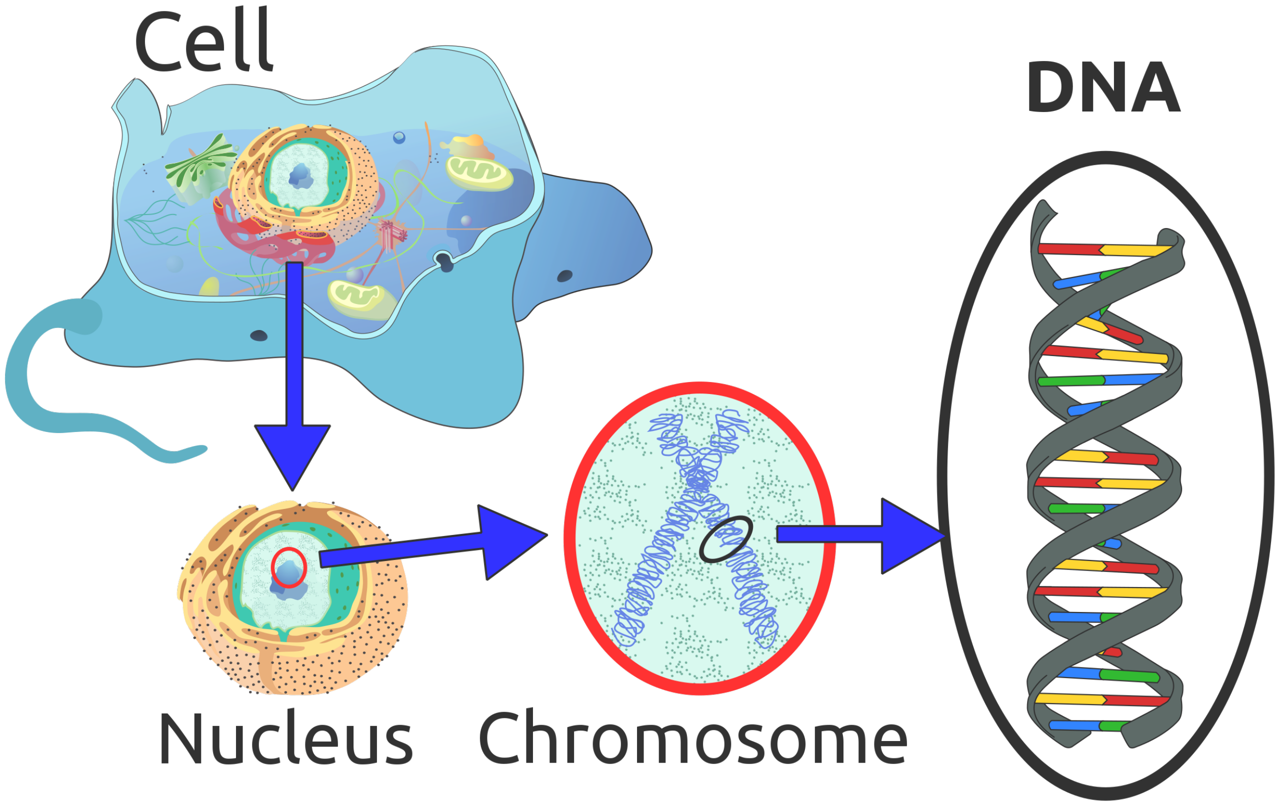


Figure 4 | Quantum beating in cross peaks. **a**, The raw amplitude of the exciton 1–3 cross-peak, with a Fourier interpolation of the points (dotted line). **b**, The power spectrum of this interpolation (dotted line), the exciton beating line spectra of both excitons 1 and 3 (black), and the 1–3 beat frequency (red). We expect that the other frequencies may couple to this cross-peak but that the dominant frequency corresponds to the red transition. The apparent low-frequency peak is due to the growth of the cross-peak amplitude and appears as a peak because the data were de-meaned (mean subtracted from the data) before the transform to improve numerical accuracy, pinning the zero-frequency component to zero.

Coming back to life



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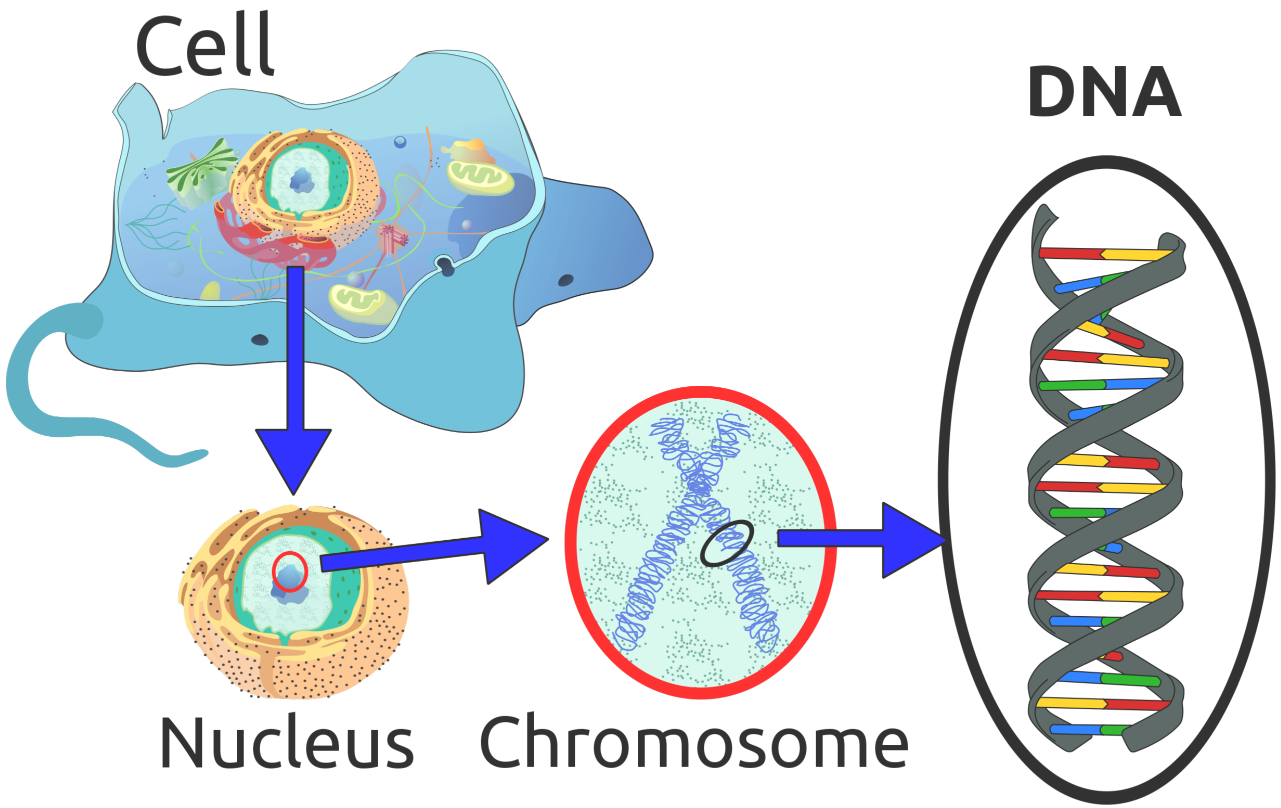
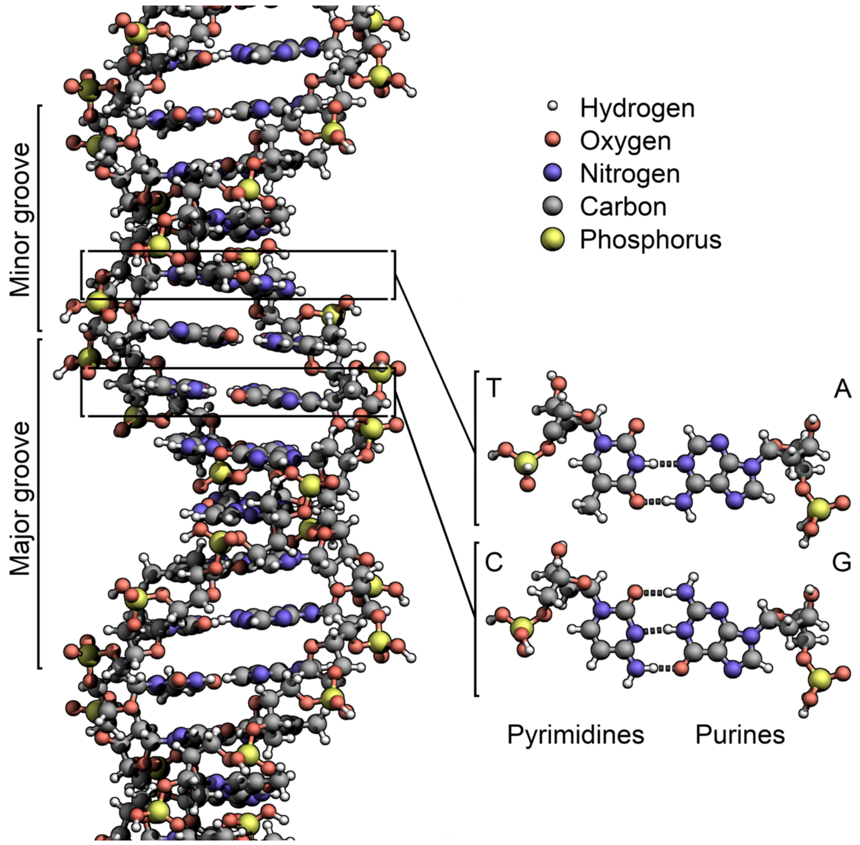
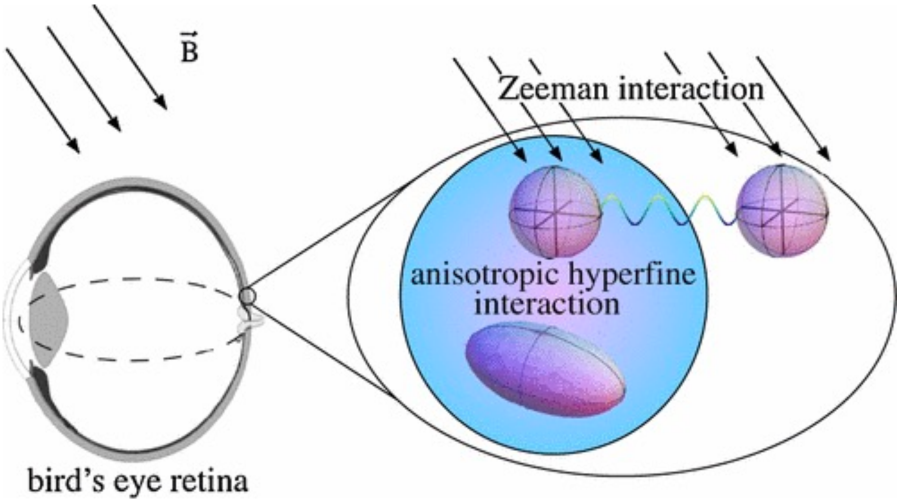
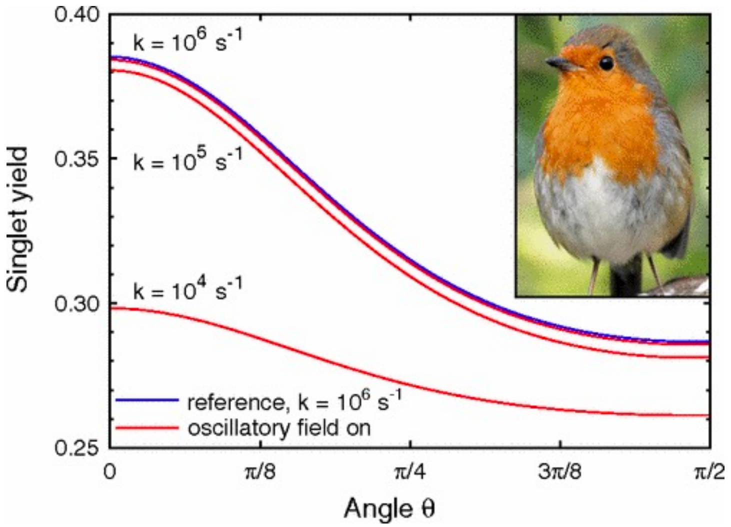


Deoxyribonucleic acid

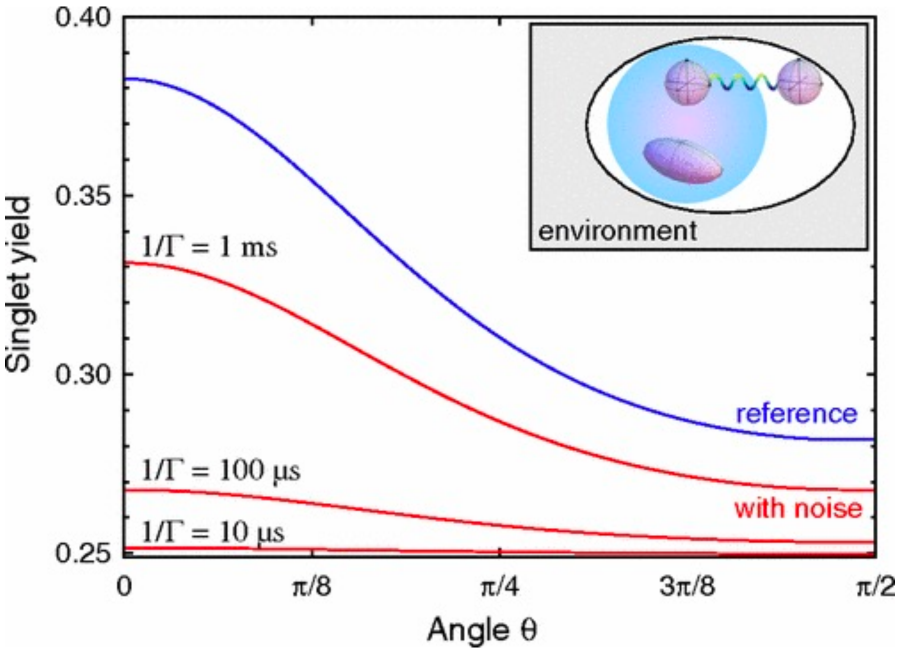






Angular dependence of the singlet yield in the presence of an oscillatory field. The blue curve provides a reference of the singlet yield in Earth's magnetic field (B0=47 μT). The reference is independent of the decay rate for k≤107 s−1, but has been shifted upwards by 0.001 for better visibility. The red curves show the singlet yield when a 150 nT field oscillating at 1.316 MHz (i.e., resonant with the Zeeman frequency of the uncoupled electron) is superimposed perpendicular to the direction of the static field. This only has an appreciable effect on the singlet yield once k is of order 104 s−1.

According to the RP model, the back of the bird's eye contains numerous molecules for magnetoreception [32]. These molecules give rise to a pattern, discernible to the bird, which indicates the orientation of the field. Note that this implies that the molecules involved are at least fixed in orientation, and possibly ordered with respect to one another [8]. In the simplest variant, each such molecule involves three crucial components (see inset): there are two electrons, initially photoexcited to a singlet state, and a nuclear spin that couples to one of the electrons. This coupling is anisotropic, so that the molecule has a directionality to it.



Angular dependence of the singlet yield in the presence of noise (for k=104). The blue curve provides a reference in the absence of noise, and the red curves show the singlet yield for different noise rates. As is apparent from the plot, a noise rate Γ>0.1k has a dramatic effect on the magnitude and contrast of the singlet yield. Inset: The partitioning between compass and environment.