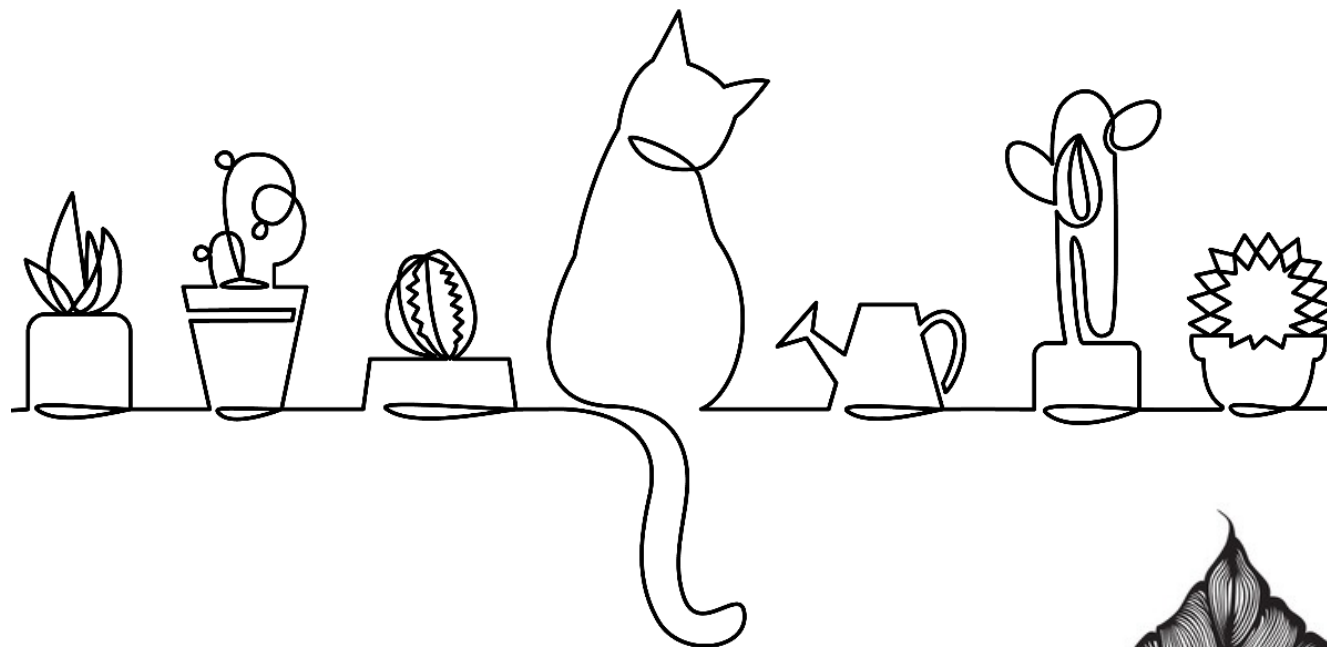




Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati



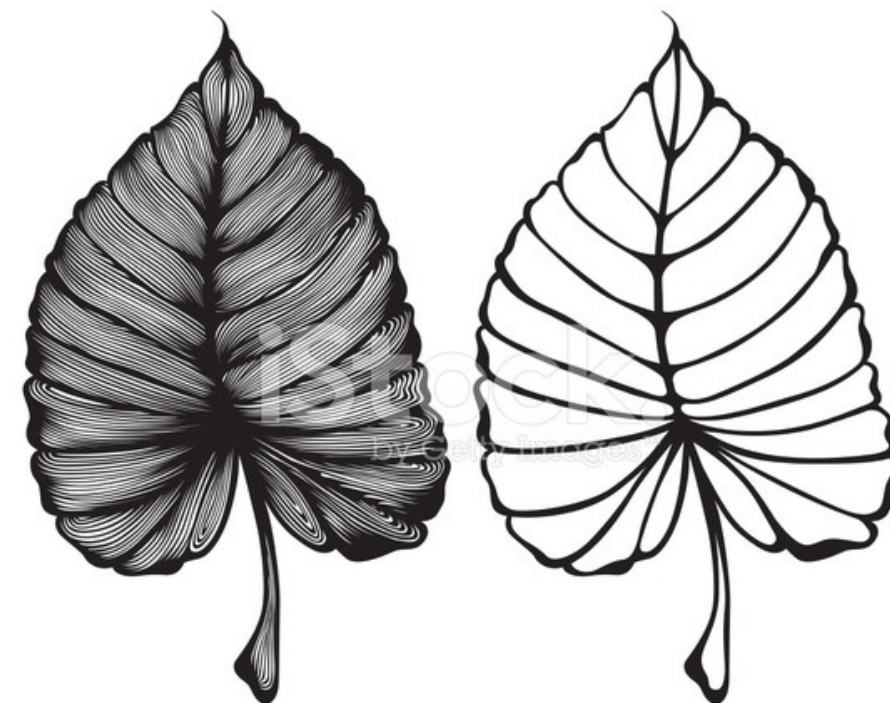
Quantum Biology

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

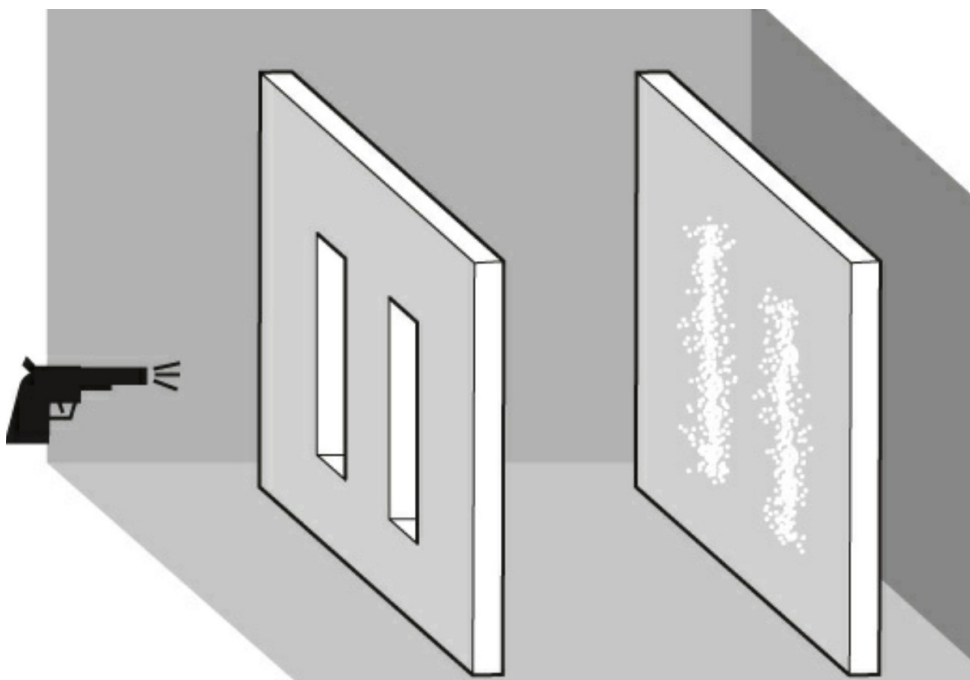
Silvia Pisano

Laboratori Nazionali di Frascati - INFN

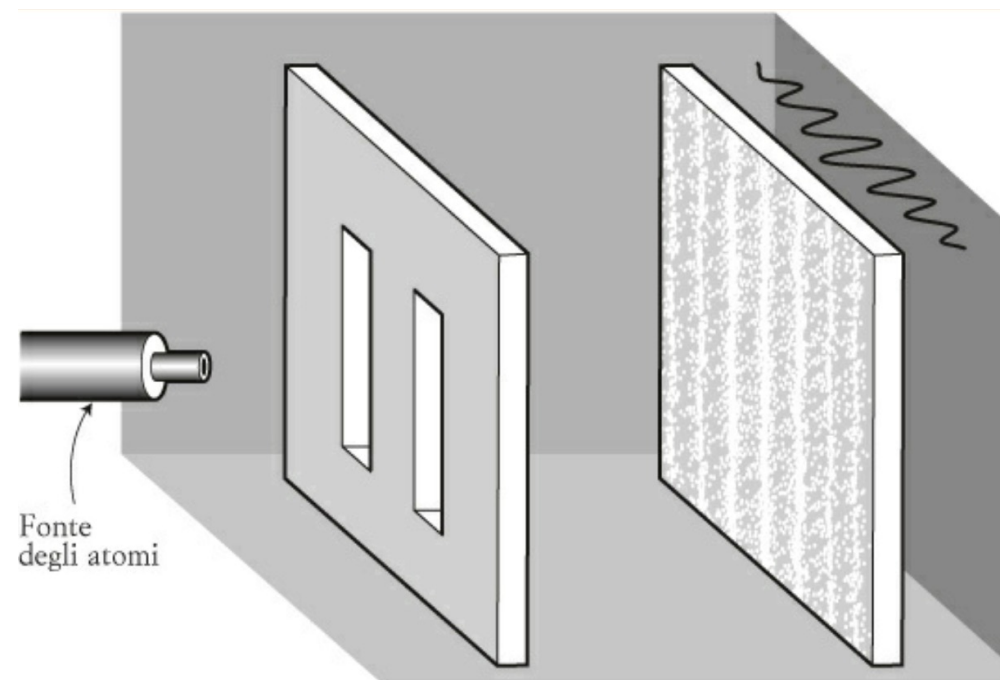
Museo Storico della Fisica e Centro Studi e Ricerche «Enrico Fermi»



Quantum vs. classic



Classical behaviour



Mechanical behaviour

Erwin Schrödinger

WHAT
IS
LIFE
?

The Physicist's approach to the

At the edge of the quantum world

$$h = 6.62607015 \times 10^{-34} \text{ m}^2\text{kg/s}$$

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

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

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

Erwin Schrödinger

WHAT
IS
LIFE
?

The Physicist's approach to the

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

WHAT
IS
LIFE
?

The Physicist's approach to the

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

WHAT IS LIFE

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

The Physicist's approach to the

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

WHAT
IS
LIFE
?

The Physicist's approach to the

At the edge of the quantum world

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

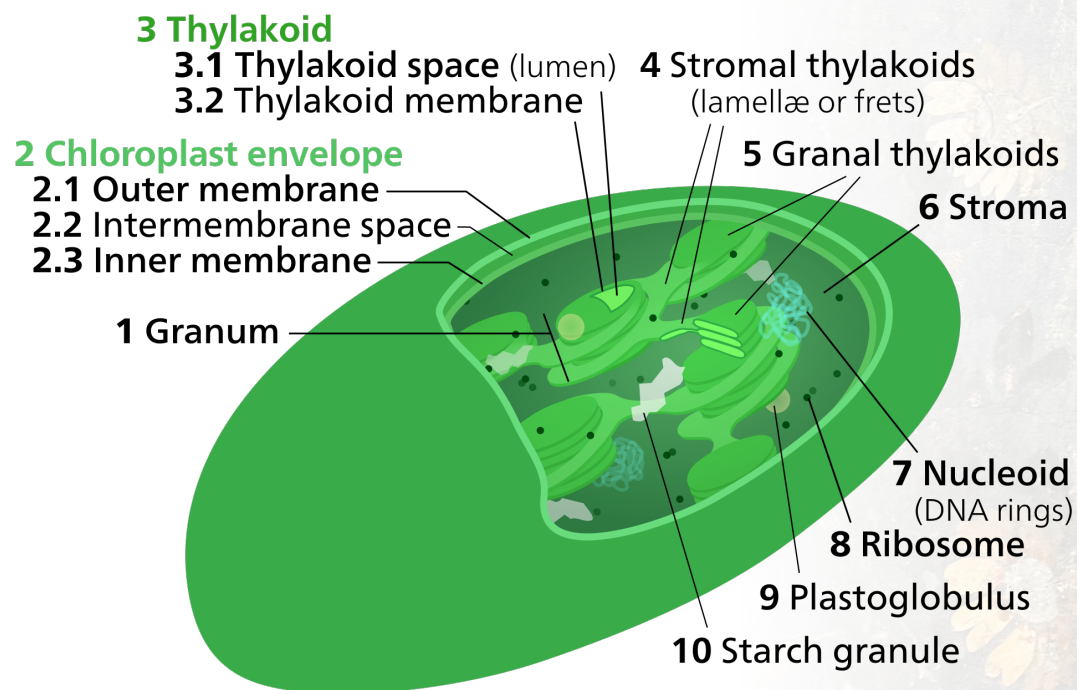
Traditionally, however, due to the vast separation of scales between systems described by QM and those studied in biology, as well as the seemingly different properties of inanimate and animate matter, has maintained some separation between the two realm of knowledge.

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

Photosynthesis

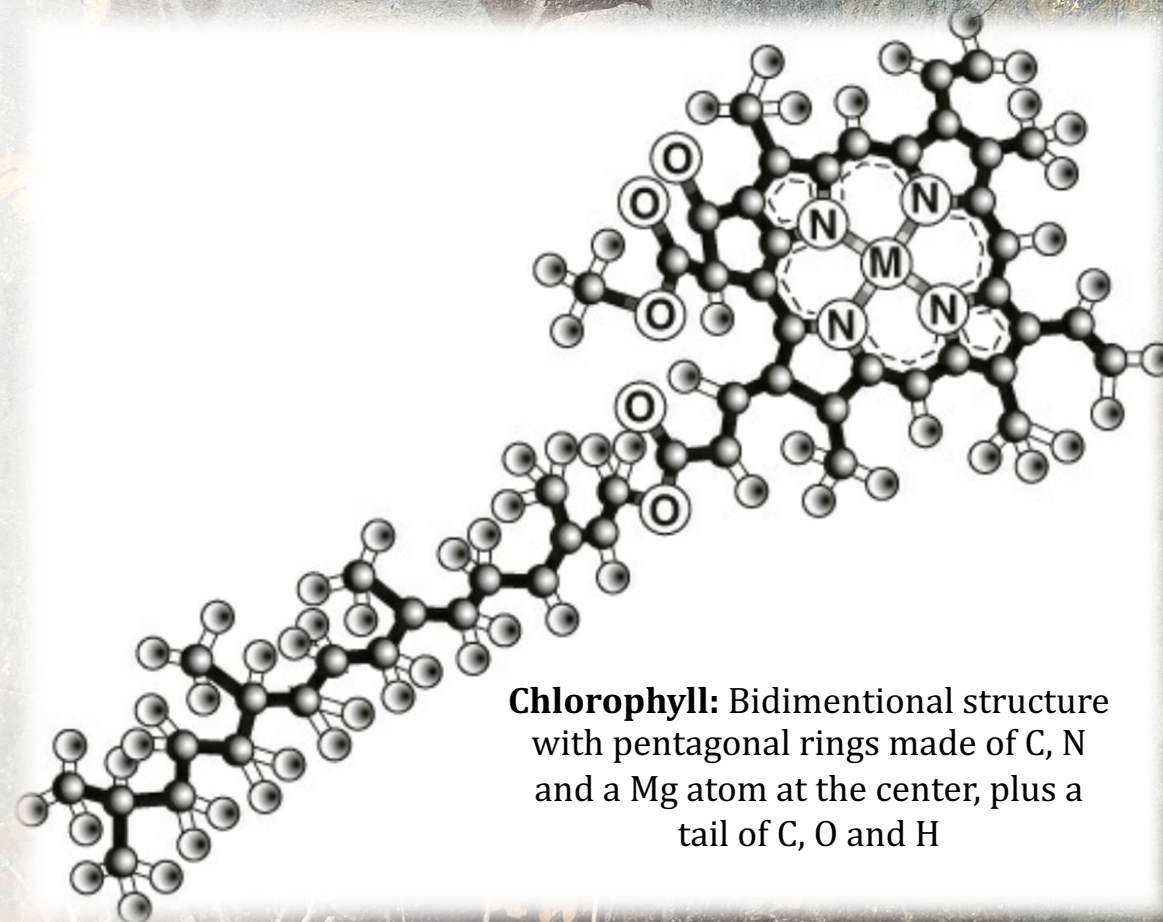
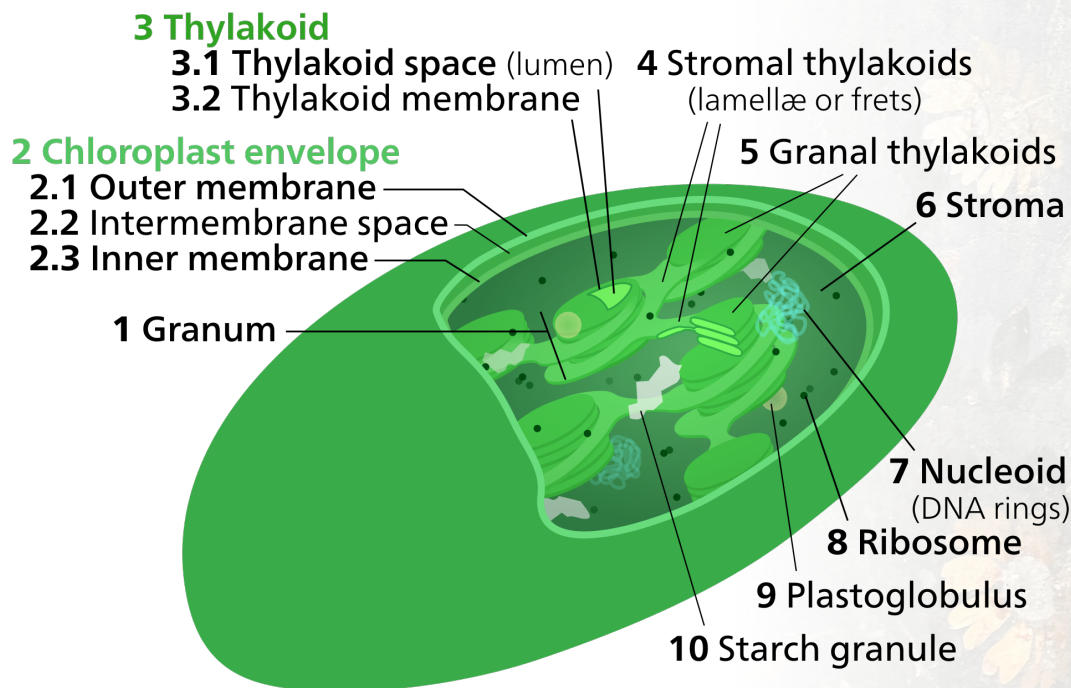
Photosynthesis

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



Photosynthesis

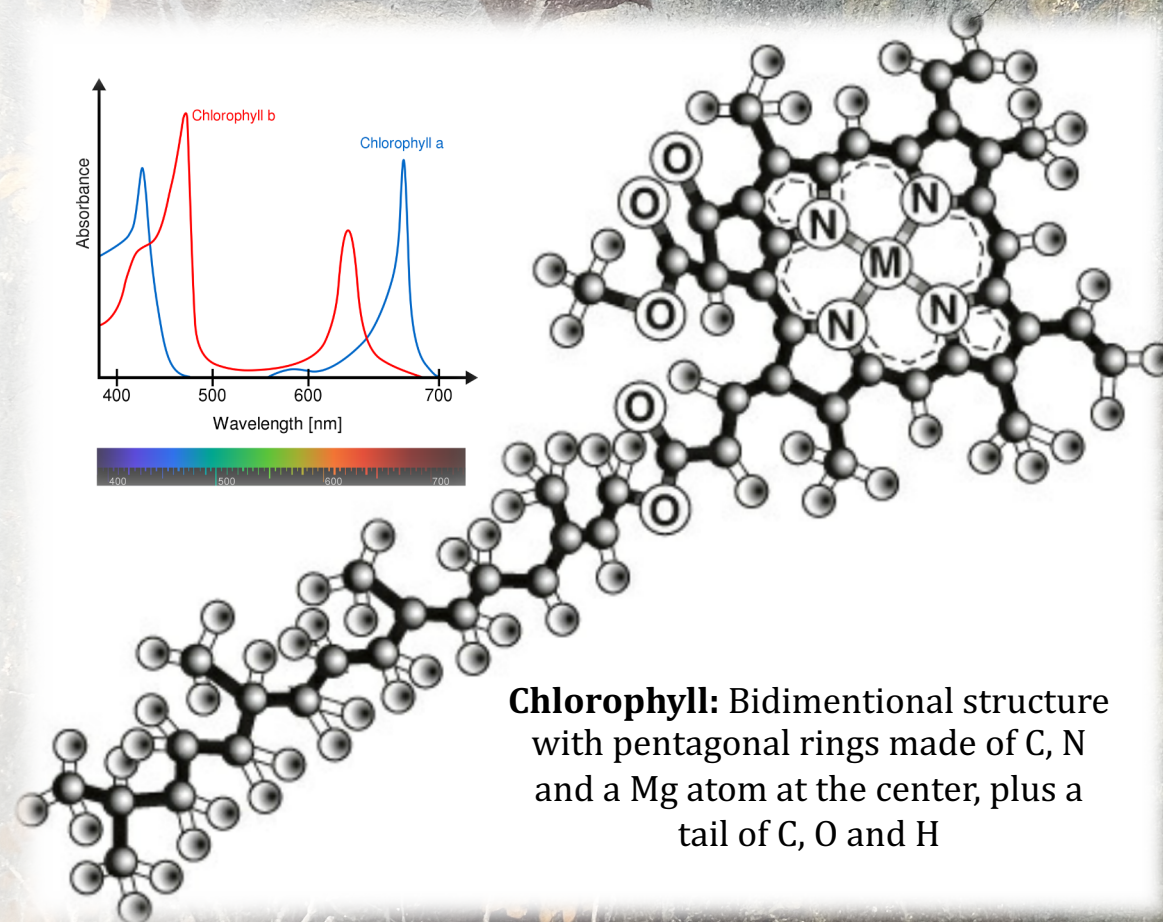
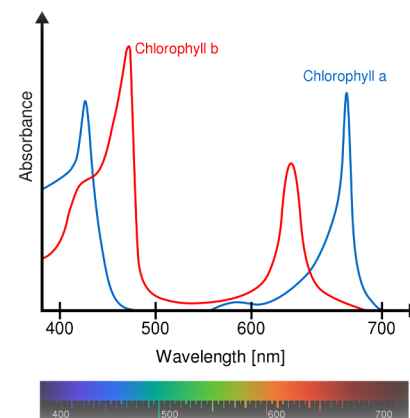
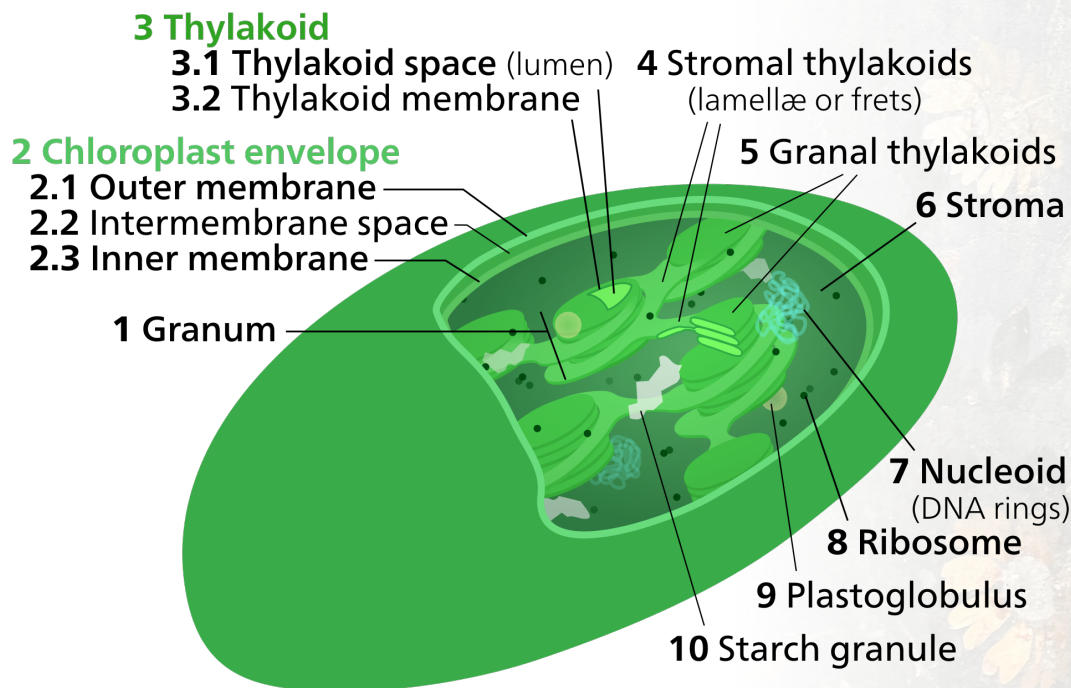
Chloroplast: membrane-bound organelle where photosynthesis takes place. In it, thylakoid containing chlorophyll molecules – *i.e.* the pigments capturing solar light - are contained.



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

Photosynthesis

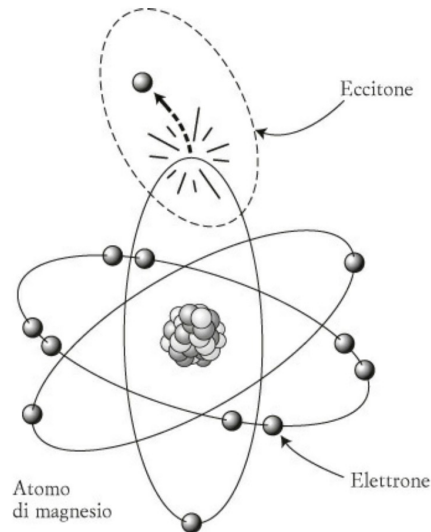
Chloroplast: membrane-bound organelle where photosynthesis takes place. In it, thylakoid containing chlorophyll molecules – *i.e.* the pigments capturing solar light - are contained.



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

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.

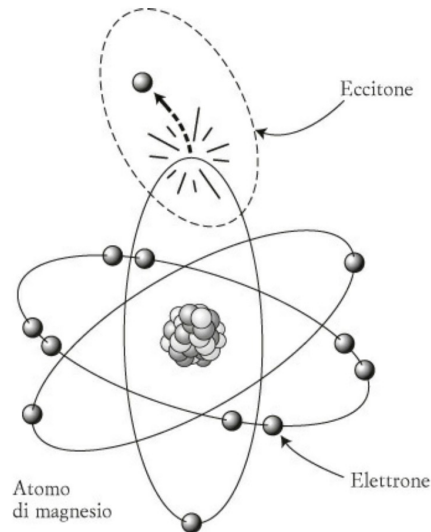


Frenkel exciton: small size exciton, almost completely localized within the molecule (typical binding energy of $0.1 \div 1$ eV)

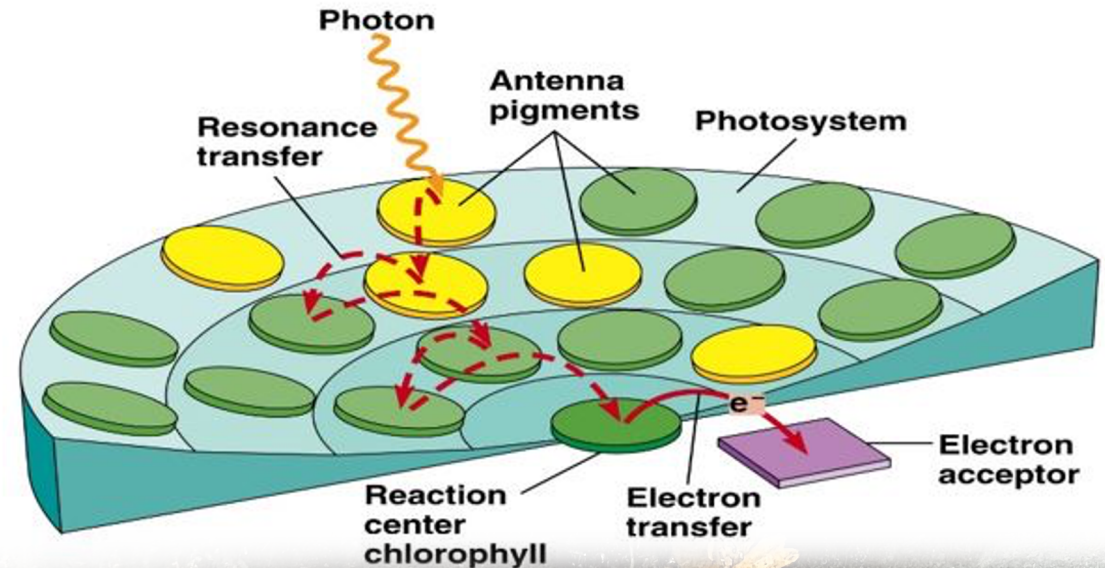
Franck and Teller, <https://doi.org/10.1063/1.1750182>

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.



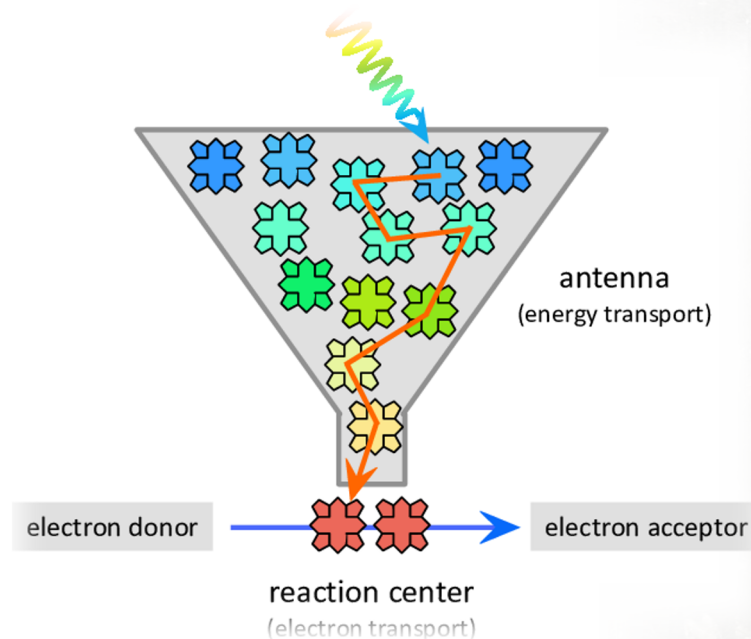
Tend to recombination → needs to be transported to a reaction center where the actual «charge separation» takes place. **The transfer proceeds through the different chlorophyll molecules.**



Photosynthesis

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*.

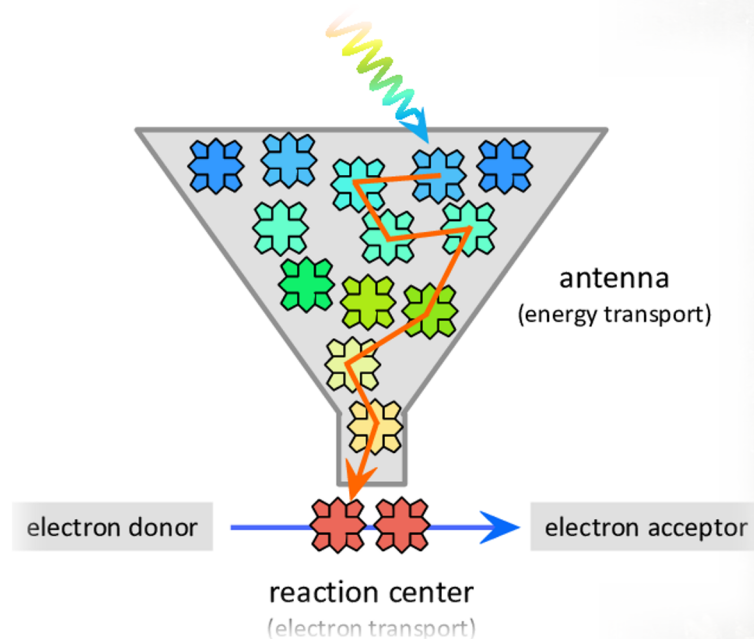


Photosynthesis

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

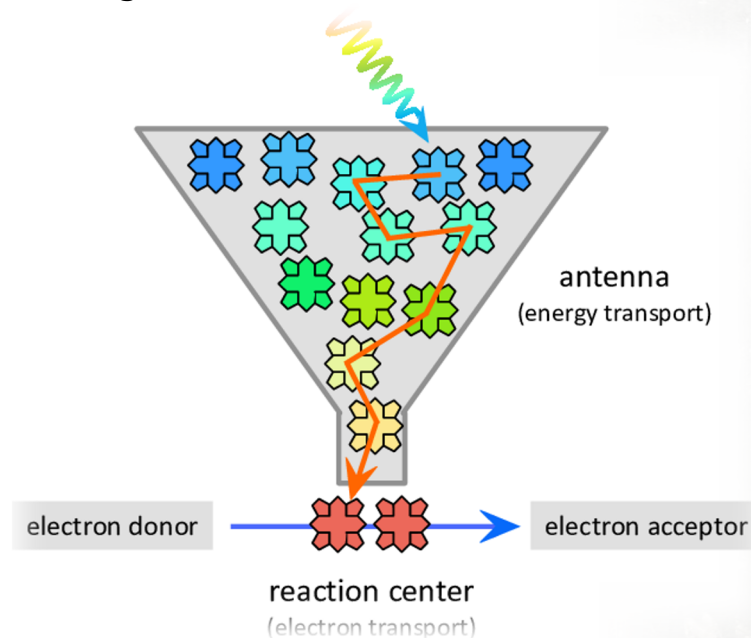
Global process time-scale $\sim 10^{-10}$ s $\Rightarrow$ to reach a high efficiency



Photosynthesis

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

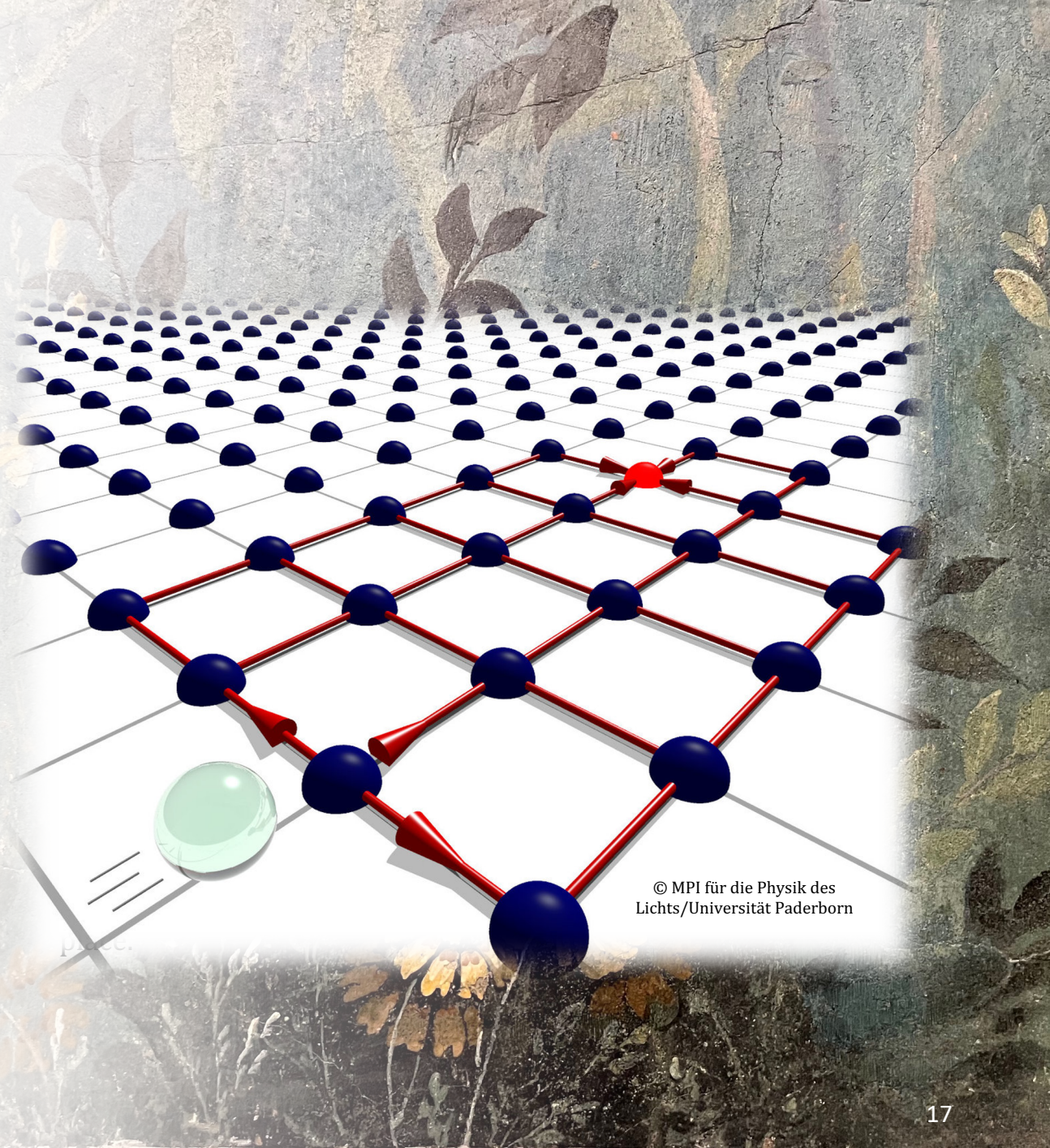
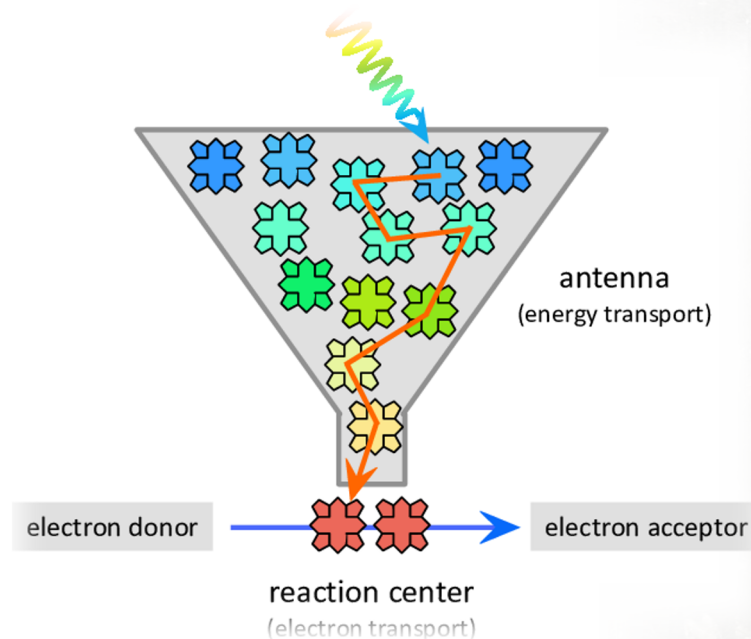
A classical «space-exploration», i.e. *classical random-walk*, would take too long, and part of the excitation will be lost before reaching the reaction center.



Photosynthesis

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

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



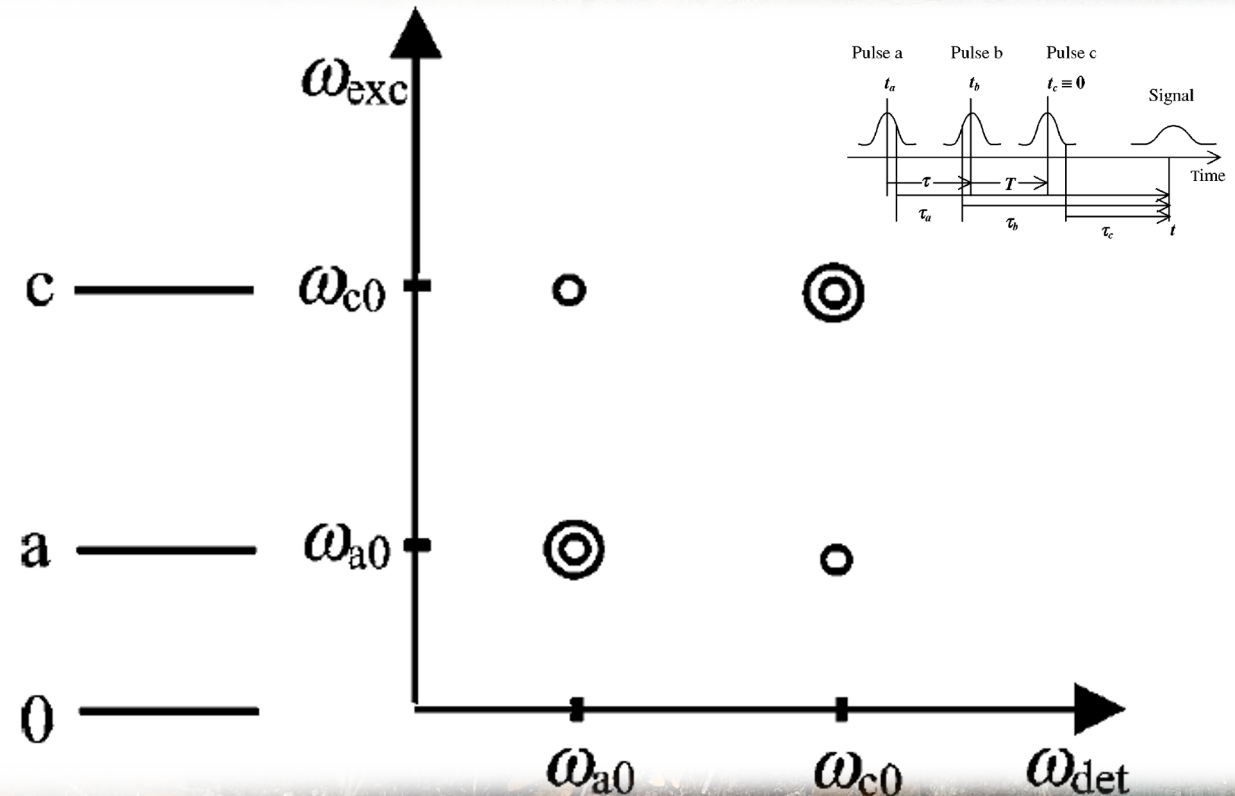
© MPI für die Physik des
Lichts/Universität Paderborn

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

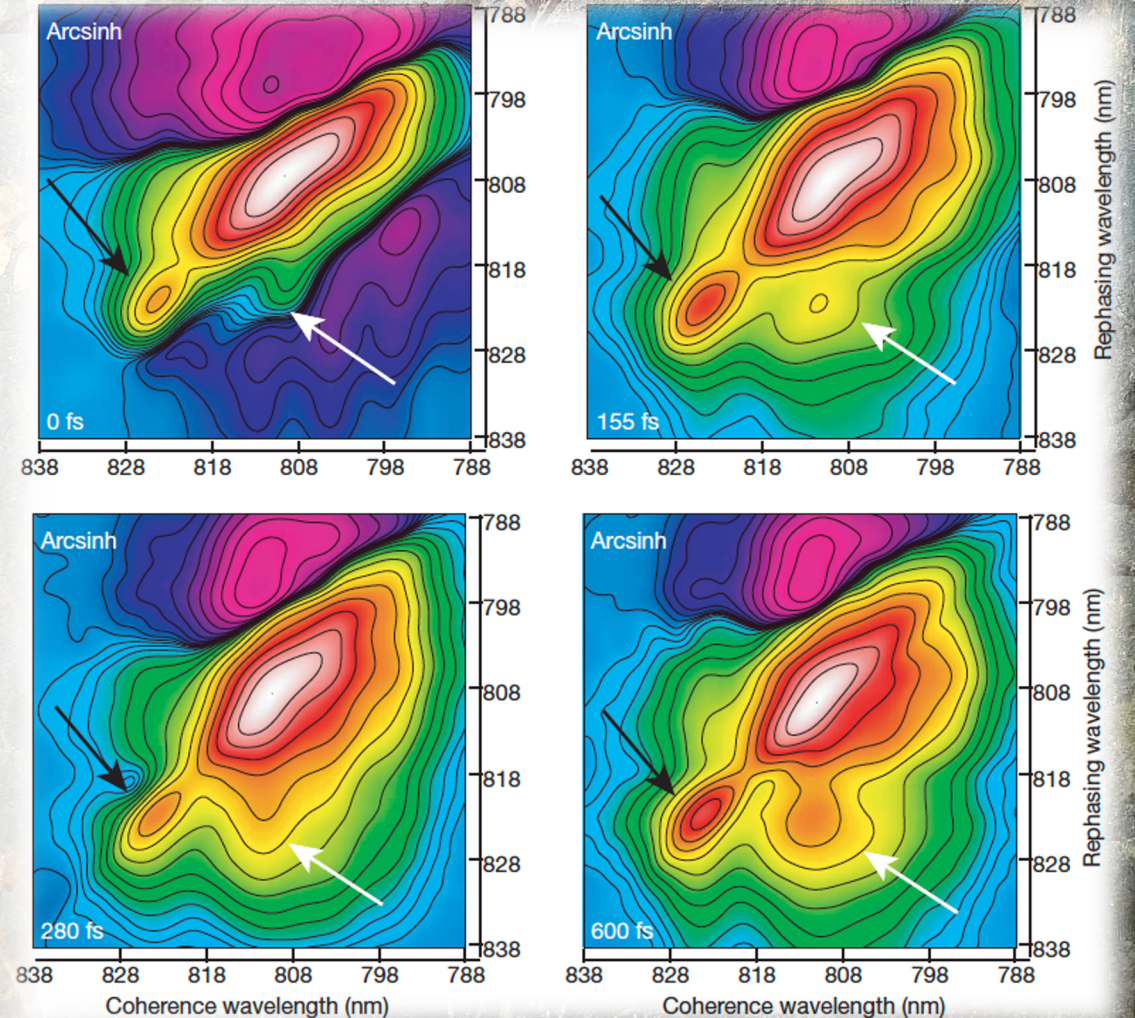
How to investigate quantum-walk in photosynthetic complexes

- 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**



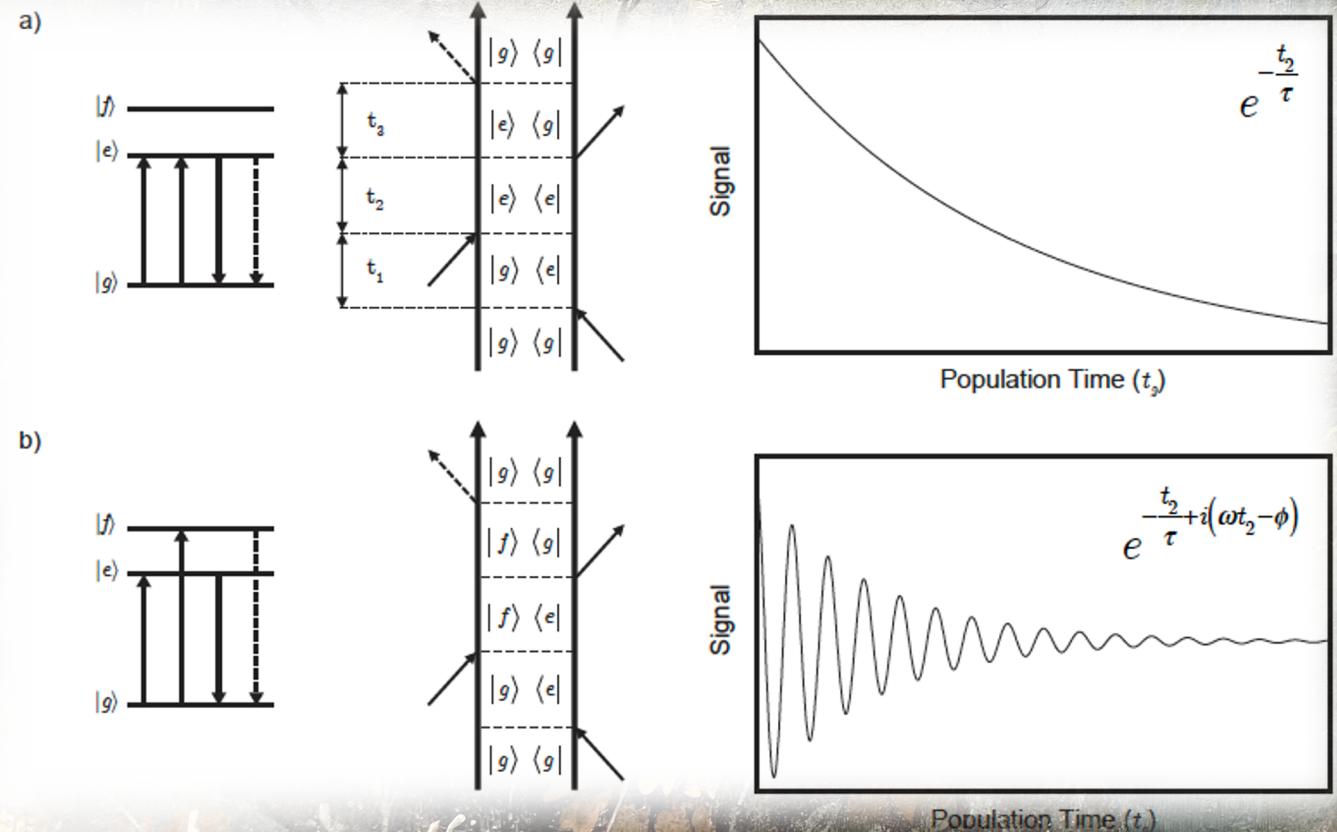
How to investigate quantum-walk in photosynthetic complexes

- 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**



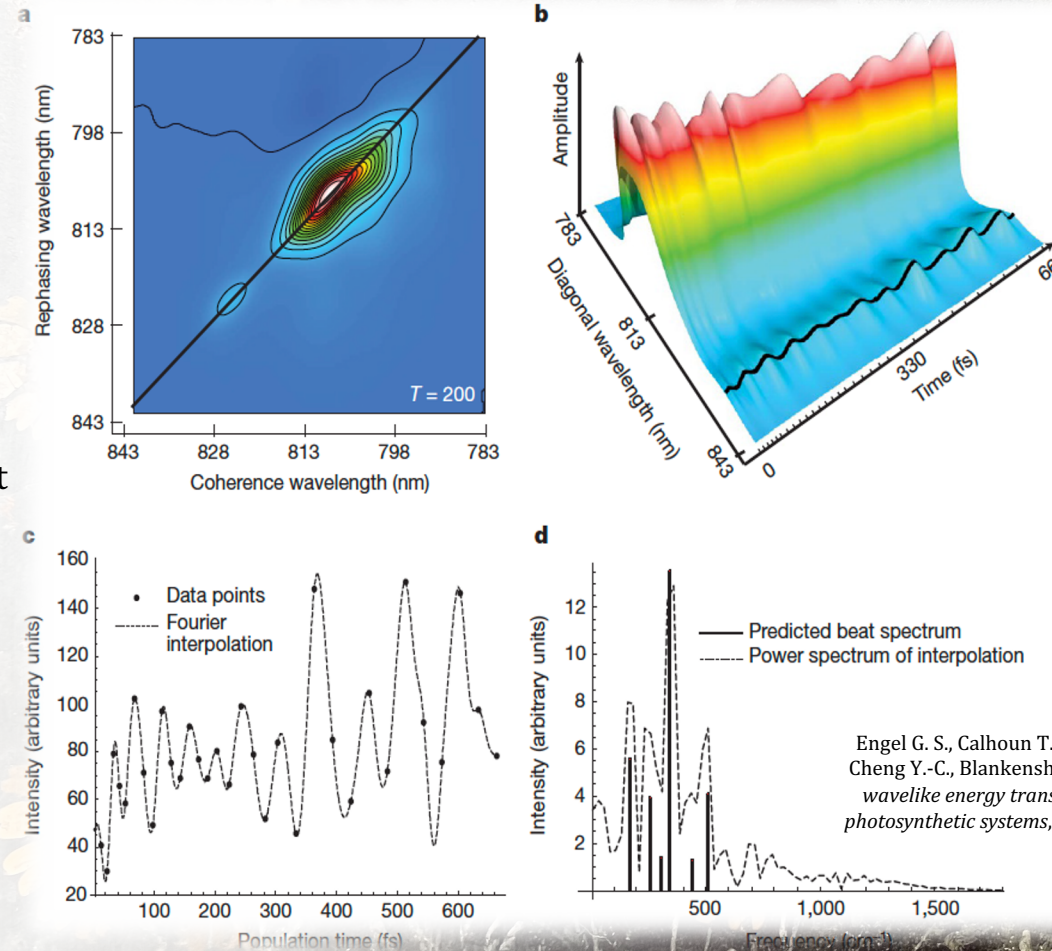
How to investigate quantum-walk in photosynthetic complexes

- 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**



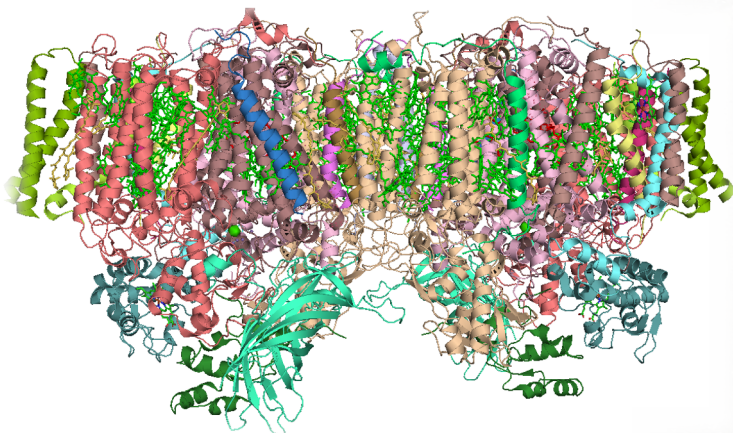
How to investigate quantum-walk in photosynthetic complexes

- 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**

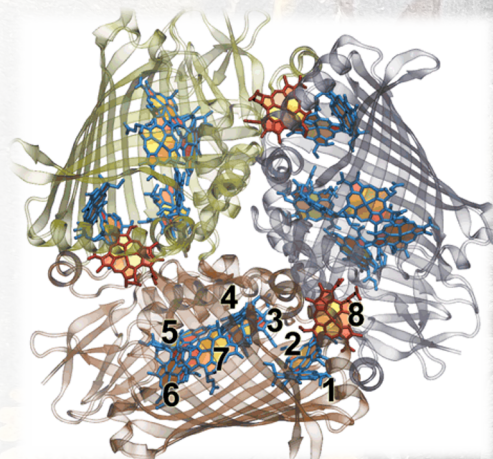


Engel G. S., Calhoun T. R., Read E. L., Ahn T.-K., Mančal T., Cheng Y.-C., Blankenship R. E. & Fleming G. R., *Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems*, «Nature», vol. 446 (2007), pp. 782–86.

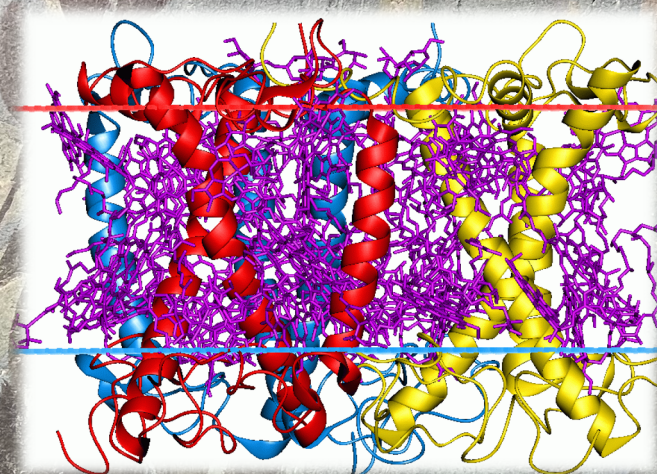
How to investigate quantum-walk in photosynthetic complexes



Cyanobacteria photosystem II, Dimer, PDB 2AXT

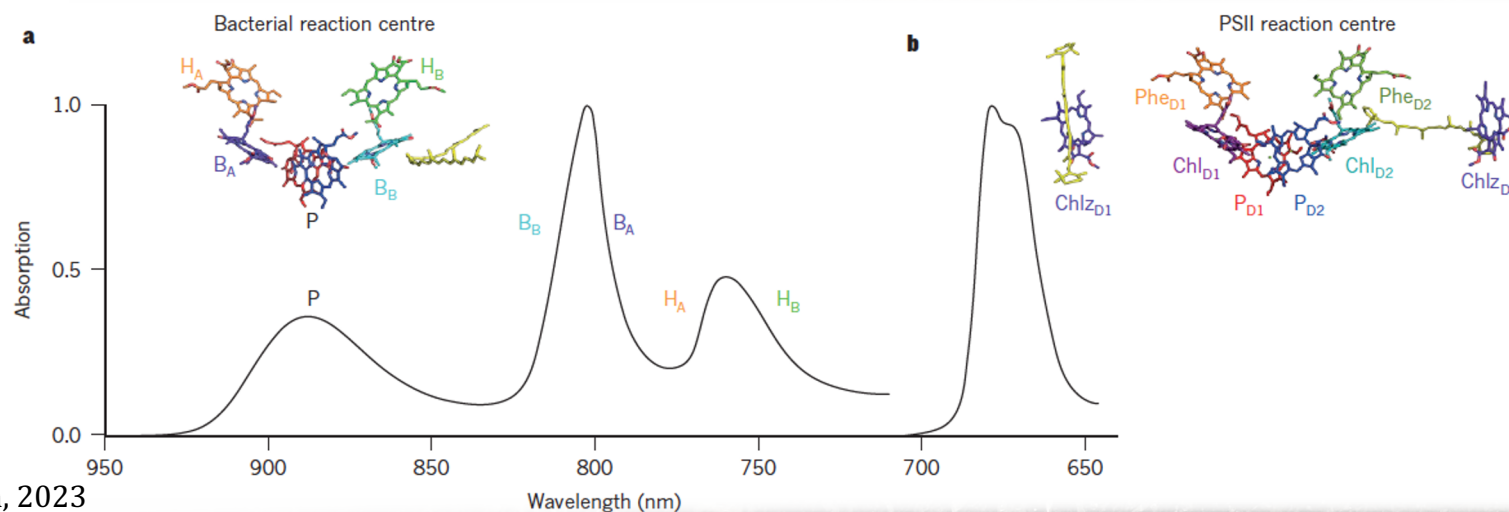


FMO homo-trimer from *Chlorobaculum tepidum*. Each monomer sandwiches 7 bacteriochlorophyll molecules for light harvesting.



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

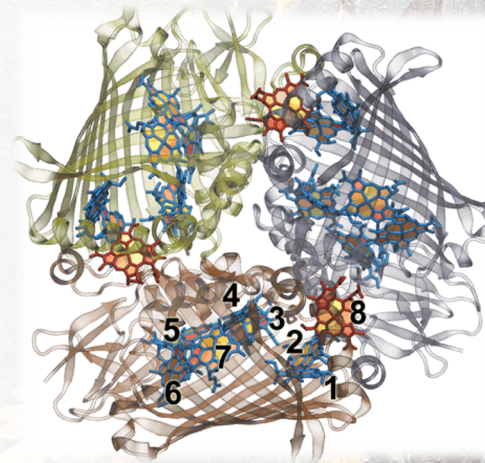
Absorption spectra and X-ray structure of the bacterial reaction centre and the PSII reaction centre. a) The absorption spectrum of the bacterial reaction centre of *Rhodobacter sphaeroides* at 77 K is shown with the X-ray crystal structure of the complex. b) The 77 K absorption spectrum of the PSII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



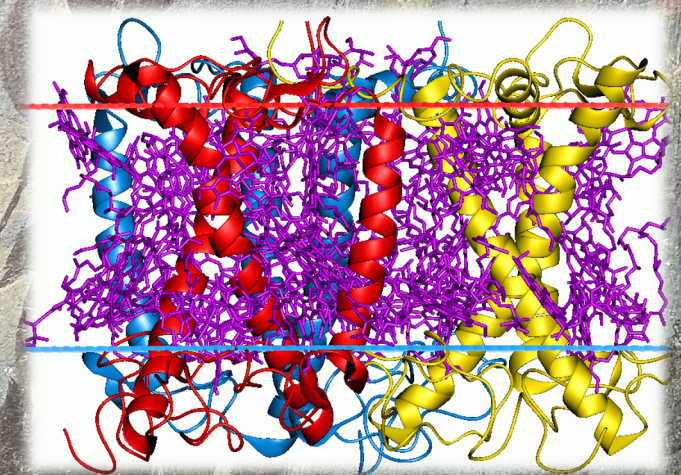
How to investigate quantum-walk in photosynthetic complexes

The most suitable experimental methods are spectroscopic techniques

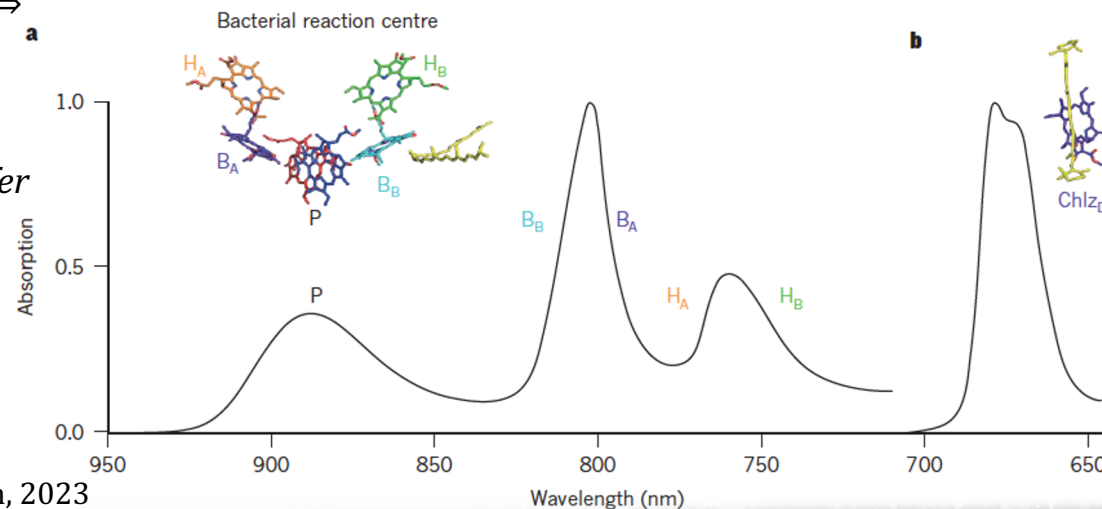
1. absorption spectroscopy $\Rightarrow$ *energy of the absorbing states*
2. fluorescence spectroscopy $\Rightarrow$ *energy of the lowest energy-emitting state*
3. linear dichroism and circular dichroism $\Rightarrow$ *pigment interactions and orientations*
4. triplet-minus-singlet spectroscopy $\Rightarrow$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



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



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



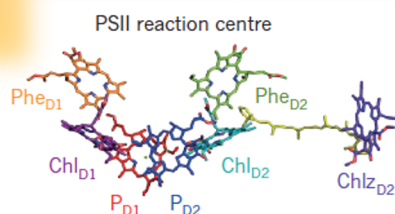
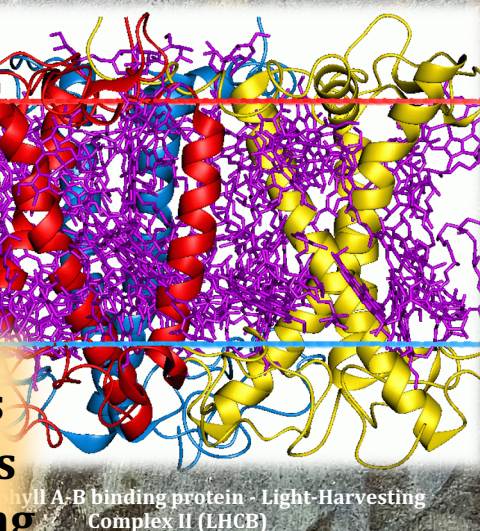
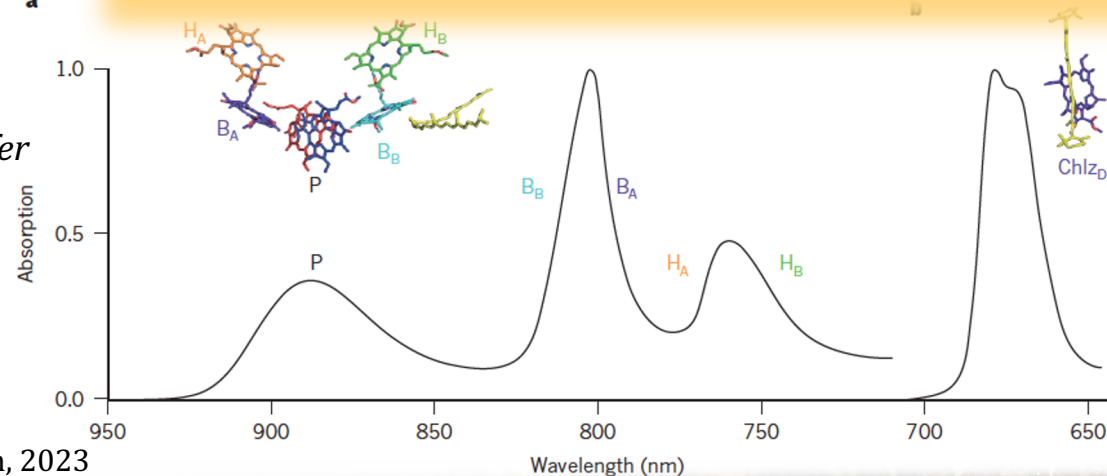
Absorption spectra and X-ray structure of the bacterial reaction centre and the PSII reaction centre. a) The absorption spectrum of the bacterial reaction centre of *Rhodospirillum rubrum* at 77 K is shown with the X-ray crystal structure of the complex. b) The 77 K absorption spectrum of the PSII reaction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

How to investigate quantum-walk in photosynthetic complexes

The most suitable experimental methods are spectroscopic techniques

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

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

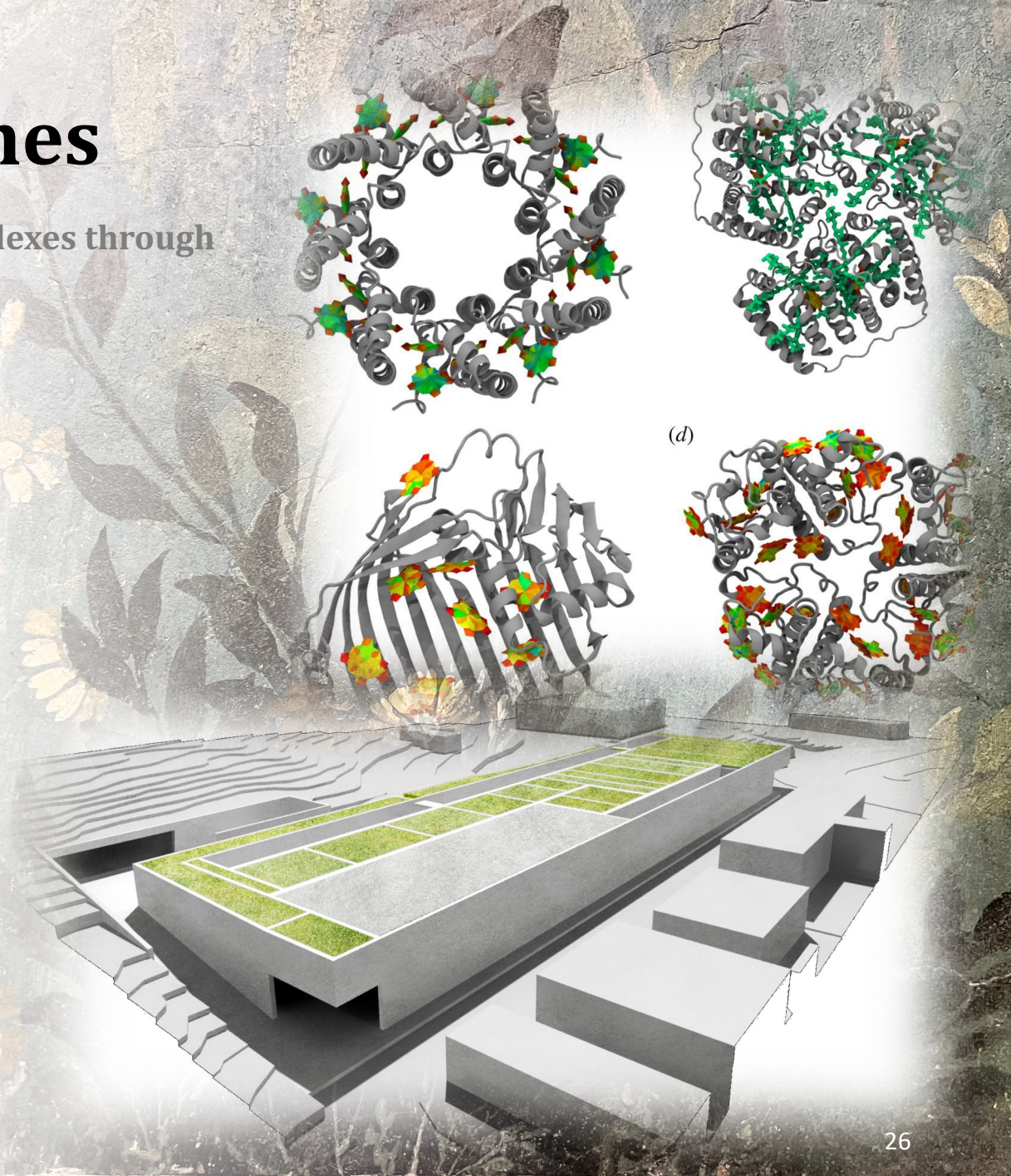


Absorption spectra and X-ray structure of the bacterial reaction centre and the PSII reaction centre. a) The absorption spectrum of the bacterial reaction centre of Rhodospirillum rubrum at 77 K is shown with the X-ray crystal structure of the complex. b) The 77 K absorption spectrum of the PSII reaction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

Possible research lines

Investigation of different photosynthetic 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



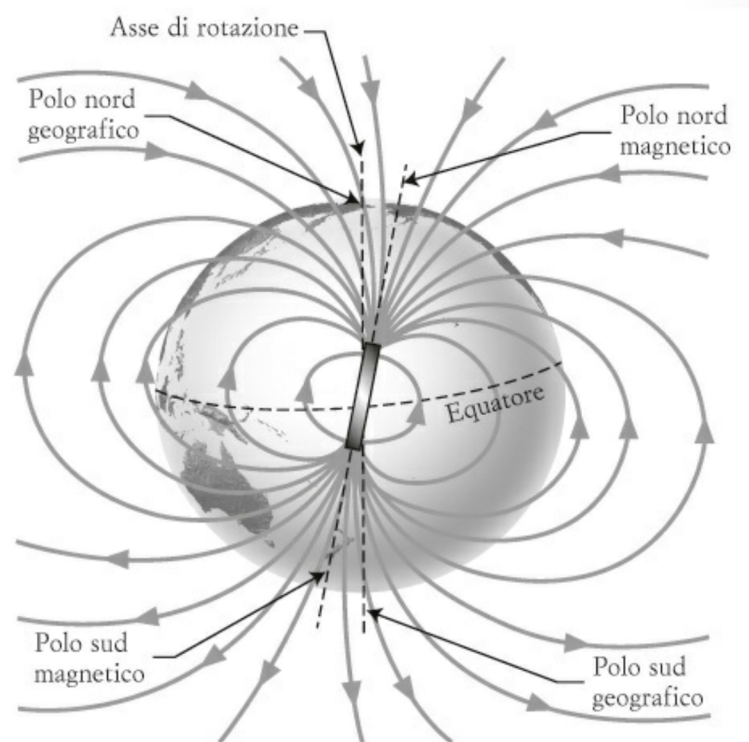
Magnetoreception

The quantum robin



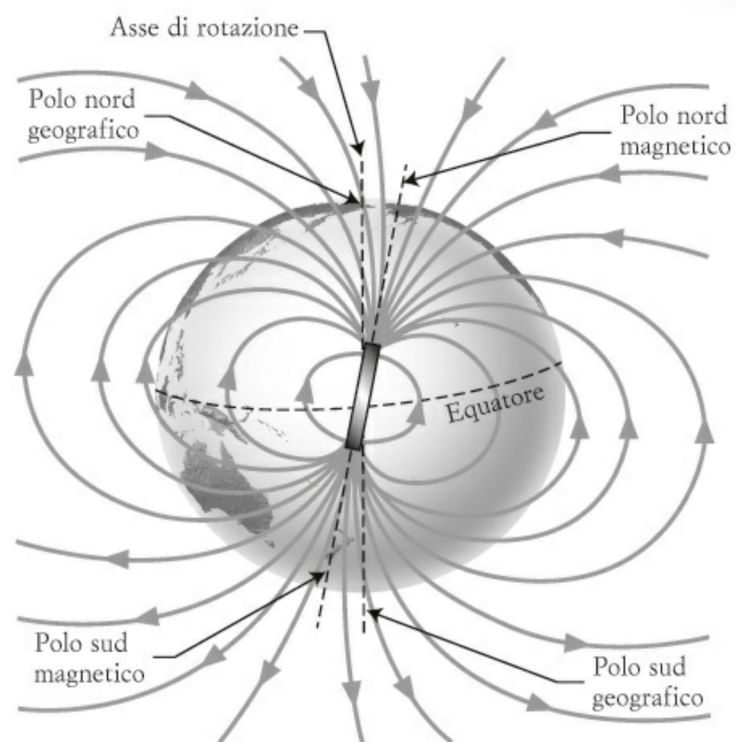
Magnetoreception

Earth's magnetic field is very low: $20 \div 70 \mu\text{T}$. The corresponding photon vehicles an energy less than 10^9 the one needed to break a chemical bond and activate, then, a physiological response

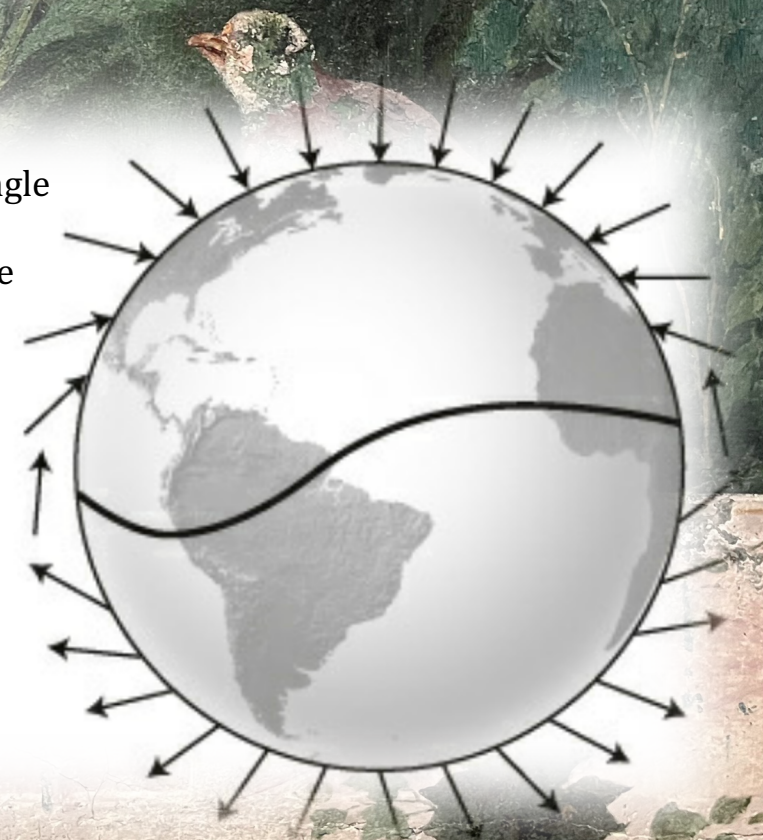


Magnetoreception

Earth's magnetic field is very low: $20 \div 70 \mu\text{T}$. The corresponding photon vehicles an energy less than 10^9 the one needed to break a chemical bond and activate, then, a physiological response

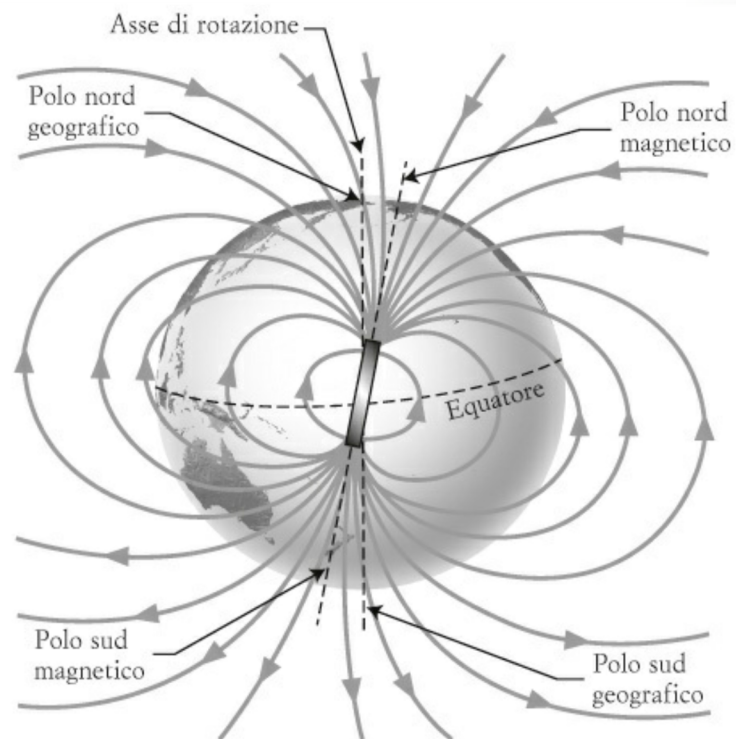


Avian compass $\Rightarrow$ tilt compass: it measures the angle between the field lines and the Earth surface, distinguishing poles from the Equator (but not the two poles)

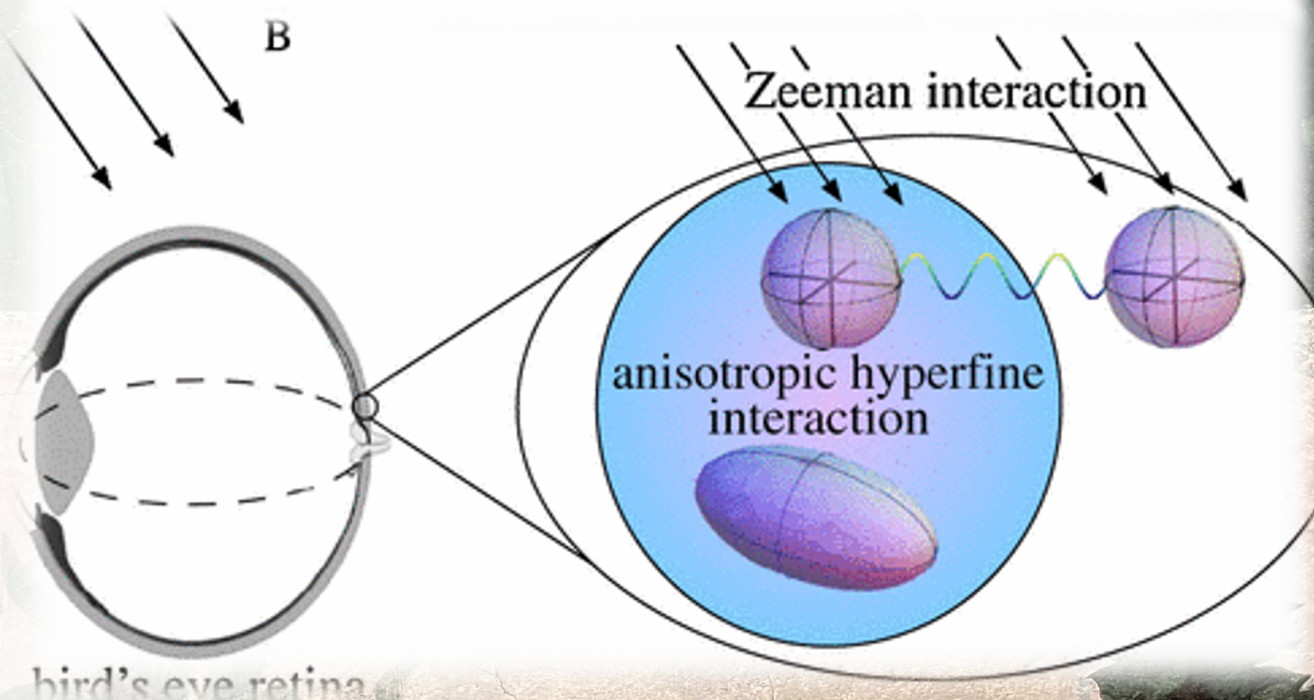


Magnetoreception

Earth's magnetic field is very low: $20 \div 70 \mu\text{T}$. The corresponding photon vehicles an energy less than 10^9 the one needed to break a chemical bond and activate, then, a physiological response



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 quantum robin

- Atoms are bound by sharing e^-
- If the molecule breaks, two free radicals are produced
- *Free radicals*: molecule with an unpaired e^- in the external orbitals $\rightarrow$ 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



The quantum robin

- Atoms are bound by sharing e^-
- If the molecule 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**



The quantum robin

- Atoms are bound by sharing e^-
- If the molecule 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**

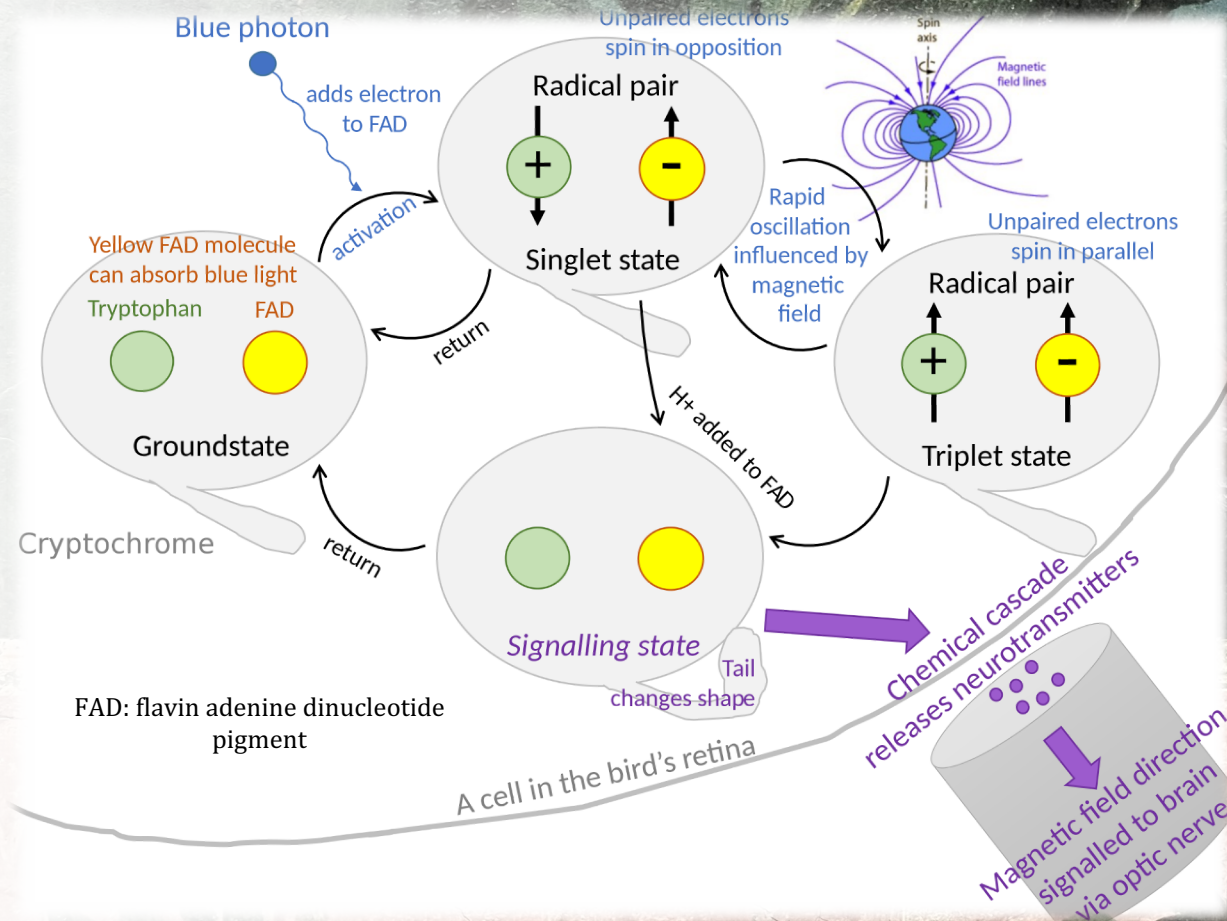
The initial break of the original molecule may be produced by a visible photon (in the blue-light region).



The quantum robin

- Atoms are bound by sharing e^-
- If the molecule 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**

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

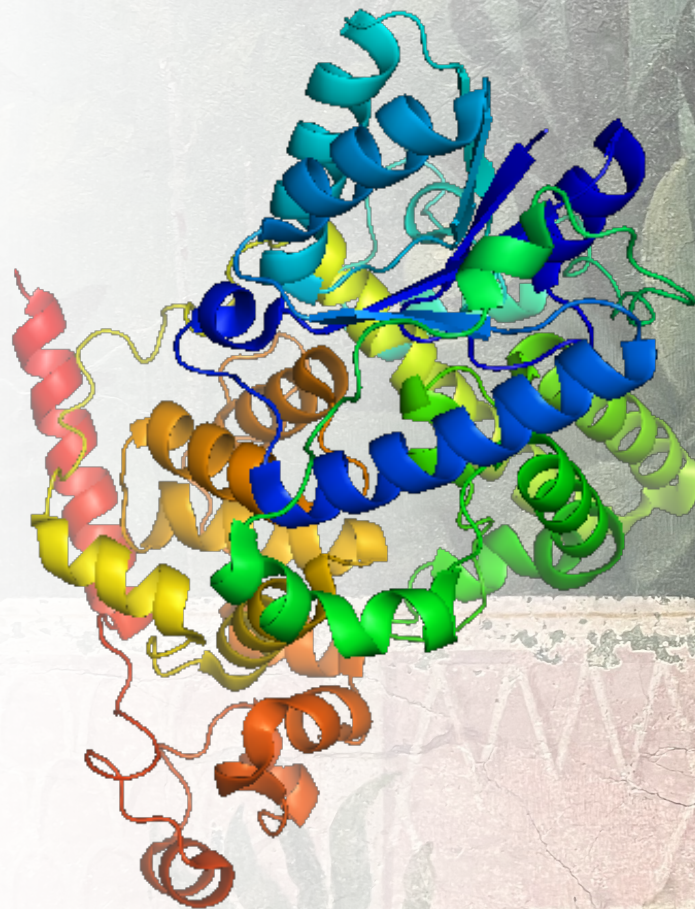


A Model for Photoreceptor-Based Magnetoreception in Birds
Volume 78, Issue 2, February 2000, Pages 707-718

The quantum robin

- 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**

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

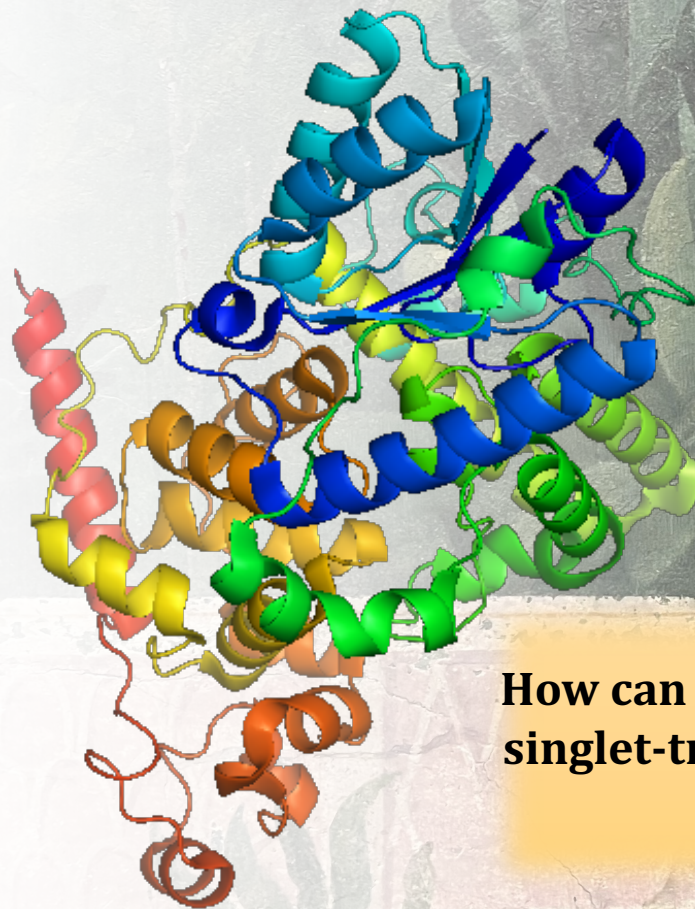


A Model for Photoreceptor-Based Magnetoreception in Birds
Volume 78, Issue 2, February 2000, Pages 707-718

The quantum robin

- 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**

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



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

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

Possible research lines

Study of the decoherence process

1. QUPLAS (QUantum interferometry and gravitation with Positrons and LASers) $\Rightarrow$ *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

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

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

1. Avian compass for low-energy magnetic field characterization
2. Cryptochrome as possible photo-detectors

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

Quantum computing

Natural selection as the new R&D approach

A detailed painting of a bird, possibly a sparrow, perched on a branch with yellow flowers. The background is dark and textured, with a large, dark, leafy plant on the left and a lighter, more detailed plant with yellow flowers on the right. The overall style is reminiscent of a classical oil painting.

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 maintaining 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?

References

Review on Quantum Biology:

1. Marais A. *et al.*, 2018 *The future of quantum biology*, J. R. Soc. Interface 15:2018064, <http://dx.doi.org/10.1098/rsif.2018.0640>
2. Cao *et al.*, *Quantum biology revisited*, <https://doi.org/10.1126/sciadv.aaz4888>

Photosynthesis:

1. Engel *et al.* Vol 446| 12 April 2007| doi:10.1038/nature05678
2. Franck and Teller, paper about the *Frankel exciton*, <https://doi.org/10.1063/1.1750182>
3. Romero *et al.*, «*Quantum design of photosynthesis for bio-inspired solar-energy conversion*», doi:10.1038/nature22012
4. Ringsmuth *et al.*, «*Multiscale photosynthetic and biomimetic excitation energy transfer*», doi: 10.1038/NPHYS2332

Magnetoreception:

1. Maeda *et al.*, «*Chemical compass model of avian magnetoreception*», doi:10.1038/nature06834
2. Zhang *et al.*, «*The Radical Pair Mechanism and the Avian Chemical Compass: Quantum Coherence and Entanglement*», DOI: 10.1002/qua.24943
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





Istituto Nazionale di Fisica Nucleare

Fondamentale



Il Passero Europeo
is the new
Gatto di Schrödinger





backup

LETTERS

Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems

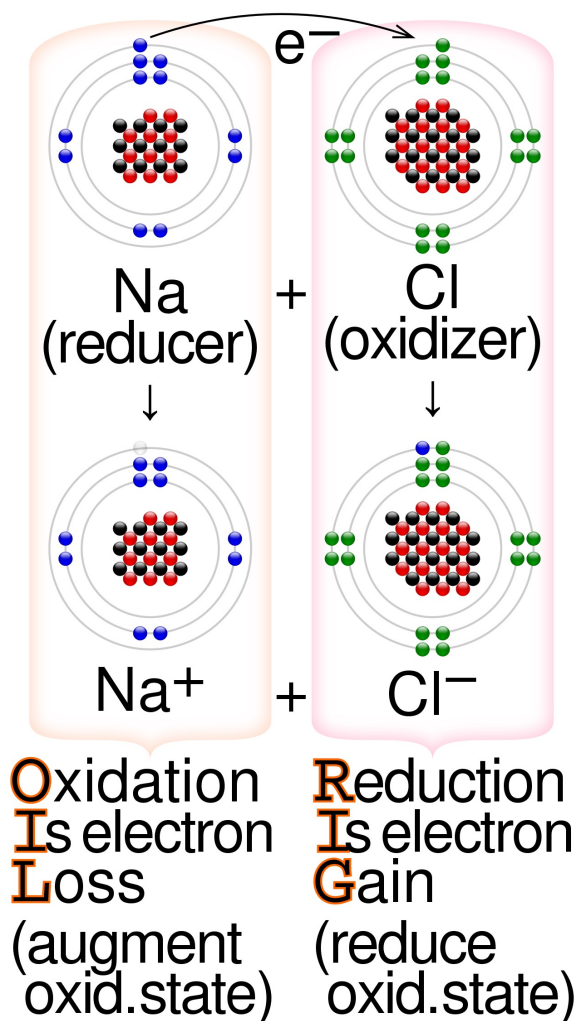
Gregory S. Engel^{1,2}, Tessa R. Calhoun^{1,2}, Elizabeth L. Read^{1,2}, Tae-Kyu Ahn^{1,2}, Tomáš Mančal^{1,2†}, Yuan-Chung Cheng^{1,2}, Robert E. Blankenship^{3,4} & Graham R. Fleming^{1,2}

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.

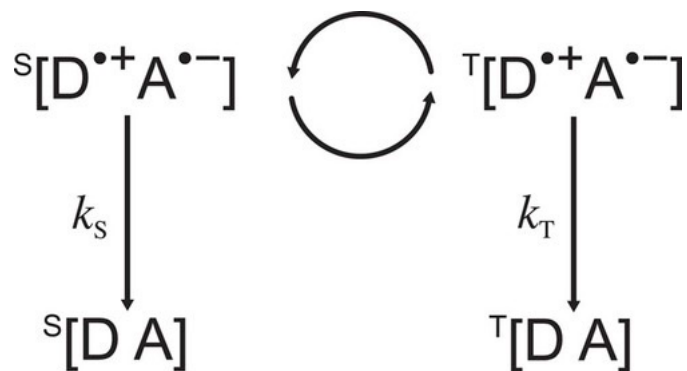


Electron-transfer reaction



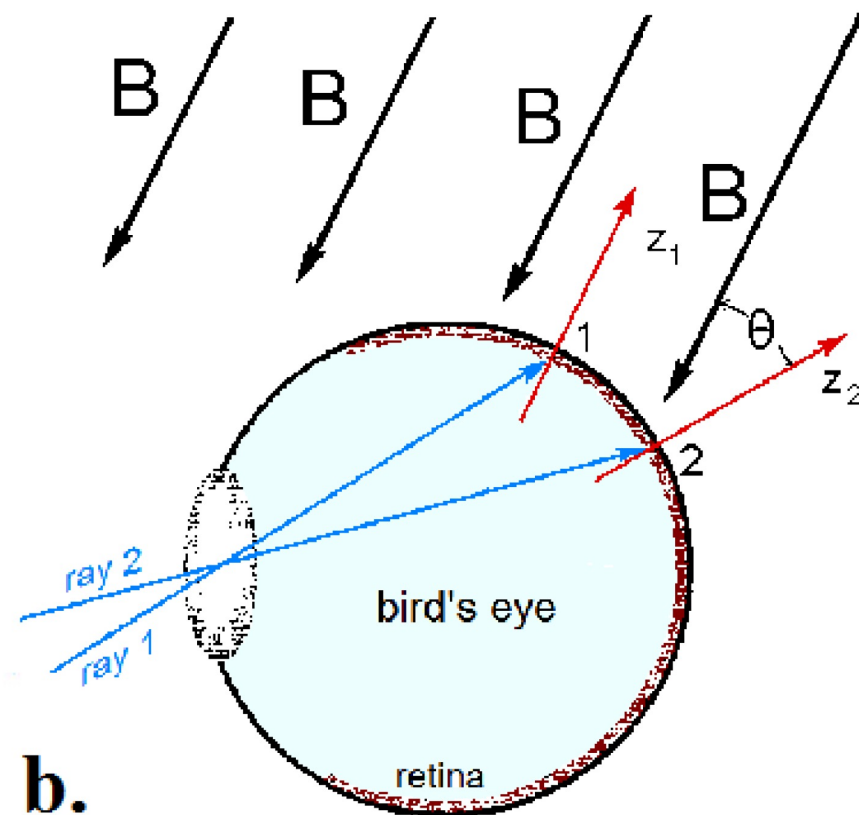
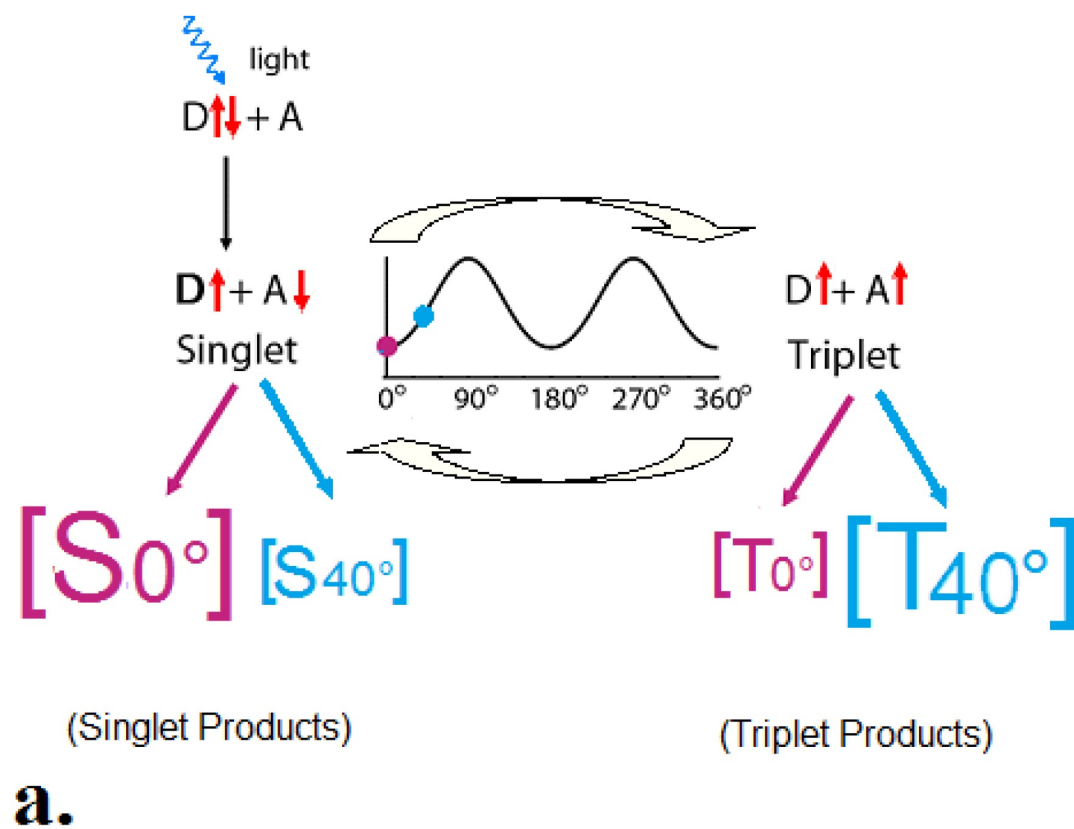
Occurs when an electron relocates from an atom or molecule to another atom or molecule.

It can eventually produce a pair of free radicals

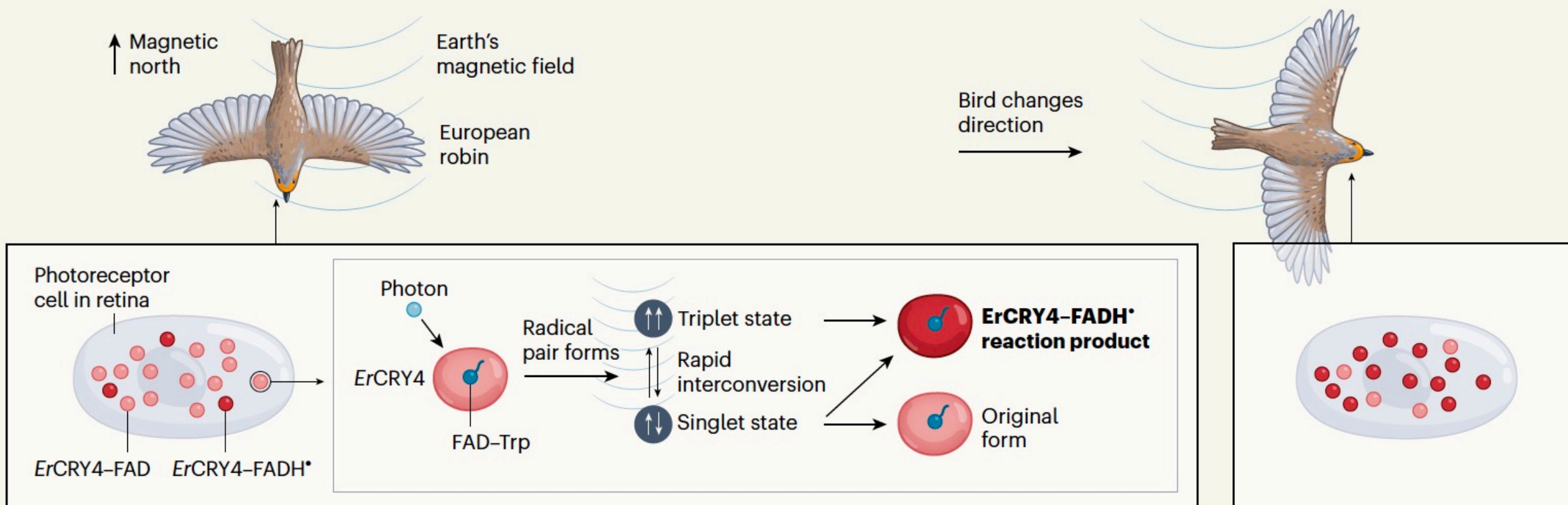


Cryptochrome Cry1a

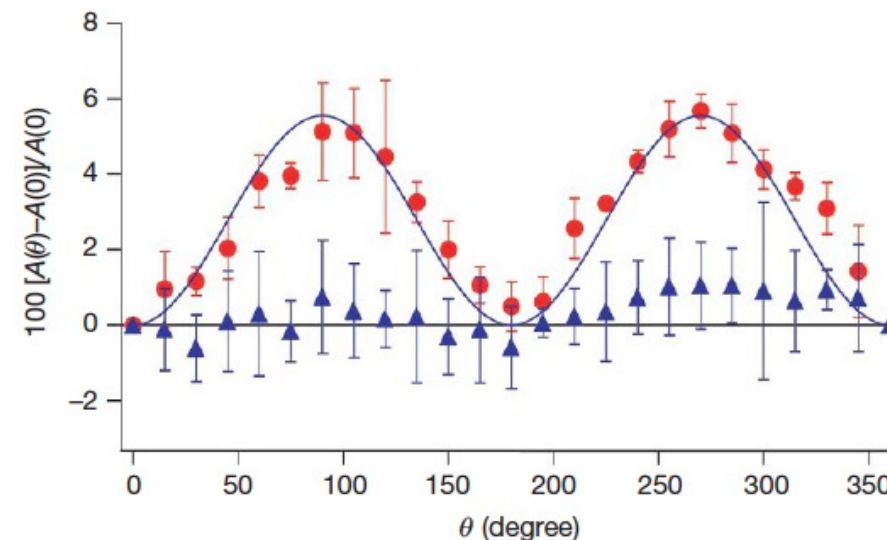
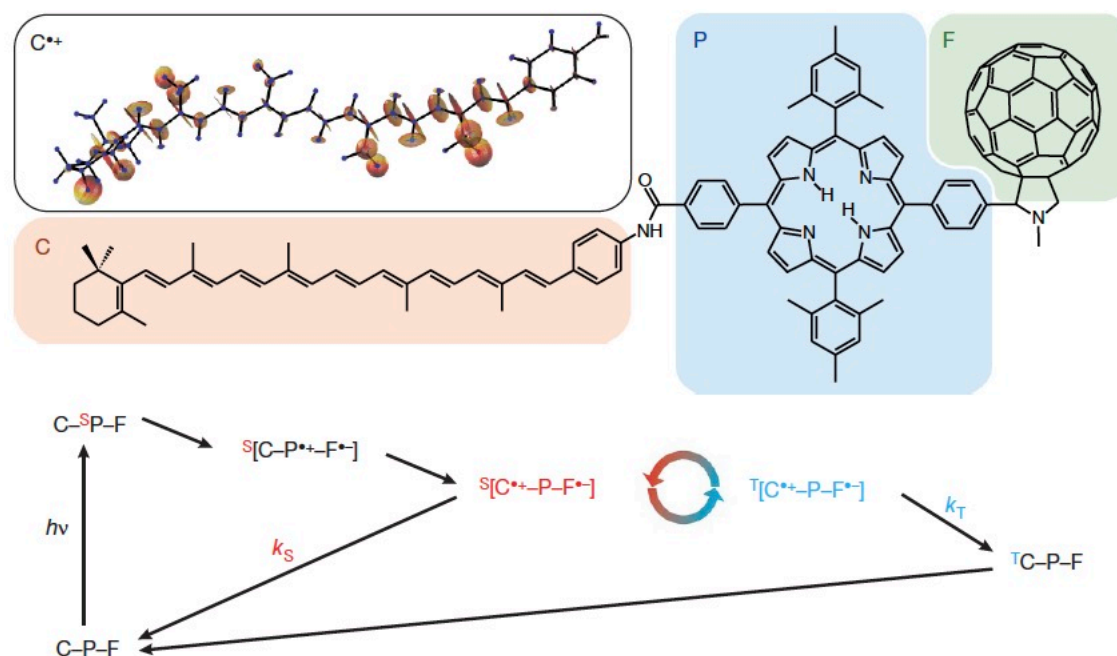
Photoreceptor proteins located in the retina and sensitive to the blue-green part of the spectrum



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 $[C^{*+}-P-F^{*-}]$ 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 $\sim 1.5\%$ and $\sim 5\%$, 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 $[C^{*+}-P-F^{*-}]$ 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

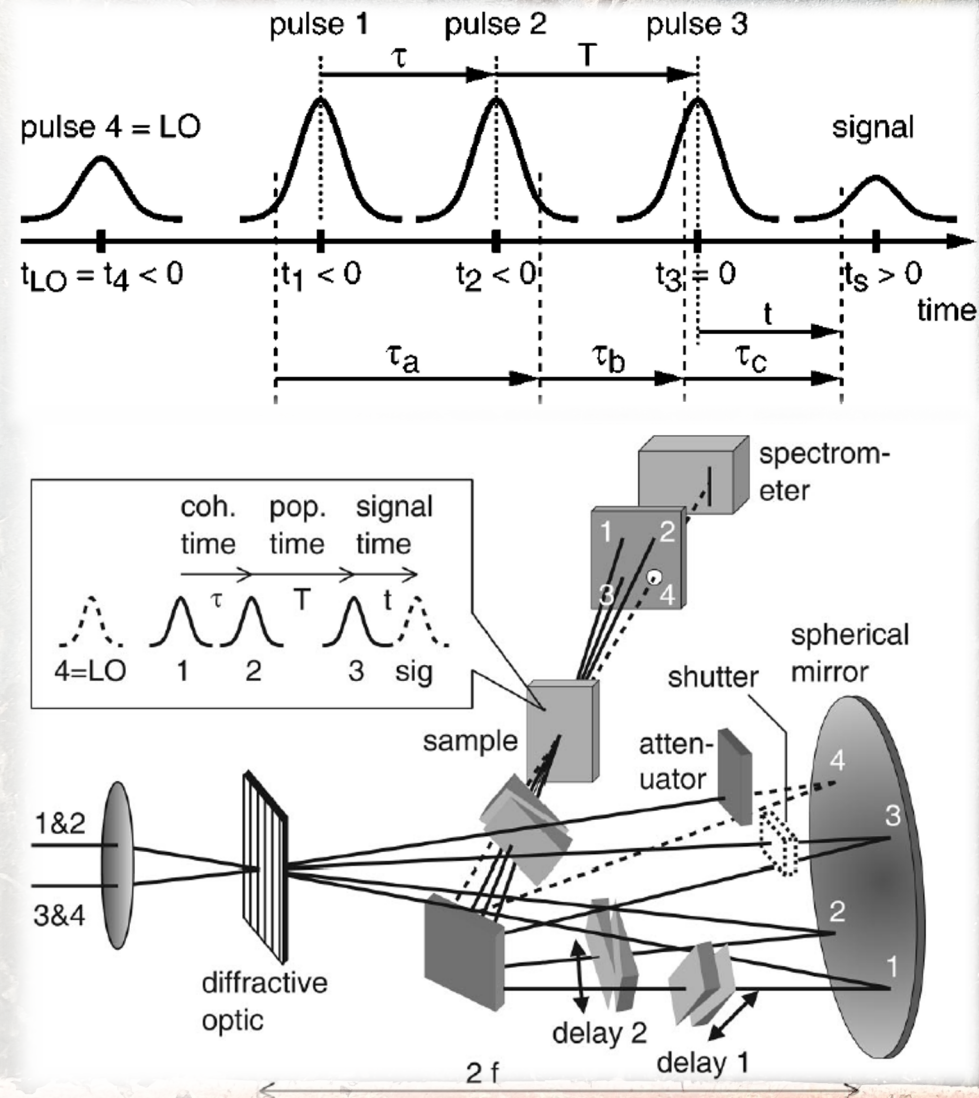


"Was the world wave function waiting to jump for thousand of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer for some highly qualified measurer, – with a Ph.D.?"

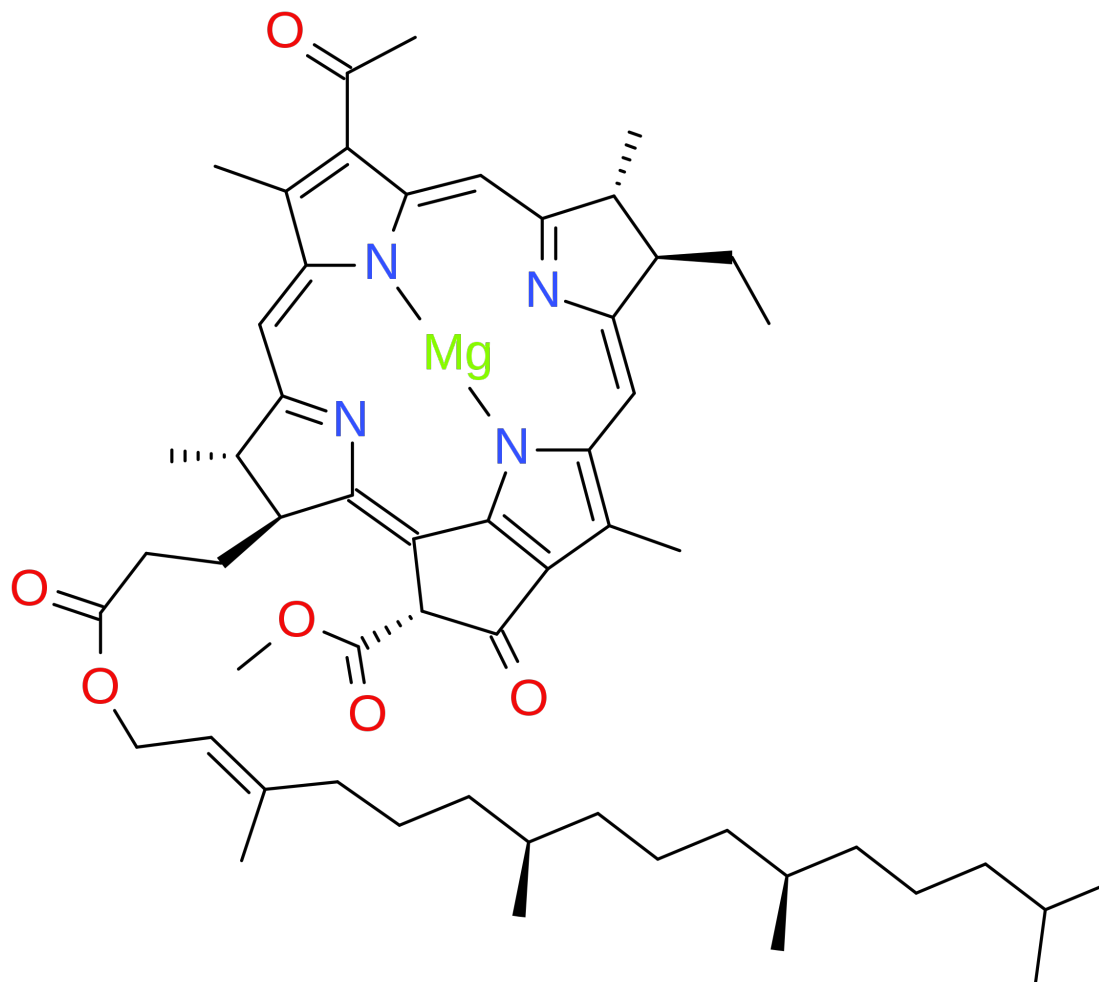
John Stewart Bell

How to investigate quantum-walk in photosynthetic complexes

- 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



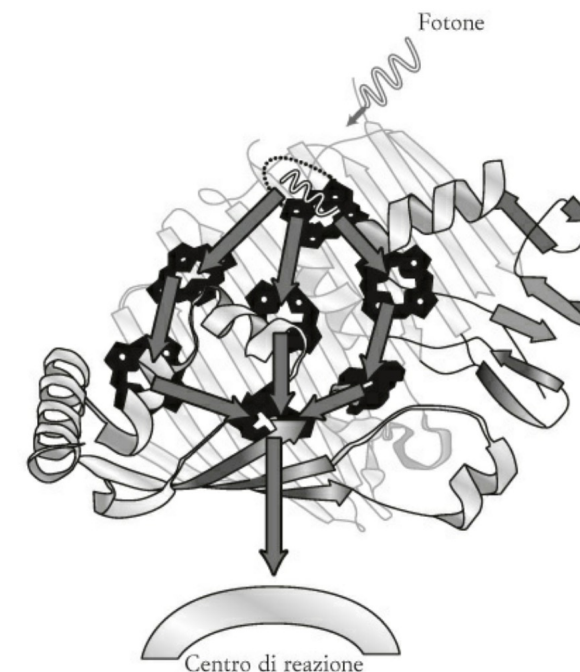
Battimenti quantistici

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*

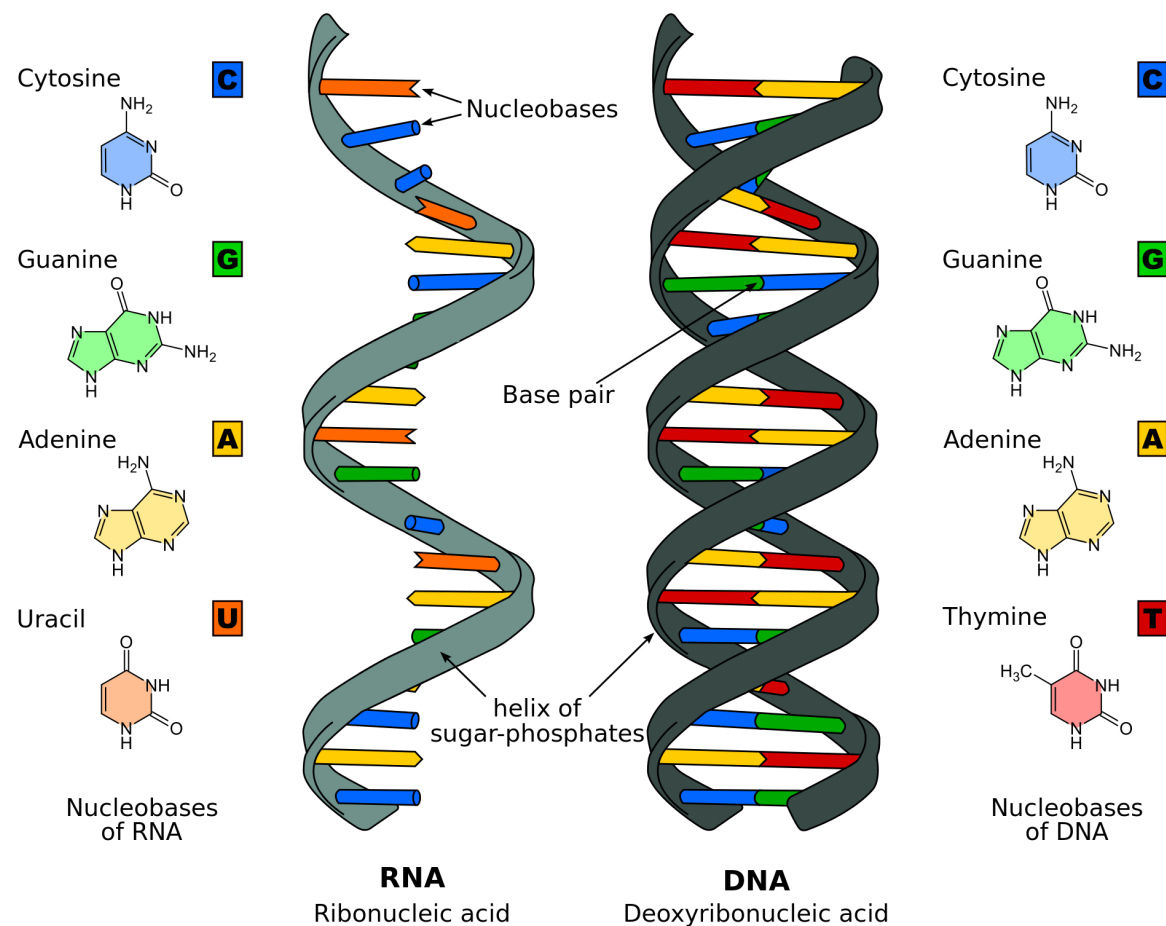
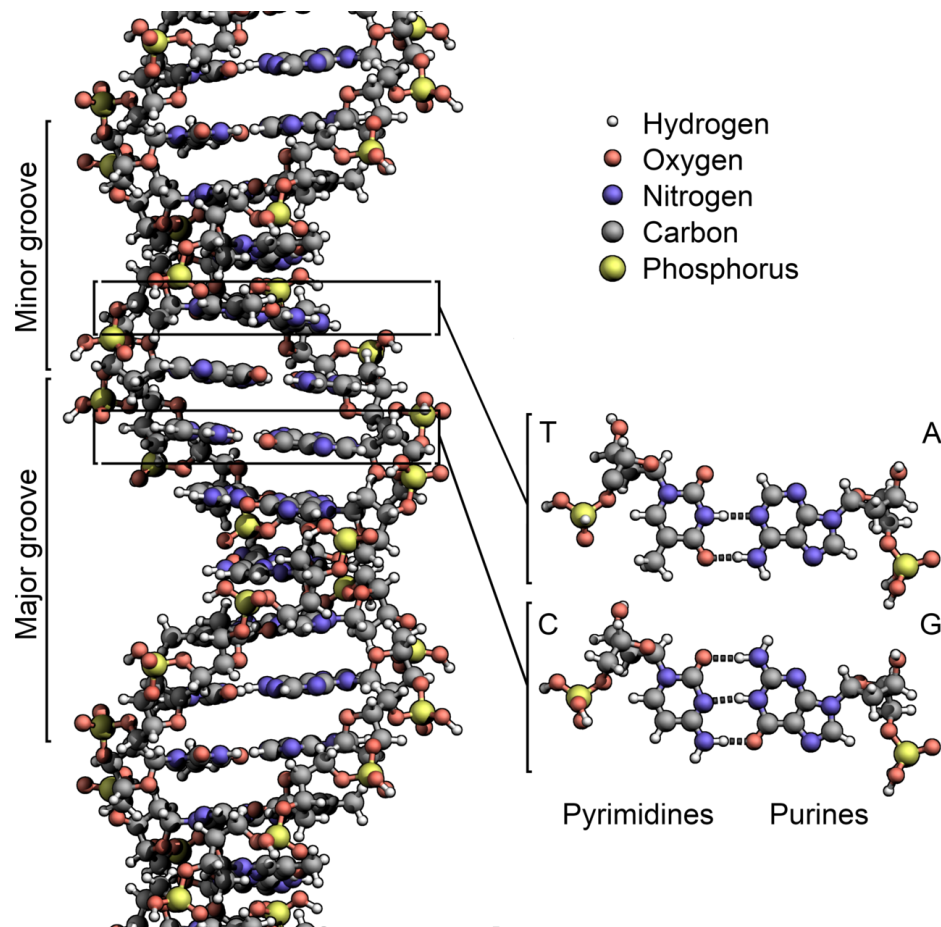
Complesso fotosintetico «Fenna-Matthews-Olson» (FMO) → microbi fotosintetici chiamati chlorobi, che si trovano nelle profondità di bacini ricchi di zolfo, come il Mar Nero.

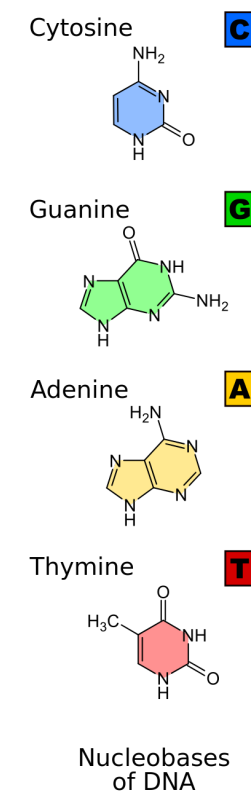
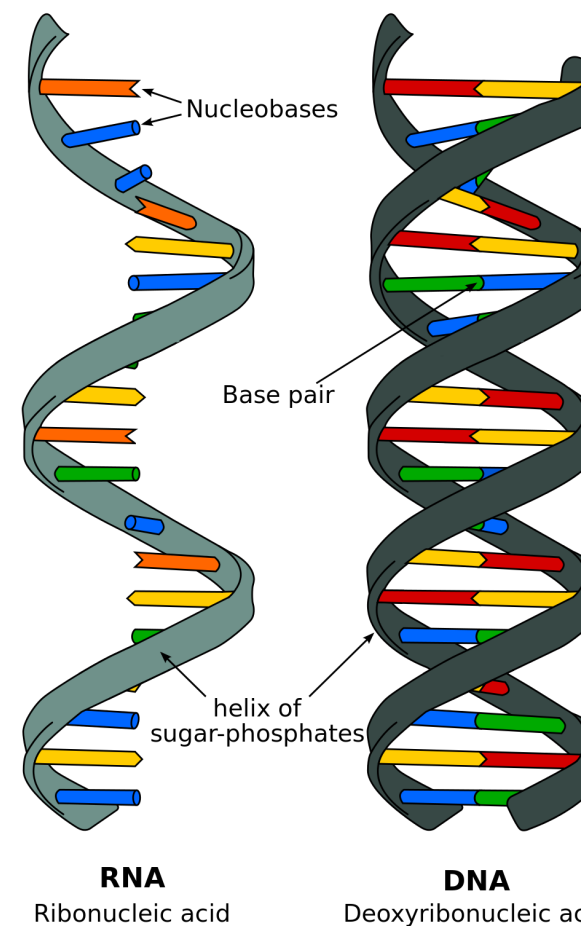
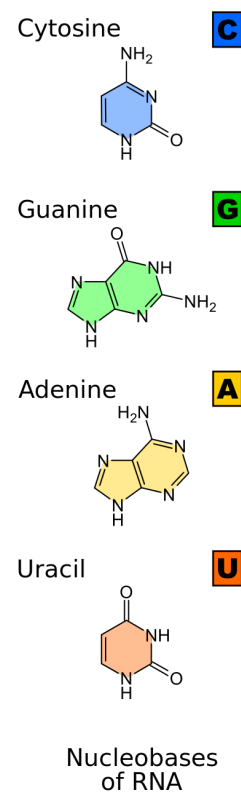
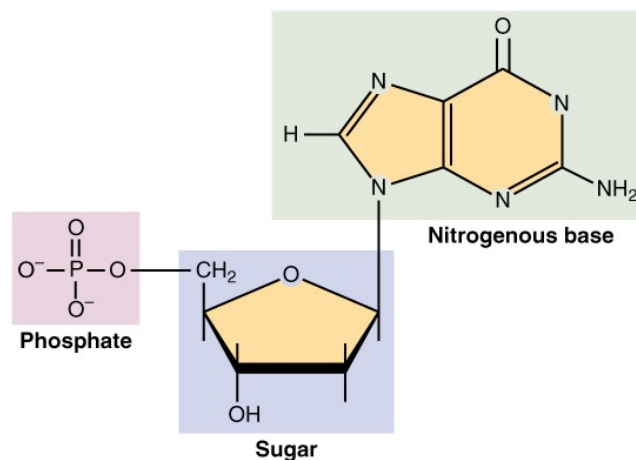
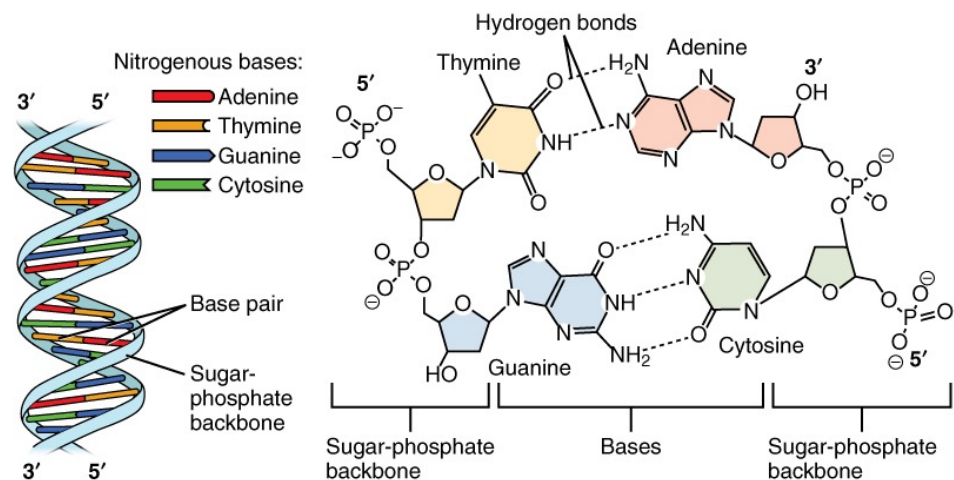
- Un laser deposita il segnale concentrato in picchi rapidi e perfettamente sincronizzati
- Si misura il segnale di luce prodotto dal campione
- *Questo permette di studiare come la luce si propaga nel sistema*



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.

Deoxyribonucleic acid







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.



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}

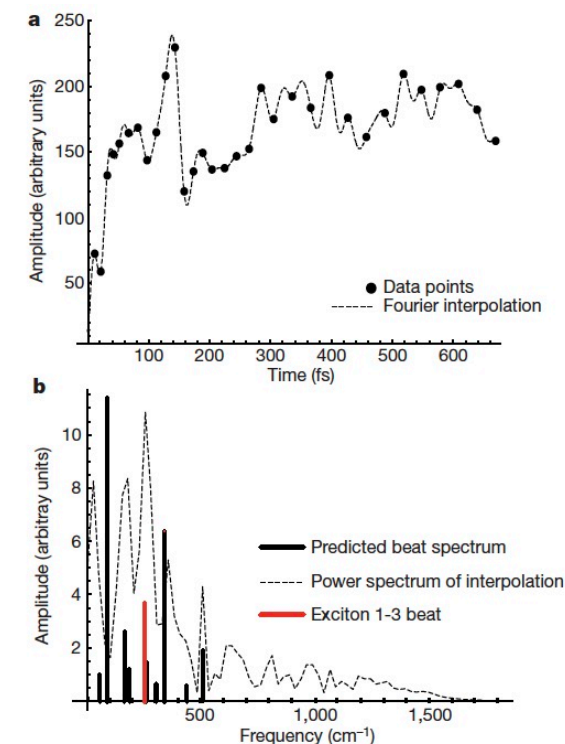
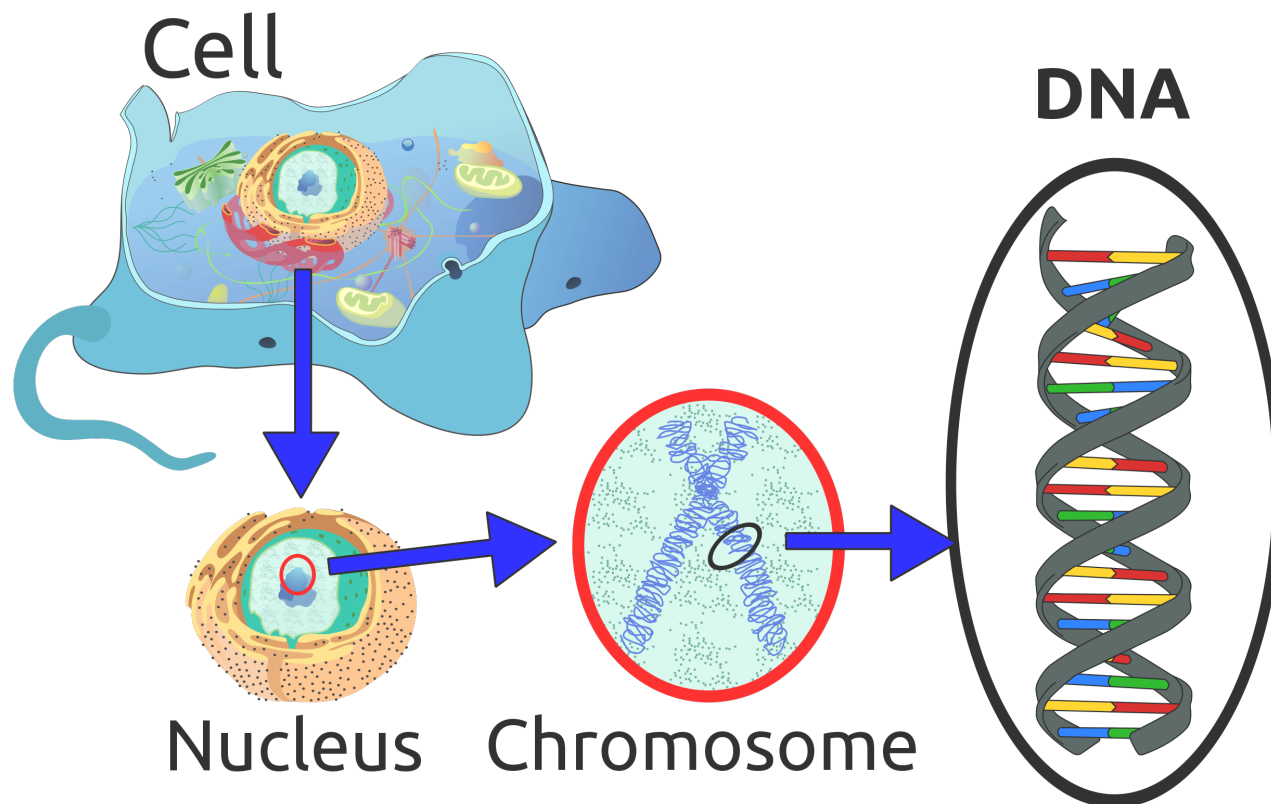
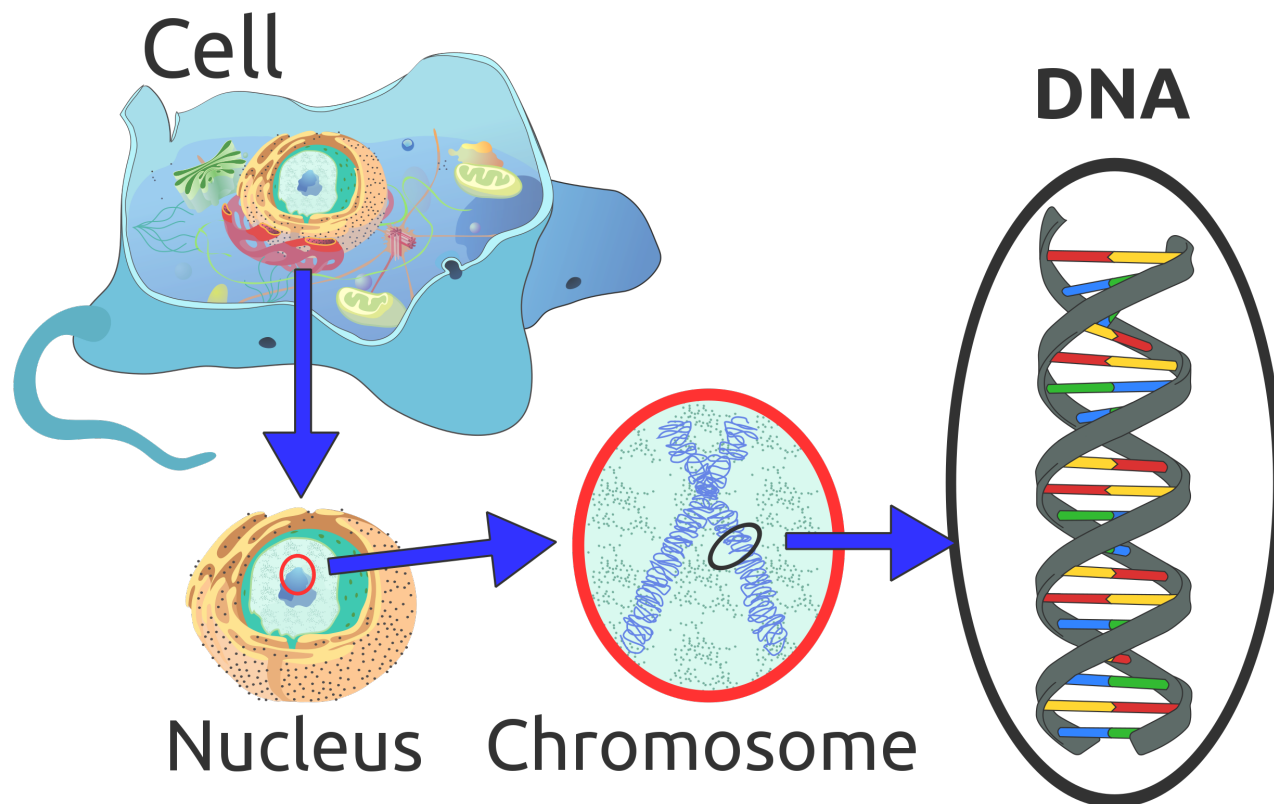


Figure 4 | Quantum beating in cross peaks. **a**, The raw amplitude of the exciton 1–3 cross-peak, with a Fourier interpolation of the points (dotted line). **b**, The power spectrum of this interpolation (dotted line), the exciton beating line spectra of both excitons 1 and 3 (black), and the 1–3 beat 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.

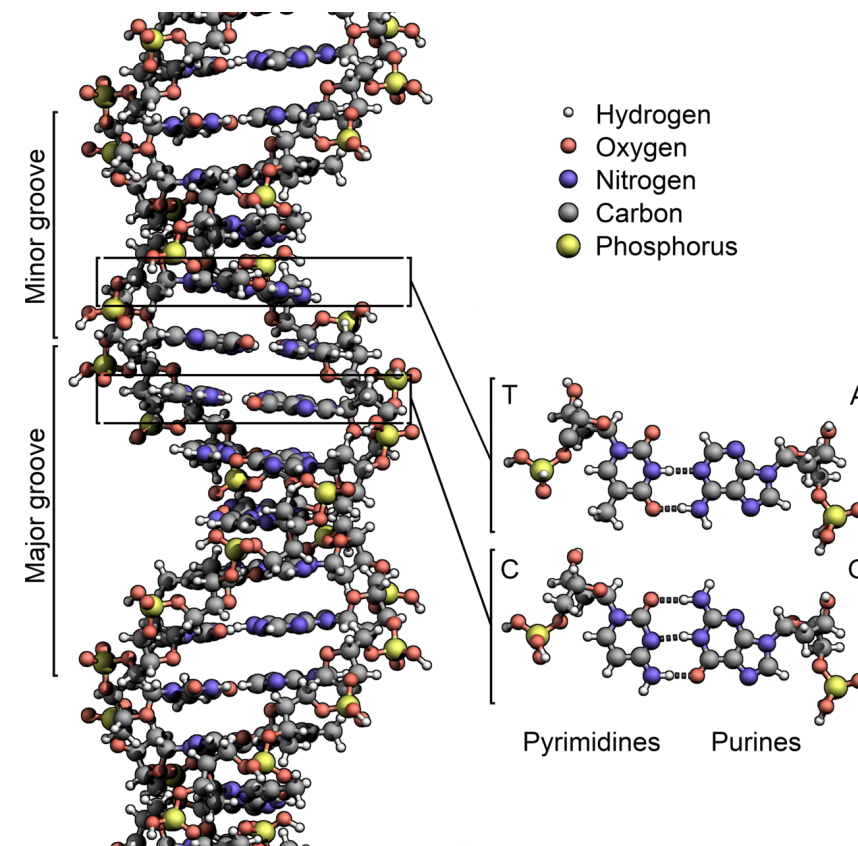
Coming back to life

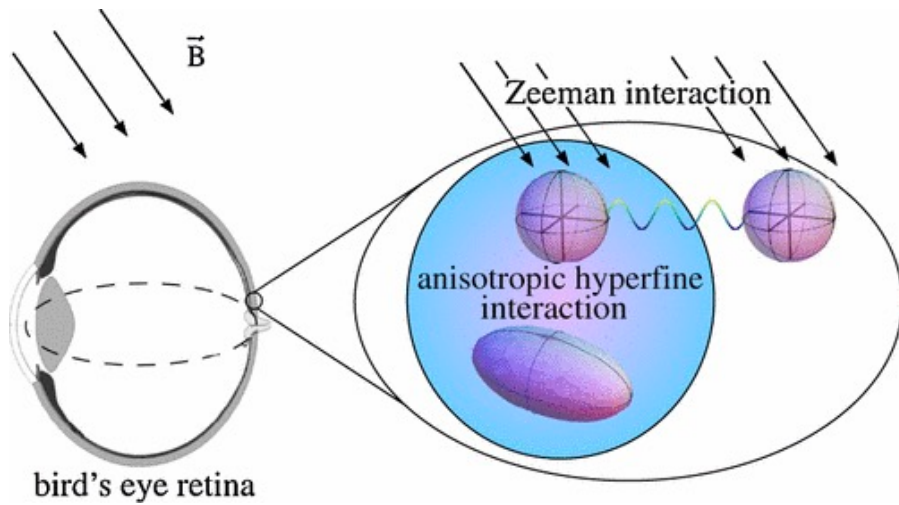


Coming back to life

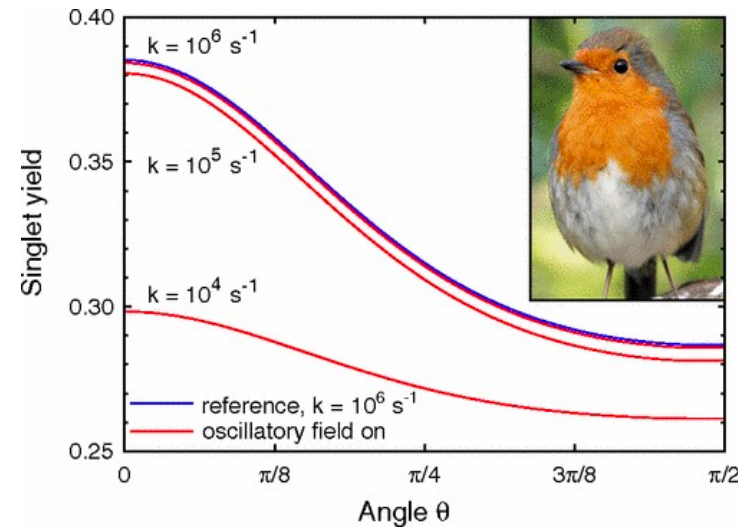


Deoxyribonucleic acid

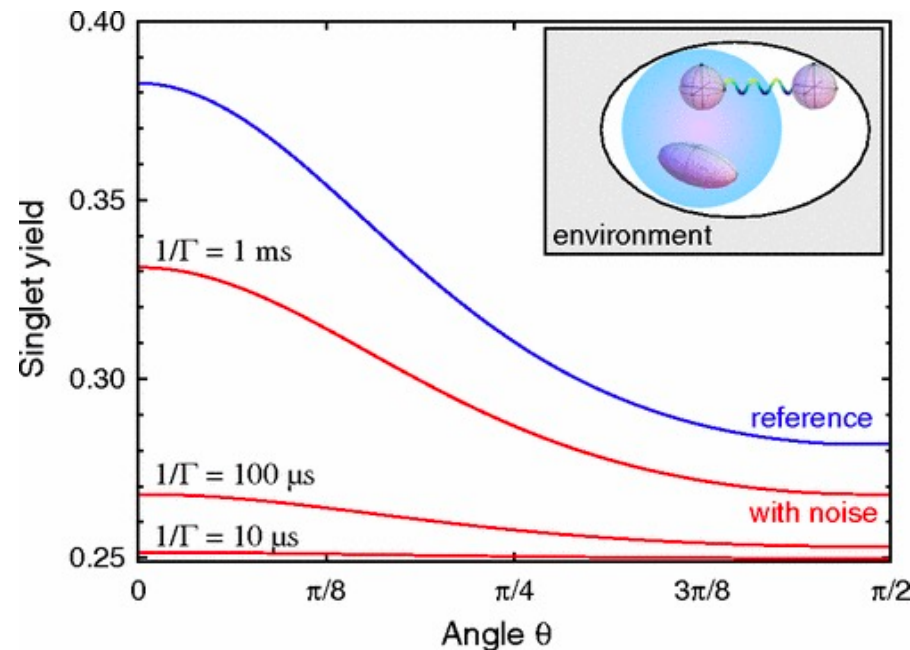




According to the RP model, the back of the bird's eye contains numerous molecules for magnetoreception [32]. These molecules give rise to a pattern, discernible to the bird, which indicates the orientation of the field. Note that this implies that the molecules involved are at least fixed in orientation, 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 an oscillatory field. The blue curve provides a reference of the singlet yield in Earth's magnetic field ($B_0 = 47 \mu\text{T}$). The reference is independent of the decay rate for $k \leq 10^7 \text{ s}^{-1}$, 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 10^4 s^{-1} .



Angular dependence of the singlet yield in the presence of noise (for $k = 10^4$). 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 $\Gamma > 0.1k$ has a dramatic effect on the magnitude and contrast of the singlet yield. Inset: The partitioning between compass and environment.