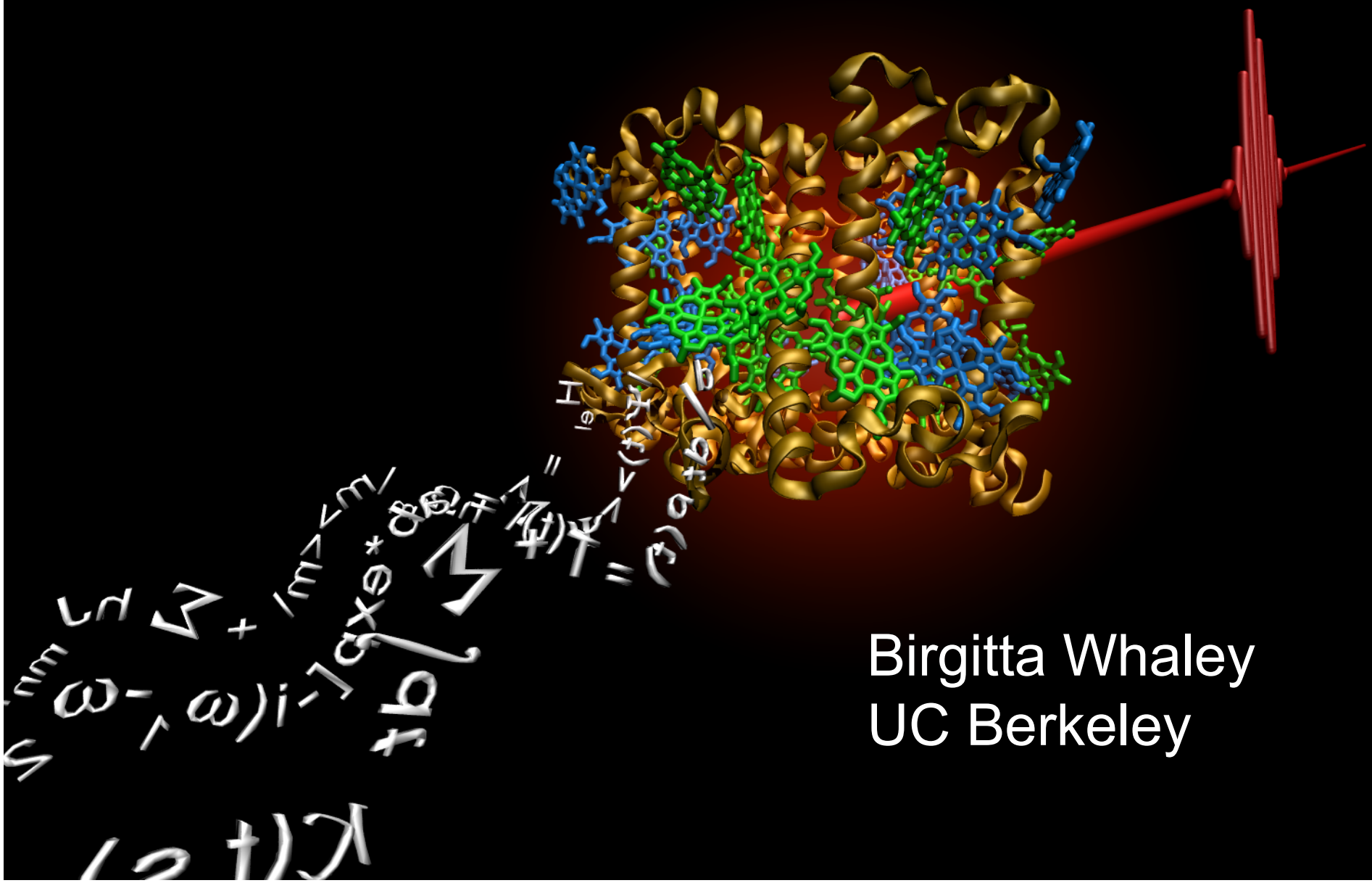
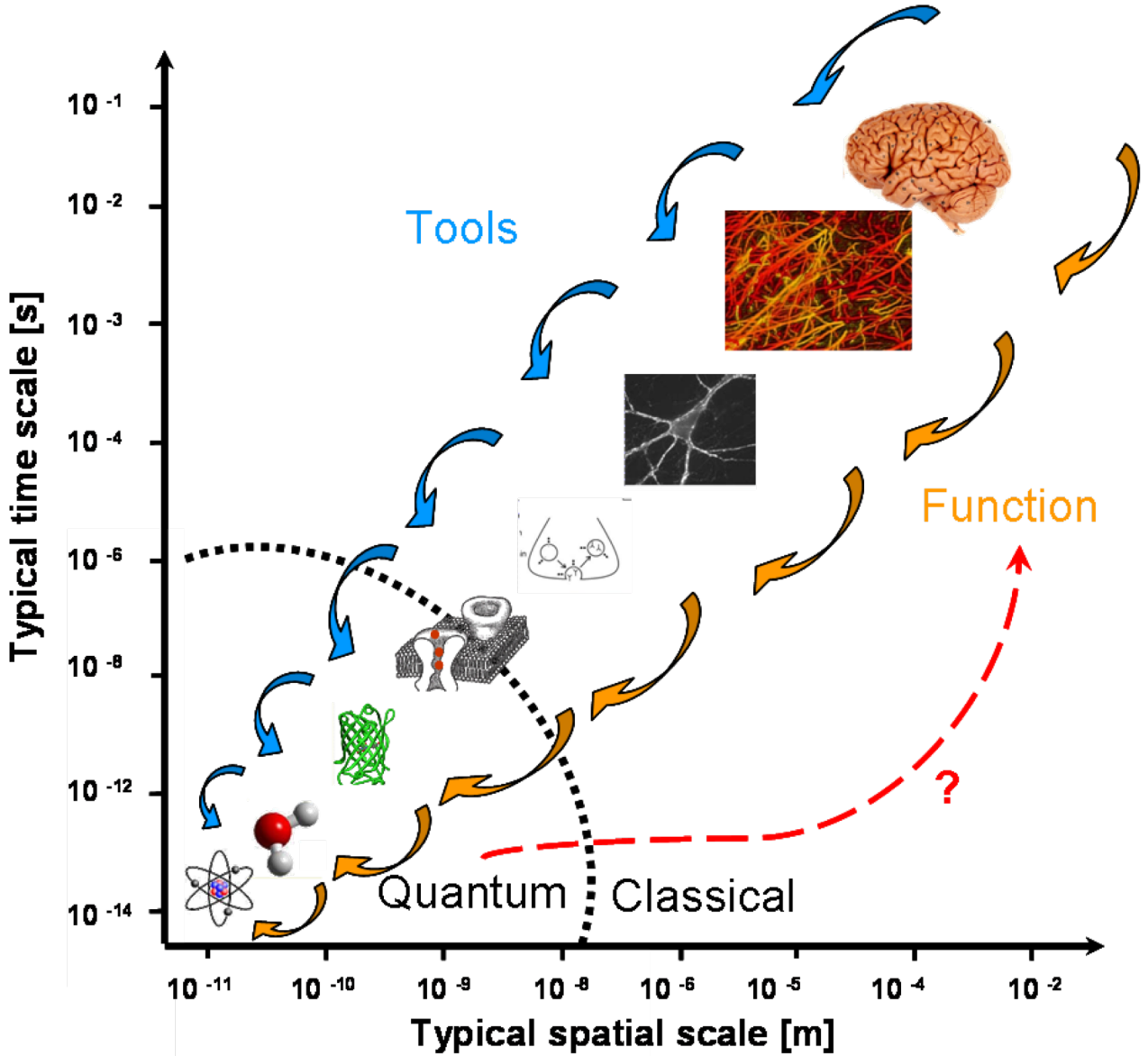
# The Renaissance of Quantum Biology



Birgitta Whaley
UC Berkeley

# Biological function across all time and size scales

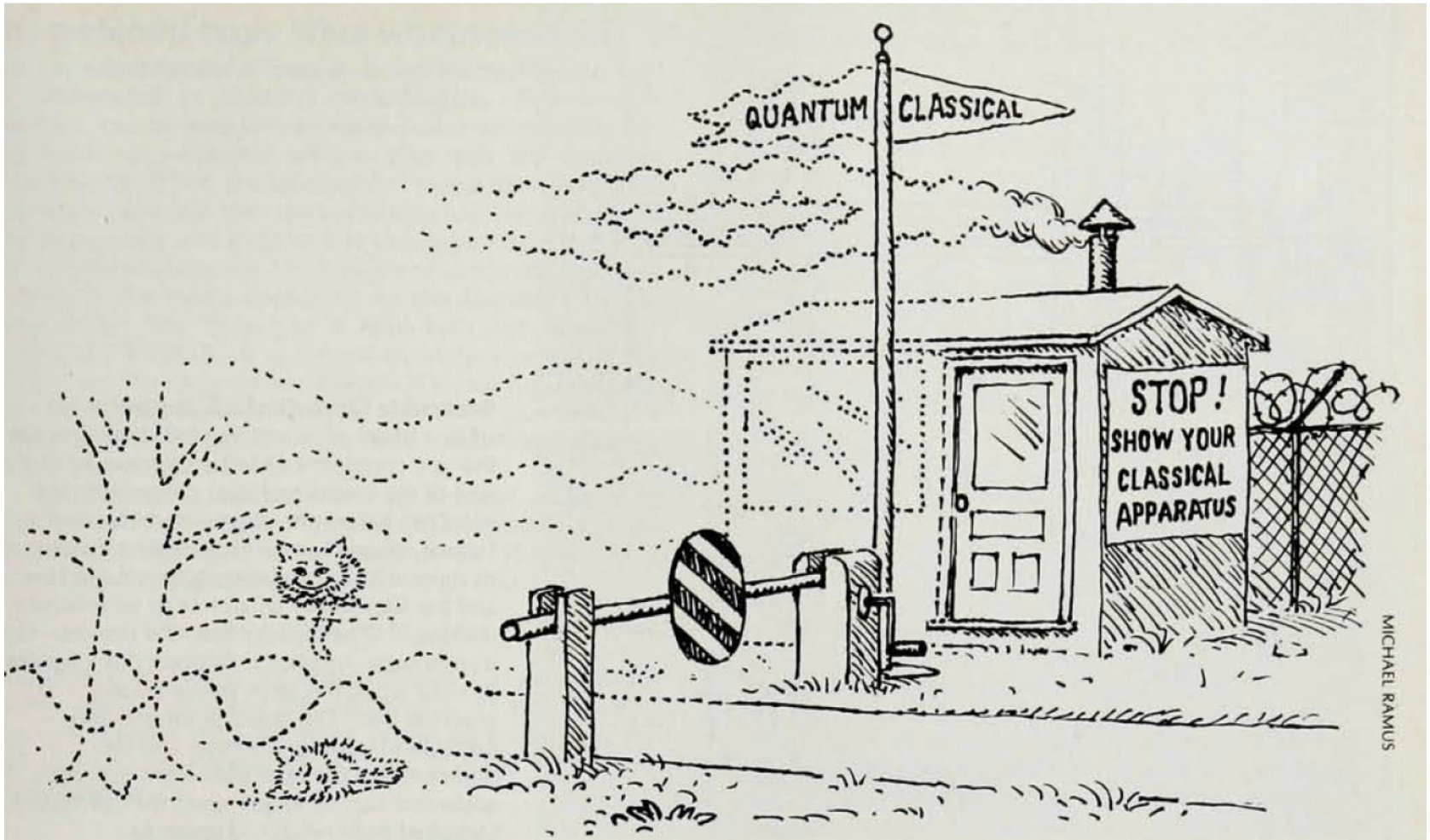



**Developing tools for studying biological structure and function at unprecedented spatial and temporal resolution**

**Can quantum coherence be relevant for biological function?**

A. Vaziri

# Quantum vs Classical ?




**Delineating the border** between the quantum realm ruled by the Schrödinger equation and the classical realm ruled by Newton's laws is one of the unresolved problems of physics.

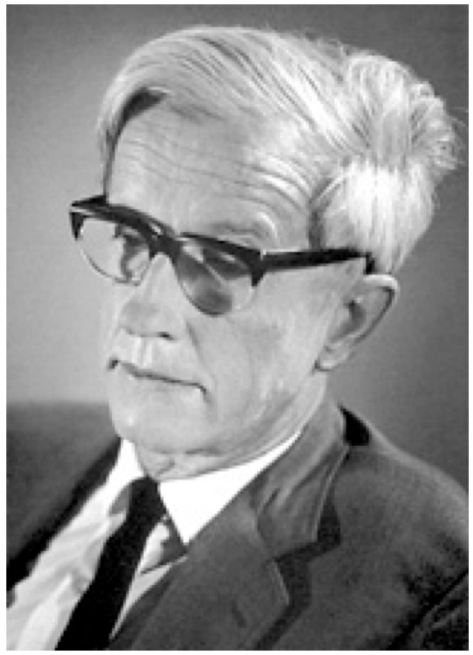
W. H. Zurek, Physics Today, Oct. 1991

# Quantum Biology has long roots:

- QM should apply to biology (life) Bohr, Jordan,… 1929 onwards
- 1935 N. Timofeev-Resovsky (genetics)
  K. Zimmer (photobiology)
  M. Delbrück (quantum physics)

probed genetic structure and mutations with X-rays

first quantum probe of biological structures and function, acknowledgement of need to understand detailed molecular structure of functional biological entities



# Chemical/Molecular Biology

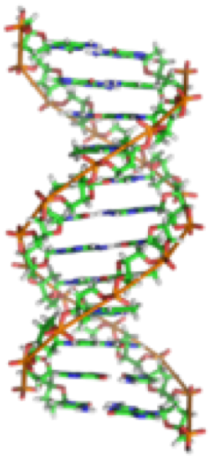
- molecules are quantum mechanical
  - energy levels, spin (fermi) statistics (essential!)
- chemical reaction rates
  - energy barriers understood in terms of quantum analysis of molecular structure
  - tunneling through these can contribute
- spectroscopy is quantum mechanical

all these features are manifest in biology

Schrödinger 1943 “What is Life: the physical aspect of the living cell”

- First Era: 1930 – 1950s (b.L.)

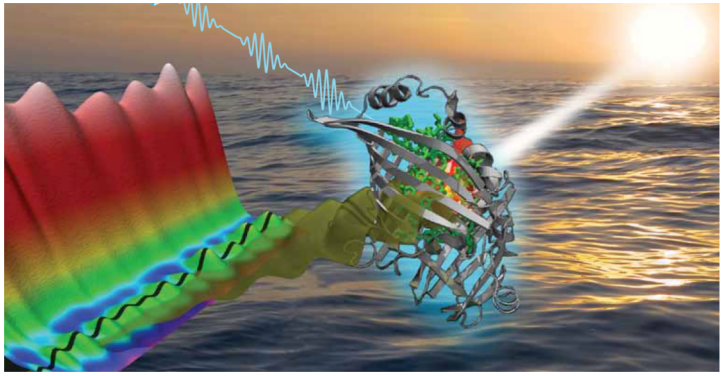
molecular structure and pathways, energetics, kinetics, stability – quantum nature of molecular energy levels, energy barriers... (Schrödinger *What is Life?* 1943)



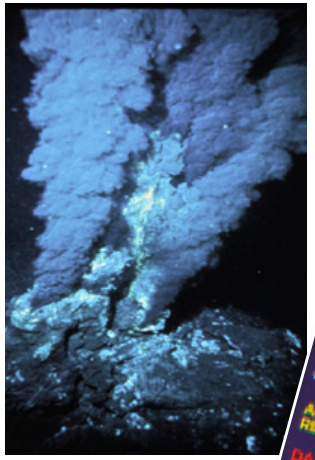
DNA 1953

- Second Era:1960s onward (a.L.)

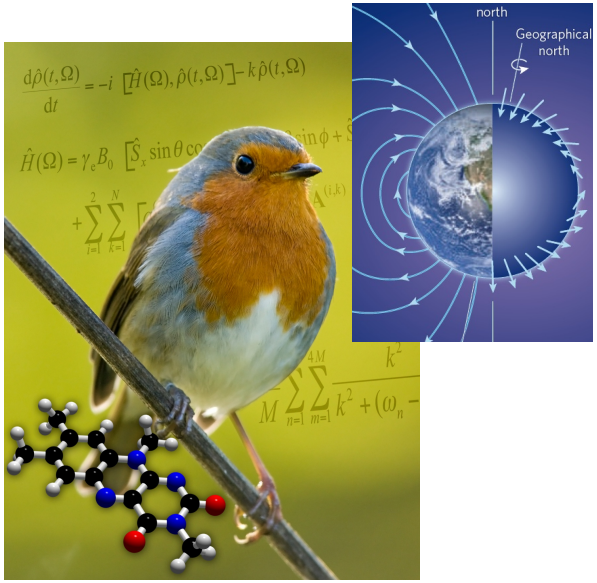
Quantum dynamical effects – new generations of dynamical probes, innovation via quantum science and technology...



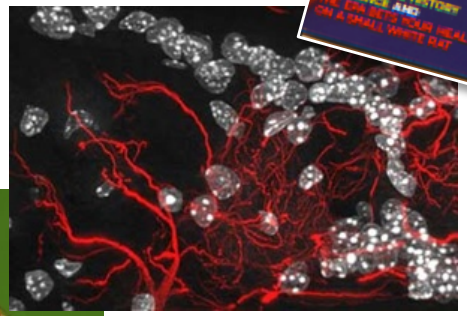
# Exploring the Quantum in Biology



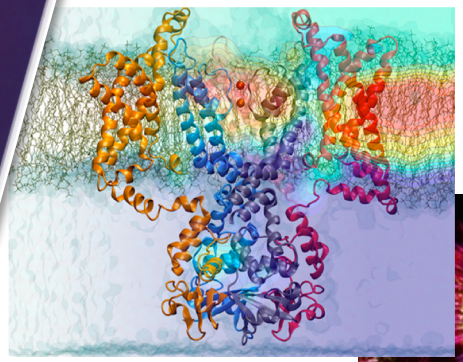
plants, bacteria:
photosynthesis


bird navigation

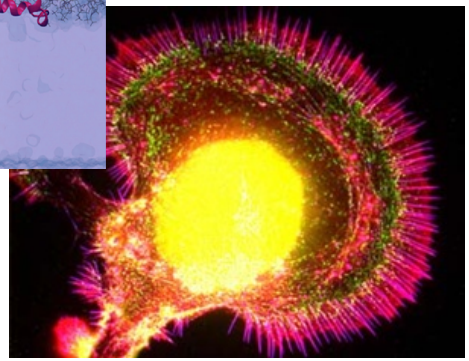


animal smell



ion channels

brain...

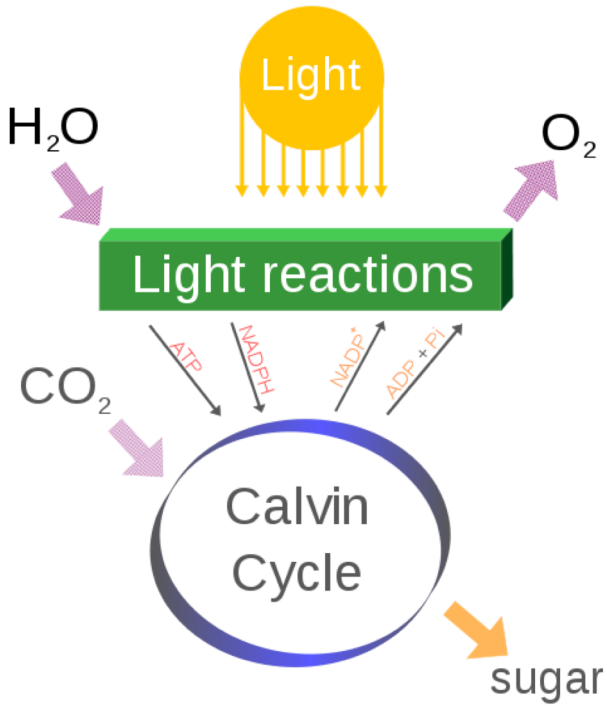


# Current research in quantum biology

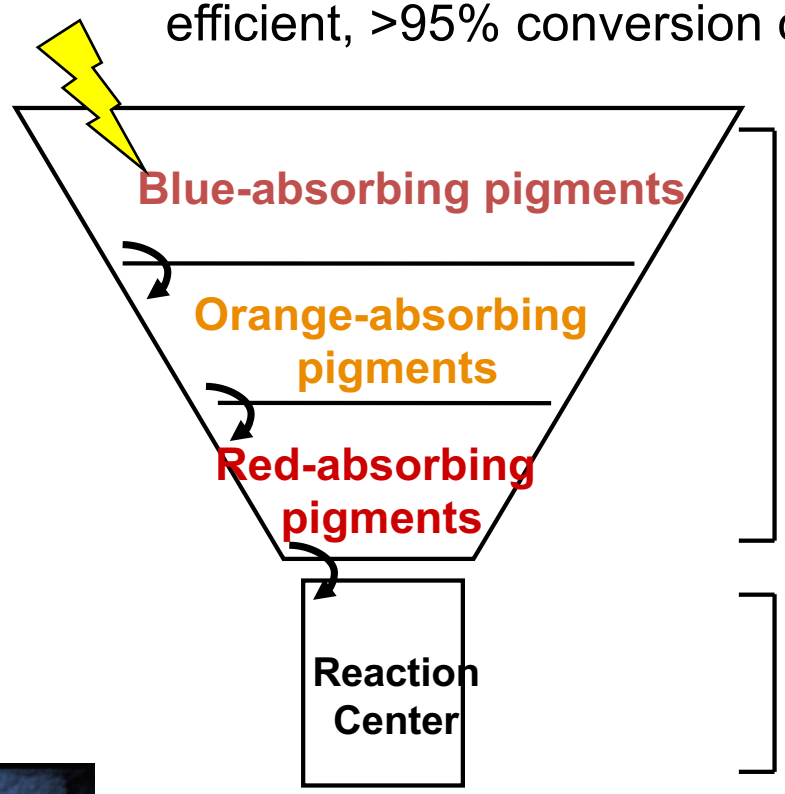
- photosynthesis
- magnetoreception – bird navigation
- vision
- olfaction
- brain – microtubules, synapses, ion channels, Posner molecules ($^{31}P$)

- relation of biophysics/chemistry to biological function?
- integrate microscopic, mesoscopic and behavioral studies…

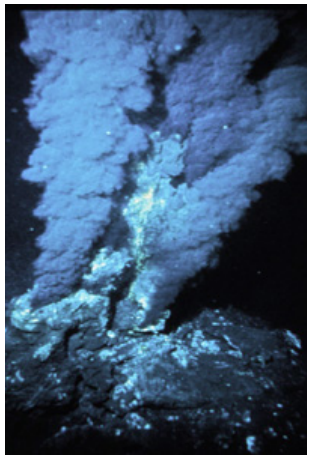
# Photosynthesis




The "light" reactions are rapid and very efficient, >95% conversion of photons



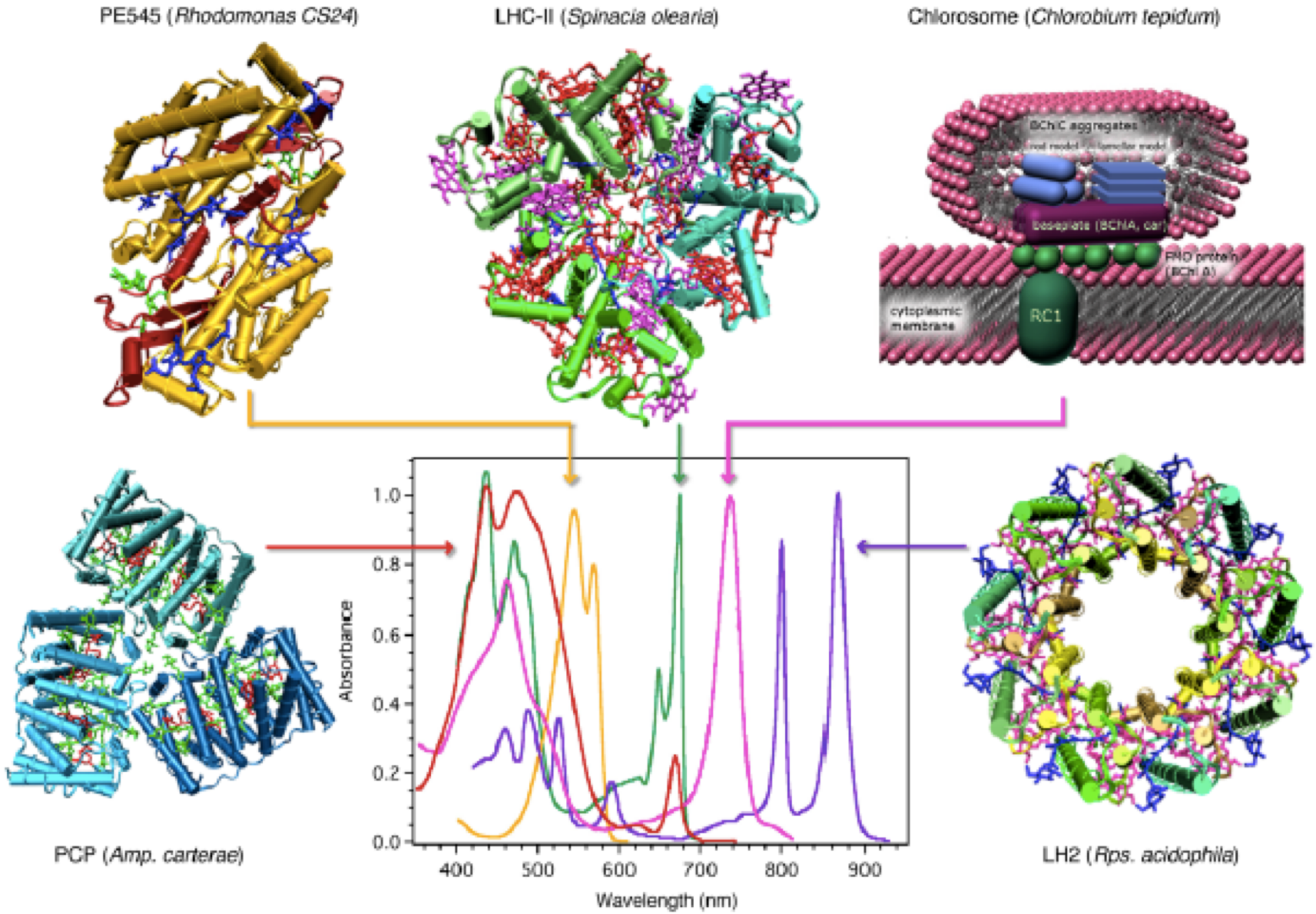

green plants



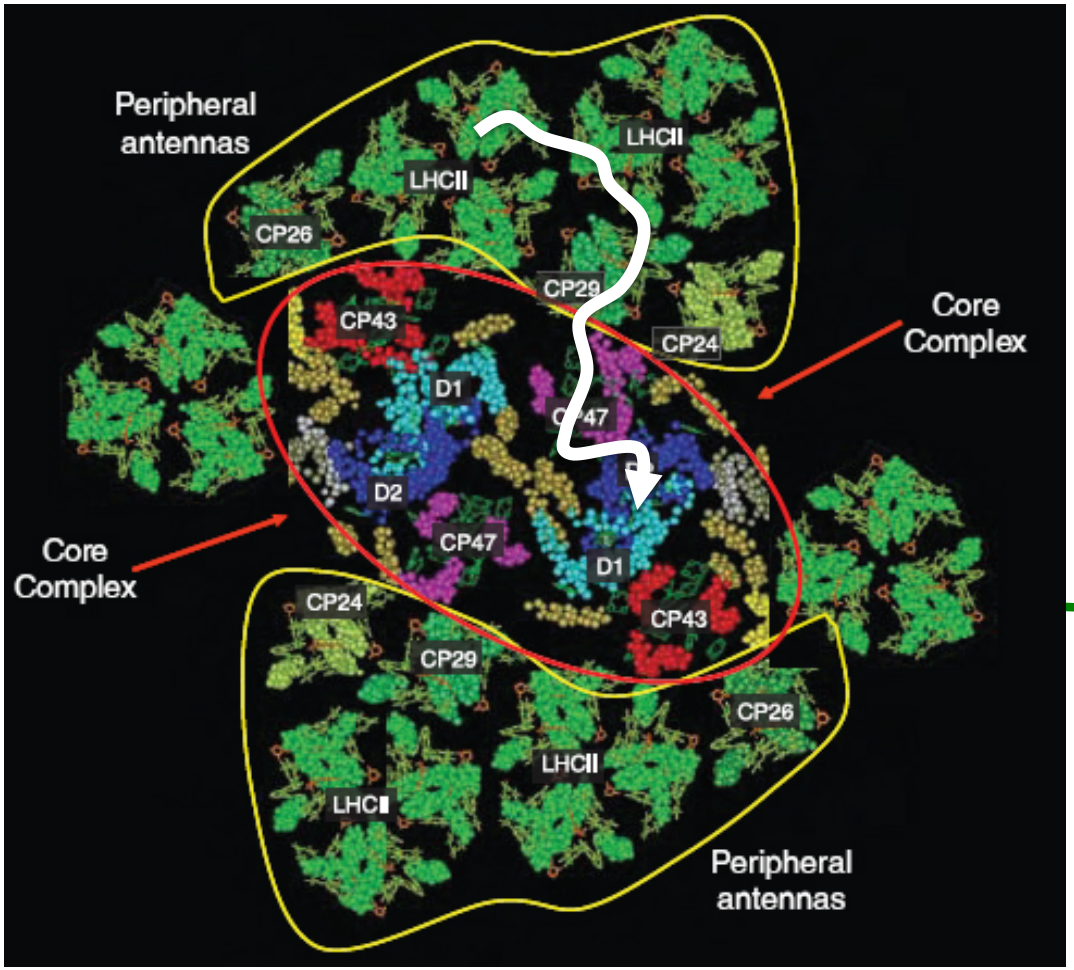
bacteria

…secondary electron transfer reactions, Water splitting, proton transport across thylakoid membrane, reduction of $NADP^+$, ATP synthesis…

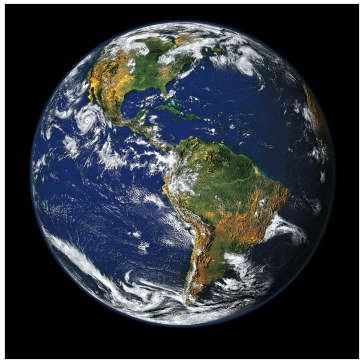
# Light harvesting complexes have diverse structures



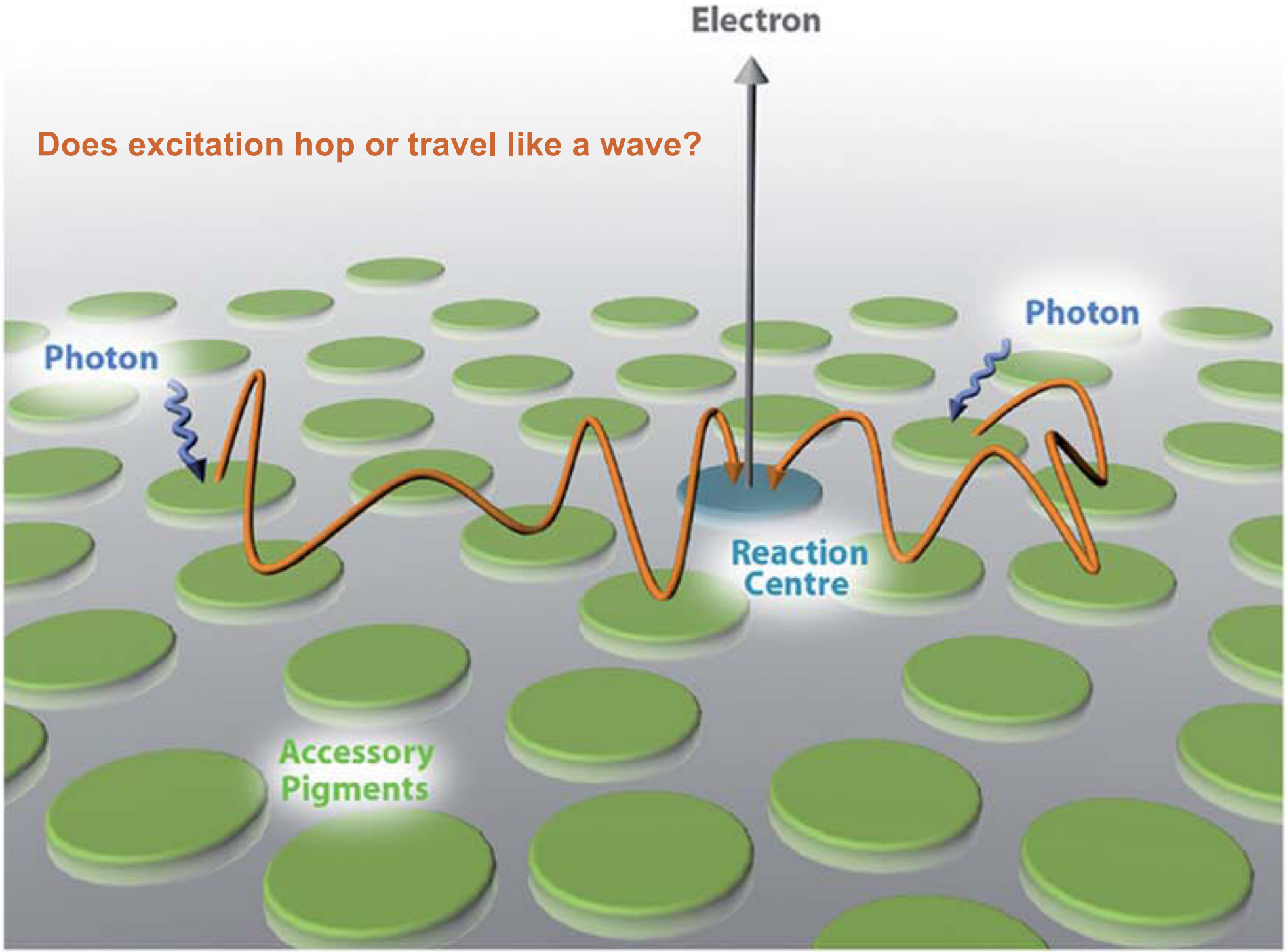
# Quantum Coherent Effects in Photosynthesis
# (the greening of quantum information)




Photosystem II super-complex
(figure courtesy of Roberto Bassi)



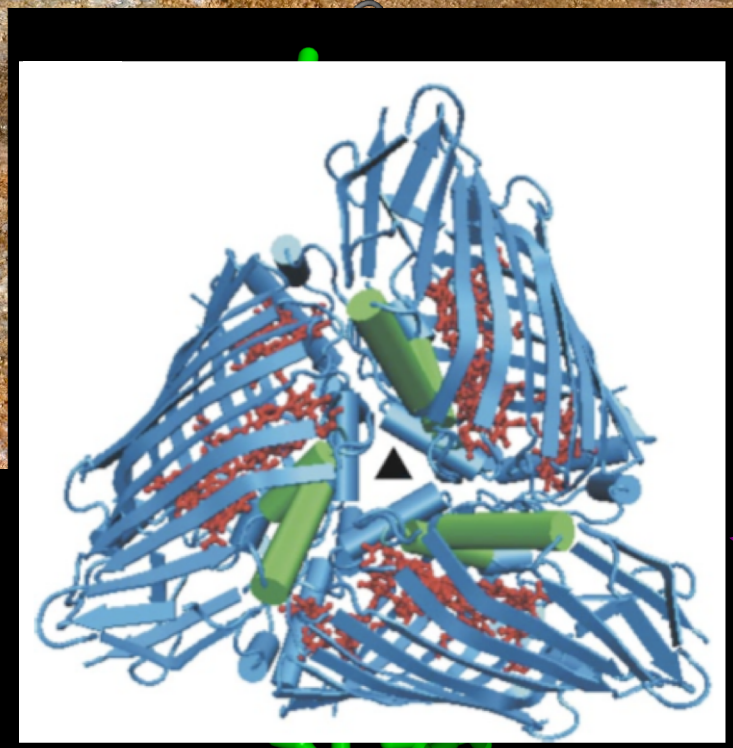
50% of green matter on earth uses PSII


Does excitation hop or travel like a wave?
Electron
Photon
Photon
Reaction Centre
Accessory Pigments

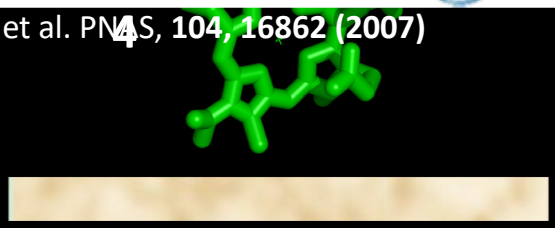
# Light harvesting apparatus of green sulfur bacteria

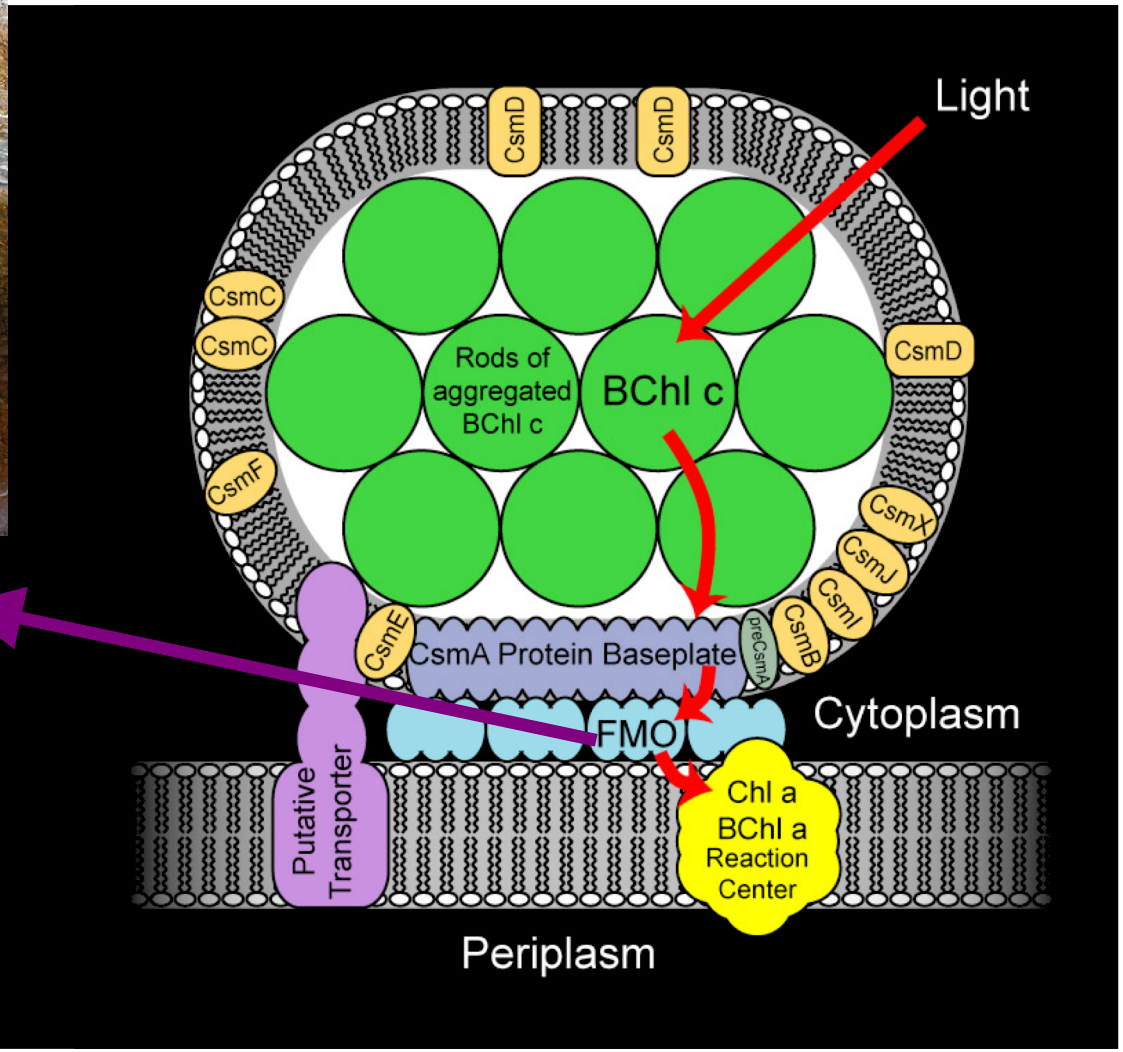
FMO: energy 'wire' connecting chlorosome to reaction center

well characterized system



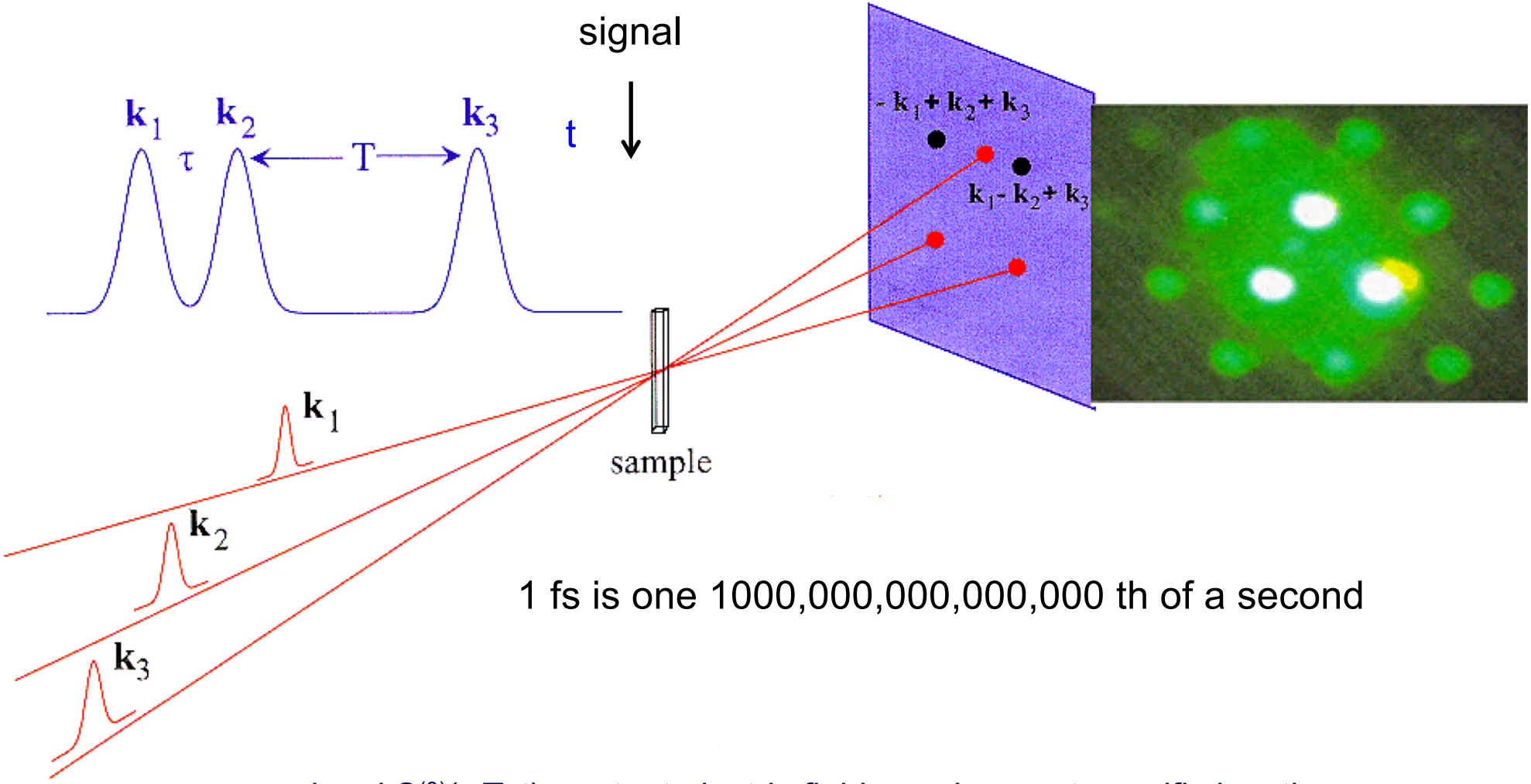
Muh et al. PNAS, **104, 16862 (2007)**






James Allen *et al.*, Photosynth. Res., **75**, 49 (2003)

# 2D Femtosecond spectroscopy

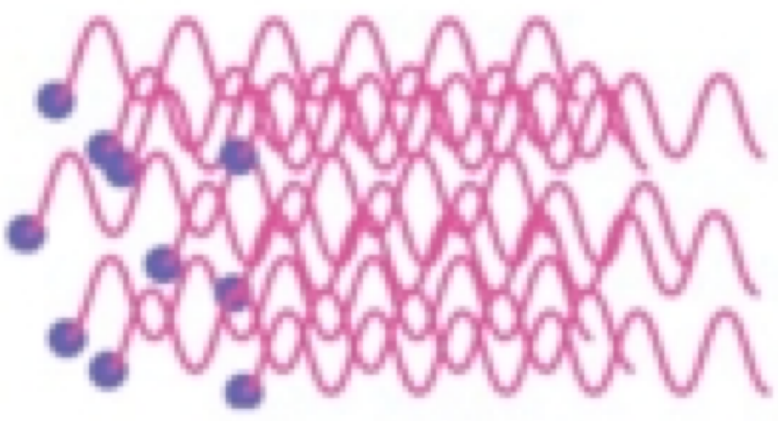



1 fs is one 1000,000,000,000,000 th of a second

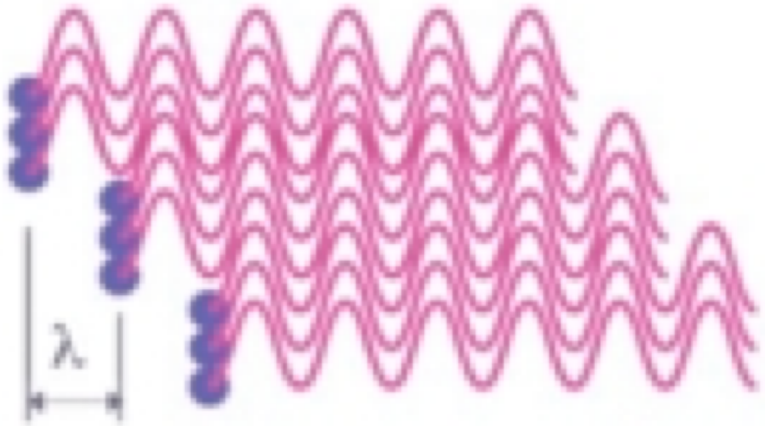
- signal $S^{(3)}(\tau,T,t)$ - output electric field, maximum at specific locations
- retrieves correlation between **absorption** and **emission** energies as a function of the time T when the light harvesting system is in excited state

# What is coherence?

All together now!
Pedalling in step

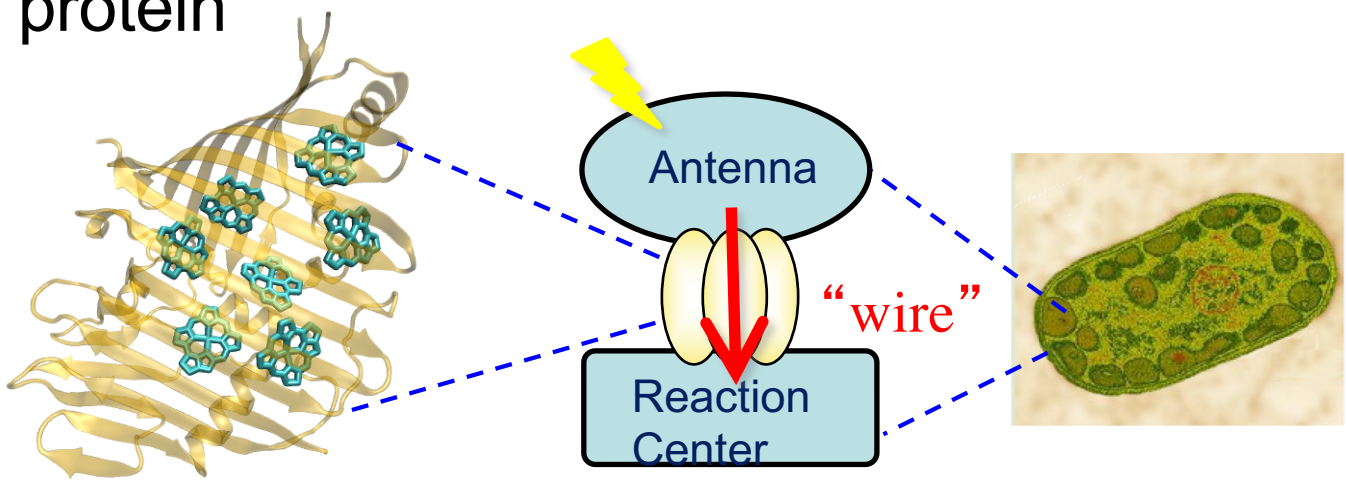


Incoherent waves

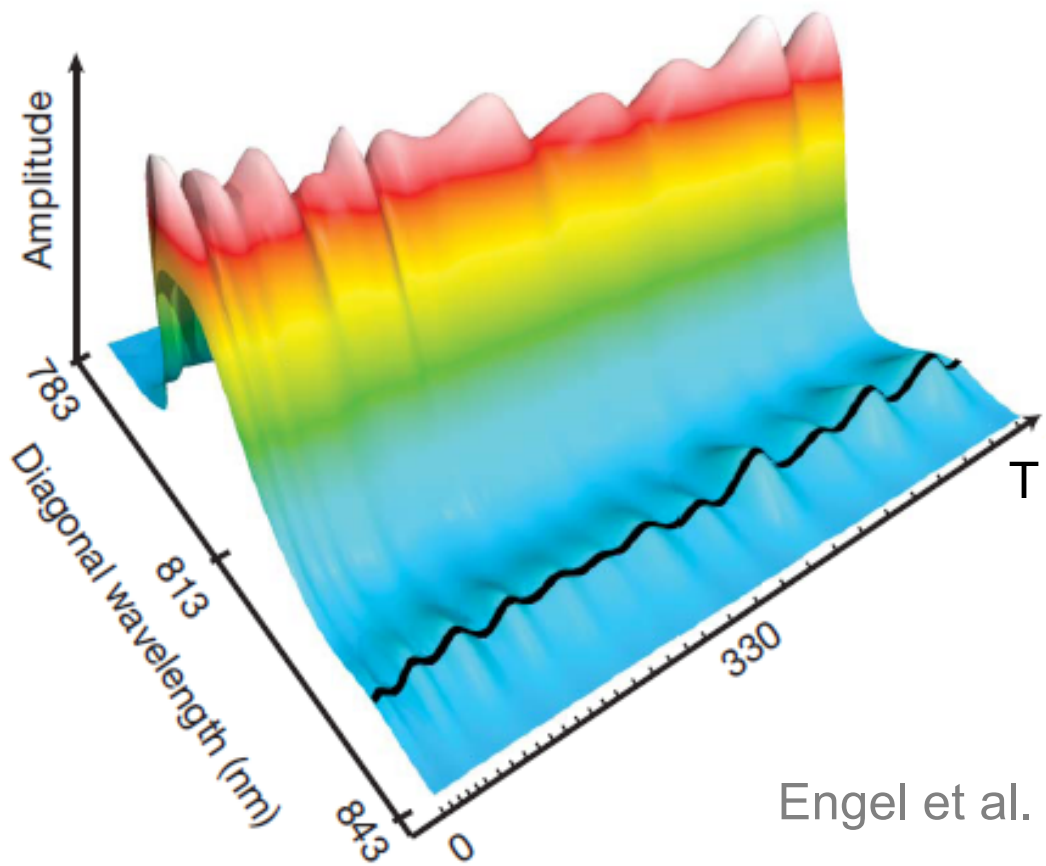



Coherent waves

# FMO protein




Photosynthetic Green Bacteria




T in femtoseconds

Engel et al. Nature 446, 782 (2007)

# Is photosynthesis performing a quantum search?

"…the system is essentially performing a single quantum computation, sensing many states simultaneously and selecting the correct answer... In the presence of quantum coherence transfer, such an operation is analogous to Grover's algorithm…"

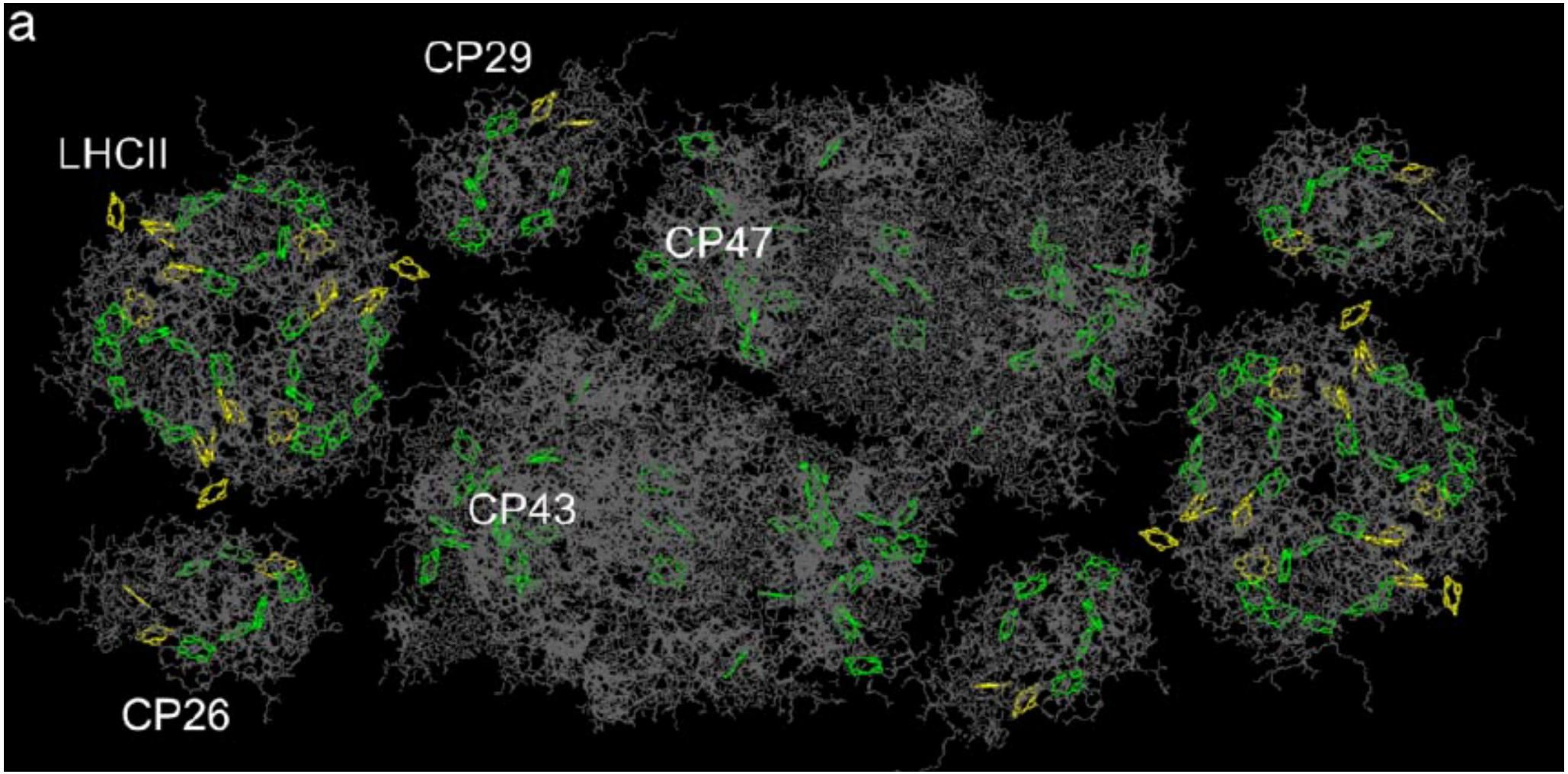
Engel *et al.*, Nature **446**, 782 (2007)


When It Comes to Photosynthesis, Computation

The wavelike motion of energetic particles through photosynthetic systems enables plants energy

Scientific American, April, 2007

# Photosystem II – green plants




green = chromophores
grey = protein

**vibrational motion of atoms suppress coherence**
**no quantum computation**

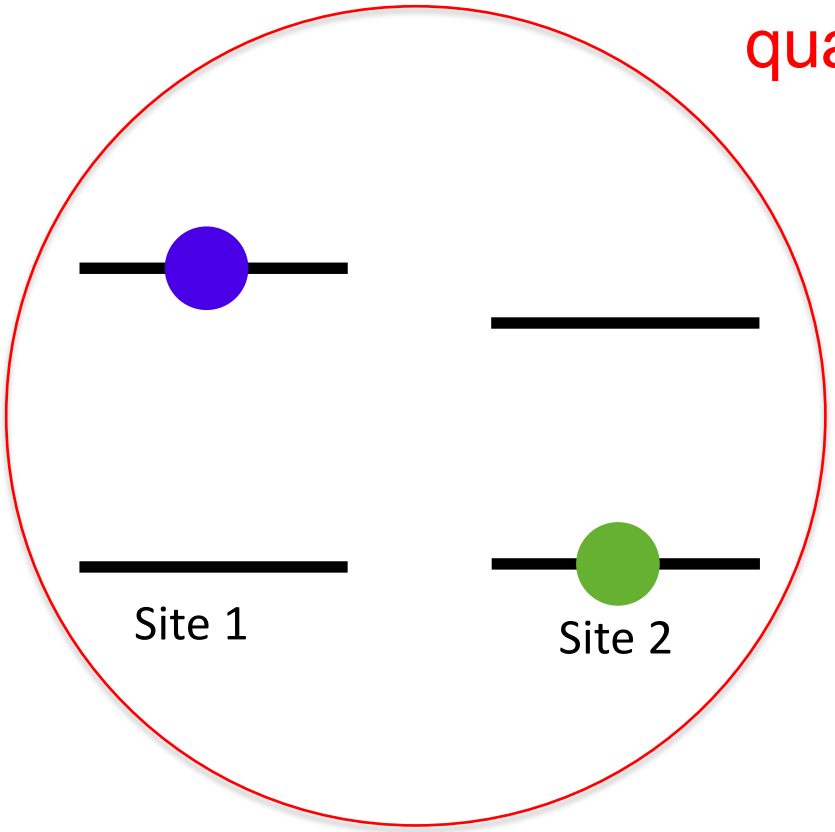
Hoyer et al NJP 12, 065041 (2010)

# Quantum entanglement in light harvesting?

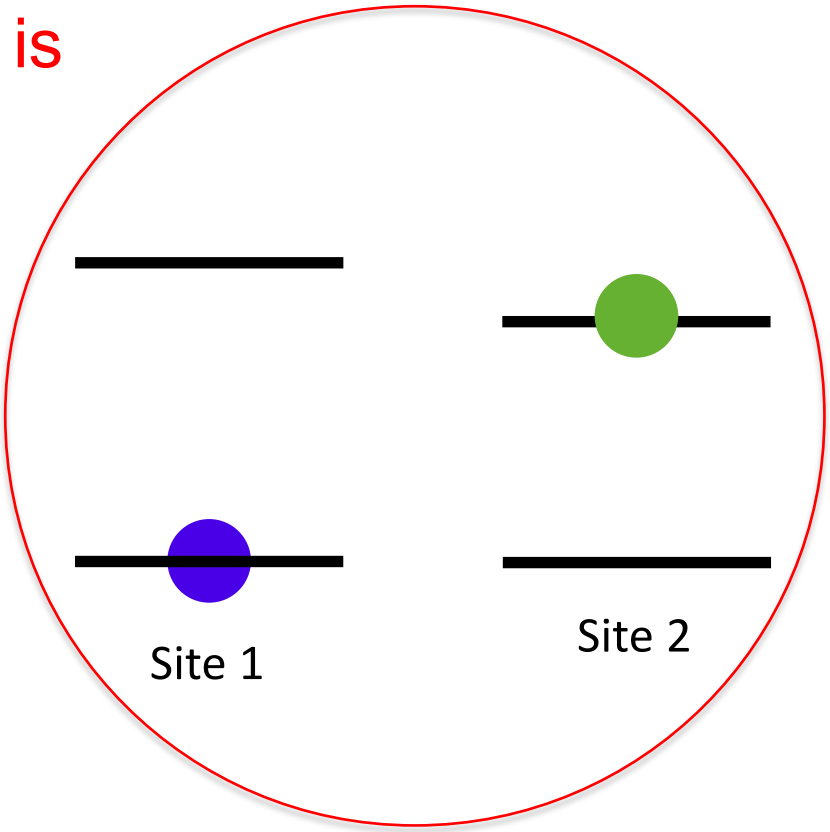
Sarovar et al ,Nat Phys 6, 462 (2010)

Quantum correlations between electronic states at distant sites:

quantum state is



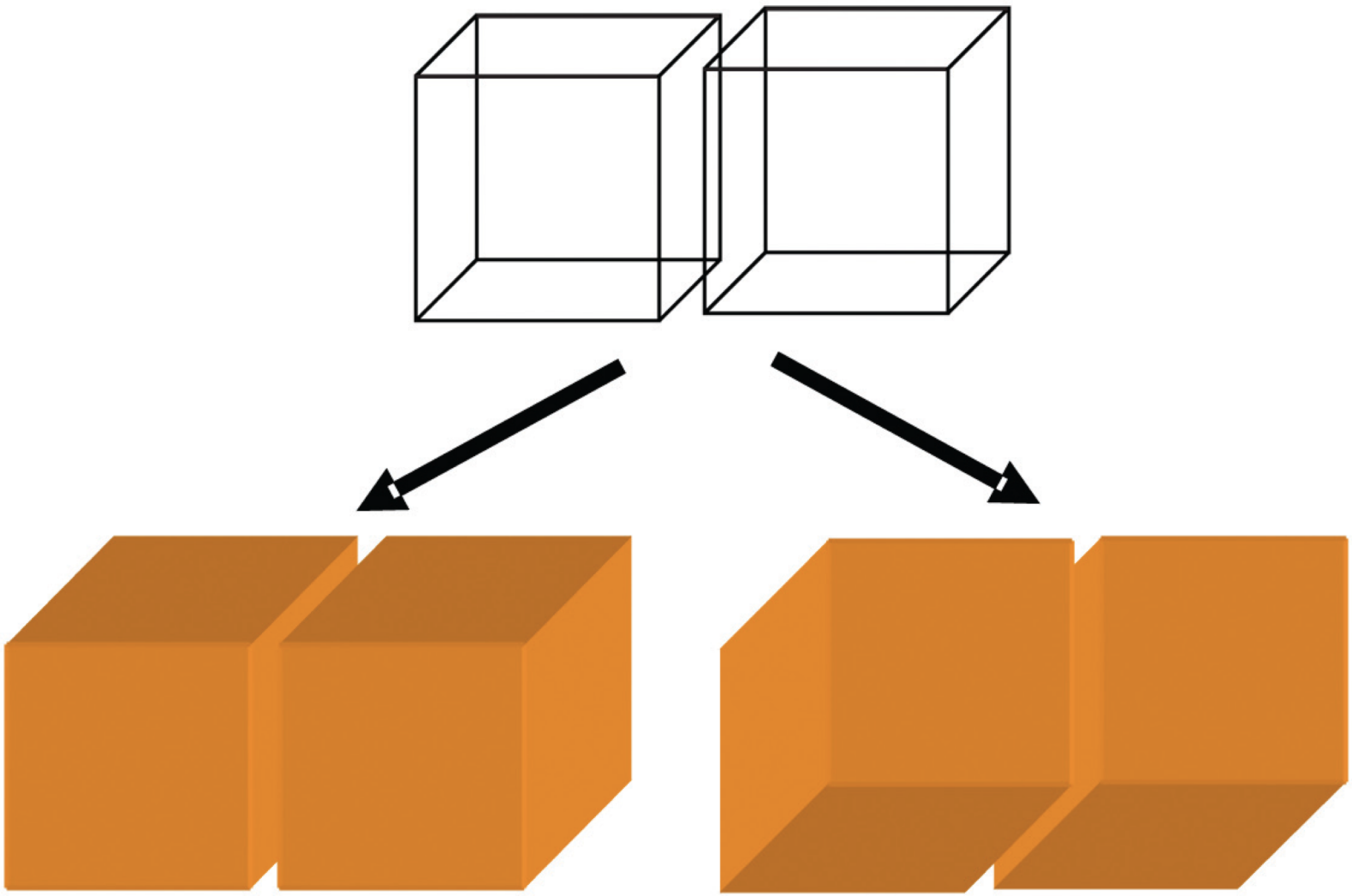

and




Open question: biological function or evolutionary role ??

# Entanglement analog with ambiguous cube:

perceive orientational correlations between boxes

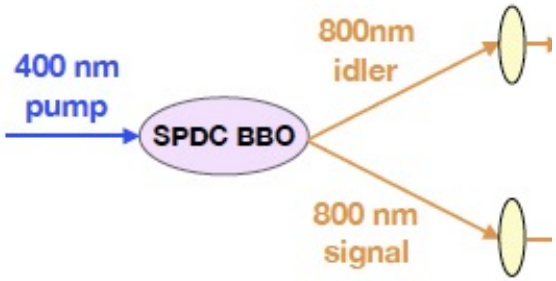


# Quantum efficiency?

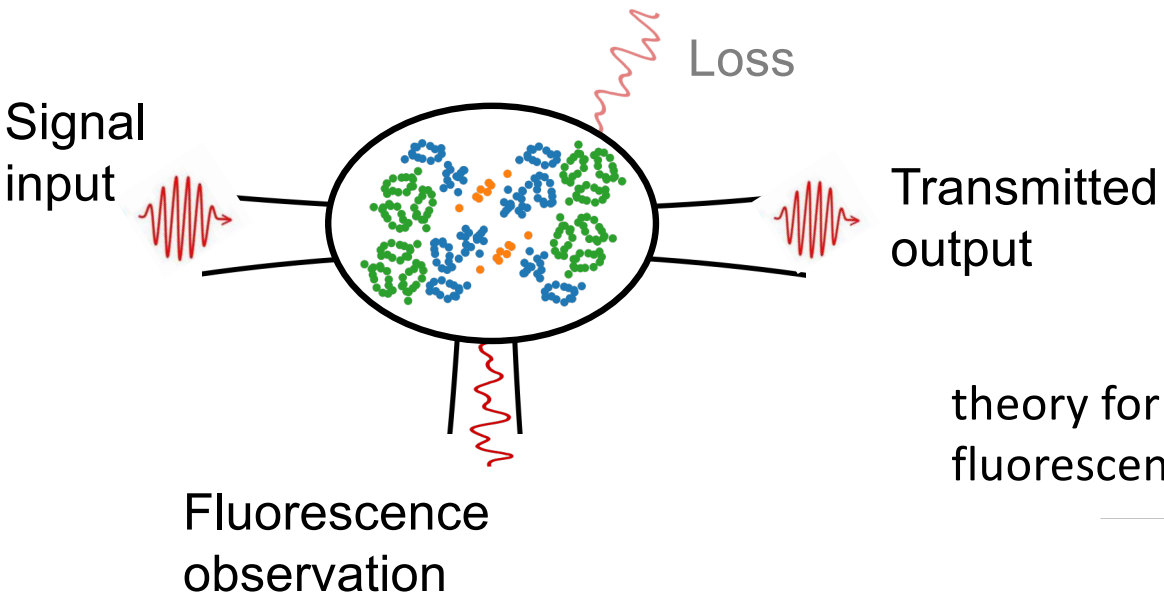
- Unusually high for biological process, ~ 95-98 %
- so 1 photon is transduced to 1 electron-hole pair
- but measurements are highly averaged over macroscopic samples


?? what is the mechanism and timescale for absorption of **1 photon** from sunlight ??

# New Quantum Tools

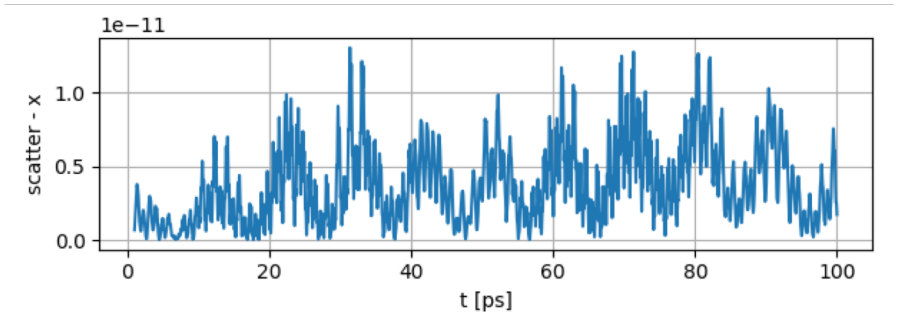



**quantum light**: controllable correlated and entangled two-photon sources




study single photon absorption and subsequent energy transfer, single photon fluorescence and electron generation

theory for PSII shows oscillations in the rate of fluorescent emission of single photons…



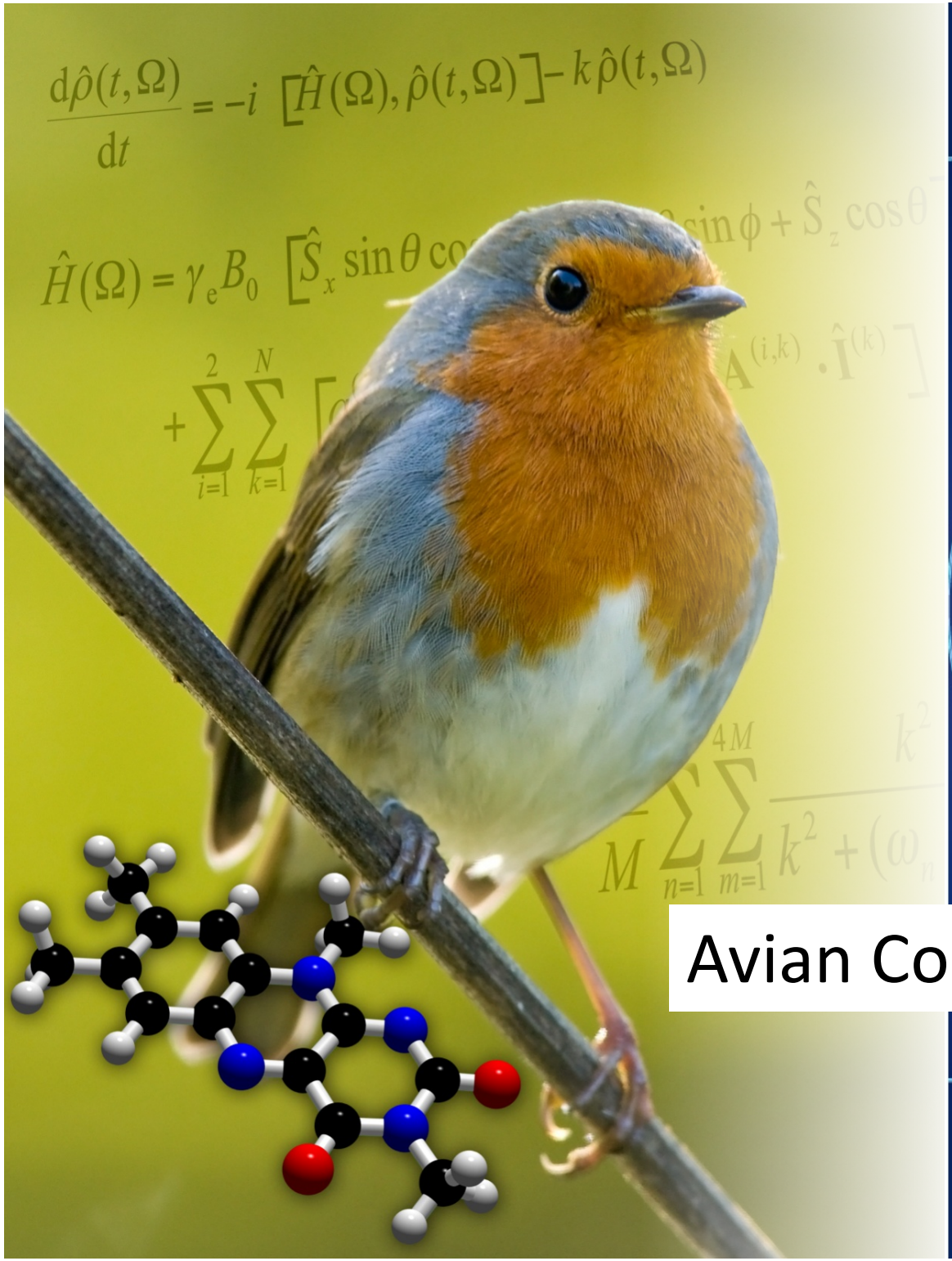
# but - light harvesting may de-optimize ‘pour encourager les autres’

*Layer of purple bacteria with quantum efficiency only 30% - dissipate enough heat to raise temperature locally and eliminate the competition*

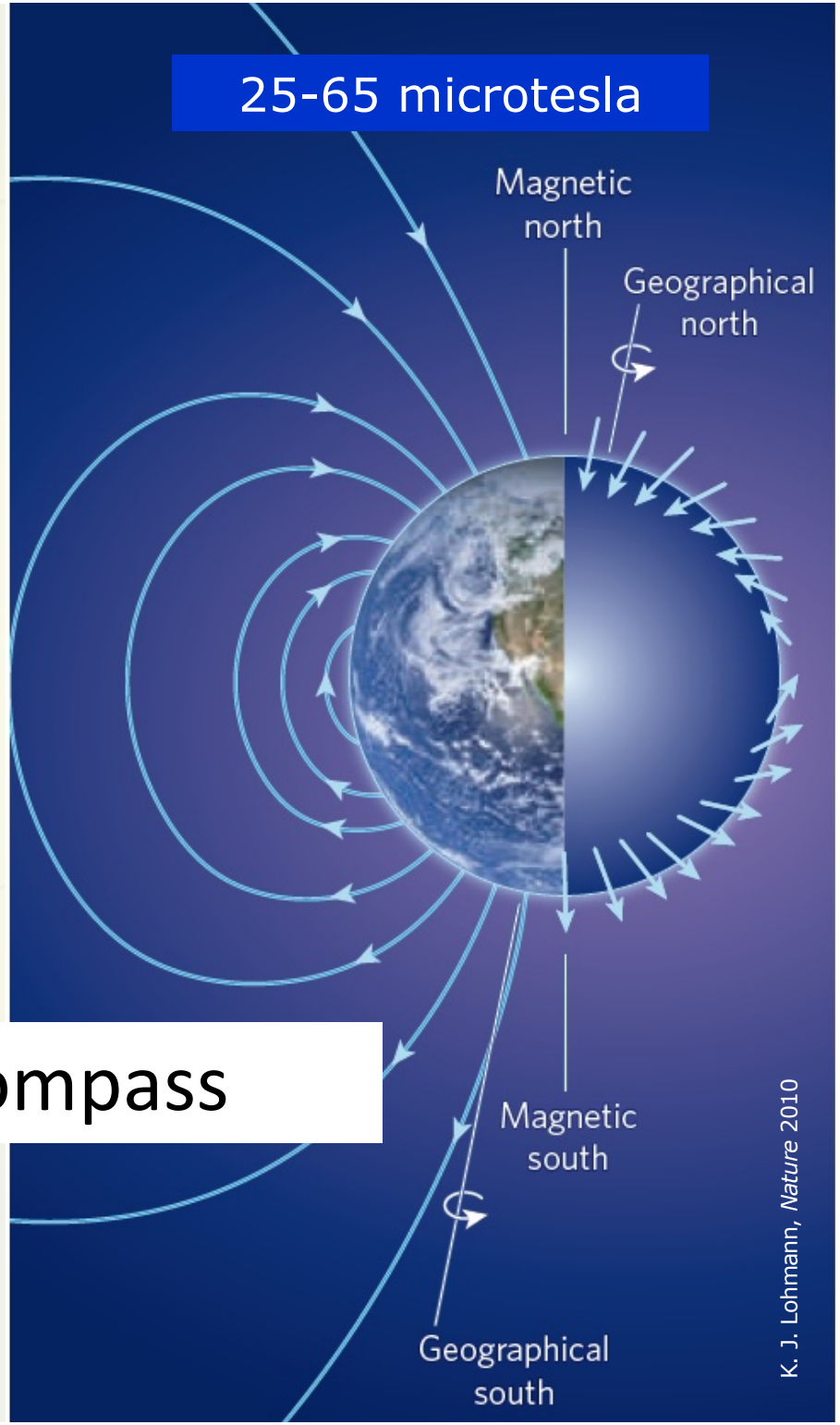
**Fig. 1** Aerial photograph of the South Andros Black Hole cave system, the Bahamas. Reprinted from Quaternary International, 121, Stephanie Schwabe and Rodney A. Herbert, Black Holes of the Bahamas: What are they and why they are black, 3–11, Copyright (2004), with permission from Elsevier

# an antenna is not enough…

- photosynthesis is optimized for survival
- light harvesting is one of many factors
- in plants overall energetic efficiency correlates with growth fitness (Arntz et al. 2000)
- competition for light, protection from excess light and oxygen…
- access to nutrients (esp. aquatic ecosystems)
- quantum efficiency may be sacrificed to fend off competitors by e.g., dissipating energy as heat…



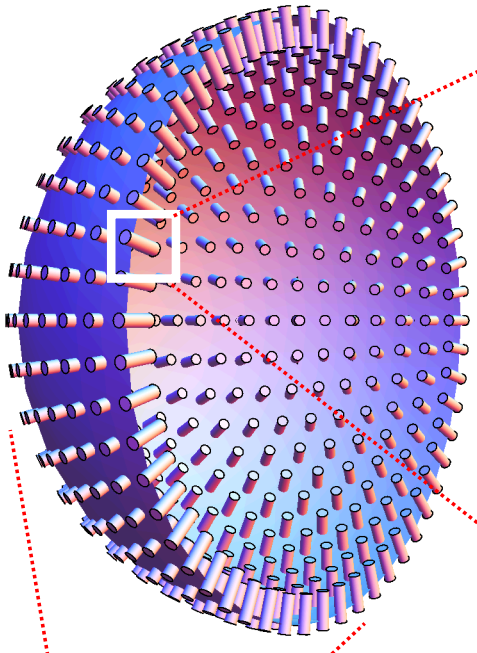
# Avian Compass




K. J. Lohmann, *Nature* 2010

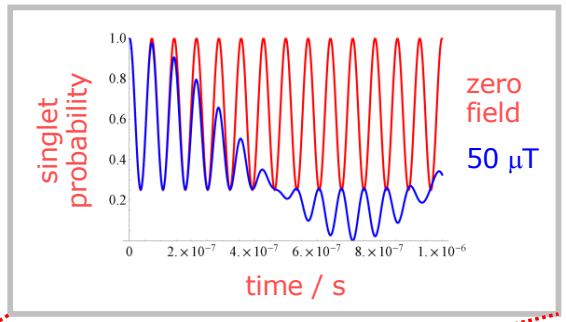
# Radical pair magnetoreception

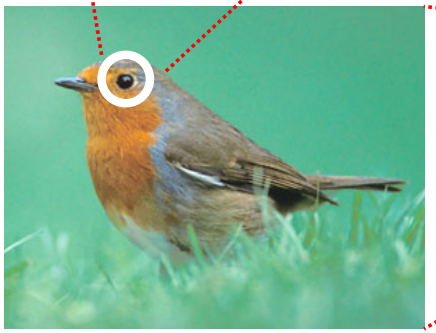
magnetoreceptor cells in retina

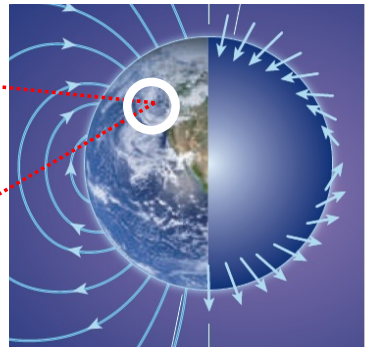


cryptochromes

coherent quantum spin dynamics



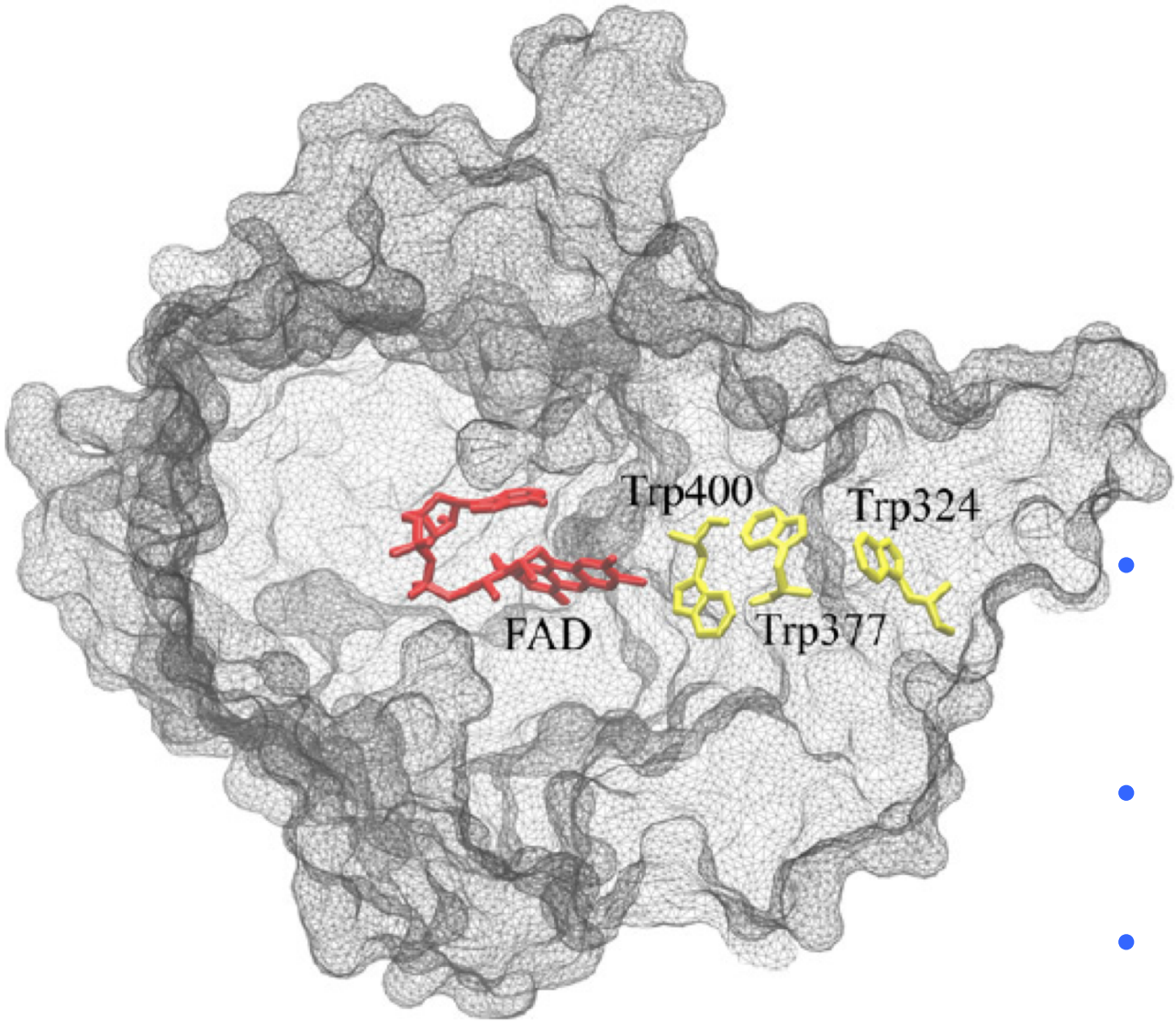


$^{S}[A^{\bullet+}B^{\bullet-}] \rightleftharpoons {}^{T}[A^{\bullet+}B^{\bullet-}]$

magnetically sensitive radical pairs

Ritz *et al*. *Biophys. J.* (2000)

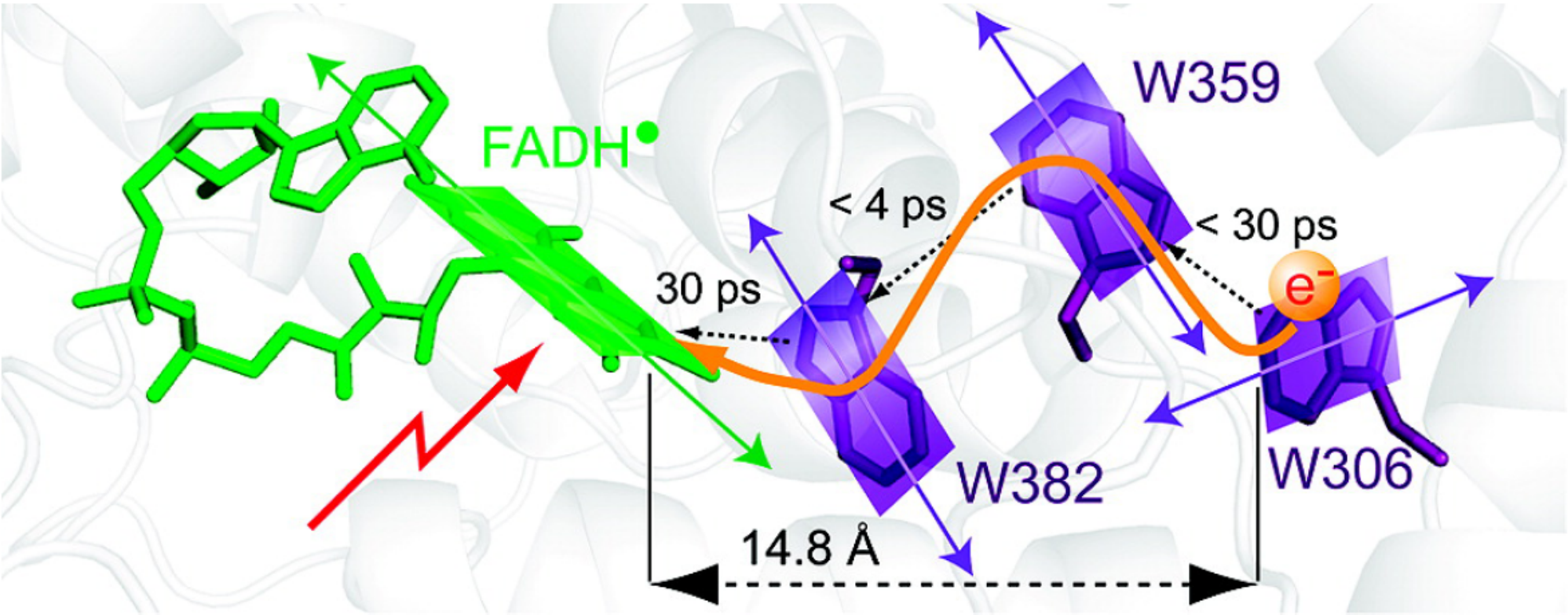
# Cryptochrome – photo receptor system




Are quantum correlated dynamics of radical pair electrons involved in the avian compass?

- Cryptochrome protein binds cofactor FAD
- FAD absorbs light
- electron transfer via Trp species generates long lived radical pair

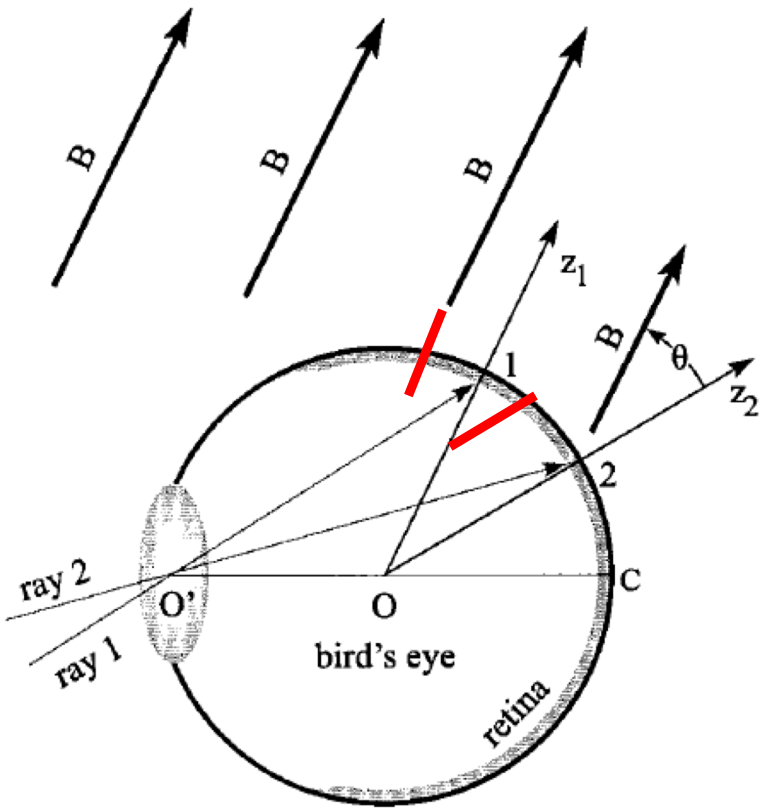
Radical pair = 2 electrons located on different molecules

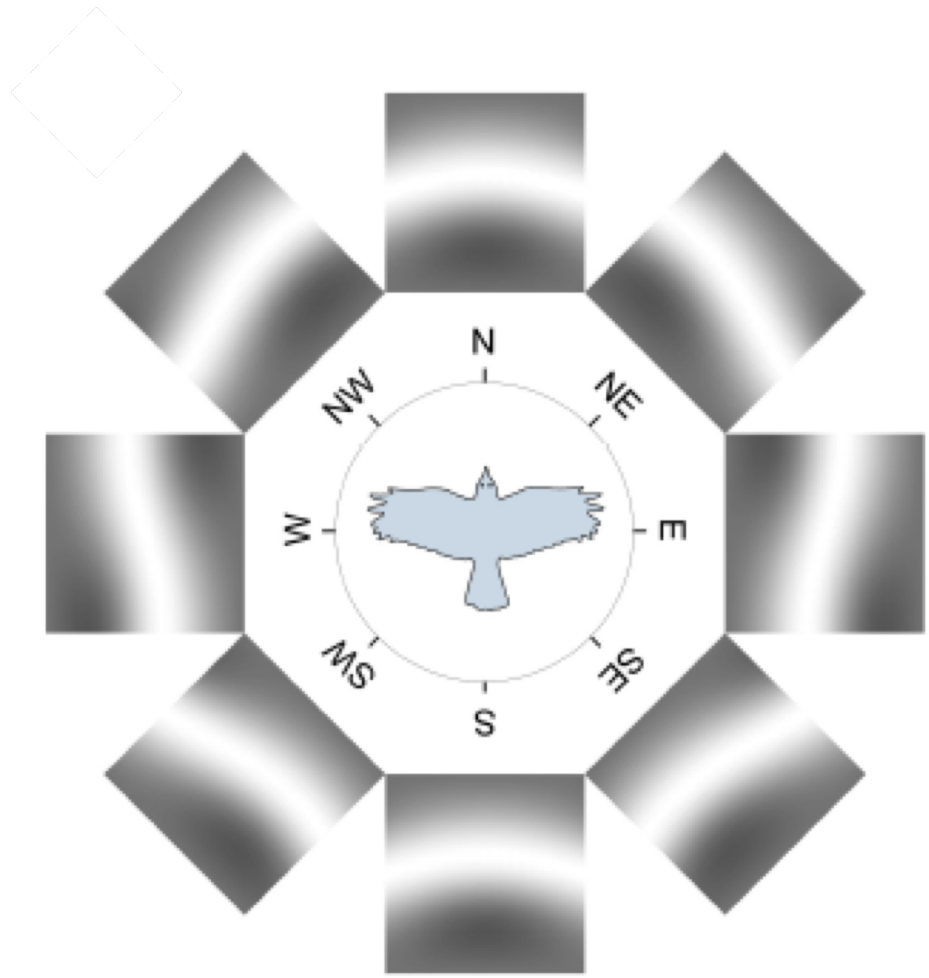



“Radical pair” of two electrons has quantum correlated, ‘entangled’ spins

4 possible spin states: 1x S and 3 x T

# Visual modulation pattern resulting from rigidly fixed receptor molecules



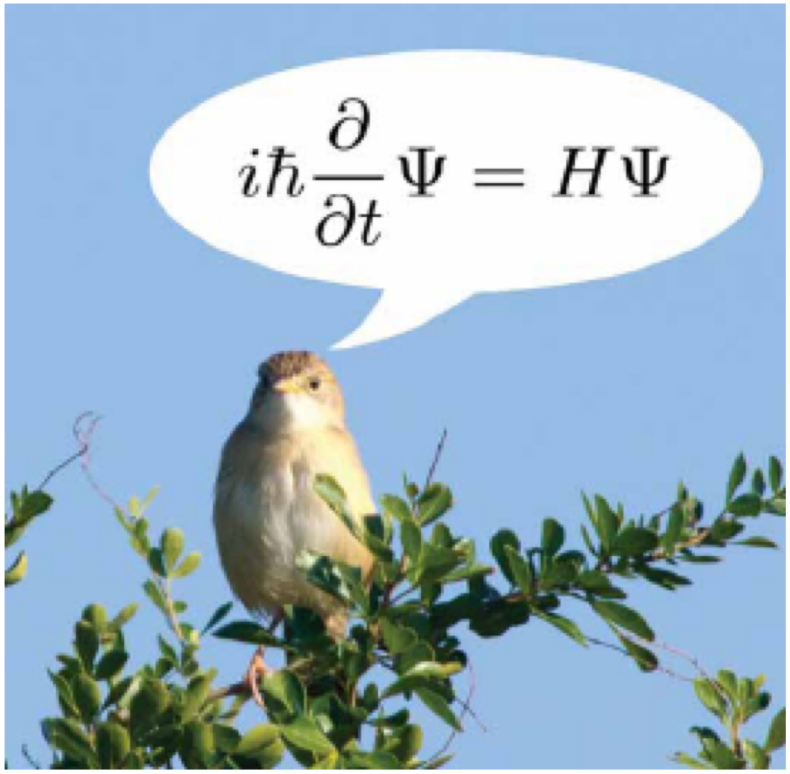



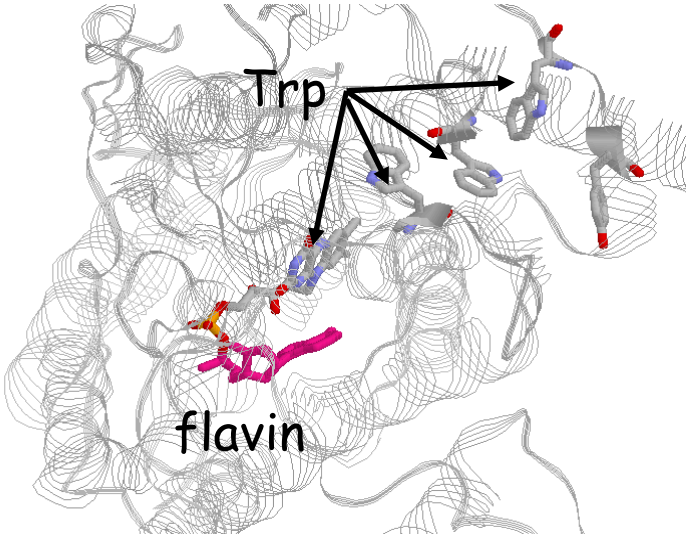

T. Ritz and K. Schulten Biophys. J, 78, 707 (2000)

experimental validation?

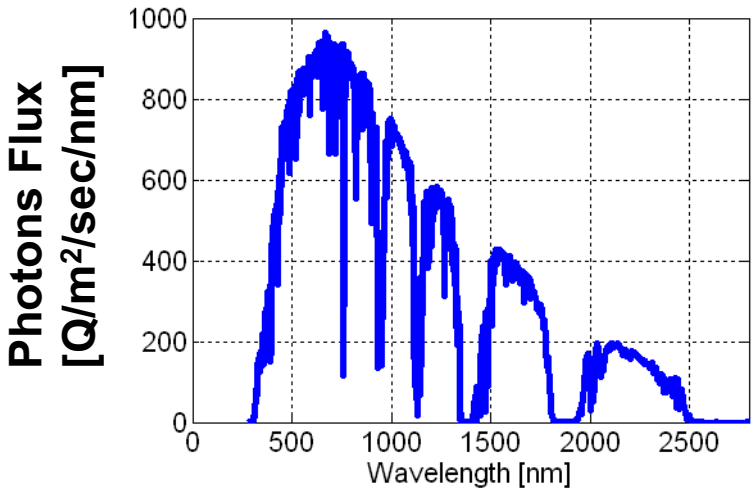
# Quantum insights for Avian Compass:

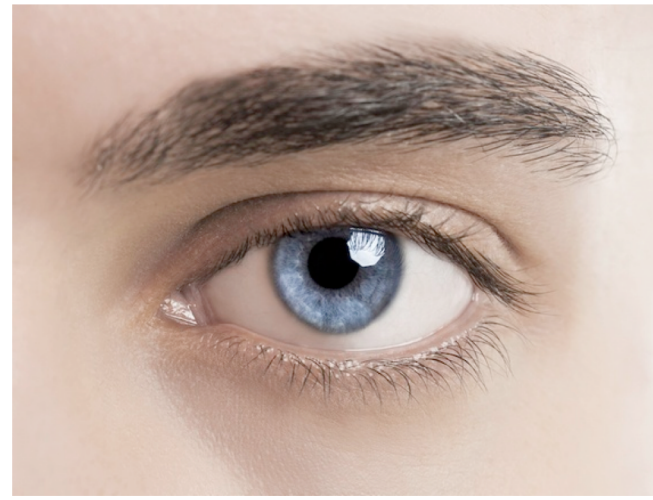
- Possible role of coherent dynamics of entangled electrons
- Needed - direct probe of coherence

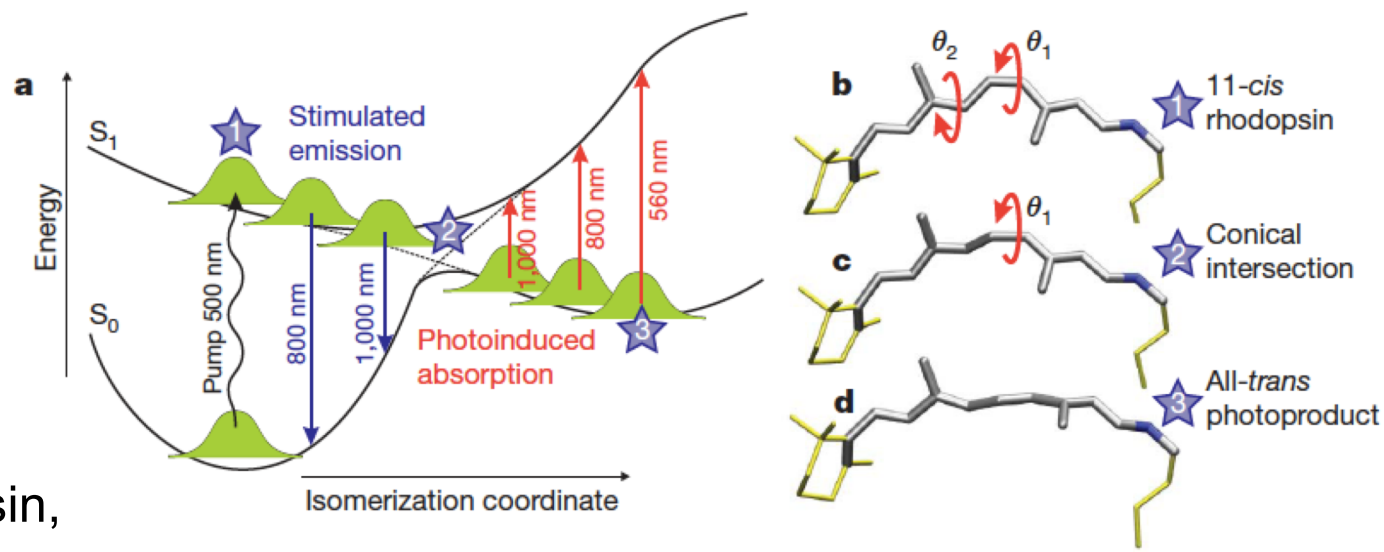



# Vision

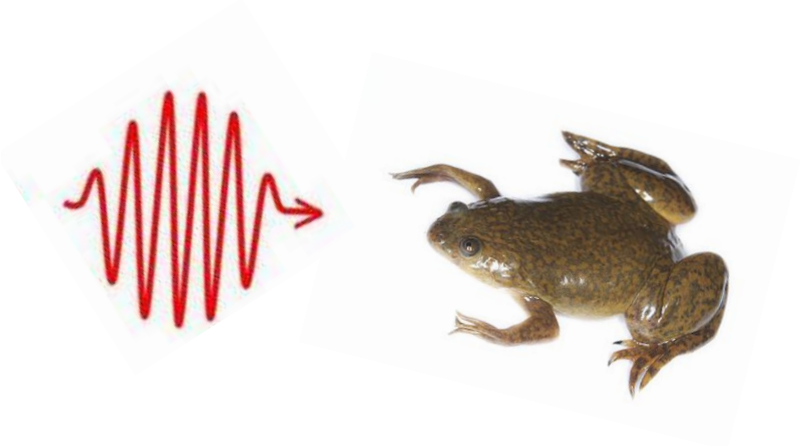


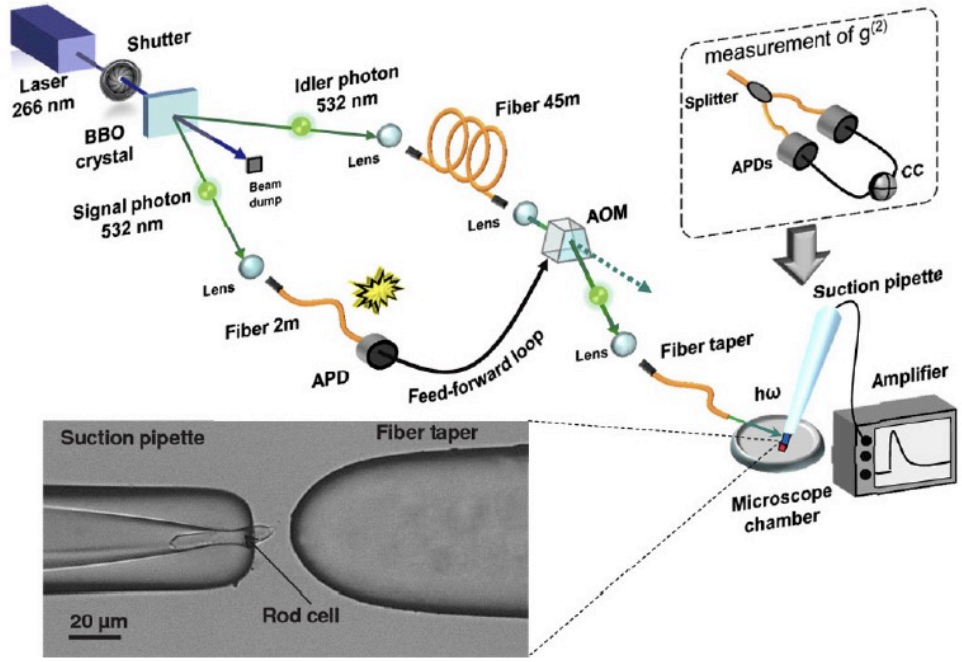






photoexcitation of rhodopsin, fast electron-nuclear dynamics in 200 fs

# Single photon perception – new quantum tools






rod cells of *Xenopus Laevi* toads are triggered by single photons

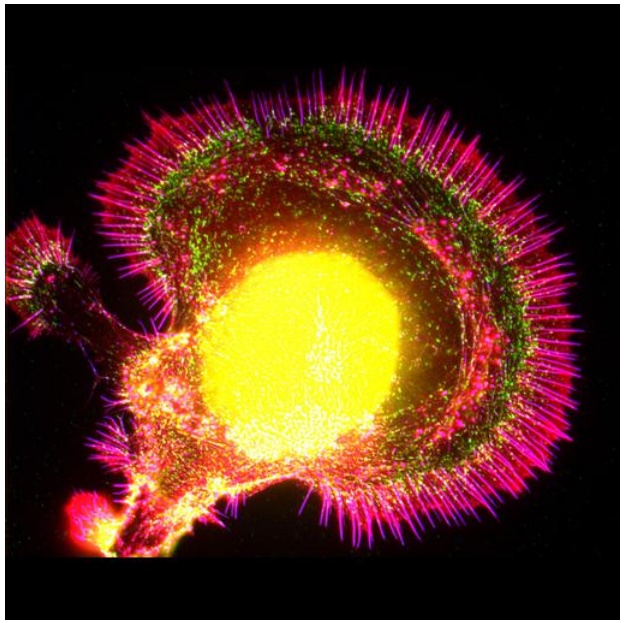
confirm response, measure single photon efficiency of rod cell absorption (27%)

Phan et al. PRL 112, 213601 (2014)

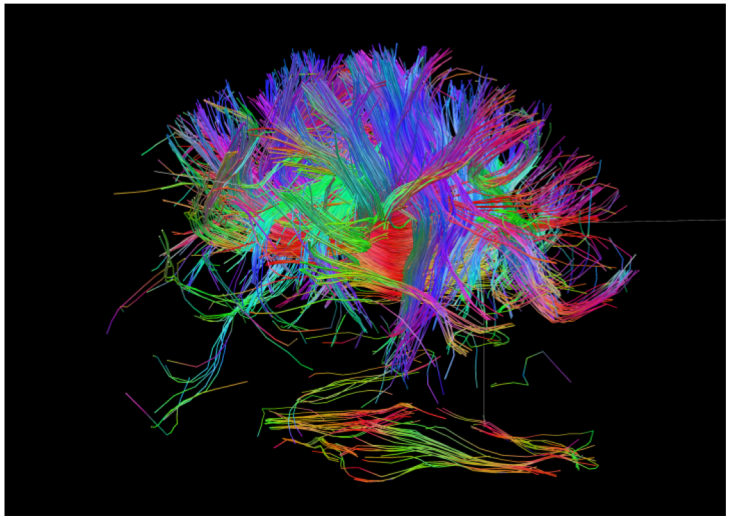
human eye can perceive single photons

Tinsley et al. Nat Comms 7, 12172 (2016)
Holmes et al. arXiv:1806.08439

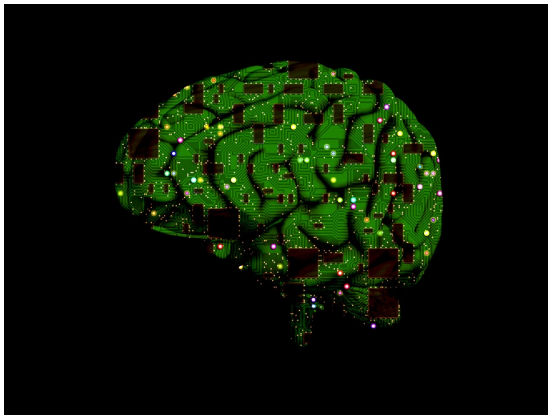
# Quantum in the Brain…



direct imaging (fluorescence) of neuron regeneration



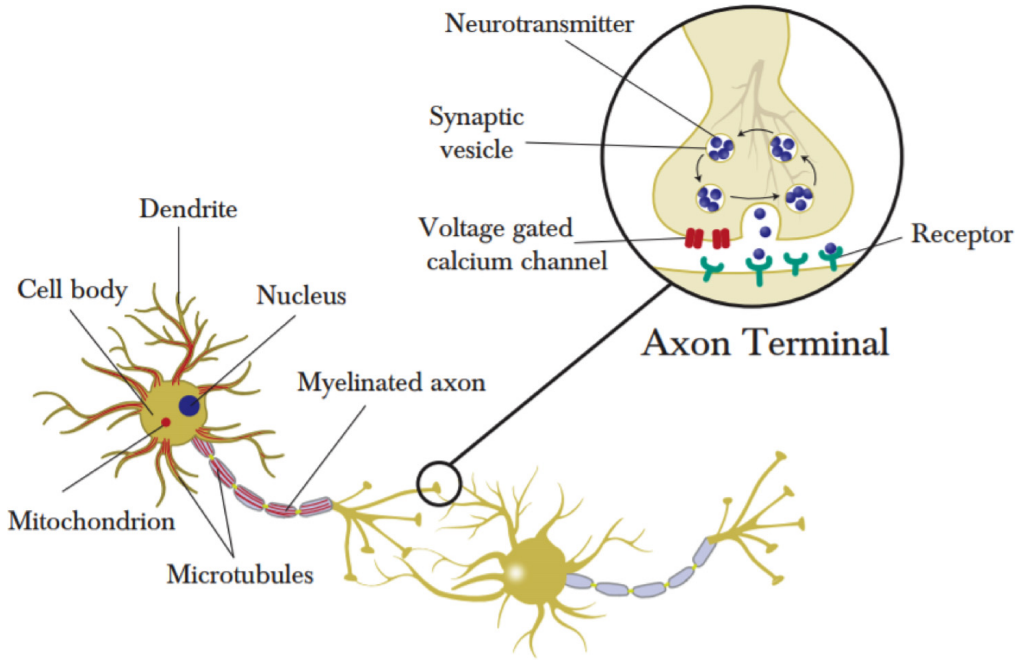
mapping neural connections (D-MRI)

is the brain a circuit?

artificial brains?

AlterEgo (MIT)



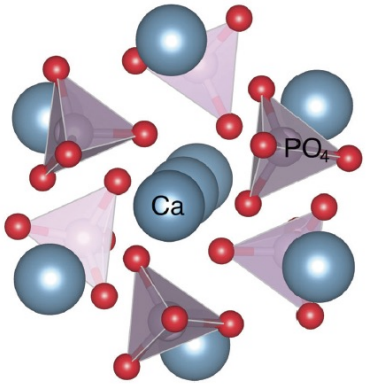

Eccles 1992
tunneling across synapses

| | | | | |
|---|---|---|---|---|
| Quantum process | Coherent energy/charge transfer | Entanglement | Quantum spin | Inelastic tunnelling |
| Neural manifestation | Energy/charge transfer in microtubules and possibly mitochondria<br><br>General anaesthetic<br><br>Biophotons | Radical pair and reactive oxygen species<br><br>Posner qubits | General anaesthetic<br><br>Radical pair and reactive oxygen species<br><br>Posner qubits | Neurotransmitters<br><br>GPCRs |

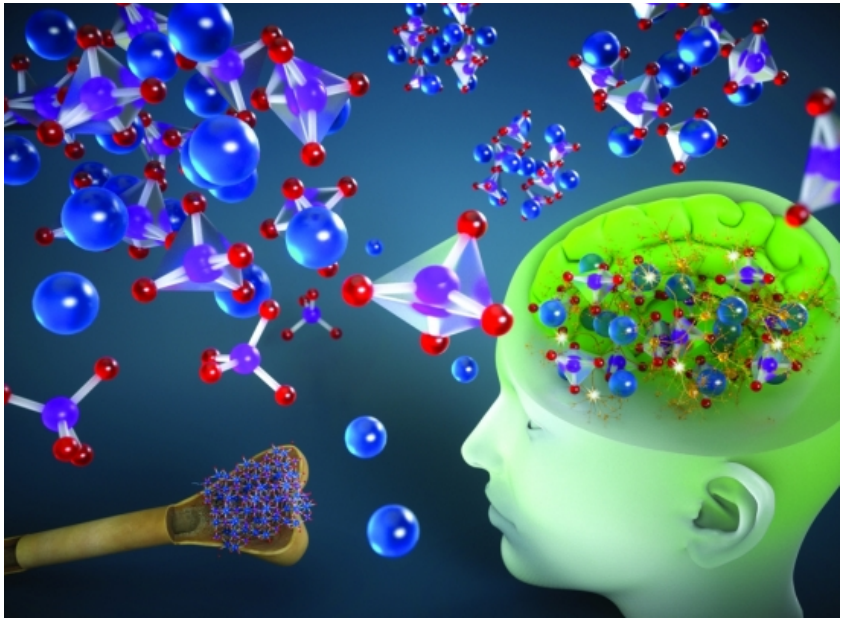
Penrose, Hameroff 1994
microtubules, macroscopic quantum coherence

Fisher 2015
entangled Posner molecules

# Quantum Cognition with nuclear spins?

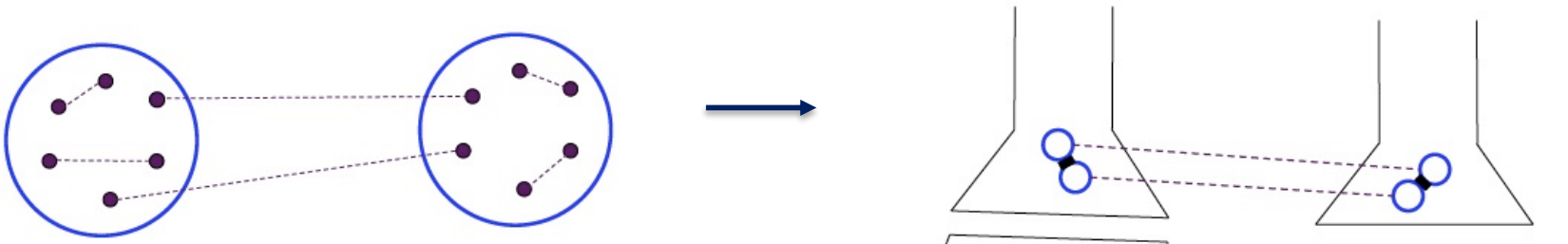



Posner “molecule”:
long lived nuclear spin $^{31}P$,
present in bone mineral,
maybe also in extracellular
bodily fluids??



Swift et al., PCCP. 20, 12373 (2018)

entangled Posner molecules trigger non-local quantum correlations
of neuron firing rates → neural quantum processing? Fisher, Ann. Phys. 362, 593 (2015)



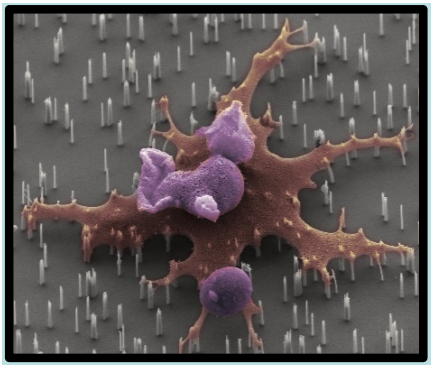
requires entanglement lifetime ~ 1 day

but… entanglement lifetime < 37 min, spin relaxation much faster…

Player, Hore, J. R. Soc. Interface 15, 20180494 (2018)

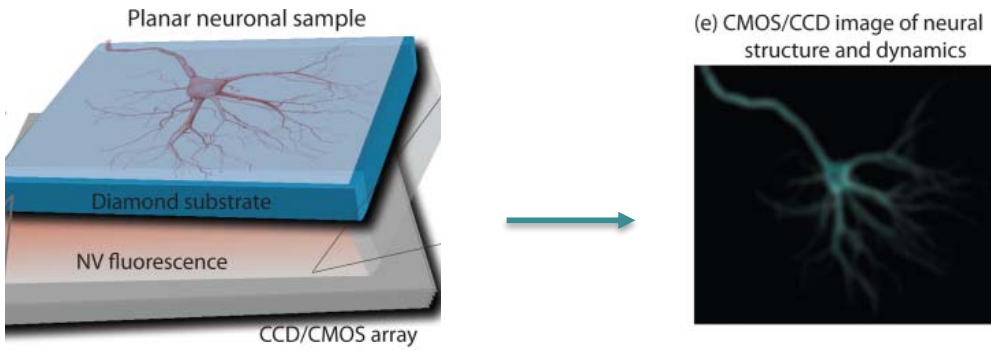
# Quantum Biology: tools of quantum science and nanotechnology give new probes of structure and dynamics of biological systems

- Microscopic probes of living cells, cellular response, biomolecule delivery, biochemical/magnetic/electrical monitoring…



Si nanorods offer cellular access

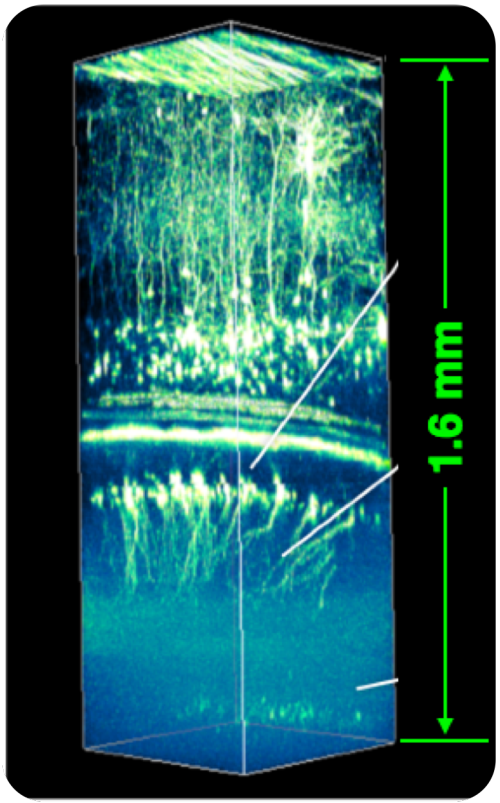
- Quantum sensing with defects in diamond…




- Ultrafast spectroscopy, e.g., for quantum dynamics of electronic energy transfer in photosynthesis
- Quantum light sources: single photons, entangled photons, photon statistics, defects in diamond, …

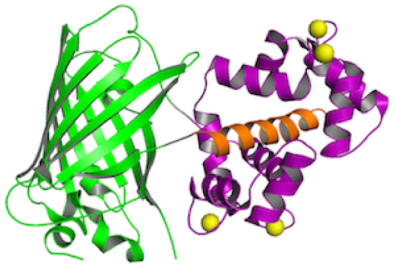
# New Quantum Tools

2-photon absorption image
of live mouse brain:

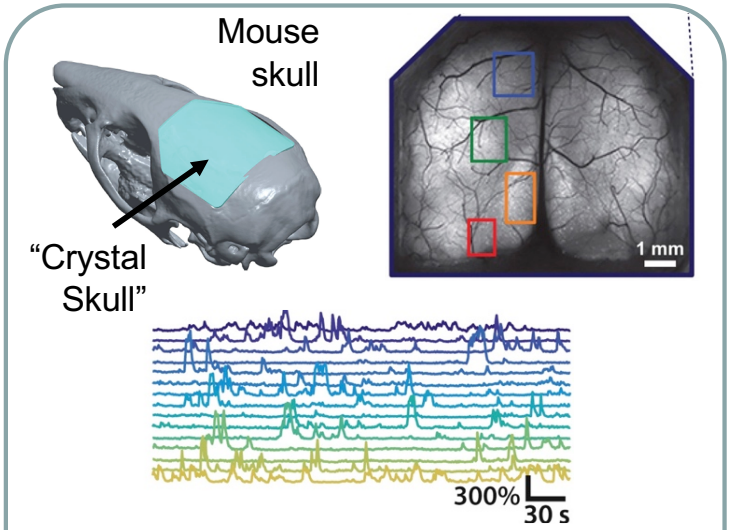



*Kawakami et al Biomed. Opt. Express* **6** 891 (2014)

2-photon microscopy of
live mouse brain:



probe molecule
(yellow fluorescent protein)

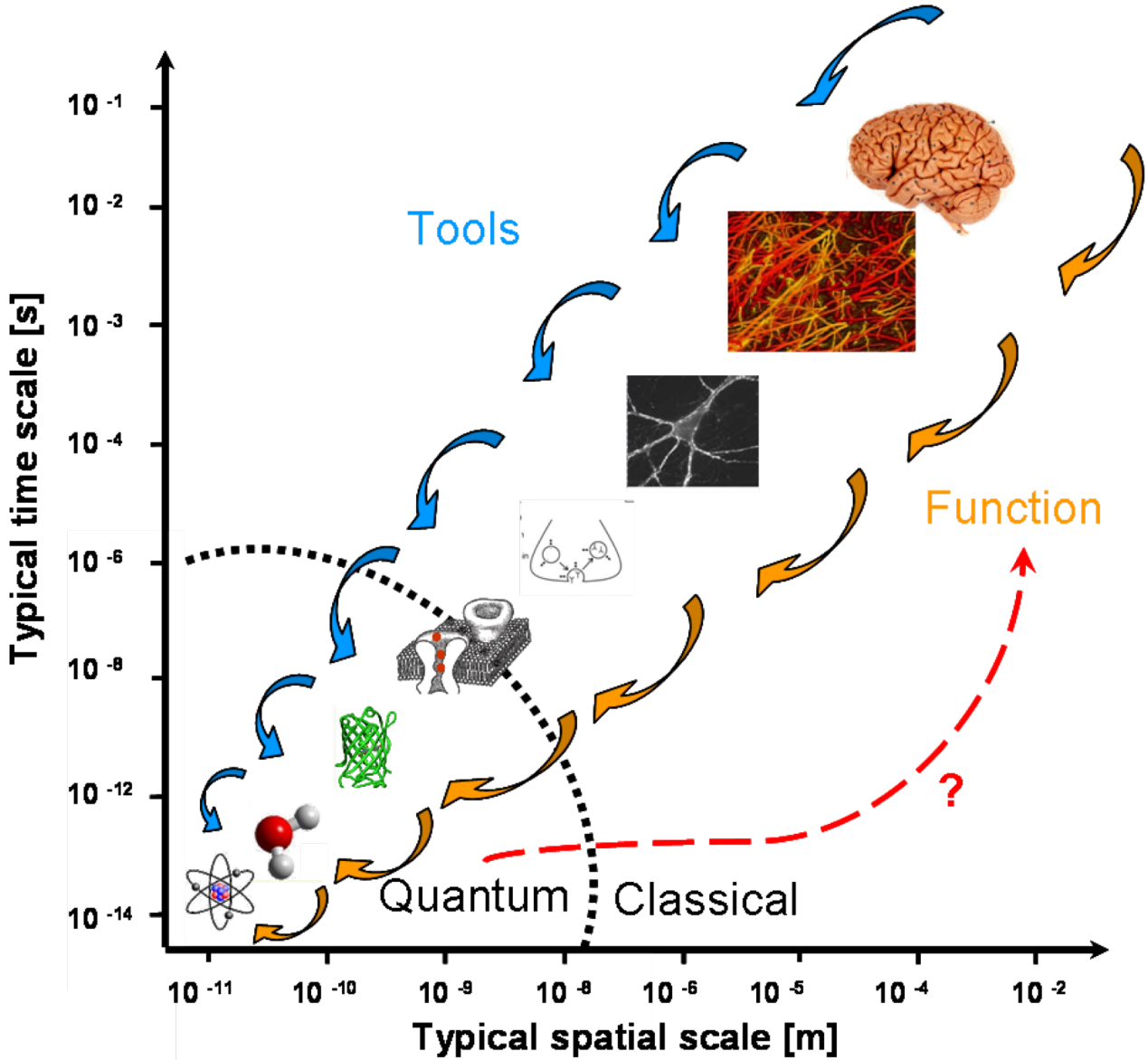



Firing of individual neurons
> 1 million neurons accessible

Kim et al *Cell Reports* 17, 3385 (2016)

entangled photon pairs can give greater resolution

# Biological function across all time and size scales




Developing tools for studying biological structure and function at unprecedented spatial and temporal resolution

Can quantum coherence be relevant for biological function?

A. Vaziri
B. HHMI/U. Vienna

# ?

One can best feel in dealing with living things how primitive physics still is

Albert Einstein

Sit down before fact like a little child, and be prepared to give up every preconceived notion, follow humbly wherever and to whatever abyss Nature leads or you shall learn nothing

Thomas Henry Huxley

# Max Delbrück
# Nobel Prize Lecture 1969

Arts versus Sciences:

*While the artist's communication is linked forever with its original form, that of the scientist is modified, amplified, fused with the ideas and results of others and melts into the stream of knowledge and ideas which forms our culture. The scientist has in common with the artist only this:* ***that he can find no better retreat from the world than his work and also no stronger link with the world than his work.***