Quantum Biology:
might nature be optimized to harness quantum mechanics?

Clarice D. Aiello
Quantum Biology Tech (QuBiT) Lab, UCLA

NSF Nanoscale Science and Engineering Conference, Dec 9 2019

current sensor

pA

magnetic sensor

μT, cryo temps

light sensor

single photon

smell sensor

...

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single e^-, ultrafast

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μT, room temp

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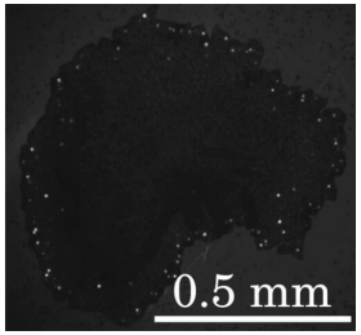

single cell

smell sensor

single molecule

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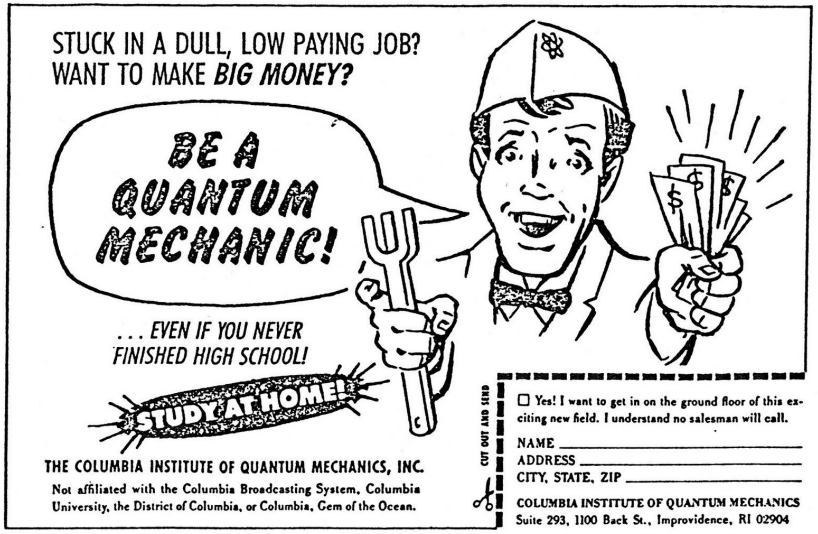

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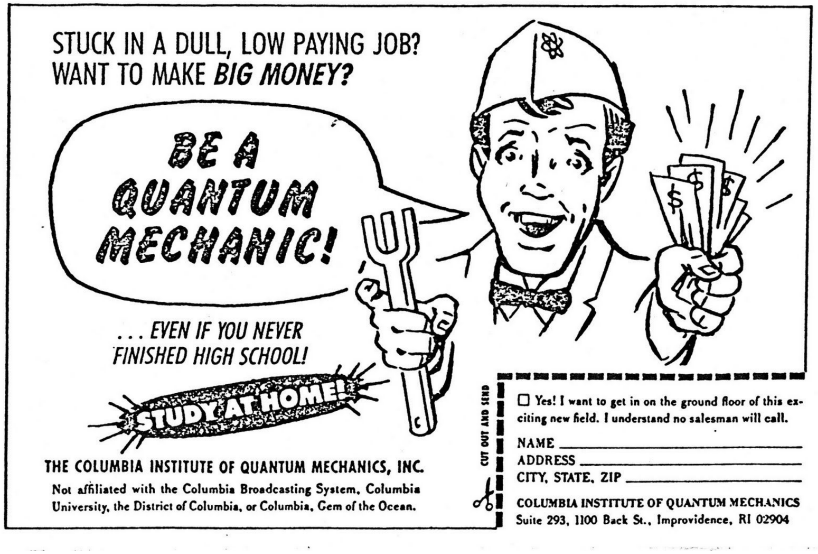
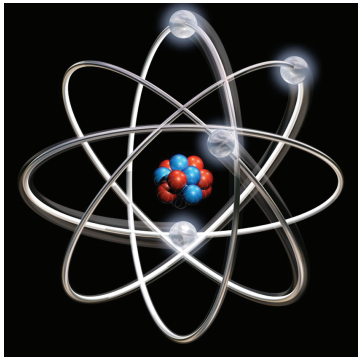


(I wish I knew what plant this is...)



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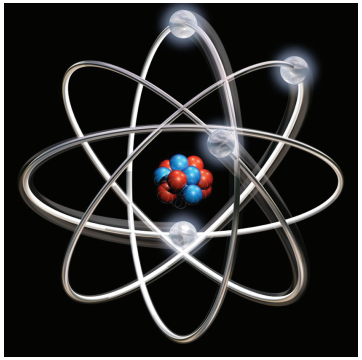

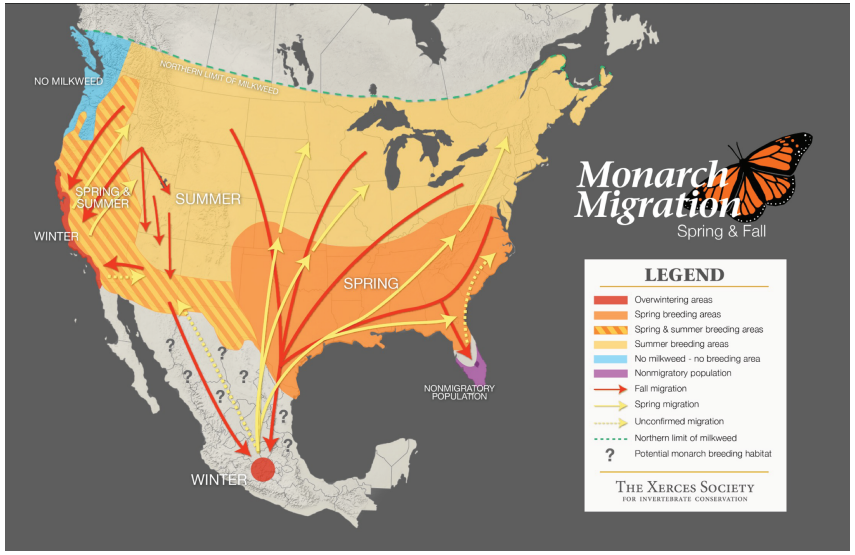

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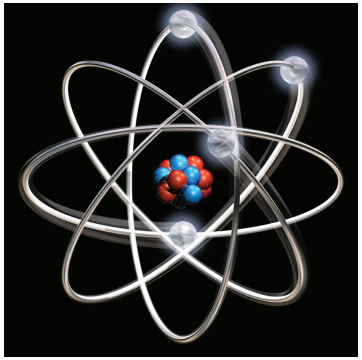

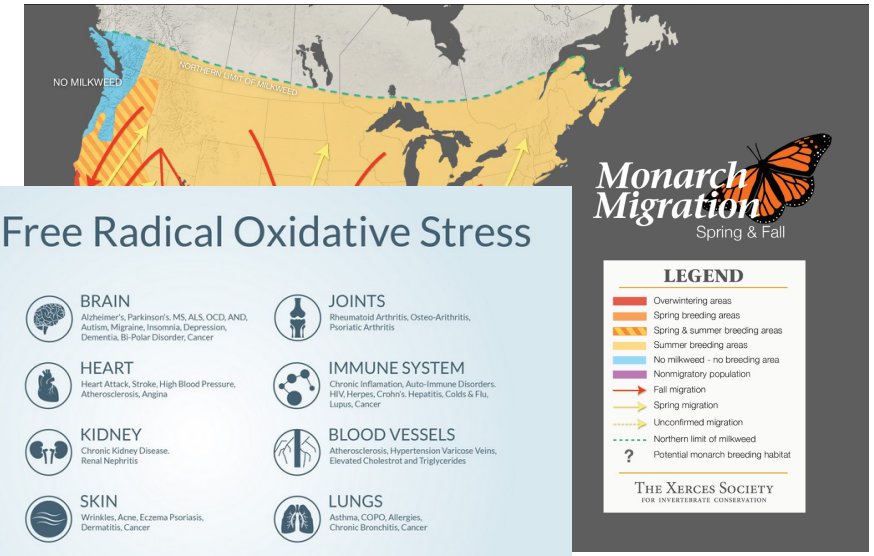

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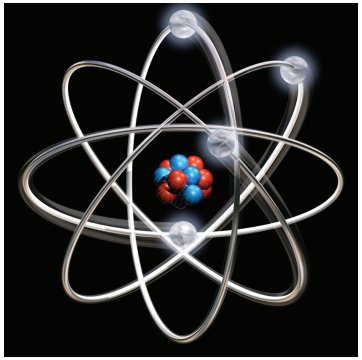

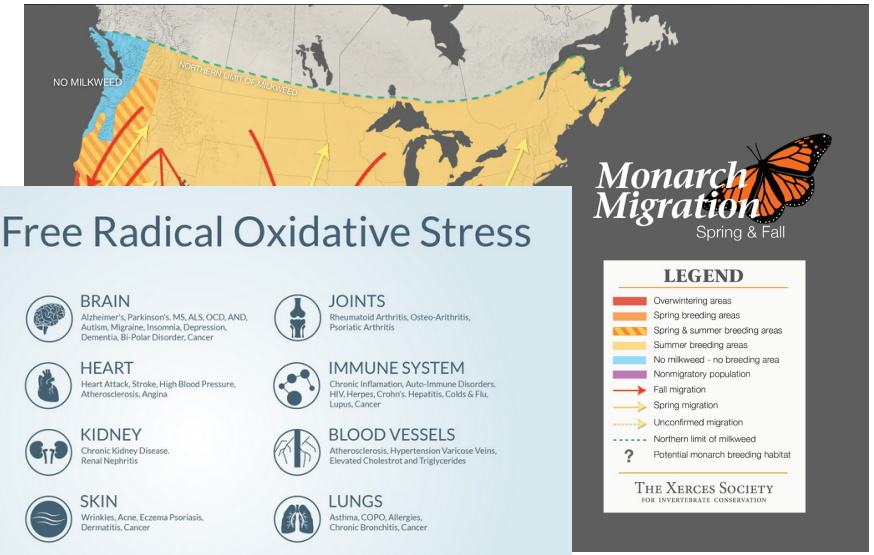

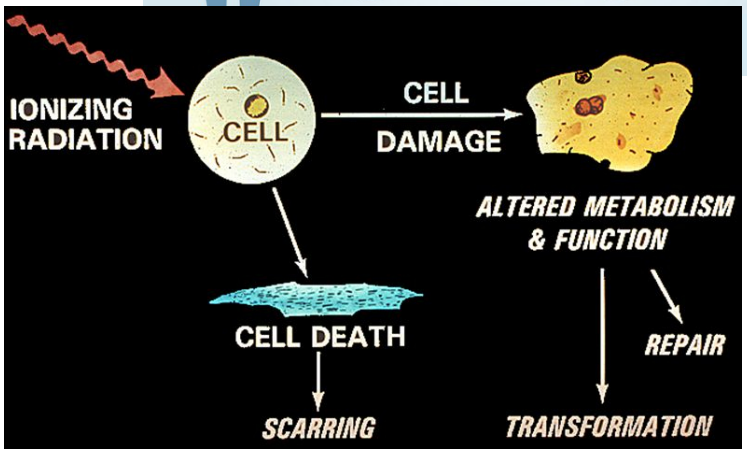

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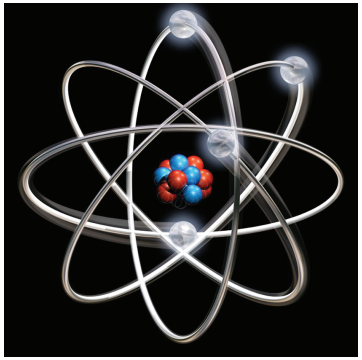

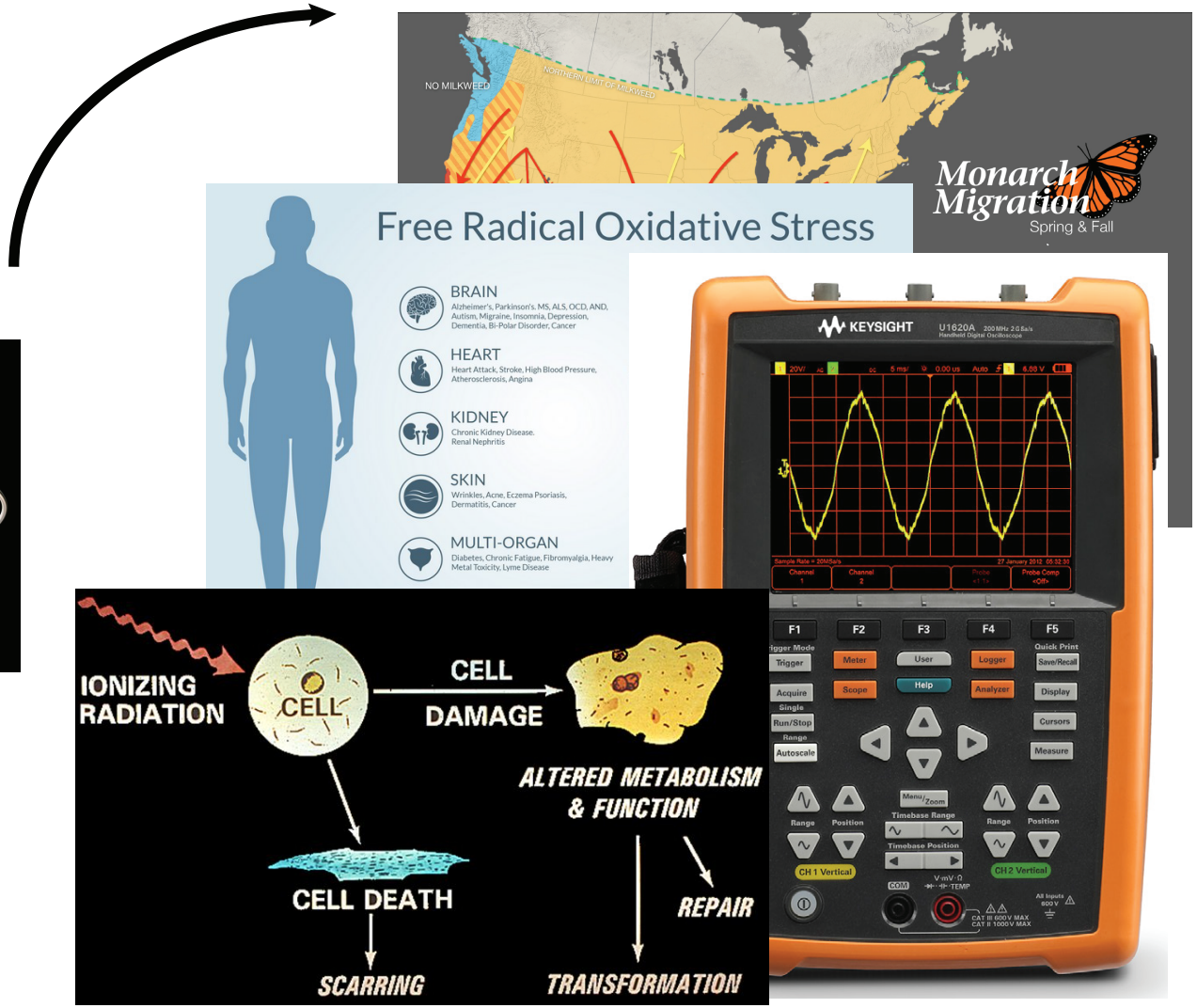

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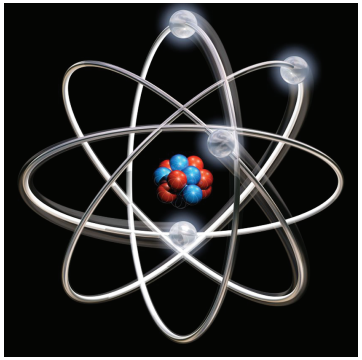
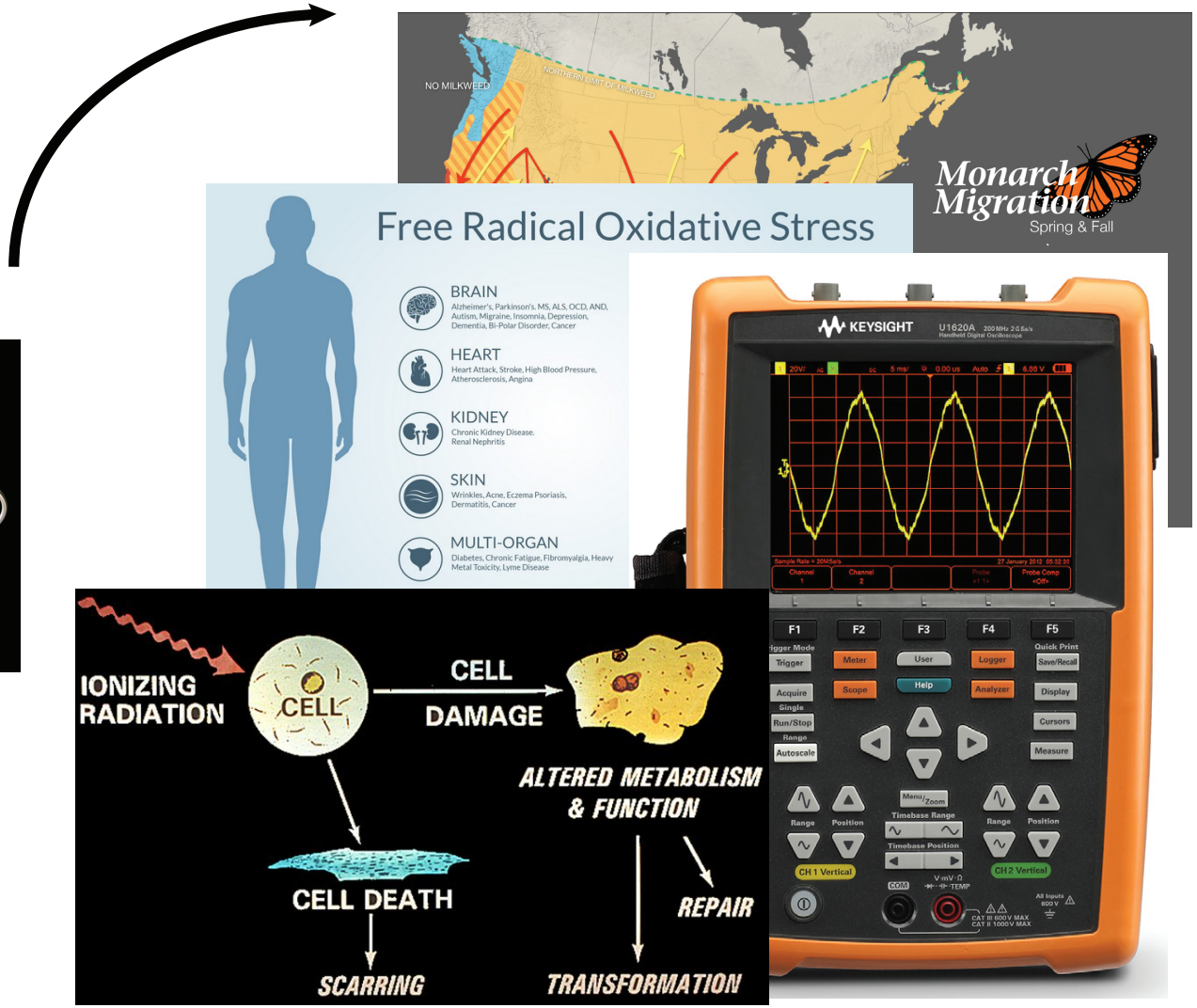
I am a quantum engineer interested in how quantum physics informs biology at the nanoscale





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Interference

Tunneling

Vibrations/noise-assisted processes

Spins 1: sensing magnetic fields

Spins 2: chiral-induced spin selectivity

Spins 3: computing with spins in the brain

Quantum (info, sensing, computing)-inspired recent approaches

Things about which I don't have an opinion

What's in it for us as nanoresearchers?

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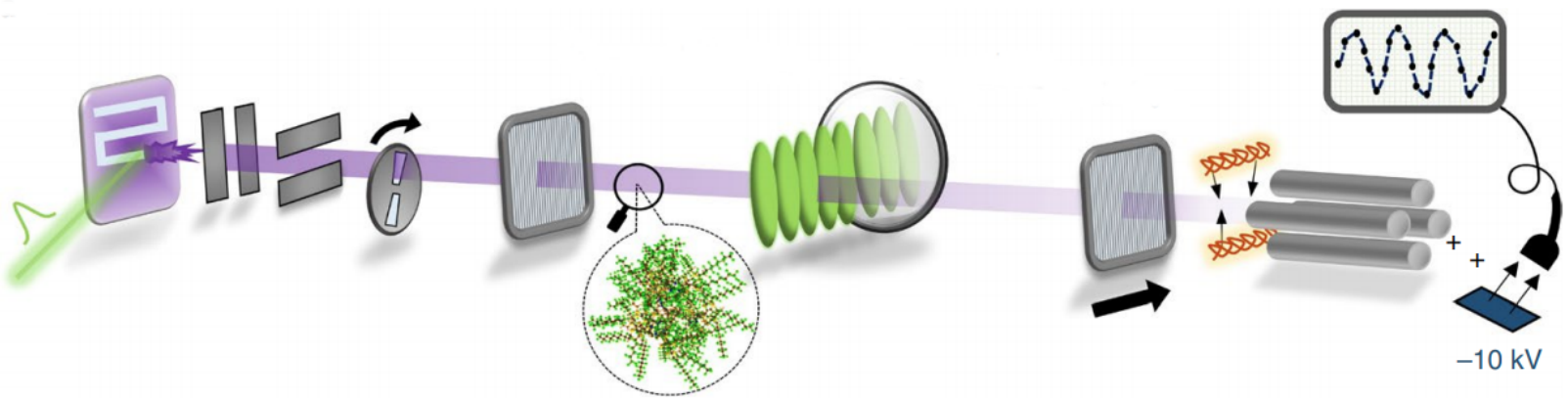
Double slit-like experiments with huge biological molecules



https://arxiv.org/abs/1910.14538

- Arndt, est '99 (started with C_{60}!)
- Record: chain of 15 amino acids interferes with itself

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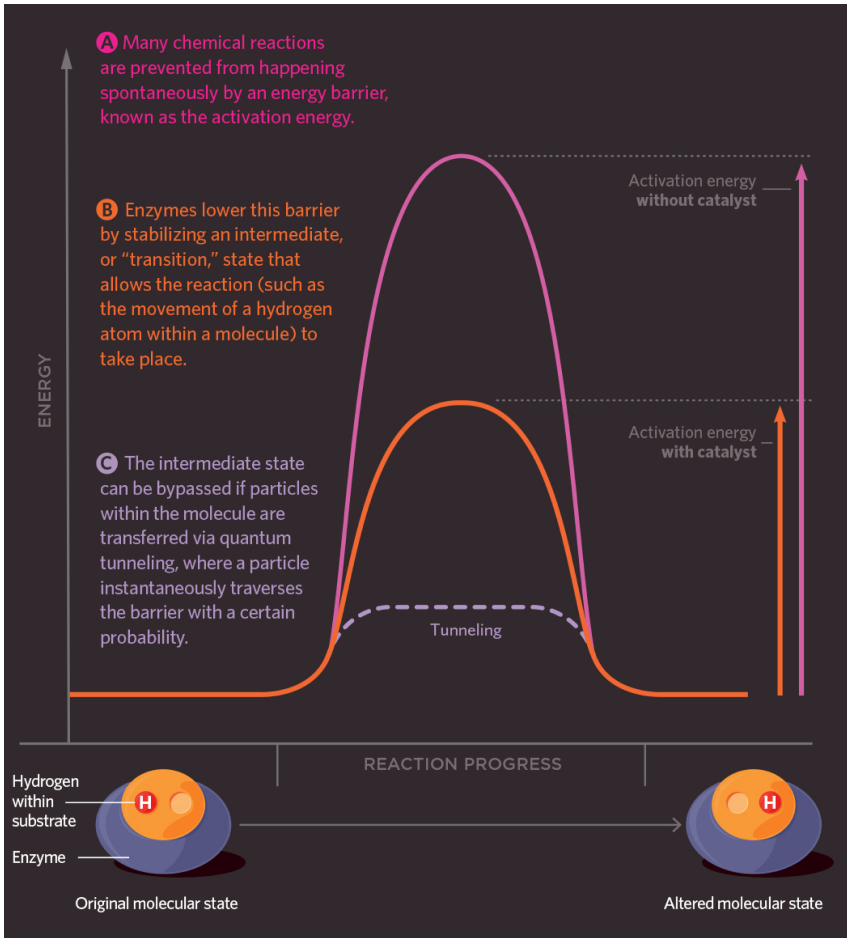
Room-temperature tunneling of both electron *and* protons have been observed

- Klinman experiments: protein tunneling links protein dynamics to enzyme catalysis
  Annu Rev Biochem. 82, 471 (13)
- Might enzymes be subjected to natural selection?
- Al-Khalili theory: might proton tunneling be responsible for DNA mutations? Biosystems 50, 203 (99)
- Theory: might ion tunneling help explain ion channels functioning (eg., high selectivity)?
  many articles; controversial



Adapted from bit.ly/quantumbio_nicearticle

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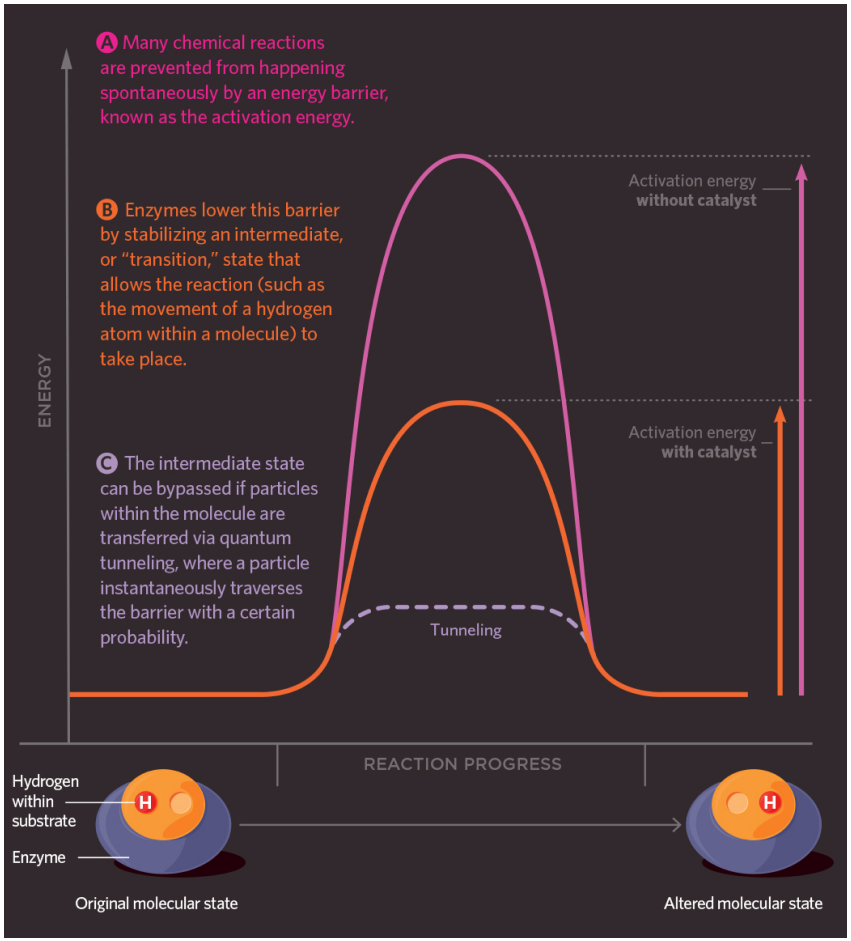

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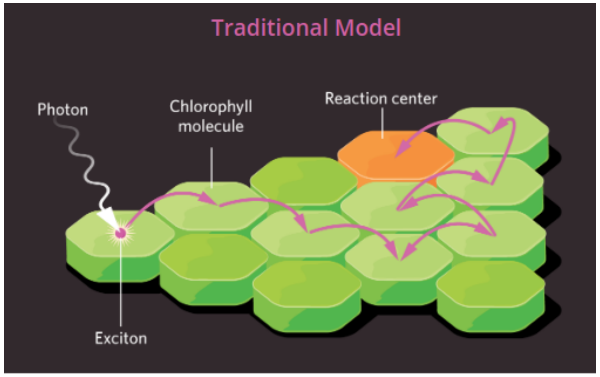
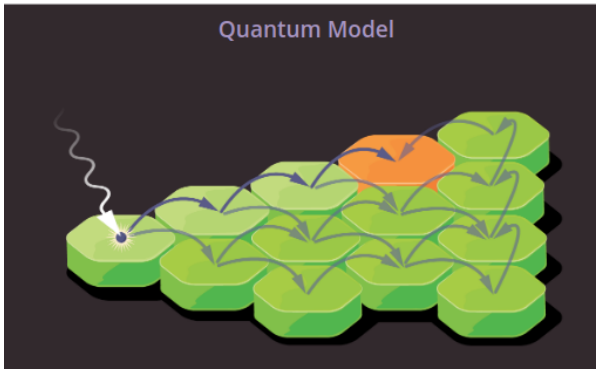
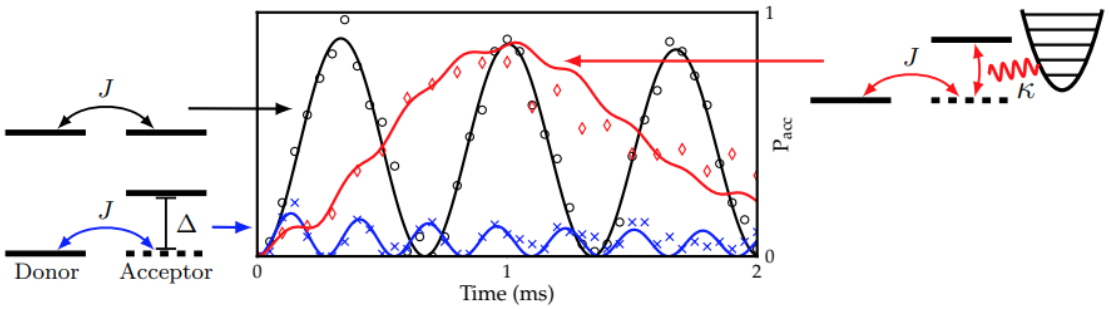
The case for photosynthesis



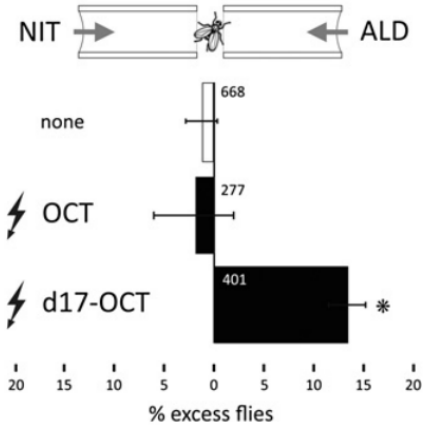


- Lots of transient absorption, 2D-spectroscopy
- Quantum (vs. classical) coherence? Fleming, Engel ✓, Scholes ✗
- Beyond coherences, overlooked: transport might be optimal because noise-assisted (as per quantum simulation)
  Phys. Rev. X **8**, 011038 (18)



The case for olfaction

- Turin's theory: lock/key mechanism + vibrational resonance (enabling tunneling)
- Turin's experiment: flies can smell deuterium vs. H ✓
  PNAS **108**, 3797 (11)
- Vosshall's experiments: humans and flies cannot smell isotopes ✗
  Nat. Neurosci. **7**, 337 (04)



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Magnetic fields can alter products of photo-dependent chemical reactions involving spin-correlated electrons (a.k.a. ‘radical pairs’)

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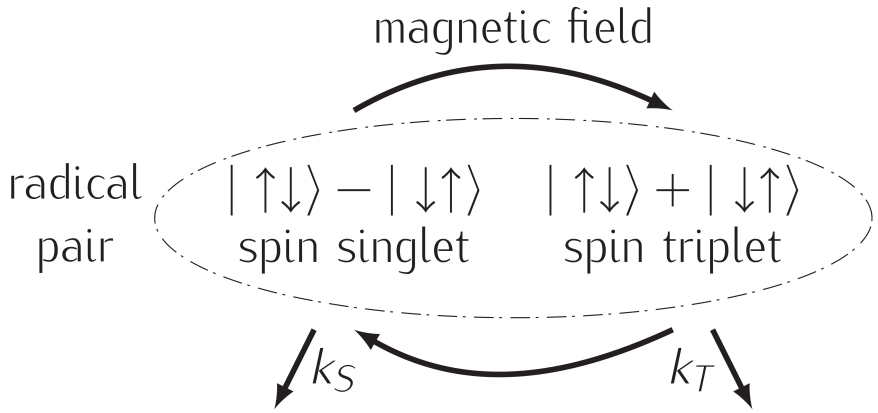
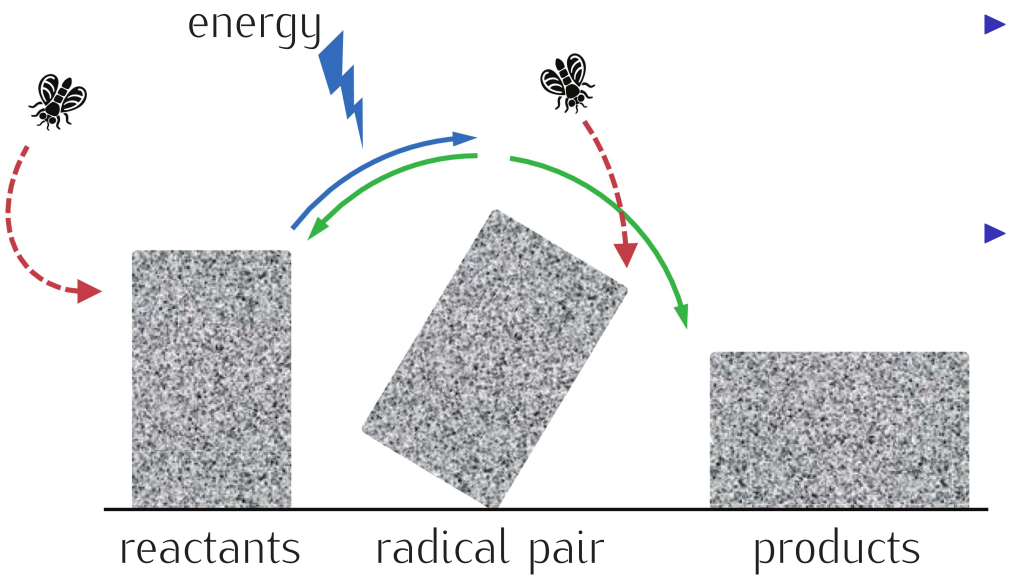


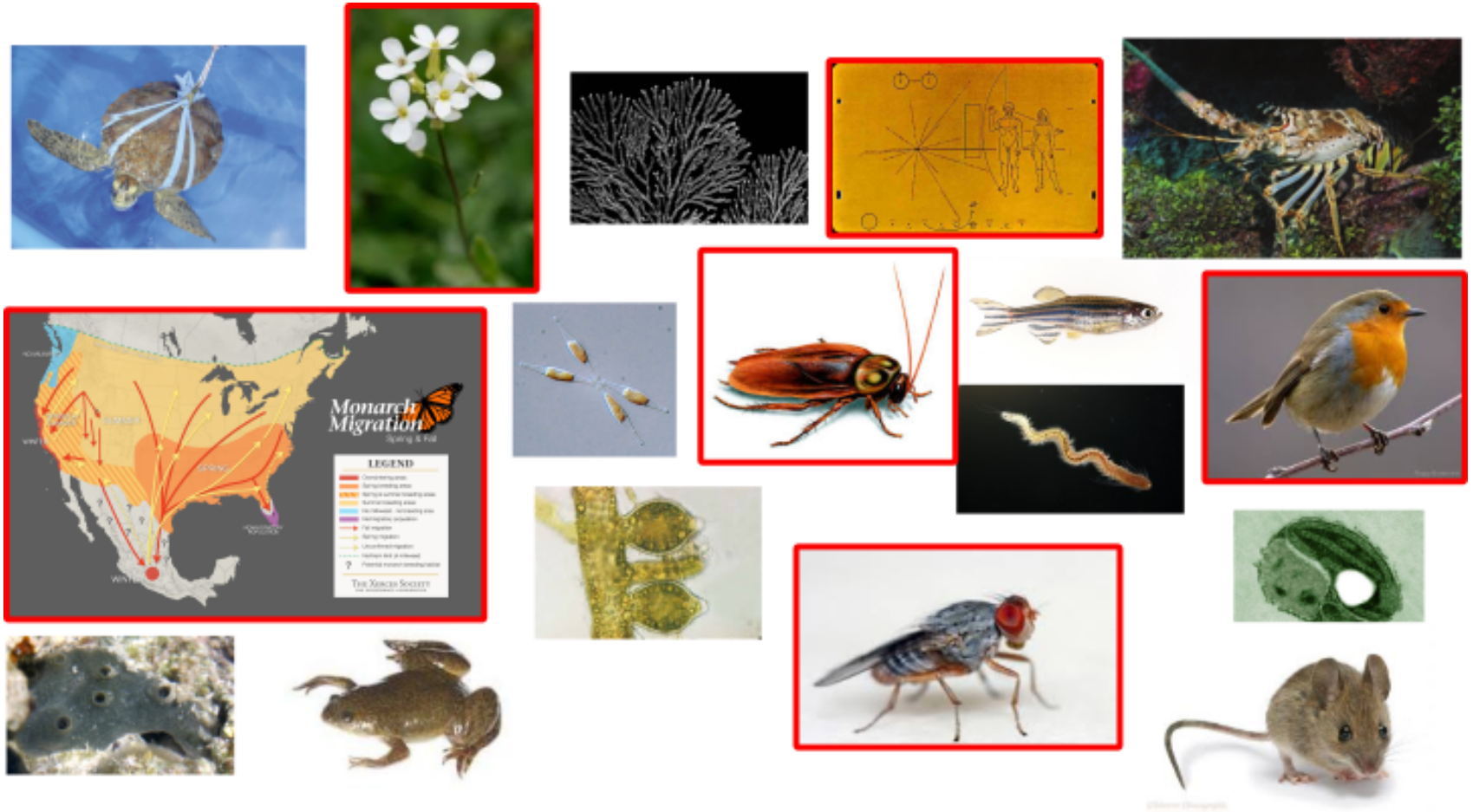


Adapted from Hore, *Annu. Rev. Biophys.* **45**, 299 (16)

- **demonstrated** at room temperature, in solution, down to geofield strengths
  Steiner, *Chem. Rev.* **89**, 51 (89)
- **known** to depend on the quantum spin state of the radical pair
- hypothesis: same mechanism under physiological conditions
  Ritz, *Nature* **429**, 177 (04); Hore, *Annu. Rev. Biophys.* **45**, 299 (16)
- only animal photoreceptor known to sustain radical pairs: cryptochrome (also clock regulation)

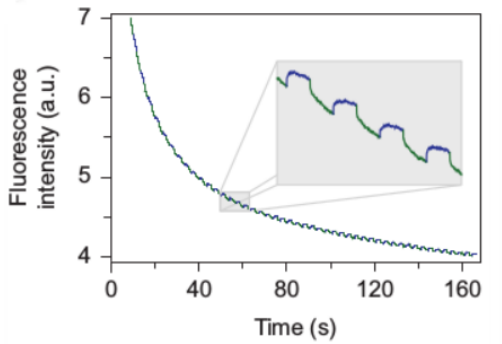
Magnetosensing mechanism may be universal across vastly diverse species

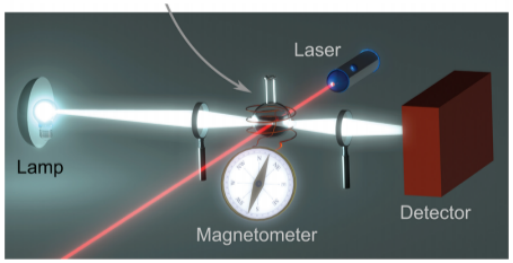
organisms known to express cryptochrome/ magnetosensing studies on cryptochrome



Evidence for cryptochrome-based magnetosensing abound...

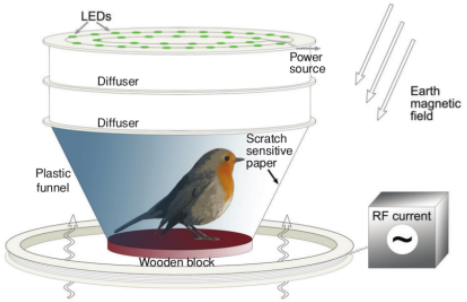
in vitro cryptochrome fluo
modulated by magnetic fields





quantum for up to $\sim 1\ \mu$s
in solution, room temperature

magnetosensing in birds lost
without right wavelength to excite
photoreceptor cryptochrome



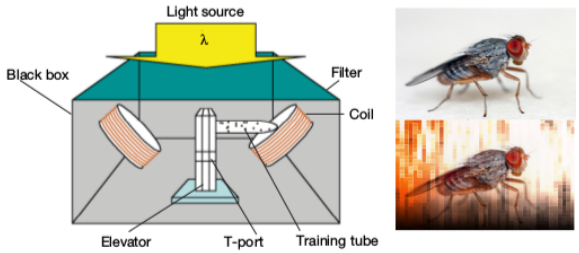


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Image credit: Kattnig, *Nat. Chem.* **8**, 384 (16); Du, *J. Photochem. Photobiol.* **90**, 989 (14); Ritz, *Nature* **429**, 177 (04); Gegear, *Nature* **454**, 1014 (08)

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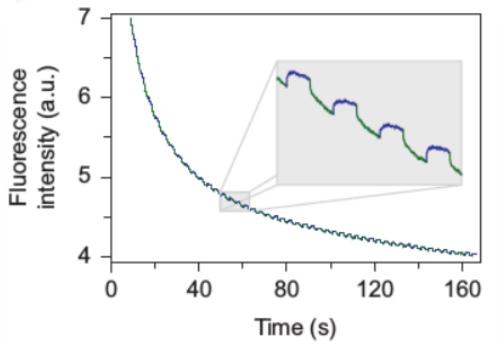

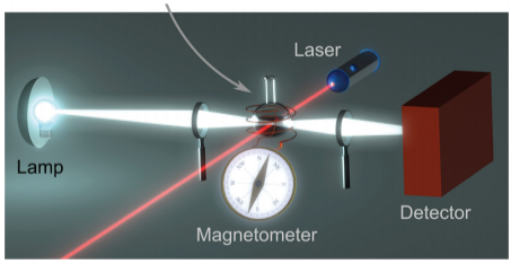

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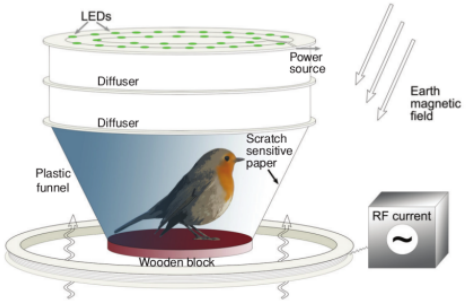

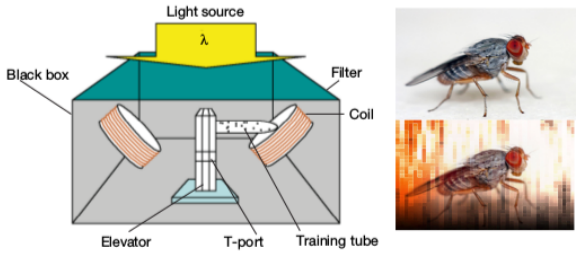

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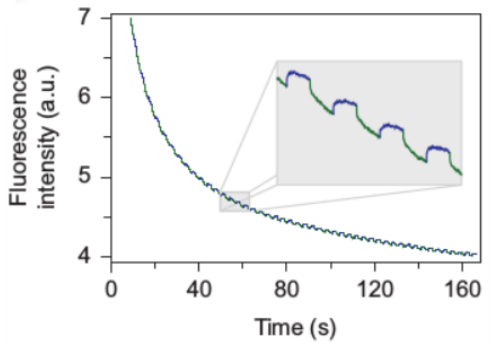

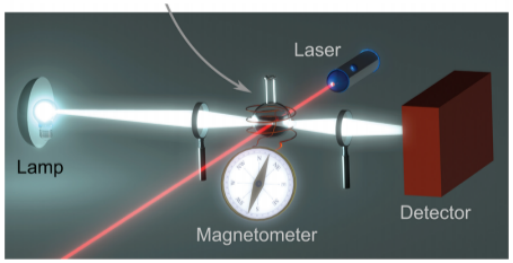

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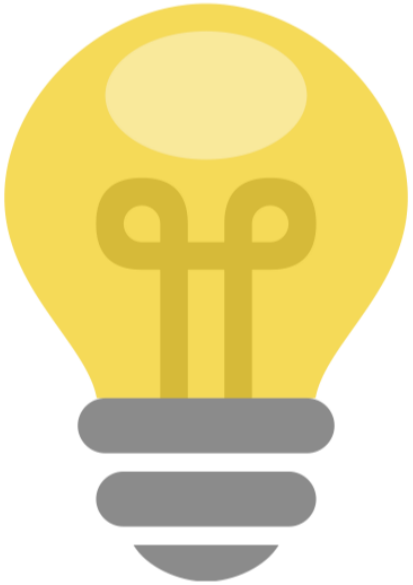

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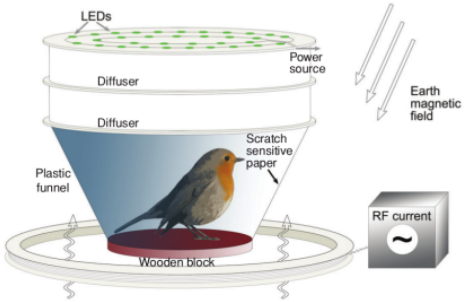

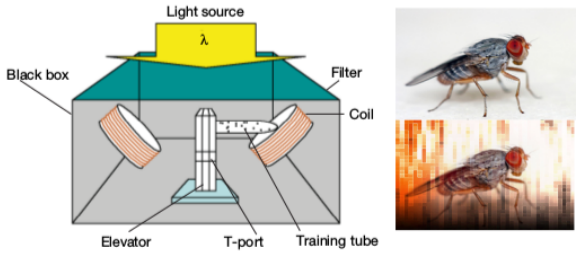

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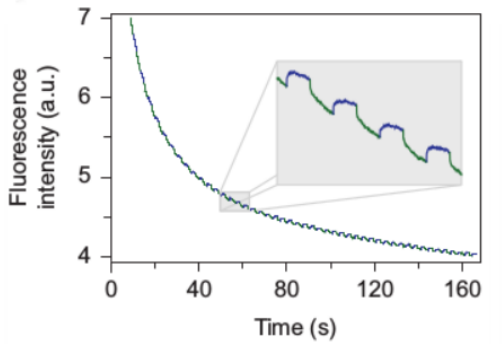

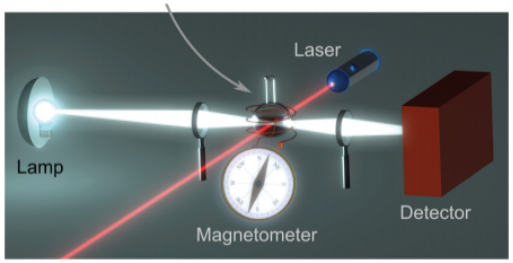

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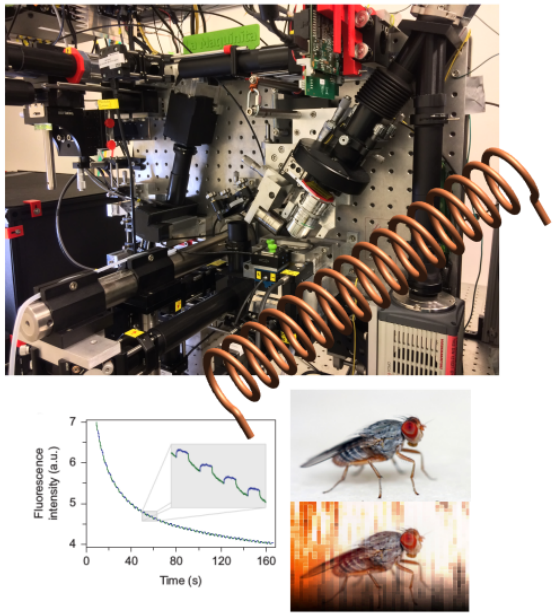

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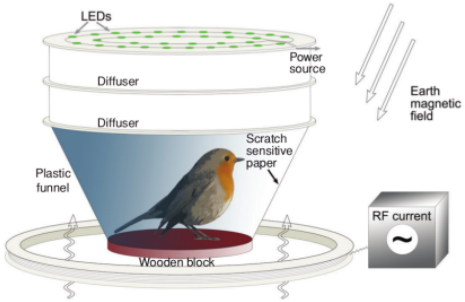

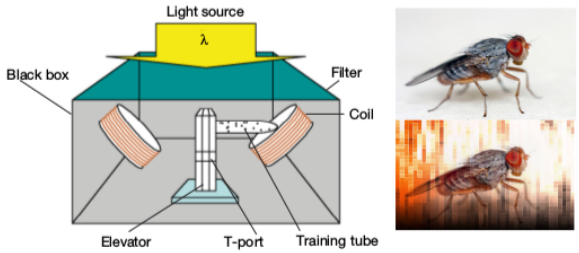

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Quantum + room temperature + noisy environments

Experimental capabilities developed for technological quantum sensing may enable establishment/refutation of living quantum sensing at physiologically relevant scales!

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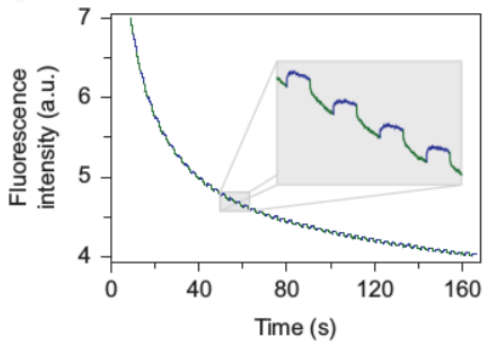
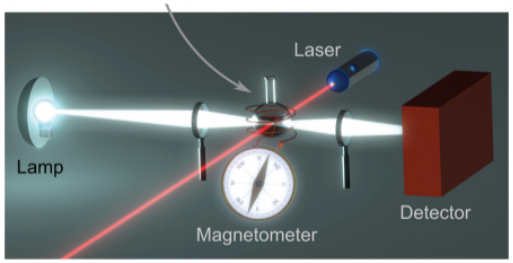
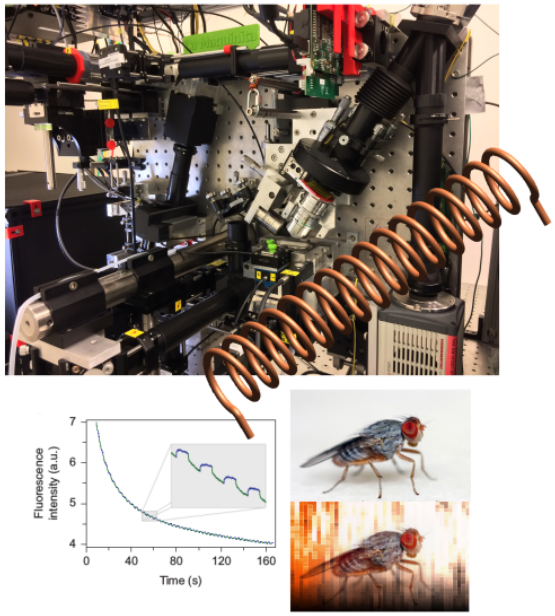
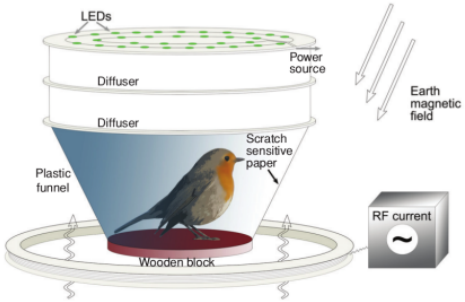


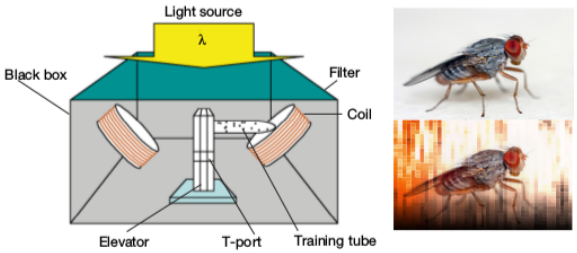


quantum for up to $\sim 1\ \mu s$ in solution, room temperature



magnetosensing in birds lost without right wavelength to excite photoreceptor cryptochrome





magnetosensing lost in cryptochrome knock-out flies

Image credit: Kattnig, *Nat. Chem.* **8**, 384 (16); Du, *J. Photochem. Photobiol.* **90**, 989 (14); Ritz, *Nature* **429**, 177 (04); Gegear, *Nature* **454**, 1014 (08)

(

Similarities with technological sensors (hello NV center!):

Quantum + room temperature + noisy environments

Similarities with technological sensors (hello NV center!):

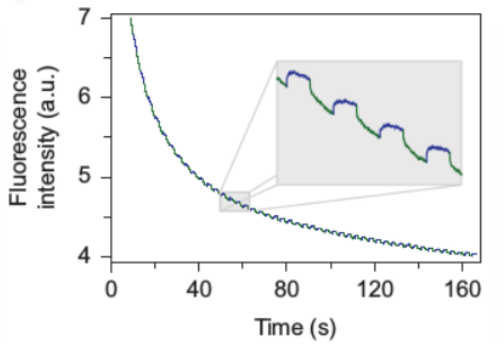
Quantum + room temperature + noisy environments

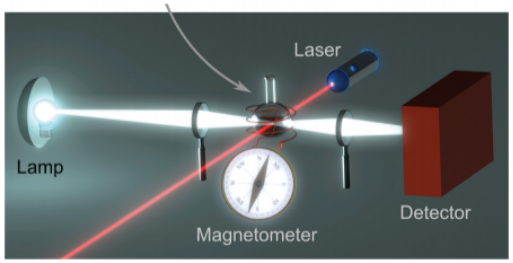
Evidence for cryptochrome-based magnetosensing abound...
...at disconnected length scales

Quantum + room temperature + noisy environments

Experimental capabilities developed for technological quantum sensing may enable establishment/refutation of living quantum sensing at physiologically relevant scales!

in vitro cryptochrome fluo modulated by magnetic fields





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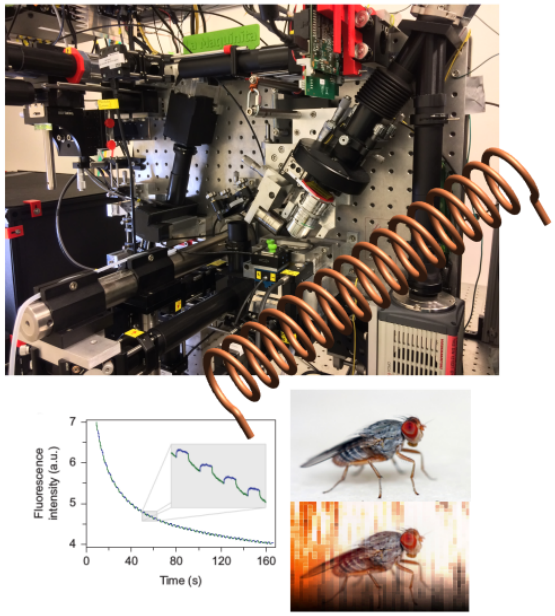

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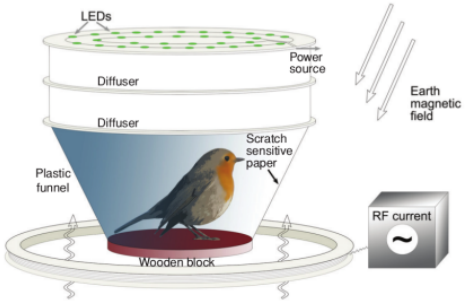

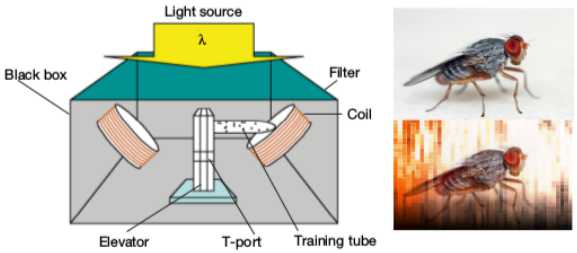

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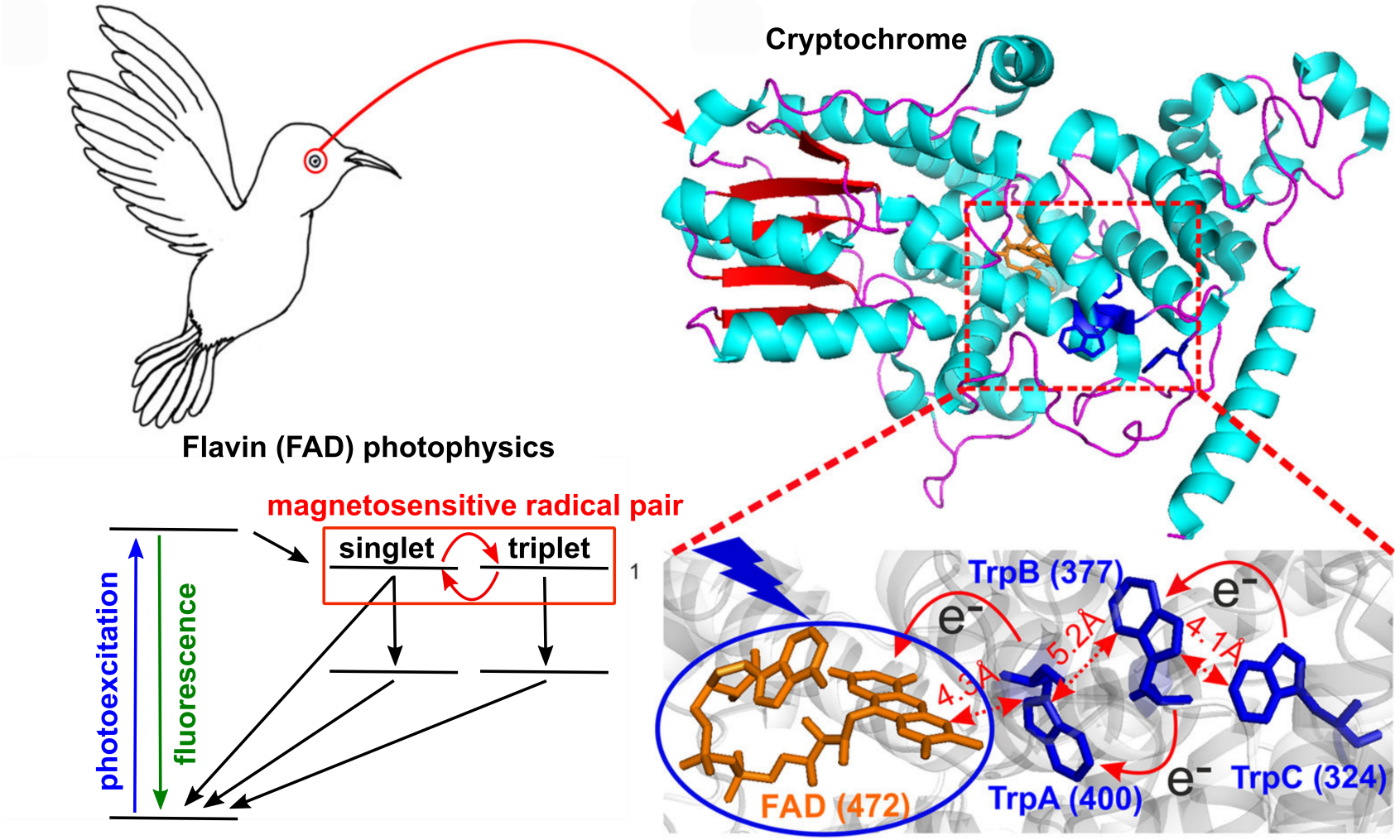
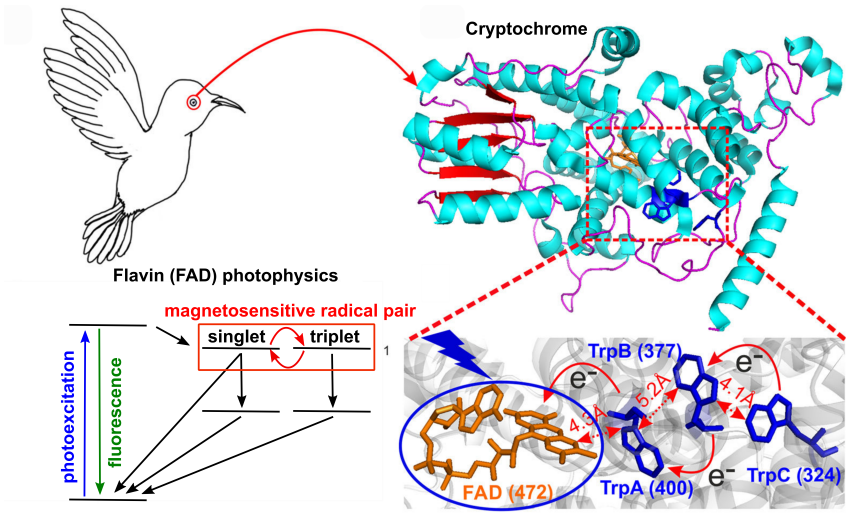
The experimental approach is driven by mathematical models

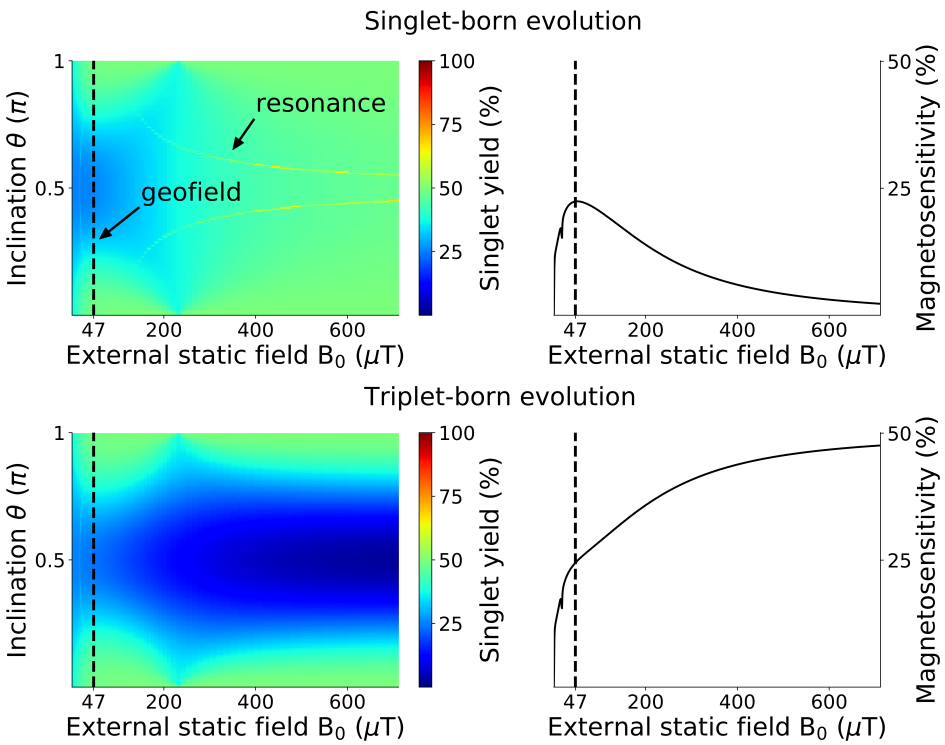
- photophysics/spin physics of cryptochrome (∼ flavin) is known



The experimental approach is driven by mathematical models

- photophysics/spin physics of cryptochrome ($\sim$ flavin) is known
- model predictions can be tested for first time at spin-physics length scales, ex.: radical pair is born in a singlet state





Same physics of magnetosensing might underlie relevant biosensing phenomena

SCIENTIFIC REPORTS

Article | OPEN | Published: 20 December 2016

The Quantum Biology of Reactive Oxygen Species Partitioning Impacts Cellular Bioenergetics

Robert J. Usselman, Cristina Chavarriaga, Pablo R. Castello, Maria Procopio, Thorsten Ritz, Edward A. Dratz, David J. Singel & Carlos F. Martino

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SHORT REPORTS

Low-intensity electromagnetic fields induce human cryptochrome to modulate intracellular reactive oxygen species

Rachel M. Sherrard, Natalie Morellini, Nathalie Jourdan, Mohamed El-Esawi, Louis-David Arthaut, Christine Niessner, Francois Rouyer, Andre Klarsfeld, Mohamed Doulazmi, Jacques Witczak, Alain d'Harlingue, Jean Mariani, Ian Mclure, Carlos F. Martino, Margaret Ahmad

Published: October 2, 2018 • https://doi.org/10.1371/journal.pbio.2006229

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BIOLOGICAL SCIENCES

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Magnetocarcinogenesis: is there a mechanism for carcinogenic effects of weak magnetic fields?

Jukka Juutilainen, Mikko Herrala, Jukka Luukkonen, Jonne Naarala, P. J. Hore

Published 23 May 2018. DOI: 10.1098/rspb.2018.0590

Same physics of magnetosensing might underlie relevant biosensing phenomena

Weak magnetic fields alter stem cell–mediated growth

Alanna V. Van Huizen[1], Jacob M. Morton[1], Luke J. Kinsey[1], Donald G. Von Kannon[1], Marwa A. Saad[1], Taylor R. Birkholz[1], Jordan M. Czajka[1], Julian Cyrus[2], Frank S. Barnes[2] and Wendy S. Beane[1,*]

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– Hide authors and affiliations

Science Advances 30 Jan 2019:
Vol. 5, no. 1, eaau7201
DOI: 10.1126/sciadv.aau7201

A Compass at Weak Magnetic Fields Using Thymine Dimer Repair

Theodore J. Zwang,[†] Edmund C. M. Tse,[†] Dongping Zhong,[*,‡] and Jacqueline K. Barton[*,†]

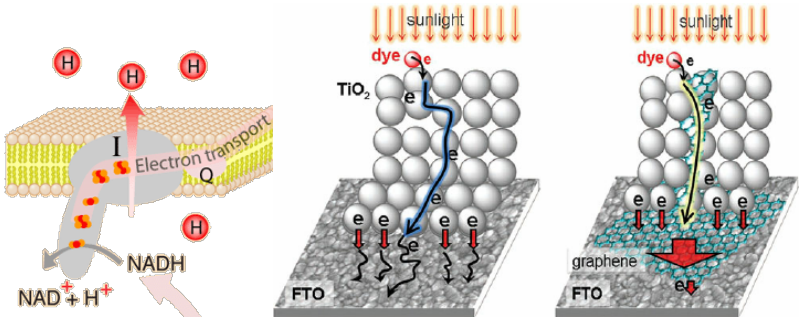
[†]Division of Chemistry and Chemical Engineering, California Institute of Technology, Pasadena, California 91125, United States

[‡]Departments of Chemistry and Physics, The Ohio State University, Columbus, Ohio 43210, United States

Supporting Information

ABSTRACT: How birds sense the variations in Earth's magnetic field for navigation is poorly understood, although cryptochromes, proteins homologous to photolyases, have been proposed to participate in this magnetic sensing. Here, in electrochemical studies with an applied magnetic field, we monitor the repair of cyclobutane pyrimidine dimer lesions in duplex DNA by photolyase, mutants of photolyase, and a modified cryptochrome. We find that the yield of dimer repair is dependent on the strength and angle of the applied magnetic field even when using magnetic fields weaker than 1 gauss. This high sensitivity to weak magnetic fields depends upon a fast radical pair reaction on the thymines leading to repair. These data illustrate chemically how cyclobutane pyrimidine dimer repair may be used in a biological compass informed by variations in Earth's magnetic field.

Technological features also driven by the same physical principles



cellular metabolism...
or improved charge transport?

Exploring the Structure of an Exchange-Coupled Triplet Pair Generated by Singlet Fission in Crystalline Diphenylhexatriene: Anisotropic Magnetic Field Effects on Fluorescence in High Fields

Kei Ishikawa, Tomoaki Yago*, and Masanobu Wakasa*
Department of Chemistry, Graduate School of Science and Engineering, Saitama University, 255 Shimo-Ohkubo, Sakura-ku, Saitama 338-8570, Japan

J. Phys. Chem. C, **2018**, *122* (39), pp 22264–22272
DOI: 10.1021/acs.jpcc.8b06026
Publication Date (Web): September 5, 2018

Cite this: *J. Phys. Chem. C* 2018, 122, 39, 22264-22272
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ELSEVIER
Organic Electronics
Volume 56, May 2018, Pages 11-15

Magnetic field effect of the singlet fission reaction in tetracene-based diodes

Magnetic Field Effects on Singlet Fission and Fluorescence Decay Dynamics in Amorphous Rubrene

Geoffrey B. Piland, Jonathan J. Burdett, Dharmalingam Kurunthu, and Christopher J. Bardeen*
Department of Chemistry, University of California, Riverside, Riverside, California 92521, United States

J. Phys. Chem. C, **2013**, *117* (3), pp 1224–1236
DOI: 10.1021/jp309286v
Publication Date (Web): December 22, 2012

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animal navigation... or improved photovoltaics?

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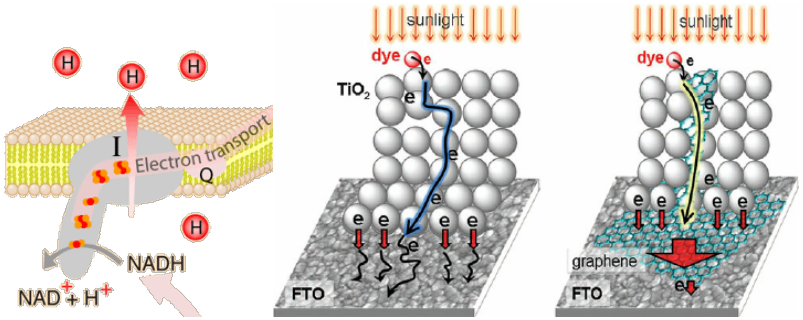

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animal navigation... or improved photovoltaics?

- electromagnetic probes utilizing technology developed over millions of years
  ⇒ ultrasensitive electromagnetic probes [health science, medical industry]
  ⇒ deployable sensors [military industry]
- understand/**control** of magnetic field effects
  ⇒ engineering of metabolic processes [health science, medical industry]
  ⇒ optimization of singlet fission (solar cells) [basic science, energy industry]
- biological information processing
  ⇒ quantum sensing/information/computing [basic science, 'quantum' industry]
- understand/**control** of electronic transport
  ⇒ optimization of charge transport (devices) [semiconductor industry]

Interference

Tunneling

Vibrations/noise-assisted processes

Spins 1: sensing magnetic fields

Spins 2: chiral-induced spin selectivity

Spins 3: computing with spins in the brain

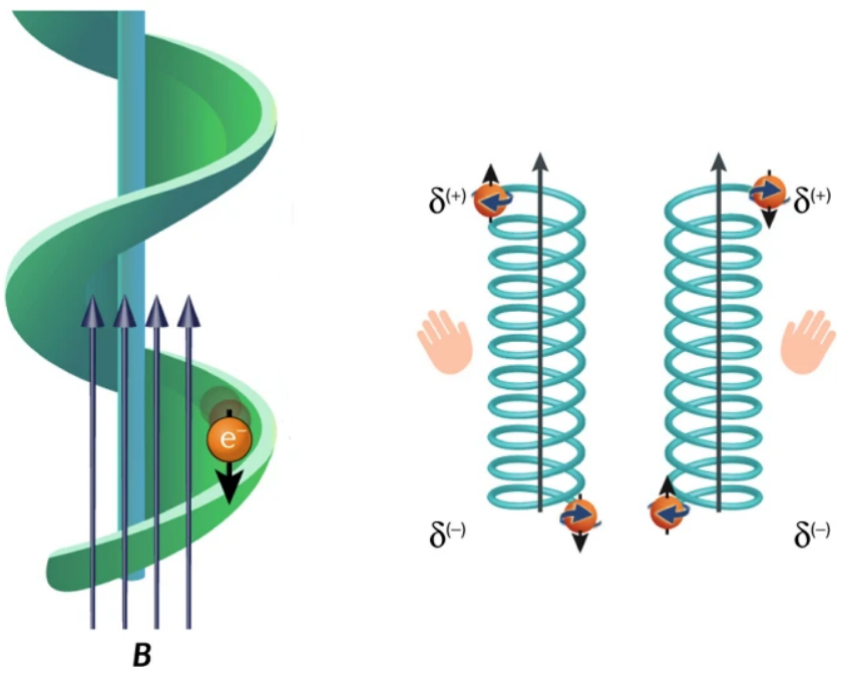
Quantum (info, sensing, computing)-inspired recent approaches

Things about which I don't have an opinion

What's in it for us as nanoresearchers?

Electron transport through nanoscopic chiral structures is more efficient than that through achiral structures due to spin-orbit coupling

- Naaman first experiments in DNA
  Science **331**, 894 (11)
- Recent spintronics boom
- All industries interested in charge transport should care!
- All biologists should care (DNA, α-helices...)!
- Surface effect?
- Spin filter vs. spin polarizer?
- Lacking definitive theoretical description



Adapted from Nat. Rev. Chem. **3**, 250 (19)

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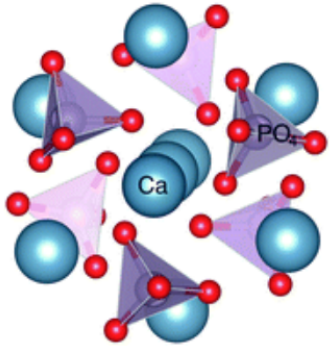
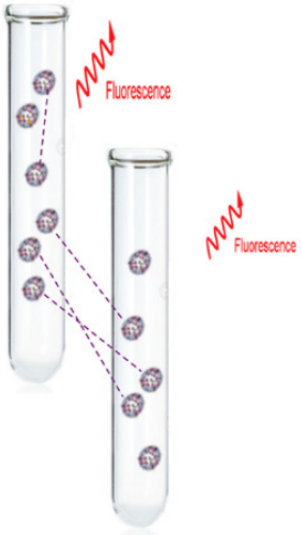
Might Posner molecules sustain long-lived coherent interactions in the brain?





Phys. Chem. Chem. Phys. **20**, 12373 (18)

- Fisher's theory: reverse-engineer possible long-lived spin interactions
- Solution: nuclear spins of P atoms bonded into nanoscale $Ca_9(PO_4)_6$
- Such 'optimal' molecules exist ('Posner'), currently being investigated by multi-researcher team at UCSB

Interference

Tunneling

Vibrations/noise-assisted processes

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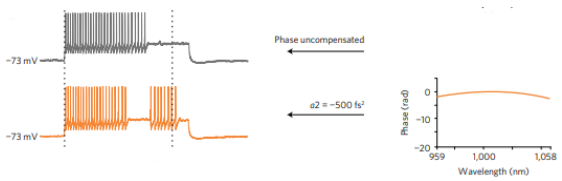
Quantum (info, sensing, computing)-inspired recent approaches

Things about which I don't have an opinion

What's in it for us as nanoresearchers?

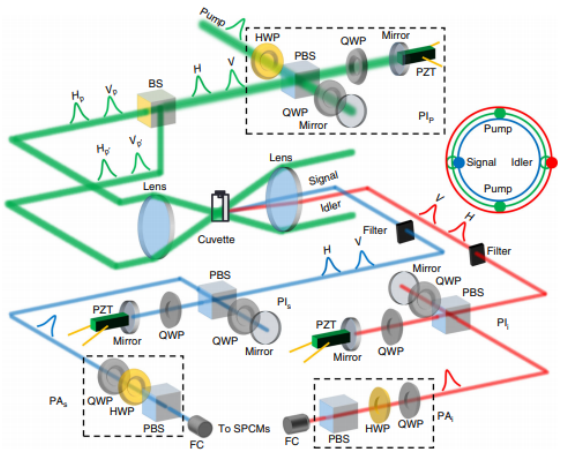
Quantum (info, sensing, computing)-inspired recent approaches

Experiment: coherent control of opsins in live tissue



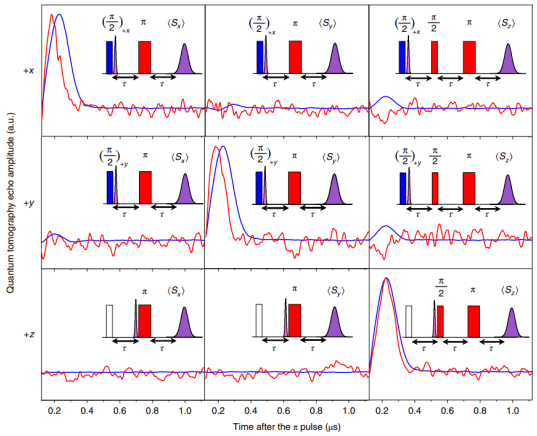
Paul et al., Nat. Phys. **13** 1111 (17)

Experiment: photon entanglement in green fluo protein



Shi et al., Nat. Comms. **8** 1934 (17)

Experiment: photodriven quantum teleportation of an electron spin in a radical system



Rugg et al., Nat. Chem. Sept 19

+ Theory: Grover's search algorithm might be naturally occurring Arxiv.org/abs/19 08.11213

Interference

Tunneling

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Quantum (info, sensing, computing)-inspired recent approaches

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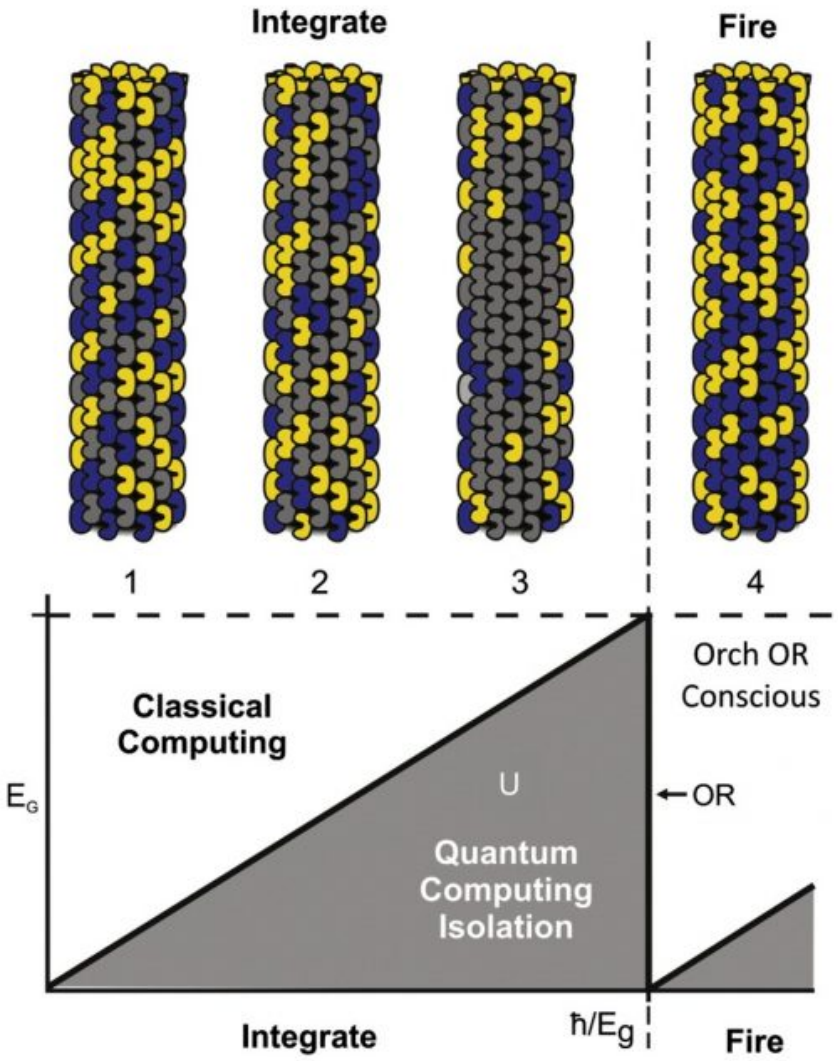
What's in it for us as nanoresearchers?

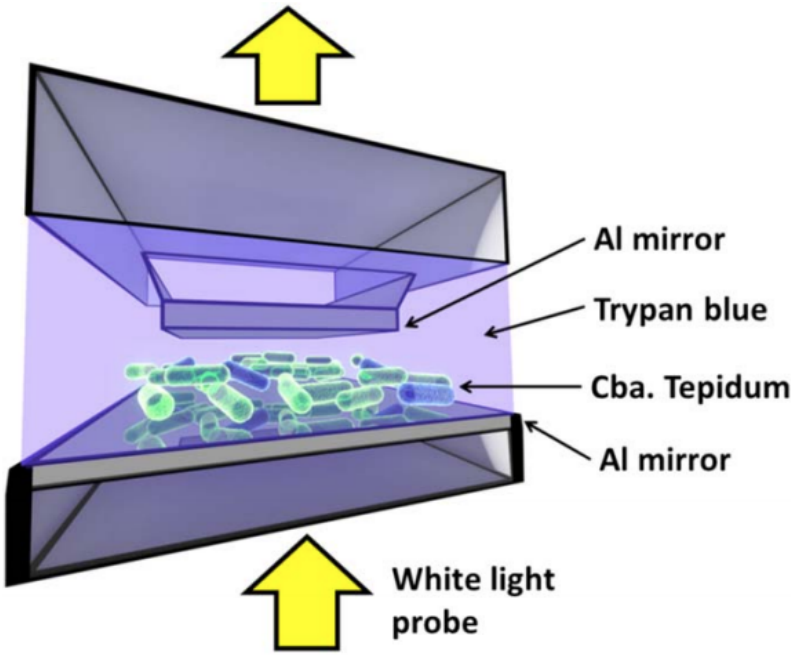
Things about which I don't have an opinion

Penrose's theory on
'quantum consciousness'



Microtubules (motivation: *symmetry*)

Vedral's theory on
the 'quantum bacterium'



Paul et al., J. Phys. Commun. **2** 101001 (17)

Claim: interpret existing data as evidence for strong coupling and entanglement between photon/bacterium

Interference

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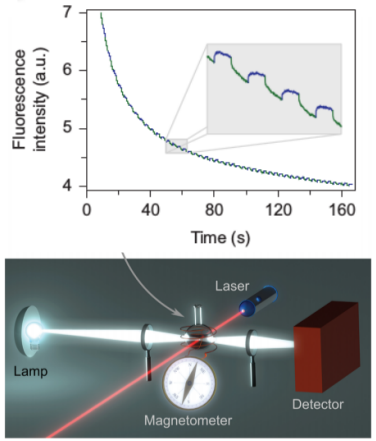
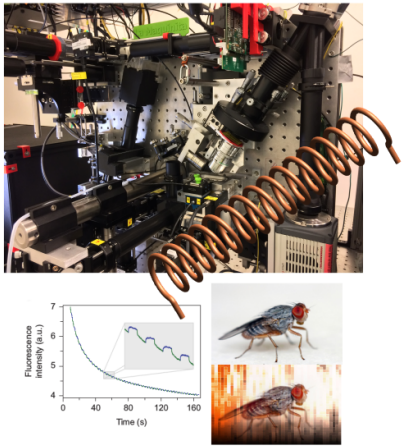
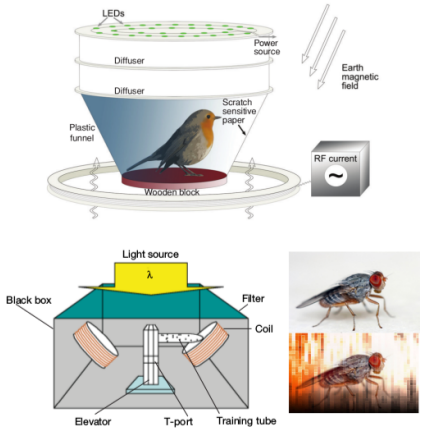
What's in it for us as nanoresearchers?

Quantum Biology as a multi-scale, multi-discipline effort





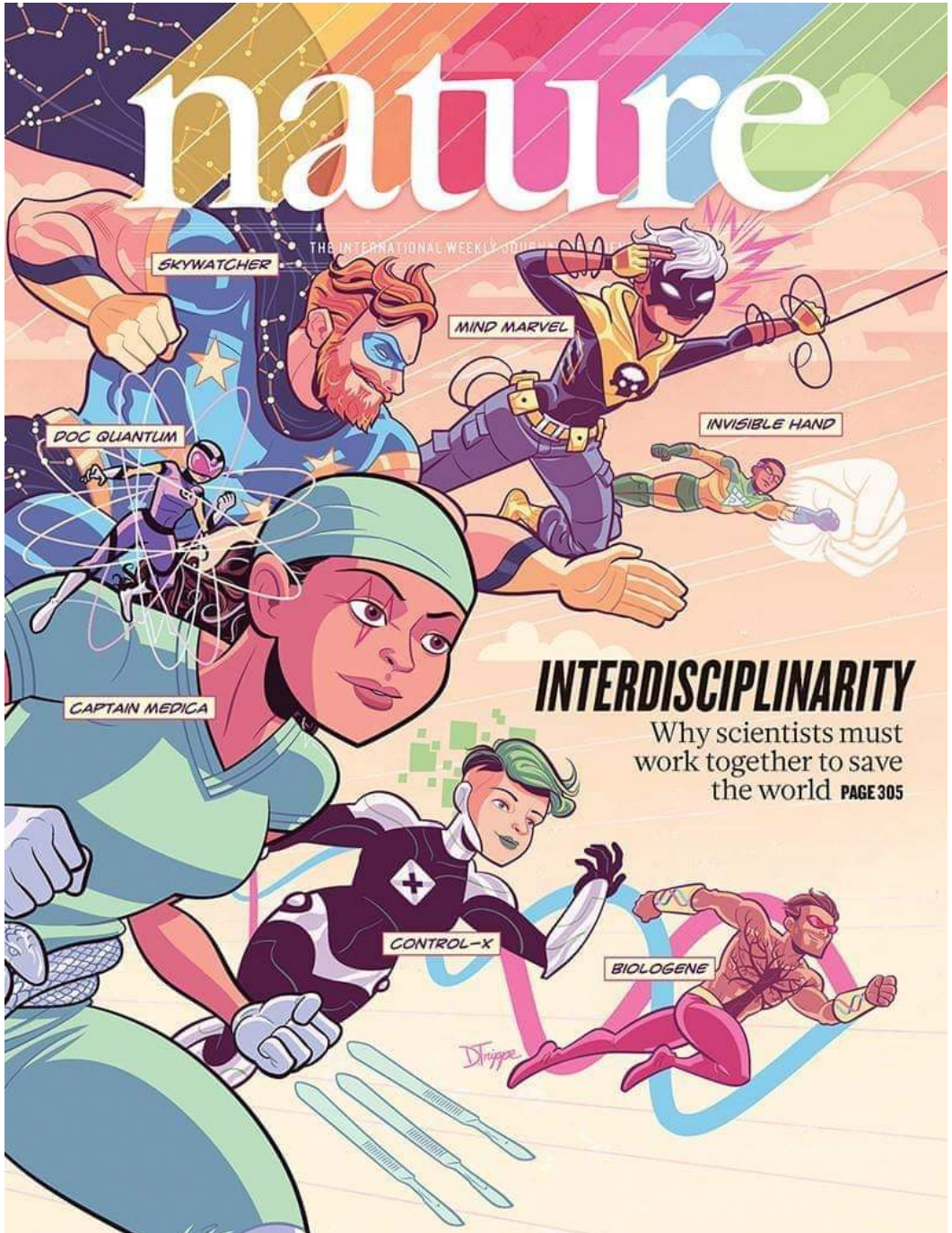


- Think about multi-scale, multi-discipline collaborations – nano expertise needed!
- More organized hubs: Germany (Center of Quantum BioScience), Japan (Institute of Quantum Life Science), England, Israel... – need one in the US!

- Surrey is the world's first (and only) Quantum Biology doctoral training center
- Efforts at ugrad level as well (ex.: $\sim$ iGEM competition, for synh. bio.)

- NSF sponsored workshop on 'Quantum Processes in Biology' (18), this talk
- 'Quantum leap' as one of NSF's big ideas – extend to biology!

Quantum Biology as a multi-scale, multi-discipline effort



Can quantum physics be established – or refuted! – to account for physiologically relevant biosensing phenomena,
and be manipulated to technological and therapeutic advantage?

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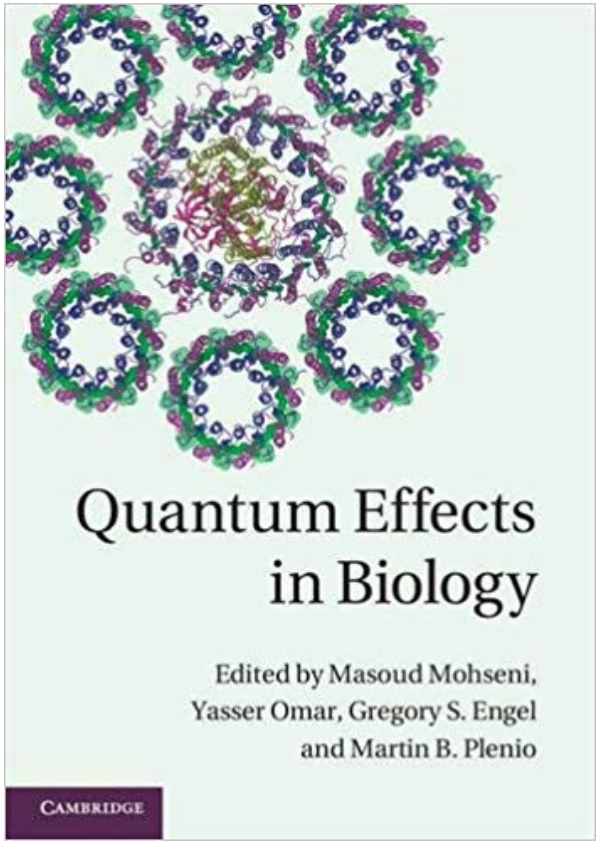

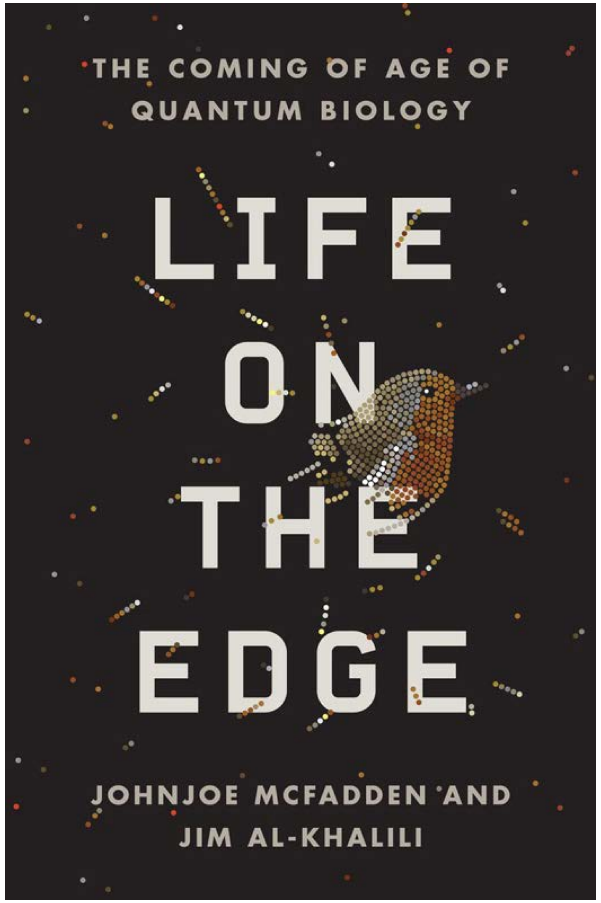

+ Article 'Quantum biology may help solve some of life's greatest mysteries' (The Scientist magazine, bit.ly/quantumbio_nicearticle)
+ Apparently new layman book in 2020

Can quantum physics be established – or refuted! – to account for physiologically relevant biosensing phenomena,
and be manipulated to technological and therapeutic advantage?

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QUantum BIology Tech Lab

We're open for collaborations! And we're hiring! At all levels! Internships too!
Interested? Let's talk!
Contact me: cla@ucla.edu