Let's talk about sensors...

Clarice Aiello

Prakash lab, Stanford University

Current sensor

pA

Magnetic sensor

μT, cryo temps

Light sensor

single photon

Smell sensor

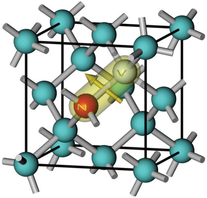
...

Before I explain where I am going, I need to tell where I come from.

(

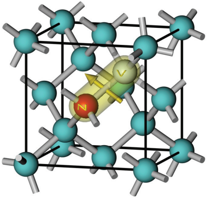
Quantum sensing and control with single spin qubit in diamond @ MIT, Cappellaro group

- vacancy next to substitutional nitrogen



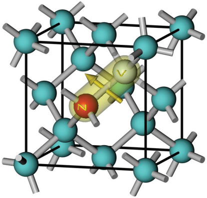
Quantum sensing and control with single spin qubit in diamond @ MIT, Cappellaro group

- vacancy next to substitutional nitrogen
- absorbs light and fluoresces:
  quantum state-dependent fluo intensity



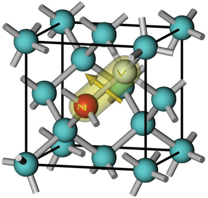
Quantum sensing and control with single spin qubit in diamond @ MIT, Cappellaro group

- vacancy next to substitutional nitrogen
- absorbs light and fluoresces:
  quantum state-dependent fluo intensity
- coherence times $\sim \mu$s
  at room-temperature,
  in messy lattice environment

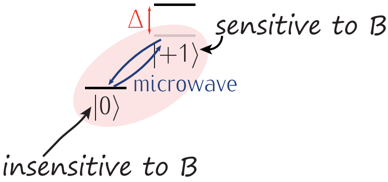


Quantum sensing and control with single spin qubit in diamond @ MIT, Cappellaro group

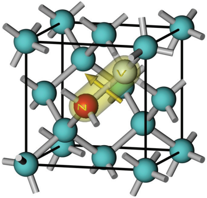
- vacancy next to substitutional nitrogen
- absorbs light and fluoresces:
  quantum state-dependent fluo intensity
- coherence times $\sim \mu s$
  at room-temperature,
  in messy lattice environment



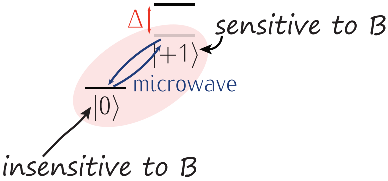
- very sensitive magnetometer...
  Taylor et al., Nat. Phys. **4**, 810 (08); Maze et al., Nature **455**, 644 (08)



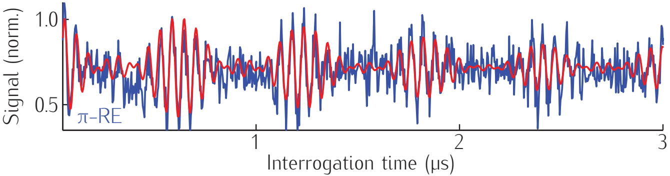
Quantum sensing and control with single spin qubit in diamond @ MIT, Cappellaro group



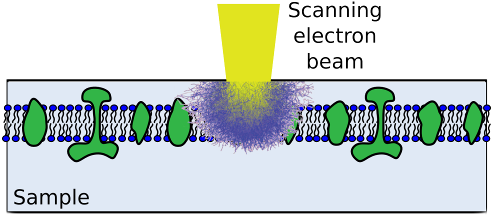
- vacancy next to substitutional nitrogen
- absorbs light and fluoresces:
  quantum state-dependent fluo intensity
- coherence times $\sim \mu s$
  at room-temperature,
  in messy lattice environment



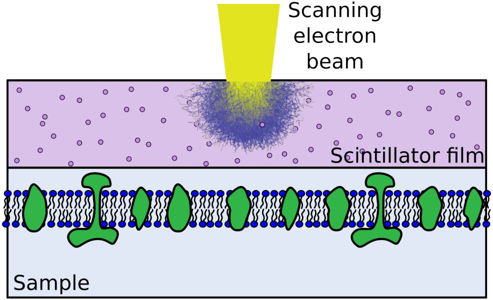
- very sensitive magnetometer...
  Taylor et al., Nat. Phys. **4**, 810 (08); Maze et al., Nature **455**, 644 (08)
- ...under different noisy environments
  Aiello et al., Nat. Comms. **4**, 1419 (13)



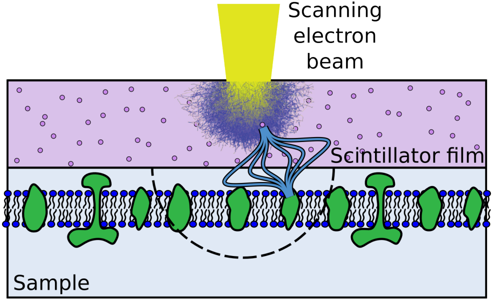
CathodoLuminescence-Activated Imaging by Resonant Energy transfer (CLAIRE) @ Berkeley, Ginsberg group

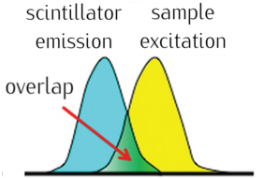


CathodoLuminescence-Activated Imaging by Resonant Energy transfer (CLAIRE) @ Berkeley, Ginsberg group



CathodoLuminescence-Activated Imaging by Resonant Energy transfer (CLAIRE) @ Berkeley, Ginsberg group

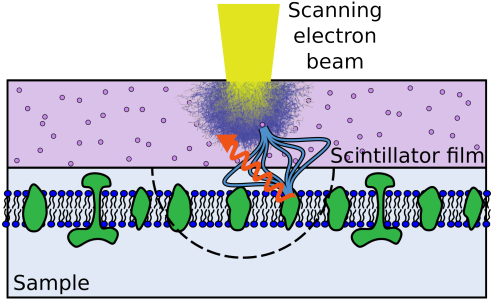


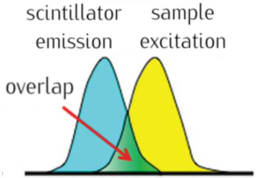


transfer radius $\sim$ 10 nm

- relies on resonant energy transfer:
  room-temperature quantum effect in messy environment

CathodoLuminescence-Activated Imaging by Resonant Energy transfer (CLAIRE) @ Berkeley, Ginsberg group

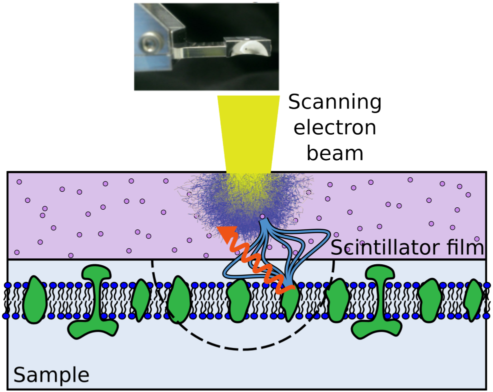


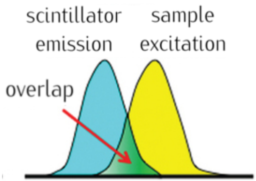


transfer radius $\sim$ 10 nm

- relies on resonant energy transfer:
  room-temperature quantum effect in messy environment

CathodoLuminescence-Activated Imaging by Resonant Energy transfer (CLAIRE) @ Berkeley, Ginsberg group

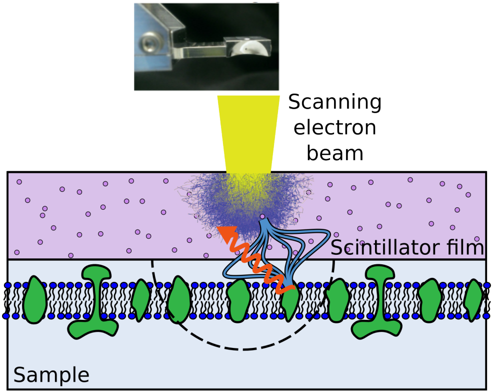


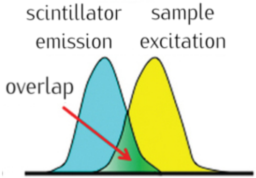


transfer radius $\sim$ 10 nm

- relies on resonant energy transfer:
  room-temperature quantum effect in messy environment
- high-resolution: electron beam imprint
- non-invasive: sample is protected from harmful radiation

CathodoLuminescence-Activated Imaging by Resonant Energy transfer (CLAIRE) @ Berkeley, Ginsberg group





transfer radius $\sim$ 10 nm

- relies on resonant energy transfer:
  room-temperature quantum effect in messy environment
- high-resolution: electron beam imprint
- non-invasive: sample is protected from harmful radiation

Serendipity: sample = cryptochrome

Until here: lots of sensing and imaging at the nanoscale...

Until here: lots of sensing and imaging at the nanoscale...

...aided by quantum phenomena

Until here: lots of sensing and imaging at the nanoscale...
...aided by quantum phenomena
at room-temperature

Until here: lots of sensing and imaging at the nanoscale...

...aided by quantum phenomena

at room-temperature

in messy environments.

)

Let's talk about sensors...

Clarice Aiello

Prakash lab, Stanford University

Current sensor	Magnetic sensor	Light sensor	Smell sensor
			
pA	μT, cryo temps	single photon	...

Let's talk about living sensors... ...because nature has a million–year head–start on engineering!

Clarice Aiello

Prakash lab, Stanford University

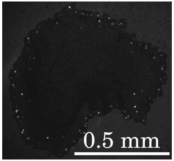
Current sensor

single e^-, ultrafast

Magnetic sensor

μT, room temp

Light sensor



single cell (?)

Smell sensor

mile–far molecule

Let's talk about living sensors...
...because nature has a million-year head-start on engineering!

Clarice Aiello

Prakash lab, Stanford University

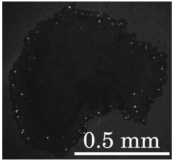
Current sensor

single e^-, ultrafast

Magnetic sensor

μT, room temp

Light sensor



single cell (?)

Smell sensor

mile-far molecule

Let's talk about living sensors...
...because nature has a million-year head-start on engineering!

Clarice Aiello

Prakash lab, Stanford University

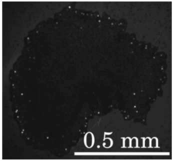
Current sensor

single e^-, ultrafast

Magnetic sensor

μT, room temp

Light sensor



single cell (?)

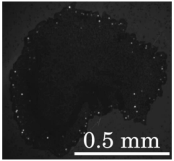
Smell sensor

mile-far molecule

Unraveling *in vivo* magnetosensing

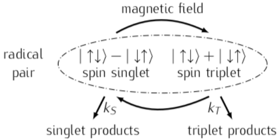
Clarice Aiello

Prakash lab, Stanford University

Current sensor	Magnetic sensor	Light sensor	Smell sensor
			
single e$^-$, ultrafast	μT, room temp	single cell (?)	mile-far molecule

Magnetic fields can alter products of photo-dependent chemical reactions involving unpaired electrons (a.k.a. 'radical pairs')

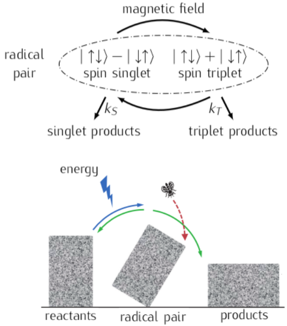
- 'tis a fact!, **demonstrated**
  at room temperature,
  in solution,
  down to geofield strengths



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

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

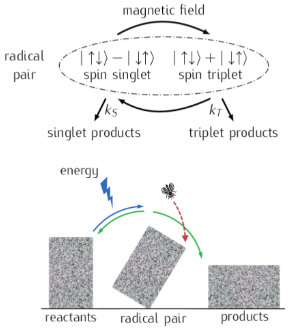
- ’tis a fact!, **demonstrated** at room temperature, in solution, down to geofield strengths
- **consistent** with depending on spin quantum state of the radical pair



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

Magnetic fields can alter products of photo-dependent chemical reactions involving unpaired electrons (a.k.a. 'radical pairs')

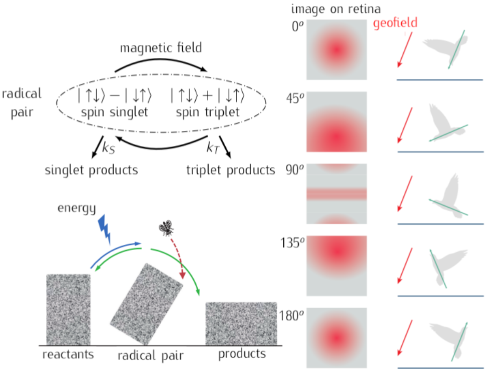
- 'tis a fact!, **demonstrated**
  at room temperature,
  in solution,
  down to geofield strengths
- **consistent** with depending
  on spin quantum state
  of the radical pair
- Hypothesis:
  same mechanism under
  physiological conditions



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

Magnetic fields can alter products of photo-dependent chemical reactions involving unpaired electrons (a.k.a. 'radical pairs')

- 'tis a fact!, **demonstrated**
  at room temperature,
  in solution,
  down to geofield strengths
- **consistent** with depending
  on spin quantum state
  of the radical pair
- Hypothesis:
  same mechanism under
  physiological conditions

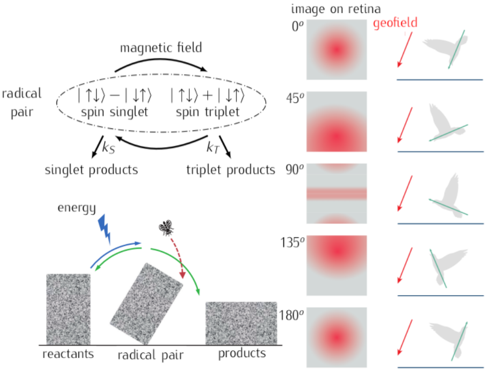


Adapted from Hore et al., Annu. Rev. Biophys. **45**, 299 (16)

- only animal protein known to sustain radical pairs: photoreceptor cryptochrome (ex.: retina of birds, fruit flies, cockroaches)

Magnetic fields can alter products of photo-dependent chemical reactions involving unpaired electrons (a.k.a. 'radical pairs')

- 'tis a fact!, **demonstrated**
  at room temperature,
  in solution,
  down to geofield strengths
- **consistent** with depending
  on spin quantum state
  of the radical pair
- Hypothesis:
  same mechanism under
  physiological conditions

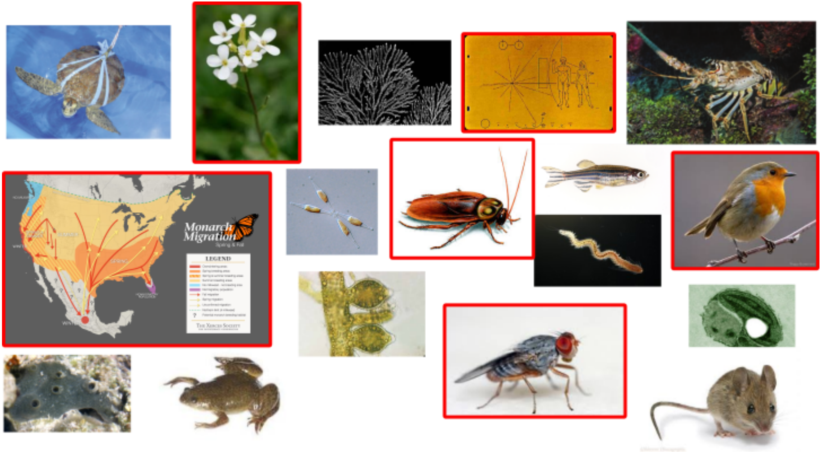


Adapted from Hore et al., Annu. Rev. Biophys. **45**, 299 (16)

- only animal protein known to sustain radical pairs: photoreceptor cryptochrome
  (ex.: retina of birds, fruit flies, cockroaches)
- cryptochrome broadly expressed
  (also circadian rhythm entrainment)

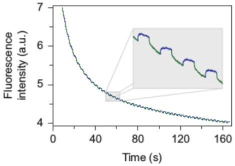
Magnetosensing mechanism may be universal across vastly diverse species

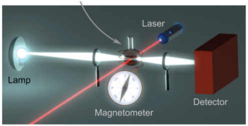
organisms known to express cryptochrome/ $\boxed{\text{magnetosensing studies on cryptochrome}}$



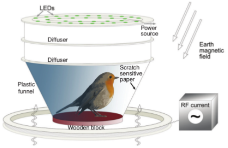
Evidence for cryptochrome-based magnetosensing abound...

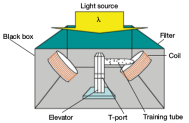
in vitro cryptochrome fluo
modulated by magnetic fields





magnetosensing in birds lost
without right wavelength to excite
photoreceptor cryptochrome



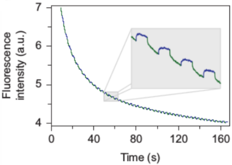


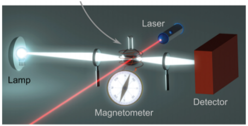
magnetosensing lost
in cryptochrome knock-out flies

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

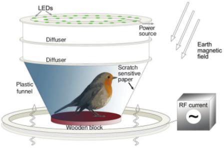
Evidence for cryptochrome-based magnetosensing abound...
...at disconnected length scales

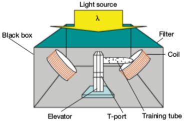
in vitro cryptochrome fluo
modulated by magnetic fields





magnetosensing in birds lost
without right wavelength to excite
photoreceptor cryptochrome

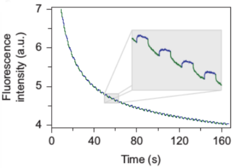


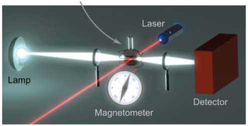


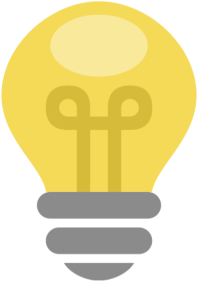
magnetosensing lost
in cryptochrome knock-out flies

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

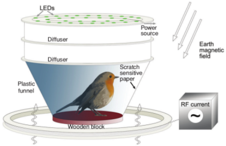
in vitro cryptochrome fluo
modulated by magnetic fields

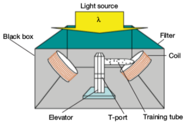






magnetosensing in birds lost
without right wavelength to excite
photoreceptor cryptochrome

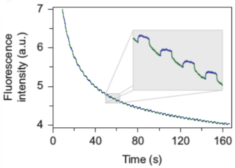


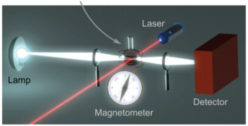


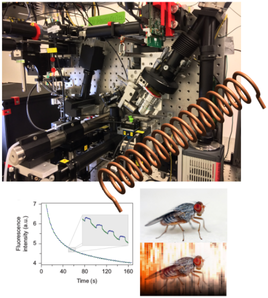
magnetosensing lost
in cryptochrome knock-out flies

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

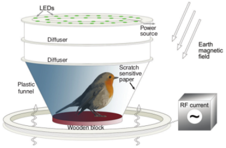
in vitro cryptochrome fluo
modulated by magnetic fields

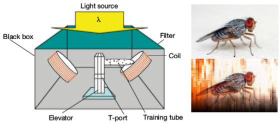






magnetosensing in birds lost
without right wavelength to excite
photoreceptor cryptochrome



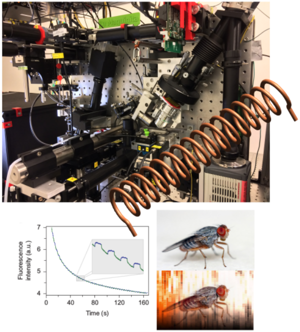


magnetosensing lost
in cryptochrome knock-out flies

lattice light-sheet microscopy + tailored magnetic field excitation
= observe *in vivo* magnetosensing signatures at physiologically relevant scales!

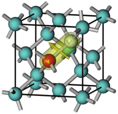
But... can radical pairs be coherent under physiological conditions?

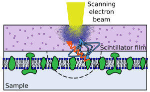
if sensitive to geofield ($\sim 50\ \mu$T)
then coherence $\gtrsim$ 1/Larmor $\sim$ 1/1.4 MHz $\sim 0.7\ \mu$s

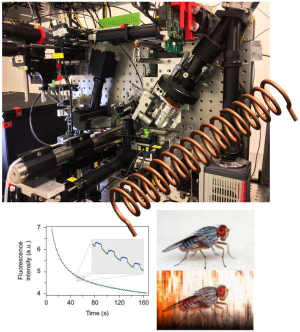


But... can radical pairs be coherent under physiological conditions?

if sensitive to geofield ($\sim 50\ \mu$T)
then coherence $\gtrsim$ 1/Larmor $\sim$ 1/1.4 MHz $\sim$ 0.7 μs



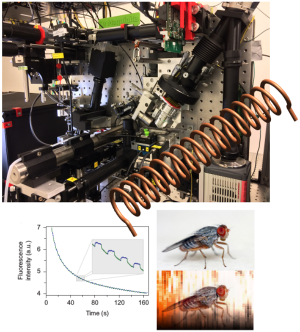




But... can radical pairs be coherent under physiological conditions?

if sensitive to geofield ($\sim$ 50 μT)
then coherence $\gtrsim$ 1/Larmor $\sim$ 1/1.4 MHz $\sim$ 0.7 μs

in vitro cryptochrome coherence at 1 ^{o}C $\sim$ 10 μs
related molecule room-temperature $\sim$ 1 μs
Biskup et al., Angew. Chem. Int. Ed **48**, 404 (09); Henbest et al., PNAS **105**, 14395 (08)



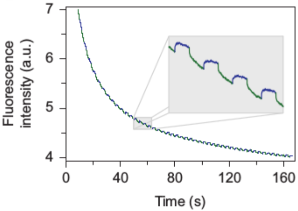
But... can radical pairs be coherent under physiological conditions?

if sensitive to geofield ($\sim 50\ \mu$T)
then coherence $\gtrsim$ 1/Larmor $\sim$ 1/1.4 MHz $\sim 0.7\ \mu$s

in vitro cryptochrome coherence at 1 ^{o}C $\sim 10\ \mu$s
related molecule room-temperature $\sim 1\ \mu$s

Biskup et al., Angew. Chem. Int. Ed **48**, 404 (09); Henbest et al., PNAS **105**, 14395 (08)

quantum state-dependent
fluo intensity



Kattnig et al., Nat. Chem. **8**, 384 (16)

in vivo modulation of cryptochrome fluorescence intensity

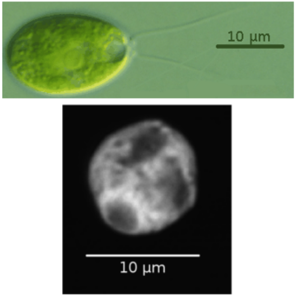
$\Leftrightarrow$

evidence that radical pairs can be coherent for long enough *in vivo*

$\Leftrightarrow$

observe *in vivo* magnetosensing signatures at physiologically relevant scales!

First cryptochrome localization assays underway in different model organisms



Chlamydomonas
(unicellular alga)

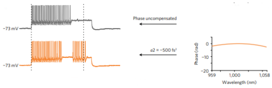
painted lady
(butterfly)

Drosophila
(fly)

Can quantum physics inform biology at the nanoscale?

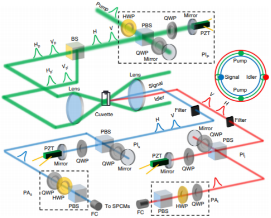
Can quantum physics inform biology at the nanoscale?

coherent control of opsins
in live tissue



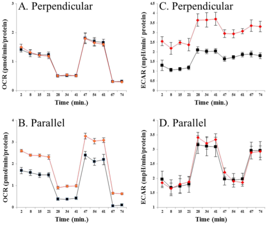
Paul et al., Nat. Phys. **13** 1111 (17)

photon entanglement
in green fluo protein

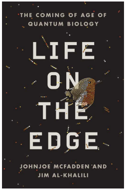


Shi et al., Nat. Comms. **8** 1934 (17)

cell metabolic differences
due to quantum effects



Usselman et al., Sci. Rep. **6** 38543 (16)



Unraveling *in vivo* magnetosensing

Clarice Aiello

Prakash lab, Stanford University

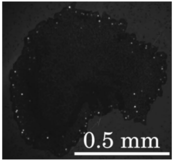
Current sensor

single e^{-}, ultrafast

Magnetic sensor

μT, room temp

Light sensor



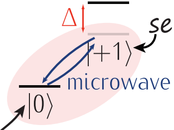
single cell (?)

Smell sensor

mile-far molecule

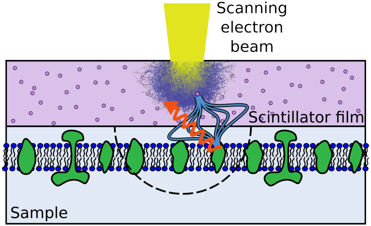
May the quantum be with you!

magnetosensing
with a qubit in diamond

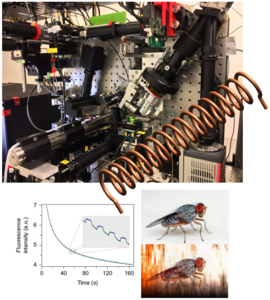


sensitive to B

insensitive to B



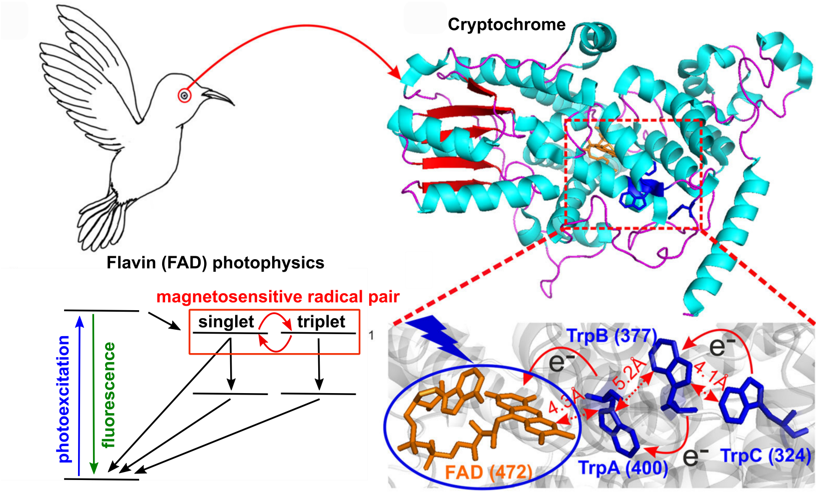
high-res imaging
via resonant energy transfer



¿ *in vivo* magnetosensing
aided by radical pairs ?

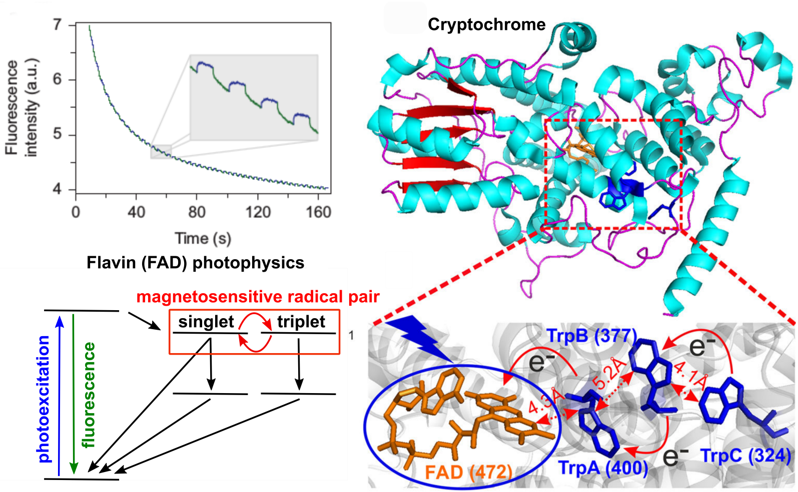
Many thanks!: Cappellaro group (Masashi Hirose), Ginsberg group (Rebecca Wai, Connor Bischak), Prakash lab (Dannielle McCarthy, Chew Chai, Laurel Kroo)

Cryptochrome photophysics is well understood



Adapted from Paul at al., Sci. Rep. **7**, 11892 (17)

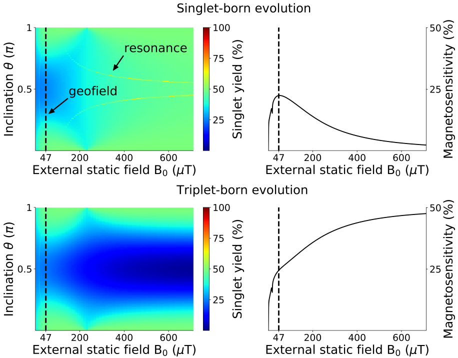
Cryptochrome photophysics is well understood



Adapted from Paul et al., Sci. Rep. **7**, 11892 (17)

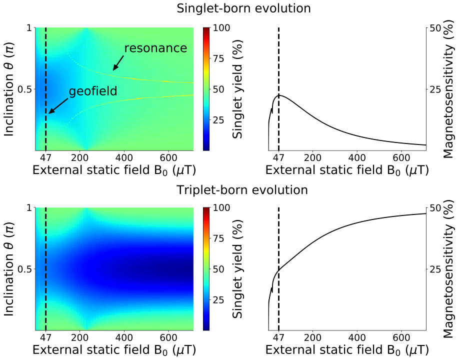
Predictions can be made and possibly experimentally verified...

ex: radical pair is born in a singlet state



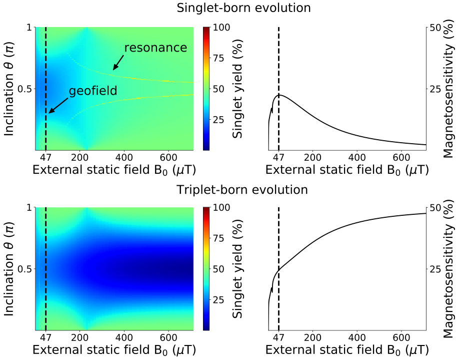
Predictions can be made and possibly experimentally verified...
(esp. using single-molecule techniques on purified cryptochrome)
(never 'been done)

ex: radical pair is born in a singlet state

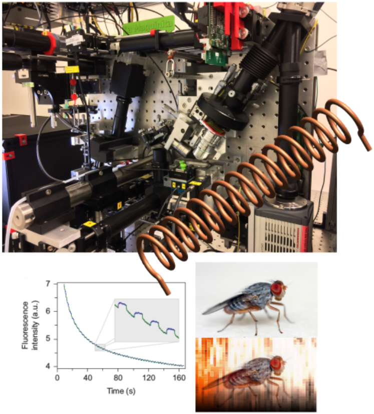


Predictions can be made and possibly experimentally verified...

ex: radical pair is born in a singlet state

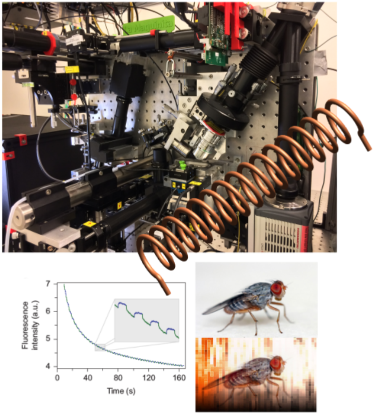


Predictions can be made and possibly experimentally verified...
...but not for now. For now:



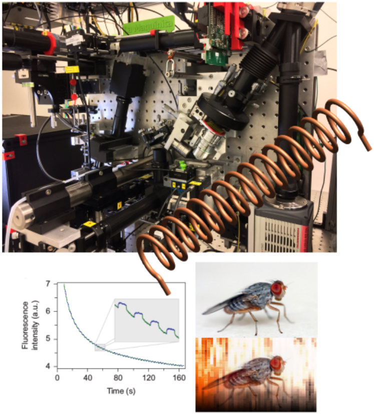
= *in vivo* modulation of cryptochrome fluorescence intensity

Predictions can be made and possibly experimentally verified...
...but not for now. For now:



= *in vivo* modulation of cryptochrome fluorescence intensity
= evidence that radical pairs can be coherent for long enough *in vivo*

Predictions can be made and possibly experimentally verified...
...but not for now. For now:



= *in vivo* modulation of cryptochrome fluorescence intensity
= evidence that radical pairs can be coherent for long enough *in vivo*
= observe *in vivo* magnetosensing signatures at physiologically relevant scales!