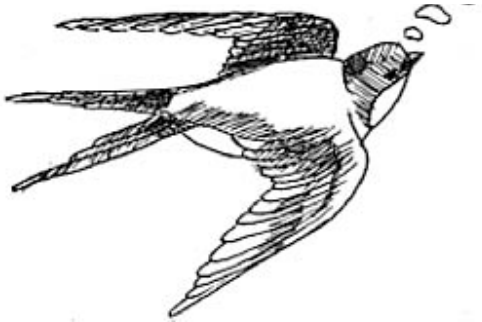
Quantum Biology of Animal Navigation



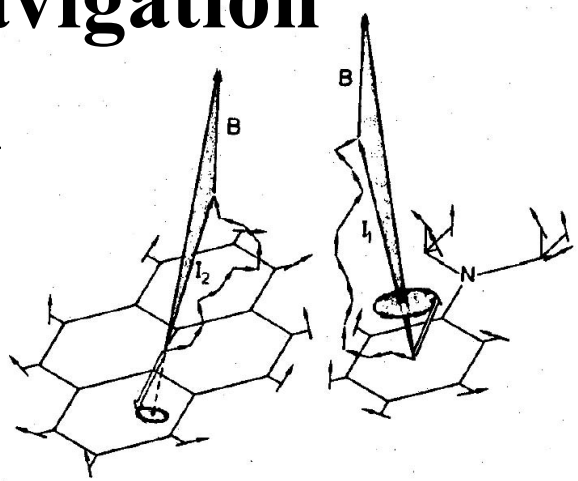
Lecture at University of British Columbia

April 2011

Klaus Schulten

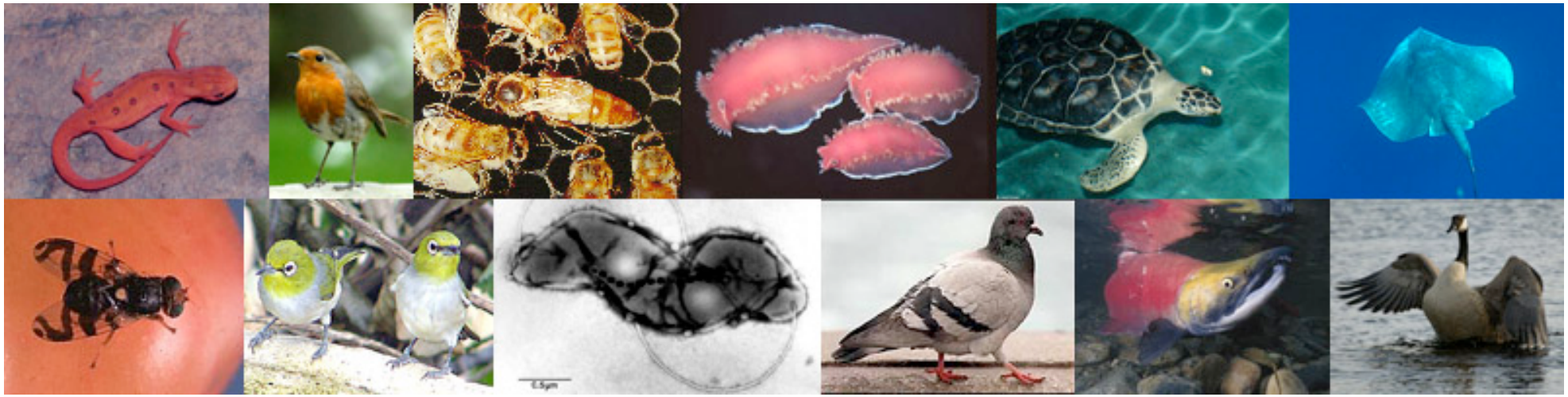
Dept. Physics and Beckman Institute

University of Illinois at Urbana-Champaign



Magnetoreception in Animals

Magnetoreception exists in a wide variety of animals, including migratory birds, sea turtles, bees, fruit flies, mollusks, fish, salamanders, and bacteria.



Magnetoreception in Animals

The use of a magnetic compass by migratory birds was first demonstrated for European robins in 1966 in Frankfurt am Main (Germany).

(Wiltschko W. and Merkel F., *Verh. Dt. zool. Ges.*, **59**, 362, 1966)

European Robin
(*Erithacus rubecula*)

Australian silvereyes
(*Zosterops lateralis*)

Garden warblers
(*Sylvia borin*)

Homing pigeons
(*Columba livia*)

Later, this sensory capability was demonstrated in 17 further species.

(Wiltschko W. and Wiltschko R., *J. Exp. Biol.* **199**, 29, 1996).

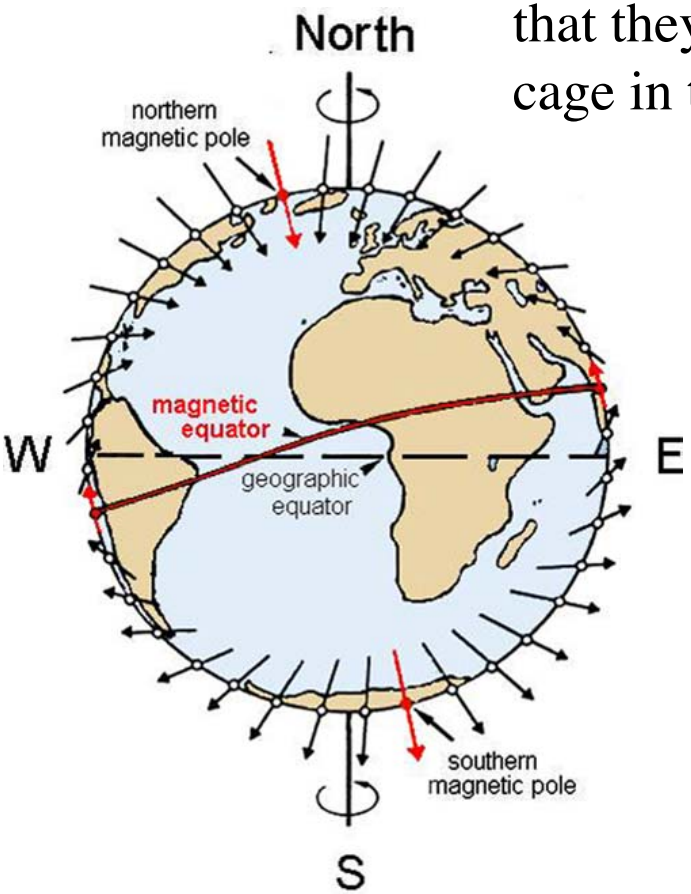
Magnetoreception in Animals

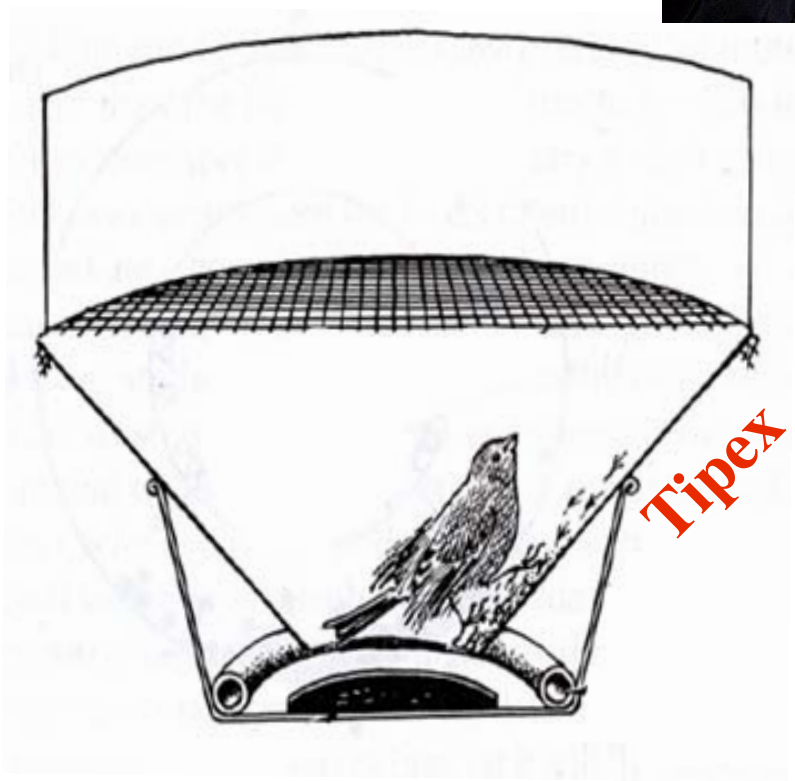
Navigating birds “cheat”, observation difficult, except for Dr. Doolitle

Avian Magnetoreception

Migratory birds use the earth's magnetic field to orient themselves during migration

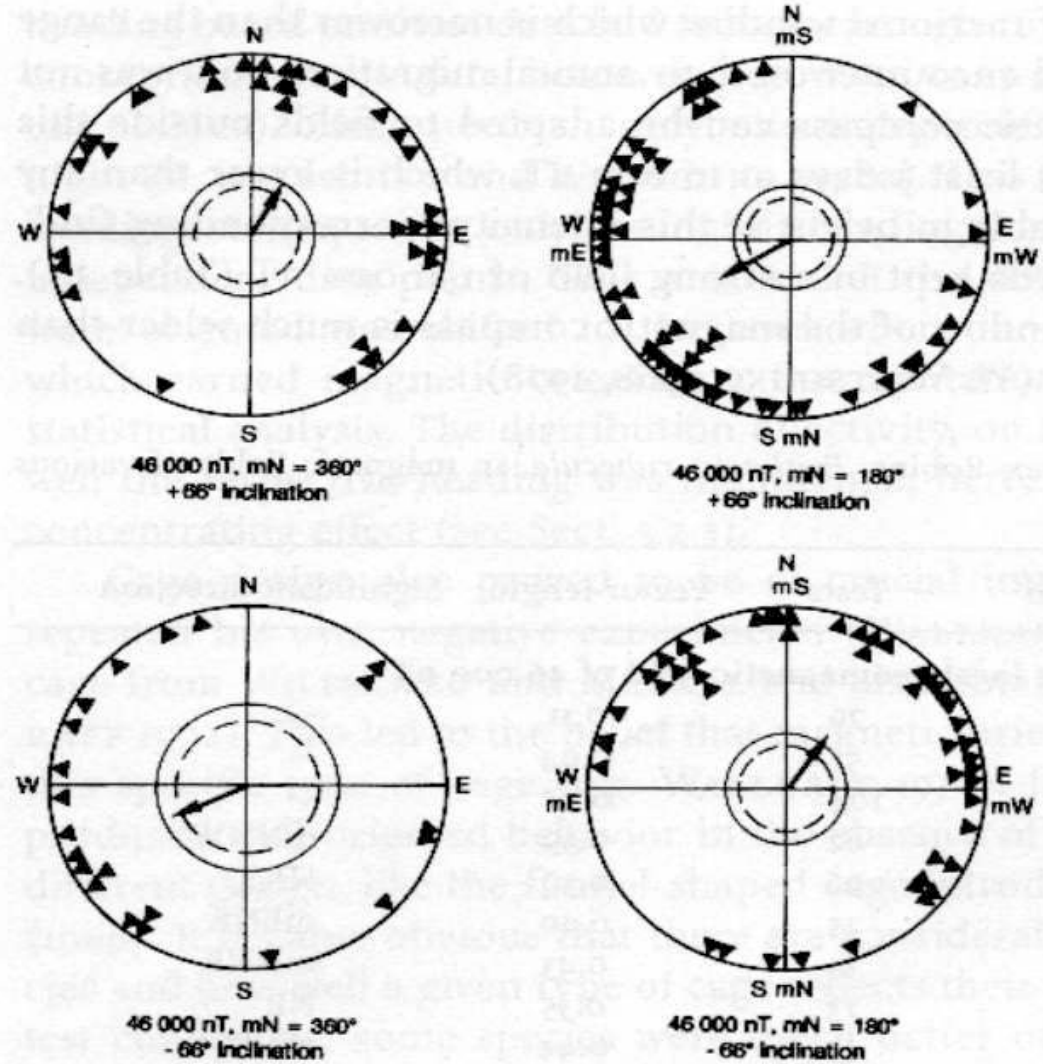
Captive birds are so eager to migrate that they will orient themselves in a cage in the direction they wish to fly.

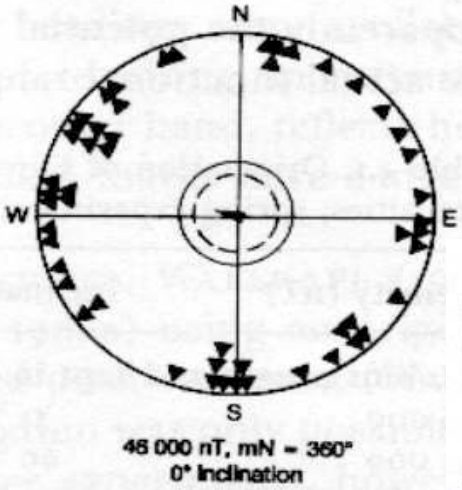




The mechanism underlying magnetoreception is still unknown!

Avian Compass - Observation





equator condition!

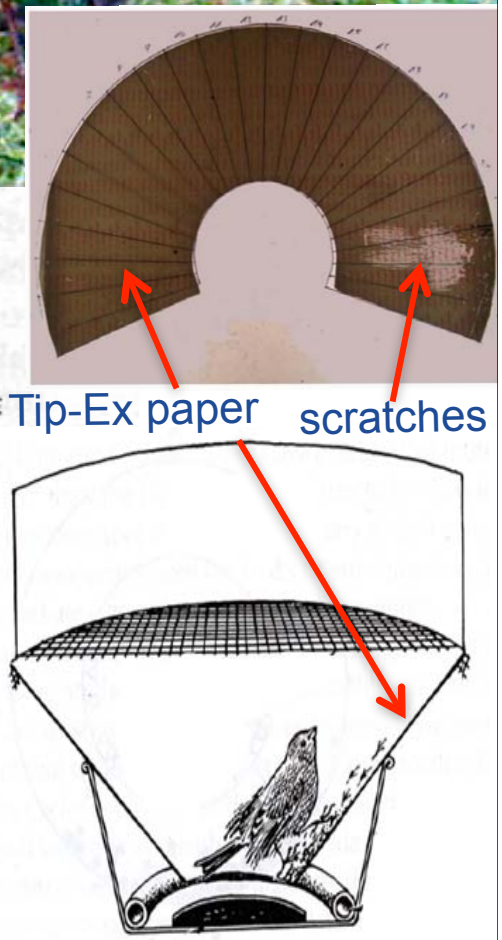


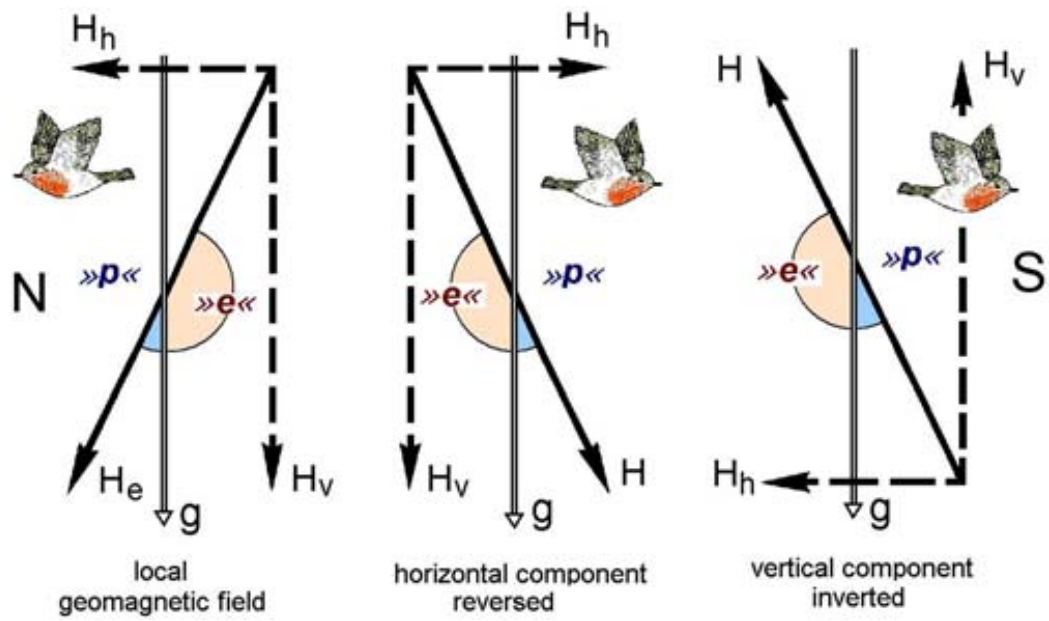
Fig. 4.3. Orientation behavior of European Robins tested in magnetic fields of equal intensity, but with various declinations and inclinations. *Symbols* as in Fig. 4.2. (After W. Wiltschko and Wiltschko 1972)

Wiltschko and Wiltschko, Science 176: 62 (1972)

Avian Compass is an Inclination Compass

European robin

Perception depends only on the inclination of the field lines, not the polarity



Birds must know the direction of “up” to differentiate North from South

First Question: Where is the Compass?

European Robin
(*Erithacus rubecula*)

Australian silvereyes
(*Zosterops lateralis*)

Garden warblers
(*Sylvia borin*)

Homing pigeons
(*Columba livia*)

It is actually difficult to locate animal magnetoreceptors:

- Magnetic fields pass freely through biological tissue, i.e., magnetoreceptors need not be in contact with the external environment and might be located anywhere within an animal's body.

- Magnetoreceptors might also be tiny and dispersed throughout a large volume of tissue

- The transduction process might involve a sequence of chemical reactions, i.e., no obvious organ or structure devoted to magnetoreception necessarily exists.

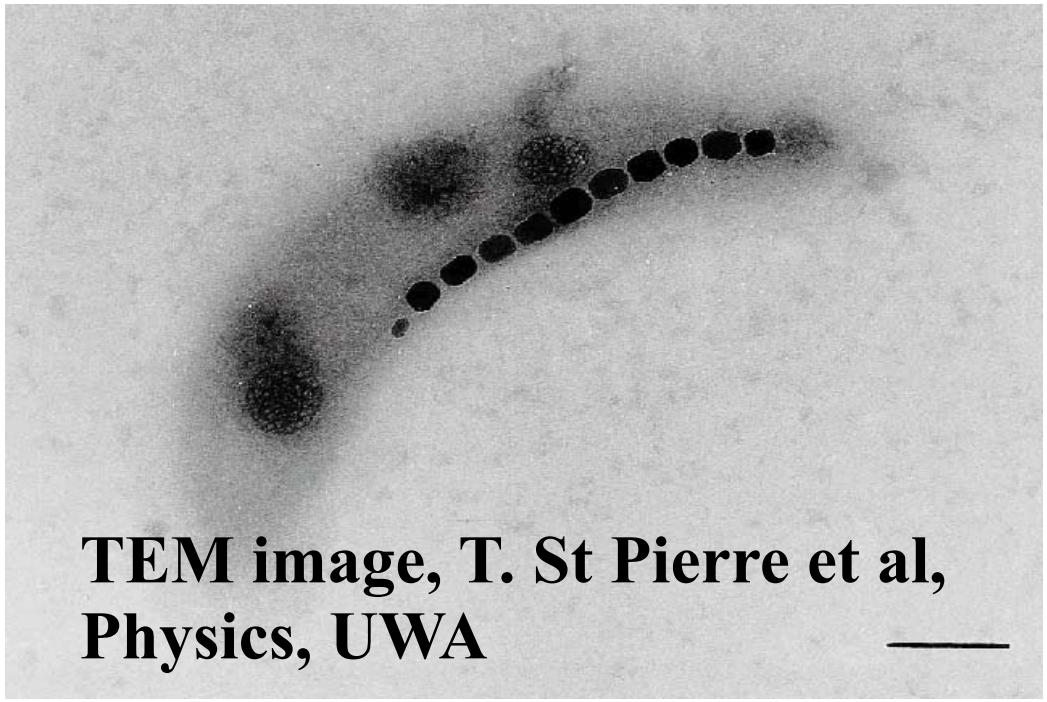
- Accessory structures such as lenses, which focus sensory stimuli on receptors and are often conspicuous, are unlikely to have evolved for magnetic field sensing because few biomaterials affect magnetic field lines.

Animal biologist, desperate, listened to theoreticians!

Two Theories for Avian Magnetoreception

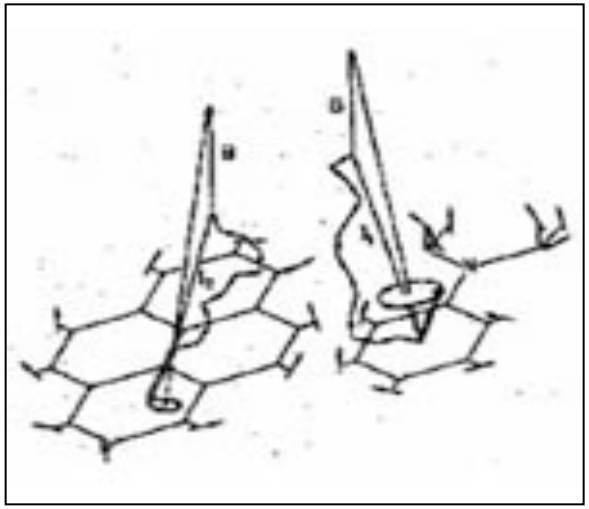
1. Use of Magnetite Particles

Magnetotactic bacteria suggest an obvious physics based mechanism for magnetotaxis, and indeed magnetite has been found in birds, but it does not explain key observations.

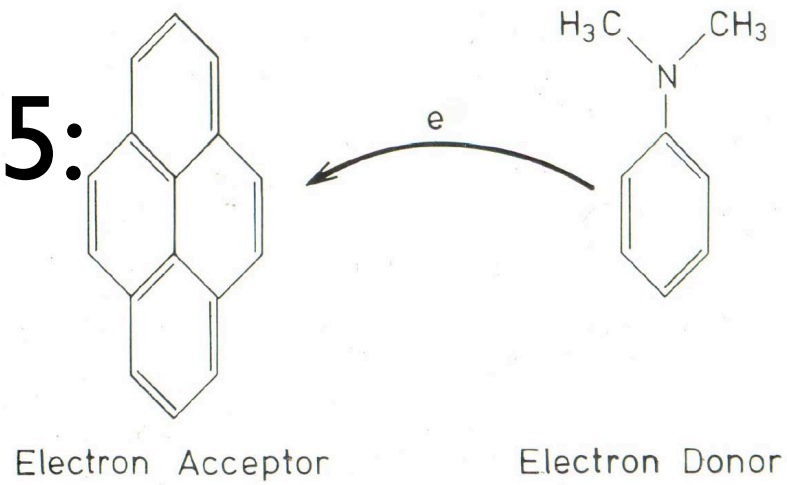


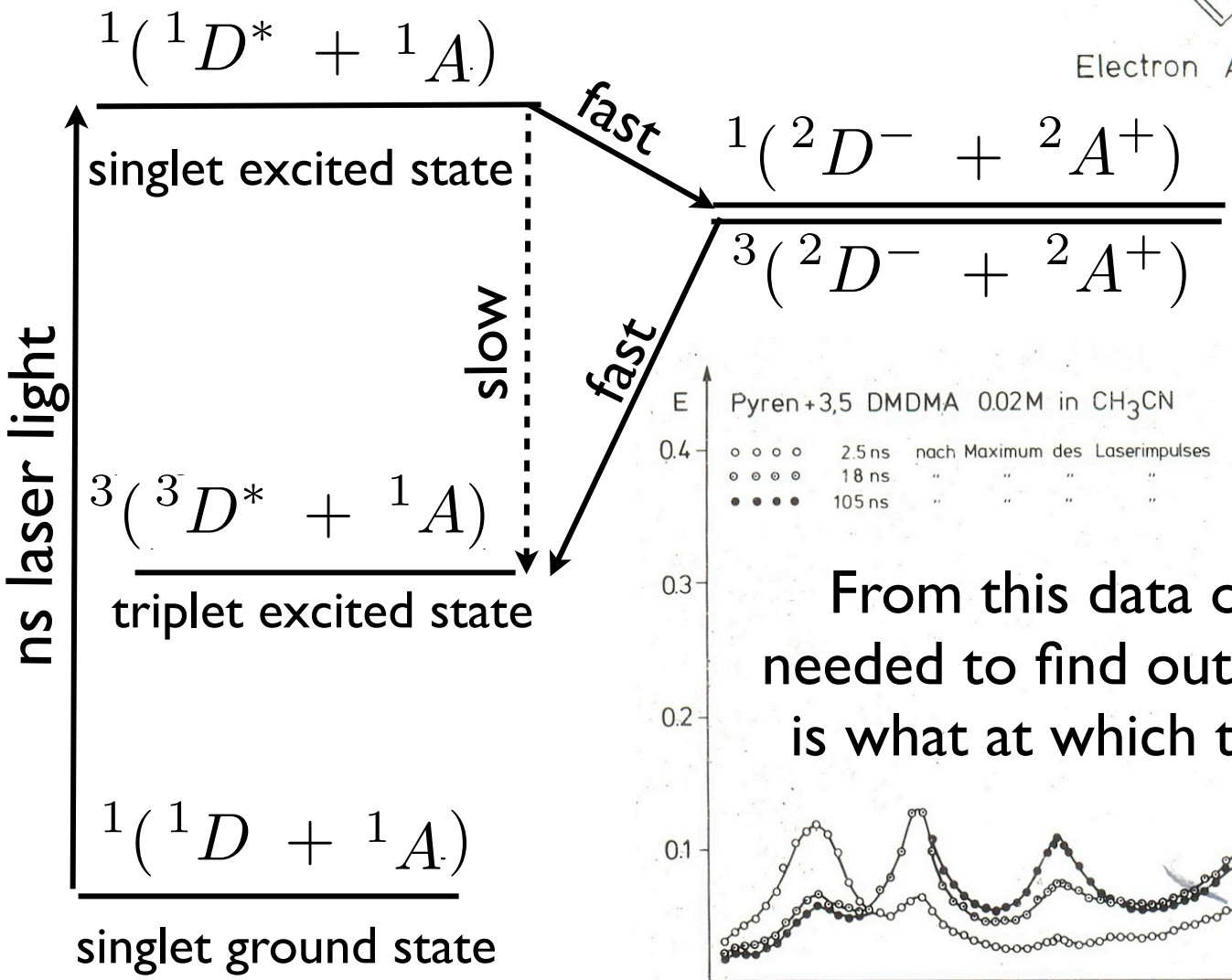
2. Radical Pair Mechanism

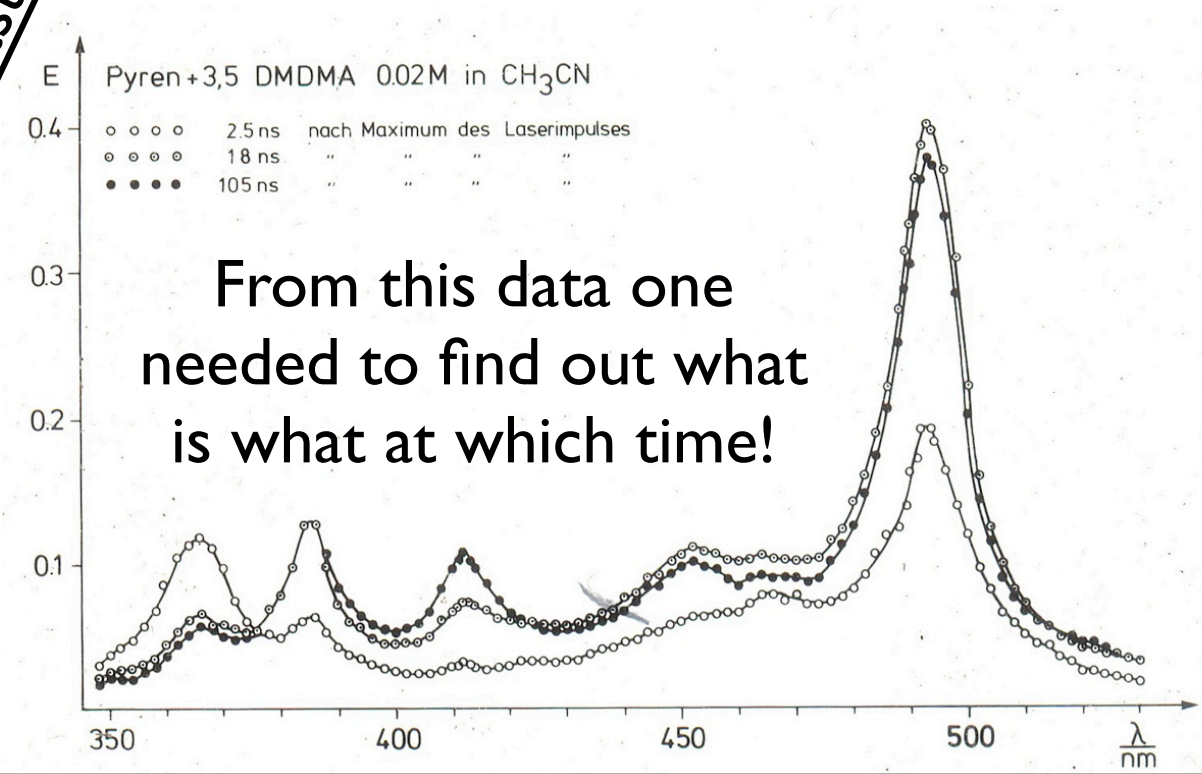
This *biochemical mechanism* was discovered in a physics laboratory while investigating a seemingly unrelated problem, so-called ***fast triplets.***



How it all started in 1975: **“Fast Triplets”**

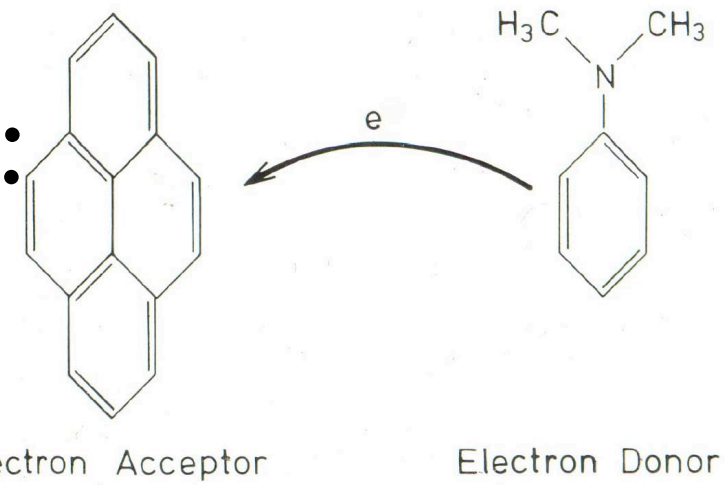


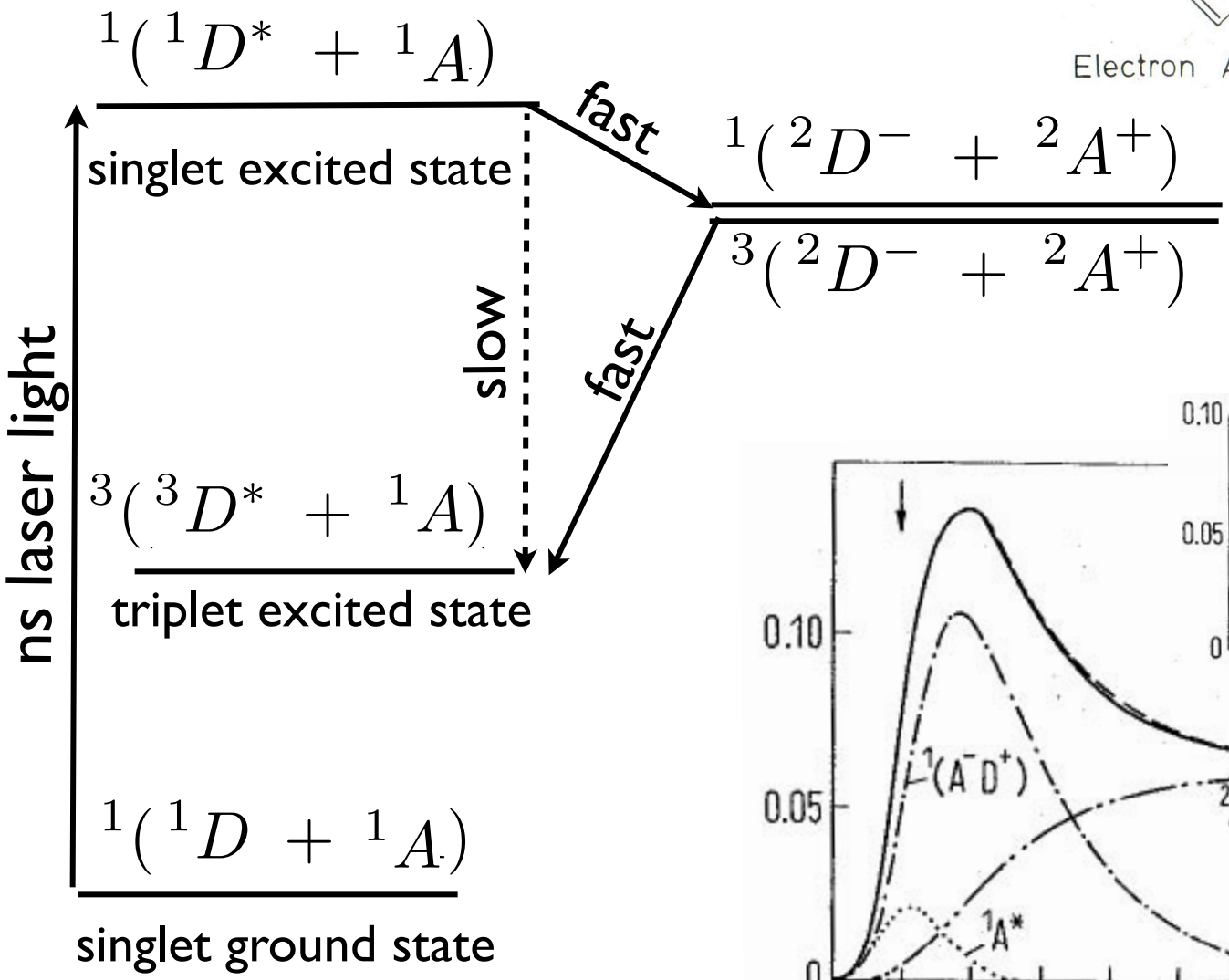




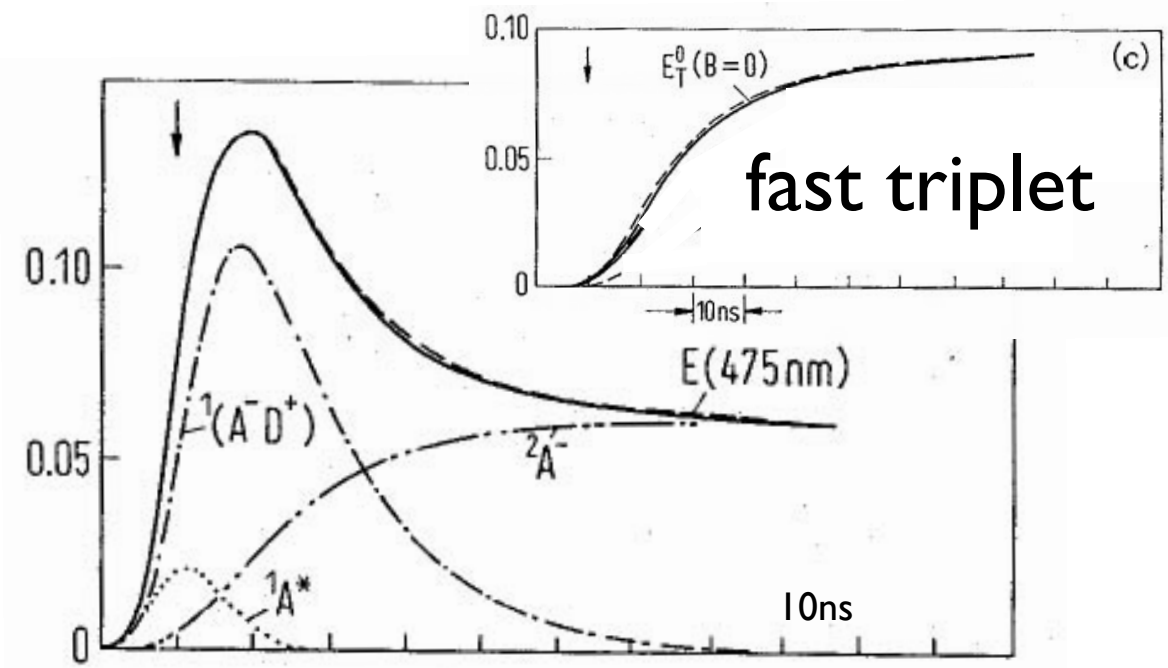
From this data one needed to find out what is what at which time!

How it all started in 1975:
“Fast Triplets”

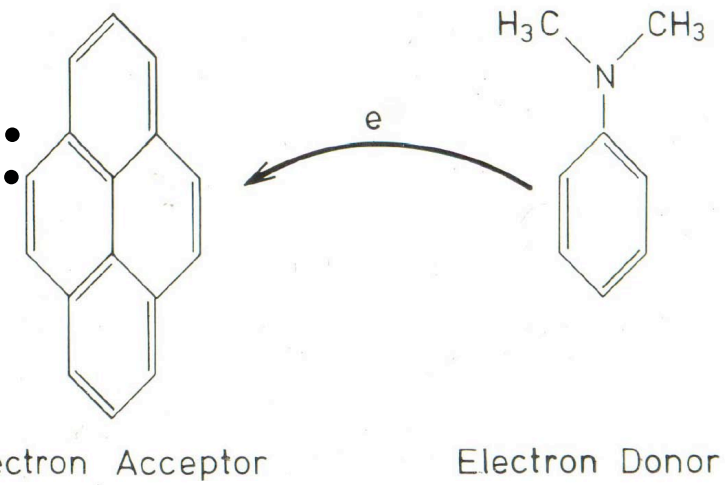


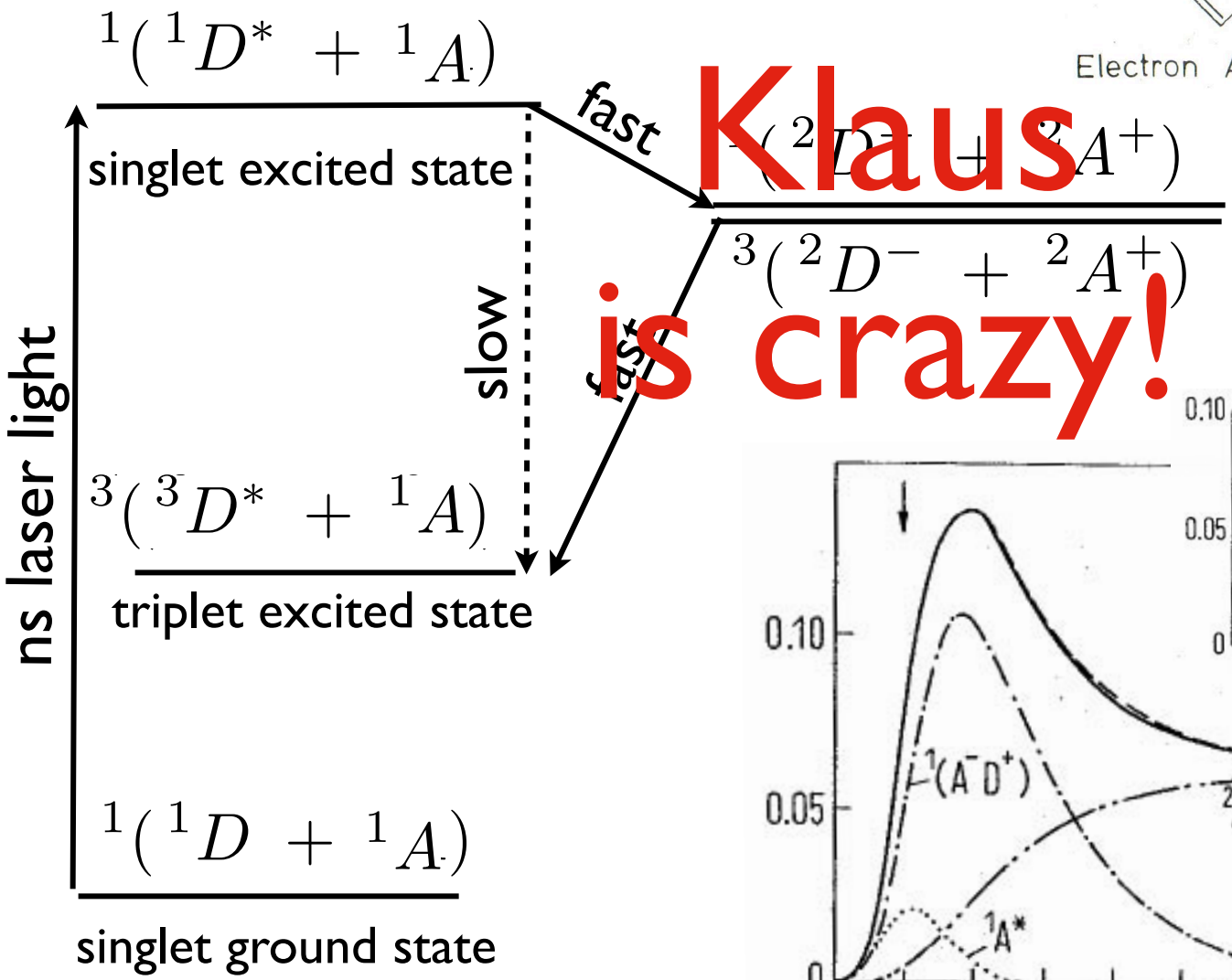


Electron Spin Entanglement

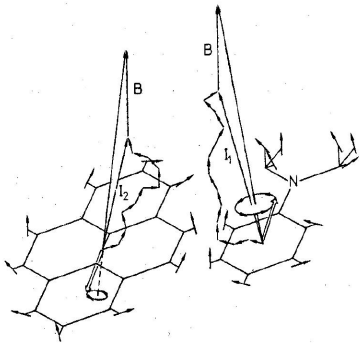


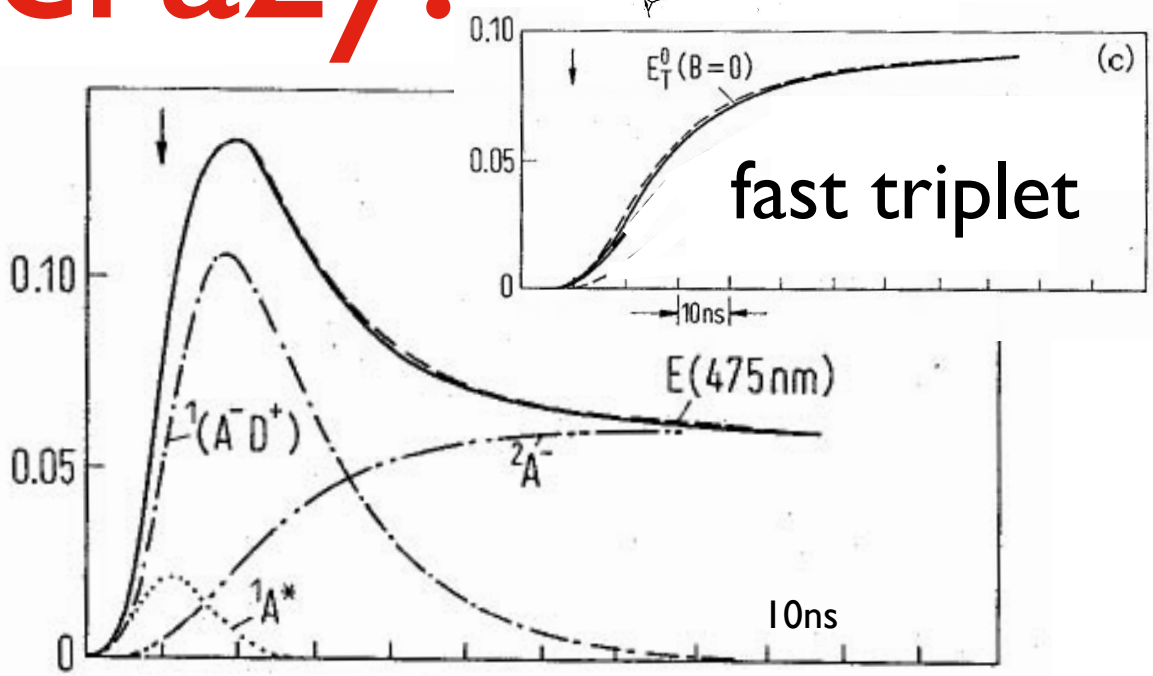
How it all started in 1975:
“Fast Triplets”





Klaus is crazy!





How it all started: **“Fast Triplets”**

Magnetic Field Dependence of the Geminate Recombination of Radical Ion Pairs in Polar Solvents

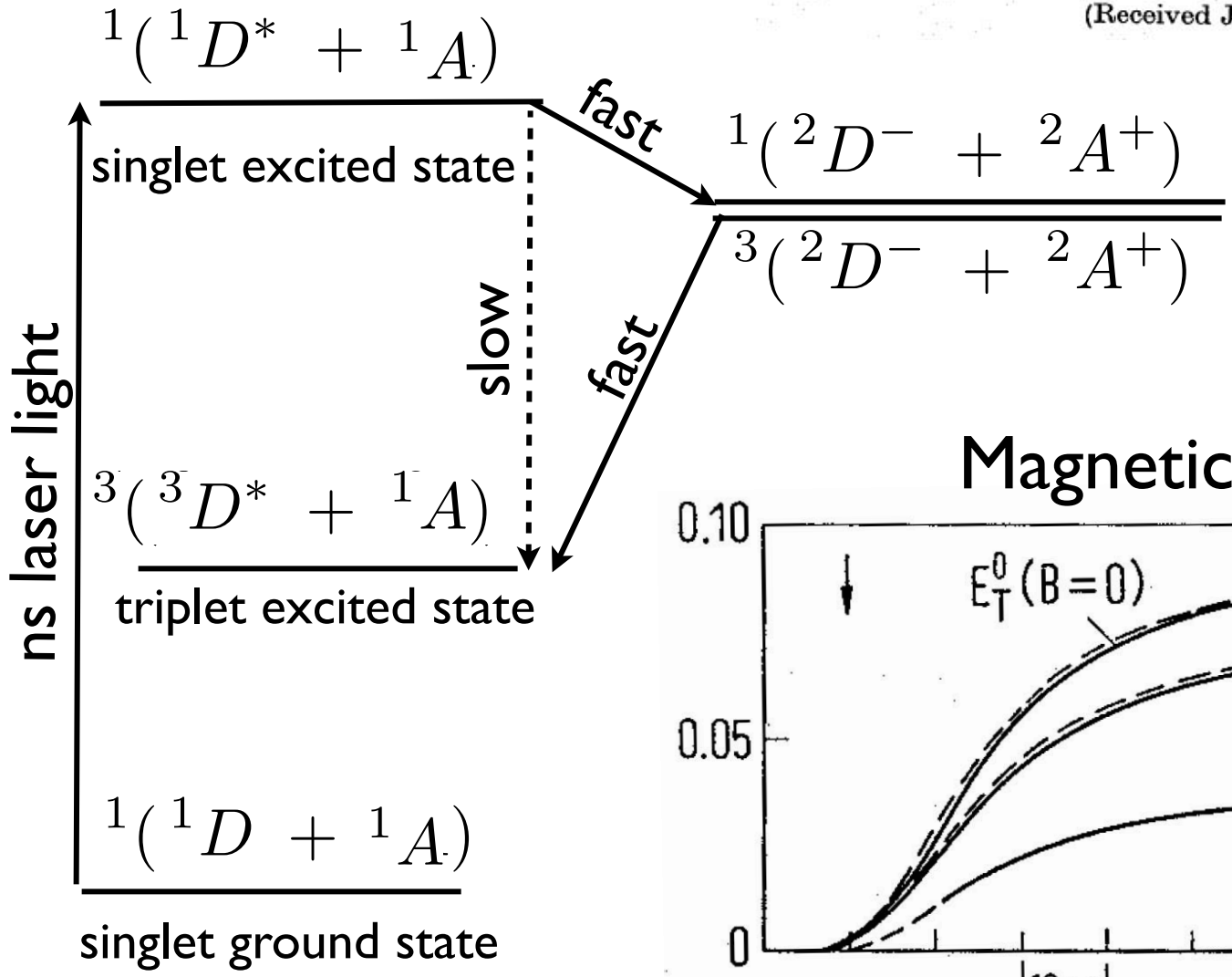
By

K. SCHULTEN, H. STAERK, A. WELLER, H.-J. WERNER and B. NICKEL

Max-Planck-Institut für biophysikalische Chemie, Göttingen, Germany

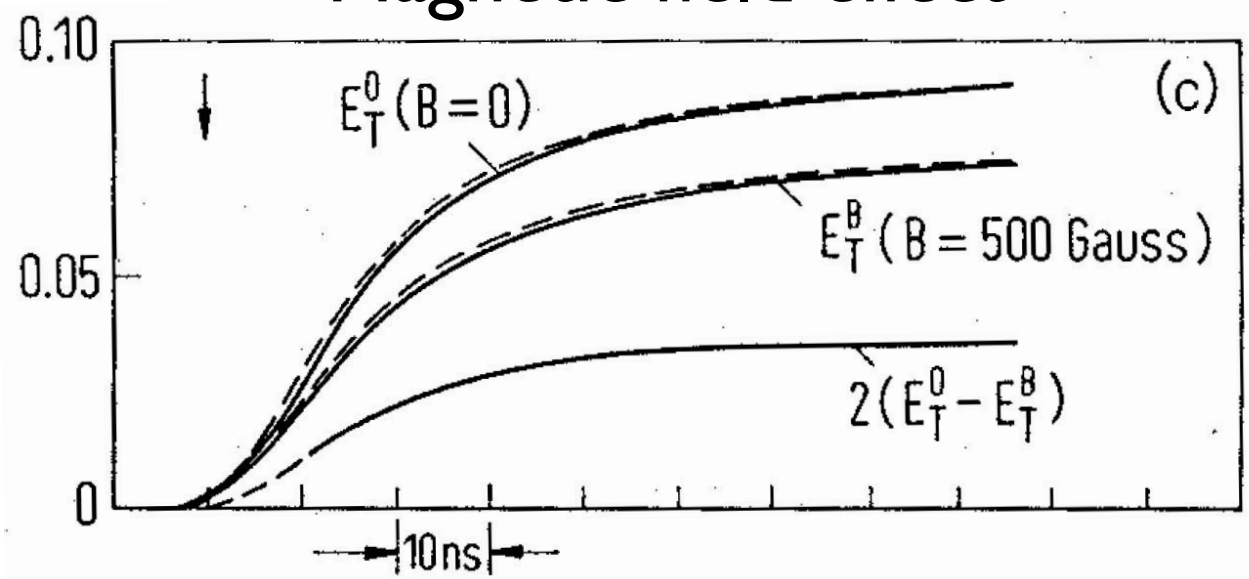
With 4 figures

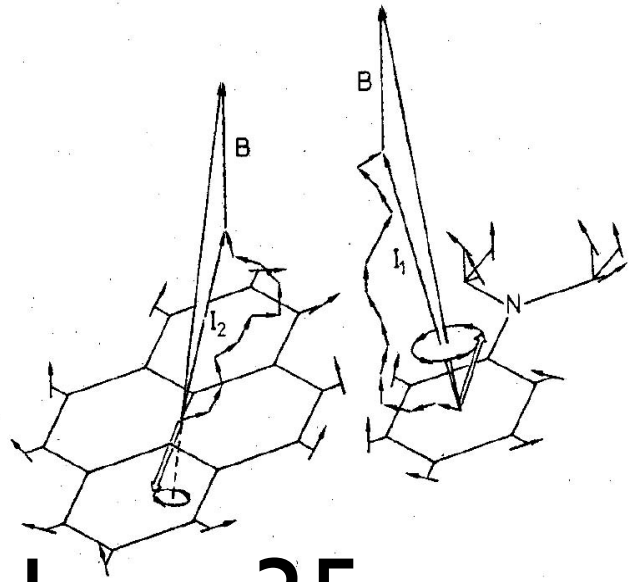
(Received January 19, 1976)



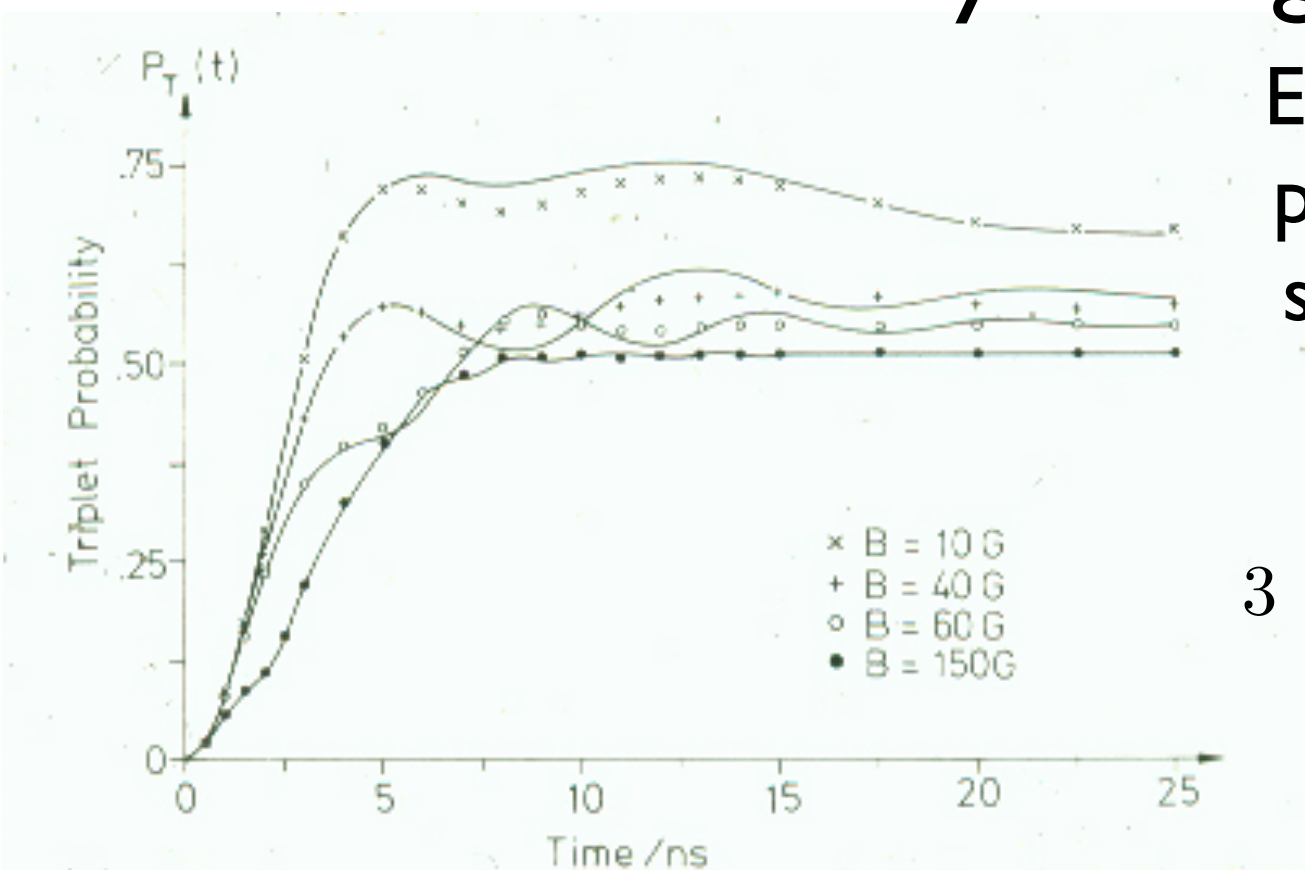
Klaus Schulten, H. Staerk, Albert Weller, Hans-Joachim Werner, and B. Nickel. **Magnetic field dependence of the geminate recombination of radical ion pairs in polar solvents.** *Zeitschrift für Physikalische Chemie*, **NF101:**371-390, 1976

Magnetic field effect





What was done 35 years ago, i.e., 1975?



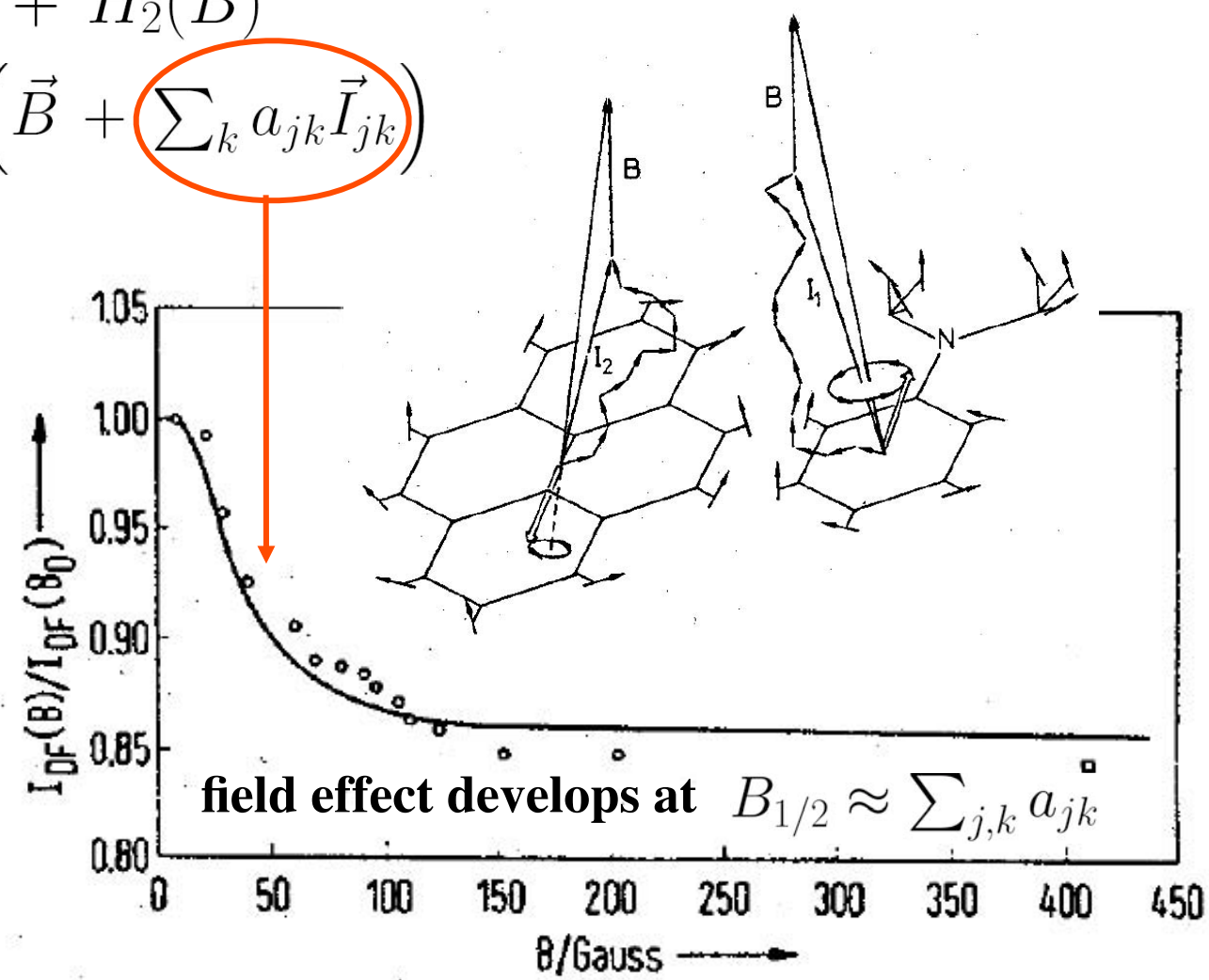
Evaluation of triplet probability through spectral expansion after block-diagonalizing the 3×2^{19} – dimensional spin Hamiltionian (in 1975!)

Predicted and Observed Magnetic Field Dependence of Triplet Yield

$$H(\vec{B}) = H_1(\vec{B}) + H_2(\vec{B})$$

$$H_j(\vec{B}) = g\mu_B \vec{S}_j \cdot \left(\vec{B} + \sum_k a_{jk}\vec{I}_{jk}\right)$$

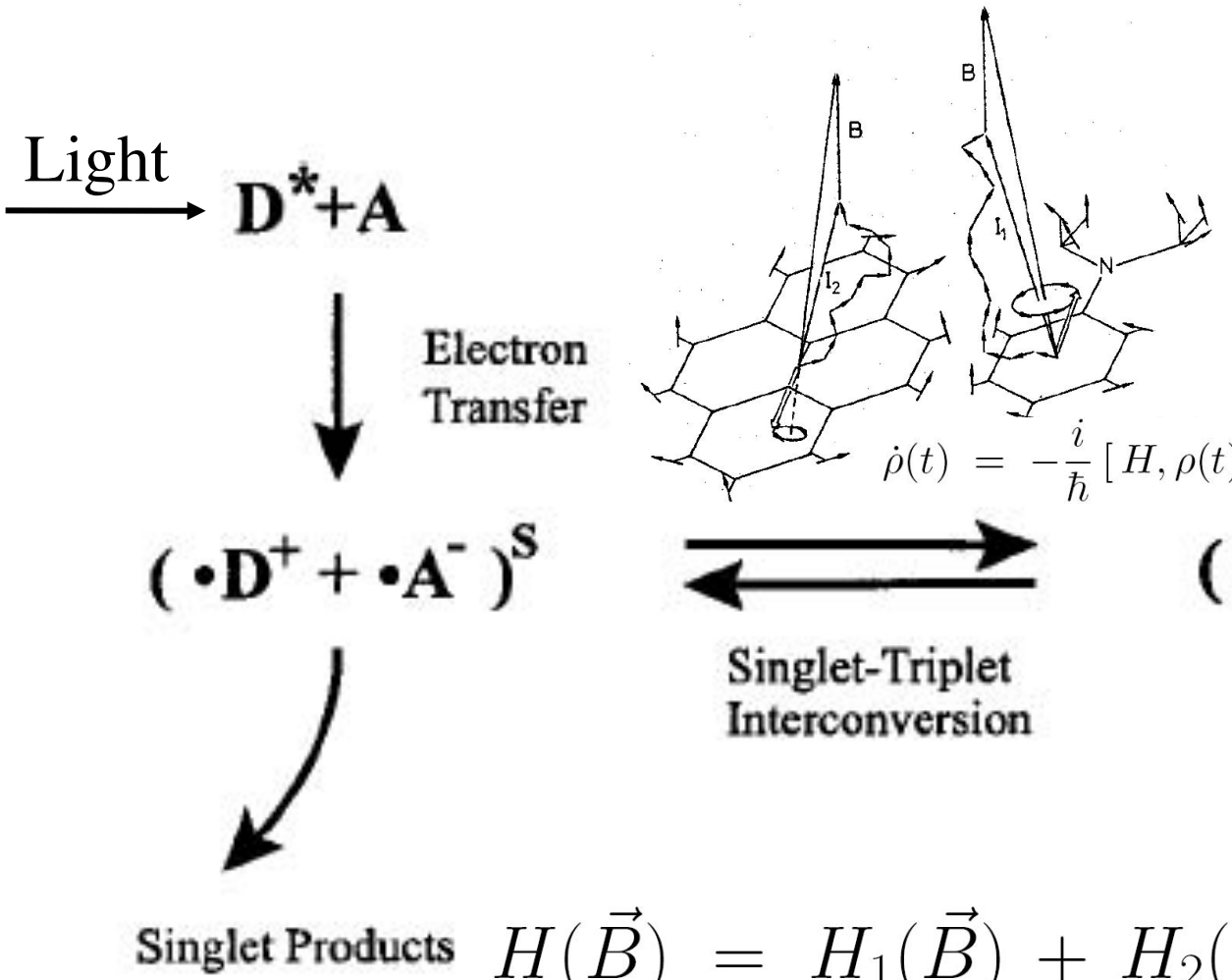
hyperfine coupling constants determine field strength needed



field effect develops at $B_{1/2} \approx \sum_{j,k} a_{jk}$

Magnetic Field Dependence of the Geminate Recombination of Radical Ion Pairs in Polar Solvents K. Schulten, H. Staerk, A. Weller, H.-J. Werner, and B. Nickel, *Z. Physik. Chemie* **NF101**: 371-390 (1976)

The radical pair mechanism explains avian magnetoreception



Liouville equation!

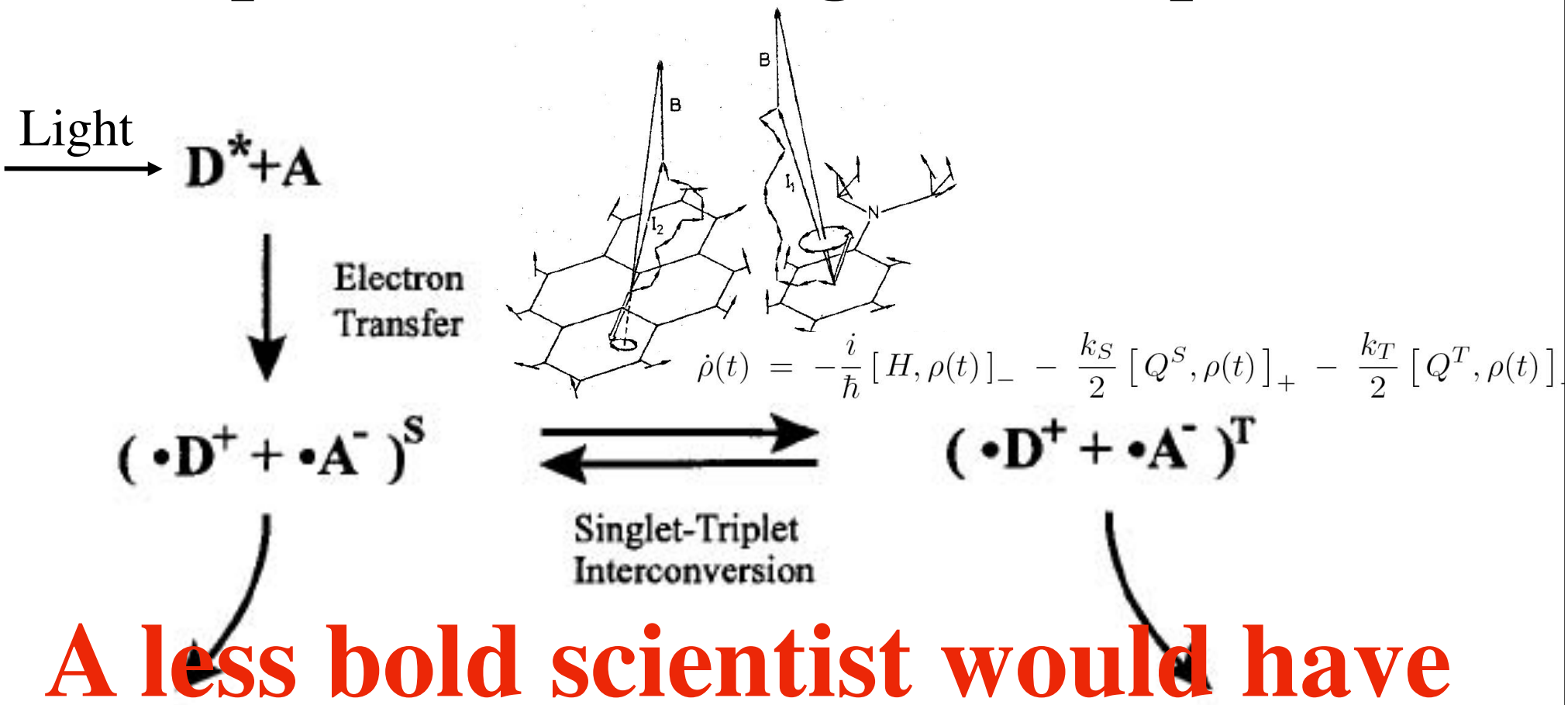
$$\dot{\rho}(t) = -\frac{i}{\hbar}[H,\rho(t)]_- - \frac{k_S}{2}[Q^S,\rho(t)]_+ - \frac{k_T}{2}[Q^T,\rho(t)]$$

$$H(\vec{B}) = H_1(\vec{B}) + H_2(\vec{B})$$

$$H_j(\vec{B}) = g\mu_B \vec{S}_j \cdot \left(\vec{B} + \sum_k a_{jk}\vec{I}_{jk}\right)$$ (in both radicals)

Zeeman - hyperfine - interaction

The radical pair mechanism explains avian magnetoreception



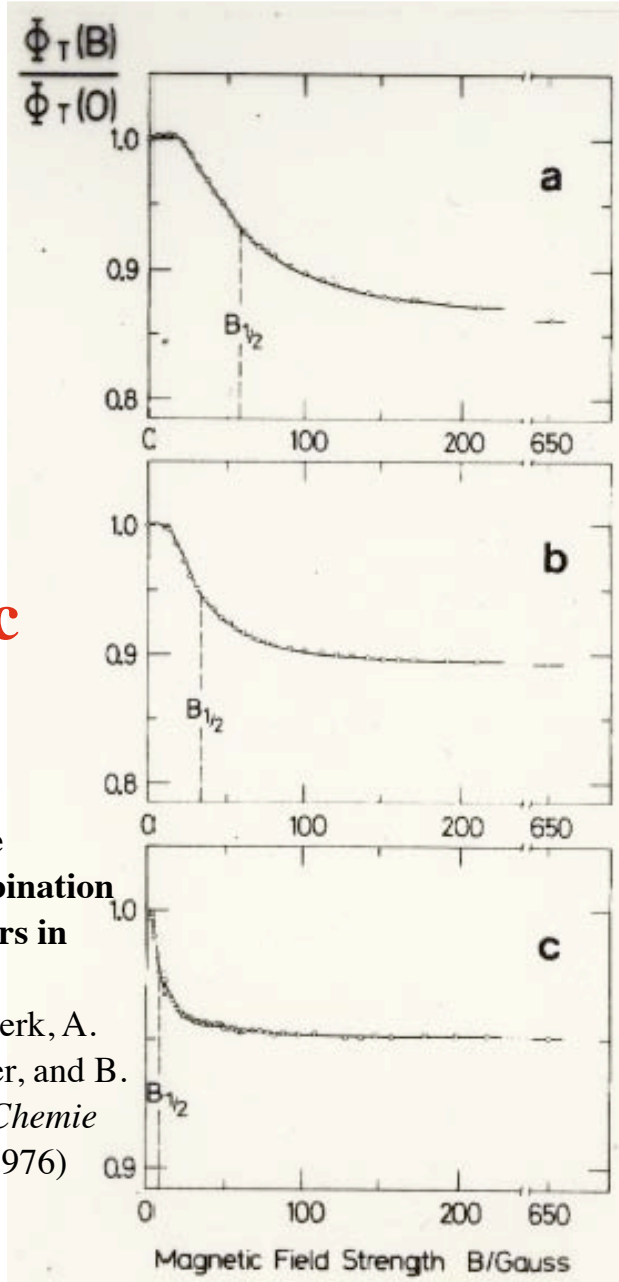
$$H(\vec{B}) = H_1(\vec{B}) + H_2(\vec{B})$$

$$H_j(\vec{B}) = g\mu_B S_j \cdot \left(\vec{B} + \sum_k a_{jk}\vec{I}_{jk}\right)$$ (in both radicals)

A less bold scientist would have thrown this work into a waste bin!

Magnetic Field Effect in Case of Anisotropic Hyperfine Coupling

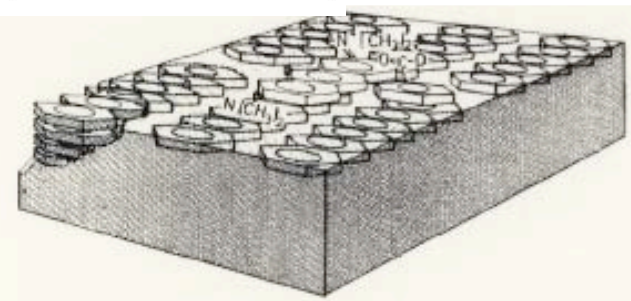
Field strength



$$H(\vec{B}) = H_1(\vec{B}) + H_2(\vec{B})$$

$$H_j(\vec{B}) = g\mu_B \vec{S}_j \cdot (\vec{B} + \mathbf{A}_j \vec{I}_j)$$

$$\mathbf{A}_1 = \begin{pmatrix} 10\,\mathrm{G} & 0 & 0 \\ 0 & 10\,\mathrm{G} & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \mathbf{A}_2 = \begin{pmatrix} 5\,\mathrm{G} & 0 & 0 \\ 0 & 5\,\mathrm{G} & 0 \\ 0 & 0 & 5\,\mathrm{G} \end{pmatrix}$$



Orientation

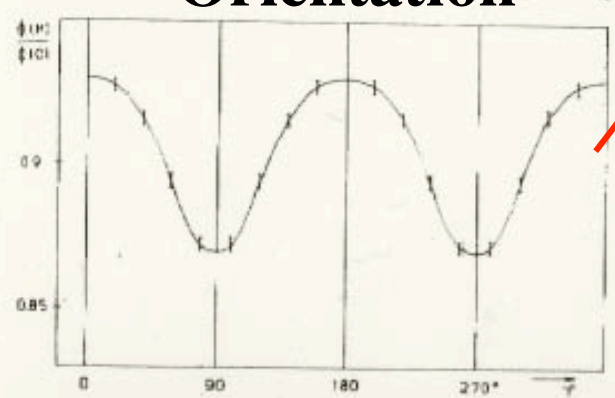


Fig. 3. Normalized magnetic field modulation of the sensitized delayed fluorescence ϕ as a function of the angle between the direction of the external magnetic field H and the a axis of the anthracene crystal.

Should work in geo-magnetic field!

Compass

But it is "only" an inclination compass! And works in narrow field window!

Magnetic Field Dependence of the Geminate Recombination of Radical Ion Pairs in Polar Solvents
K. Schulten, H. Staerk, A. Weller, H.-J. Werner, and B. Nickel, *Z. Physik. Chemie* **NF101**: 371-390 (1976)

But Klaus, Where's the Laser?

Dudley Herschbach, 1976

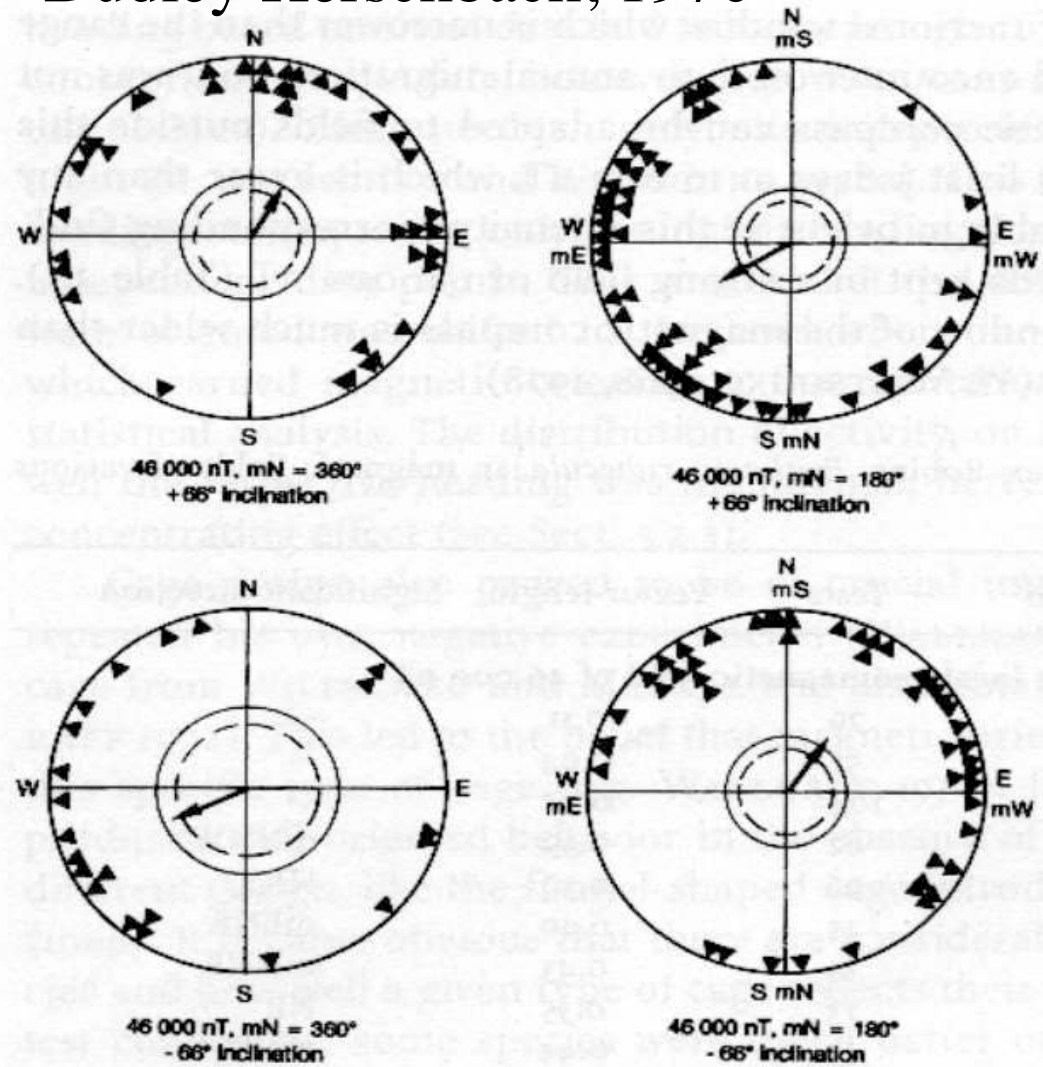
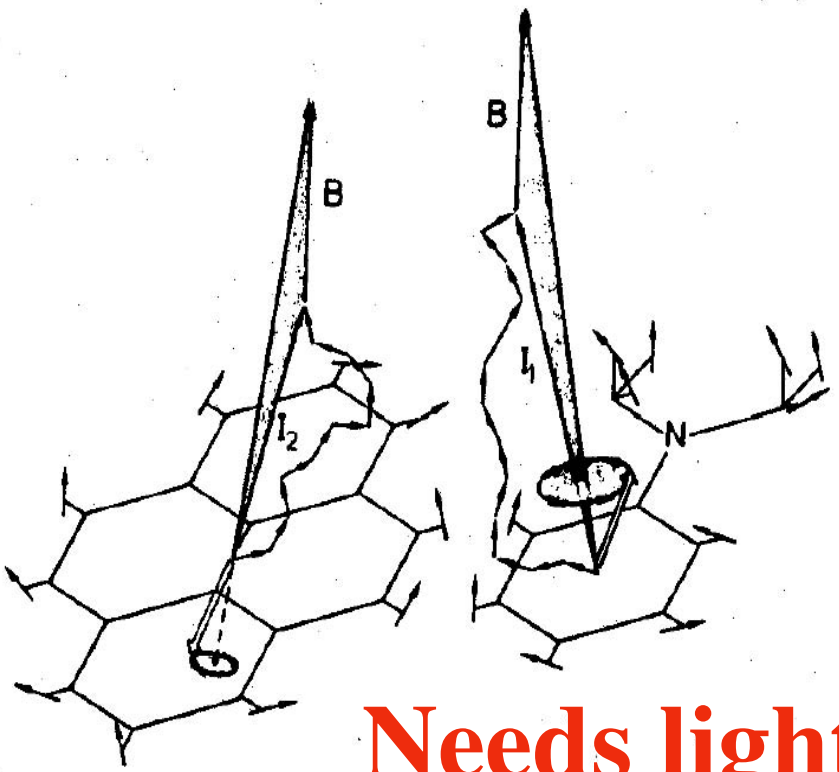


Fig. 4.3. Orientation behavior of European Robins tested in magnetic fields of equal intensity, but with various declinations and inclinations. *Symbols* as in Fig. 4.2. (After W. WILTSCHKO and WILTSCHKO 1972)

Wiltschko and Wiltschko, Science 176: 62 (1972)



Needs light!

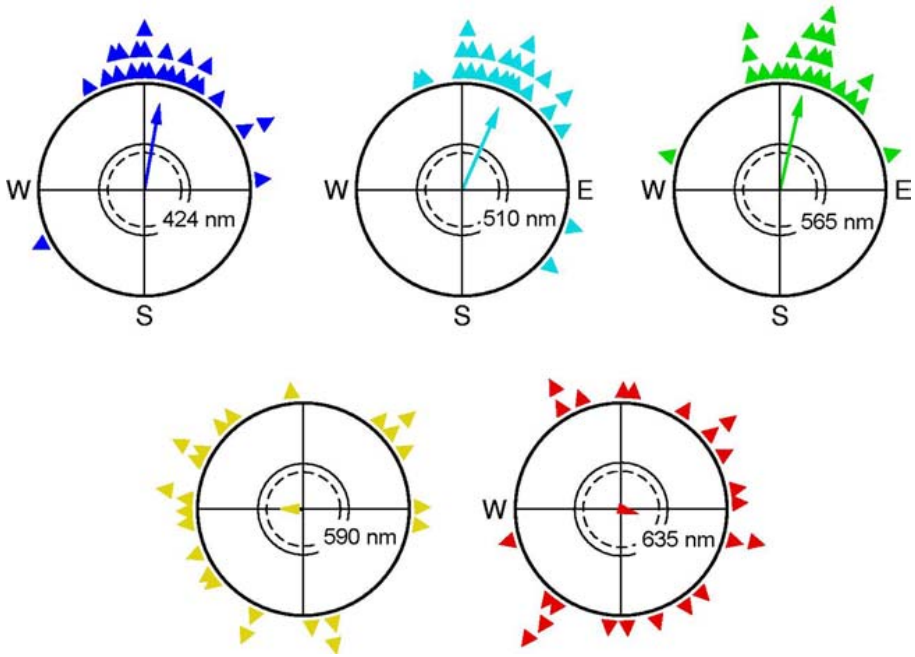
Avian Compass is Light-Dependent

Migratory birds require light above a threshold wavelength to sense magnetic fields

- disoriented in darkness and in red or yellow light
- orient only under green or blue light

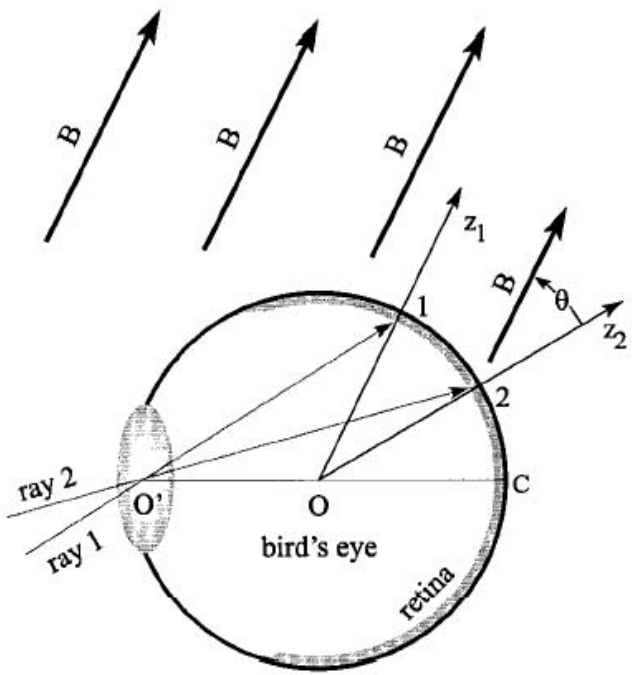
each triangle represents the orientation of one bird

(Wiltschko 2005)

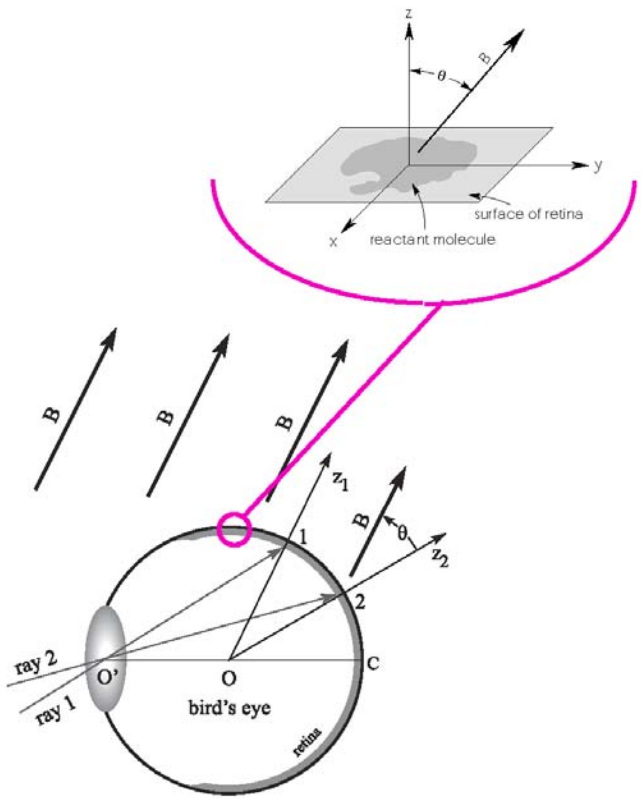


Visual Modulation Compass

What a Bird Might See!



What a Bird Might See



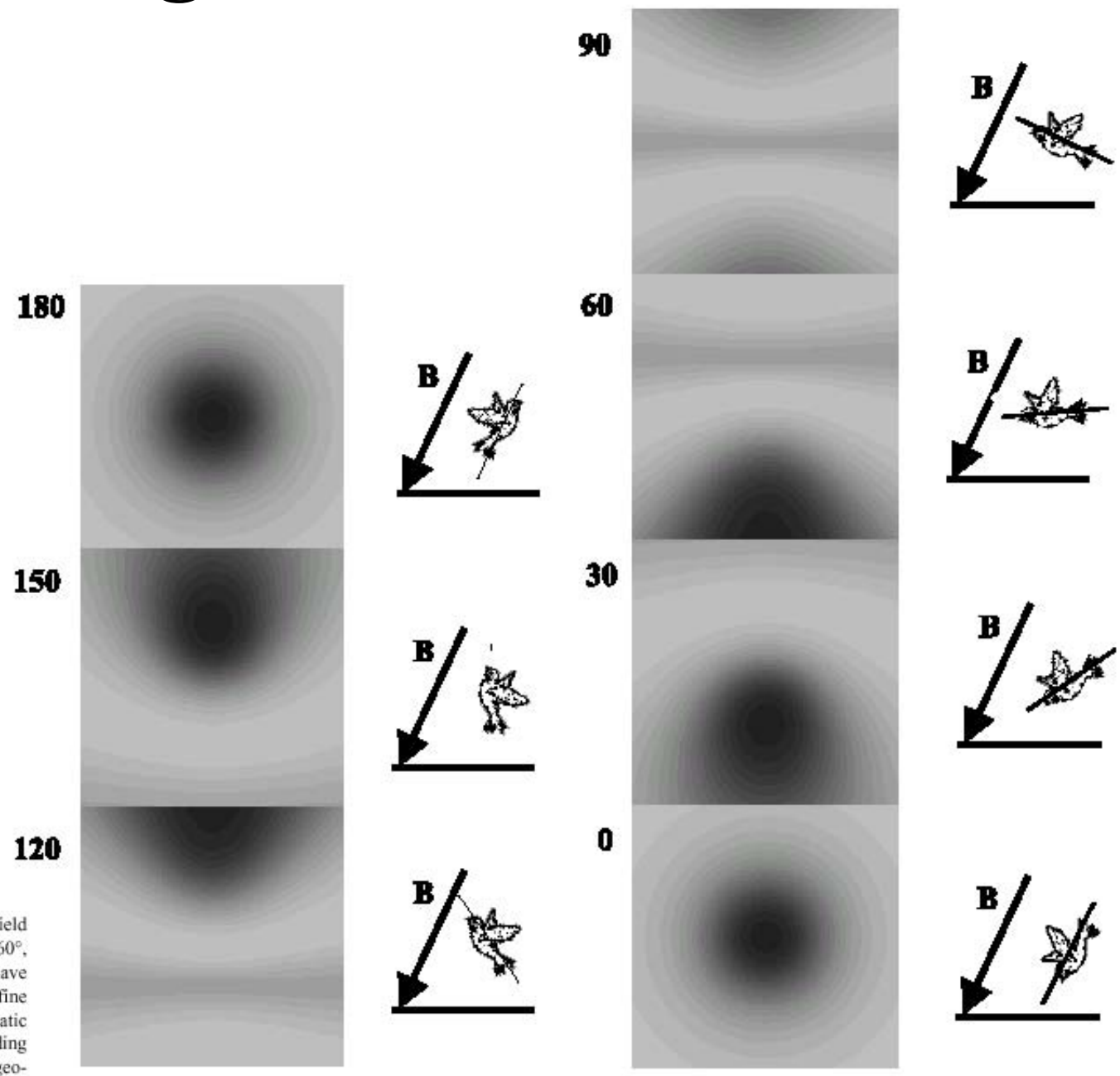


FIGURE 6 Visual modulation patterns through the geomagnetic field (0.5 G) for a bird looking into different directions at angles 0°, 30°, 60°, 90°, 120°, 150°, and 180° with the magnetic field vector. The patterns have been evaluated assuming radical-pair receptors with anisotropic hyperfine couplings arranged in the eye model depicted in Fig. 5. The schematic illustrations next to the modulation patterns indicate the corresponding direction into which a bird would be flying at Urbana-Champaign (geomagnetic field inclination of 68°).

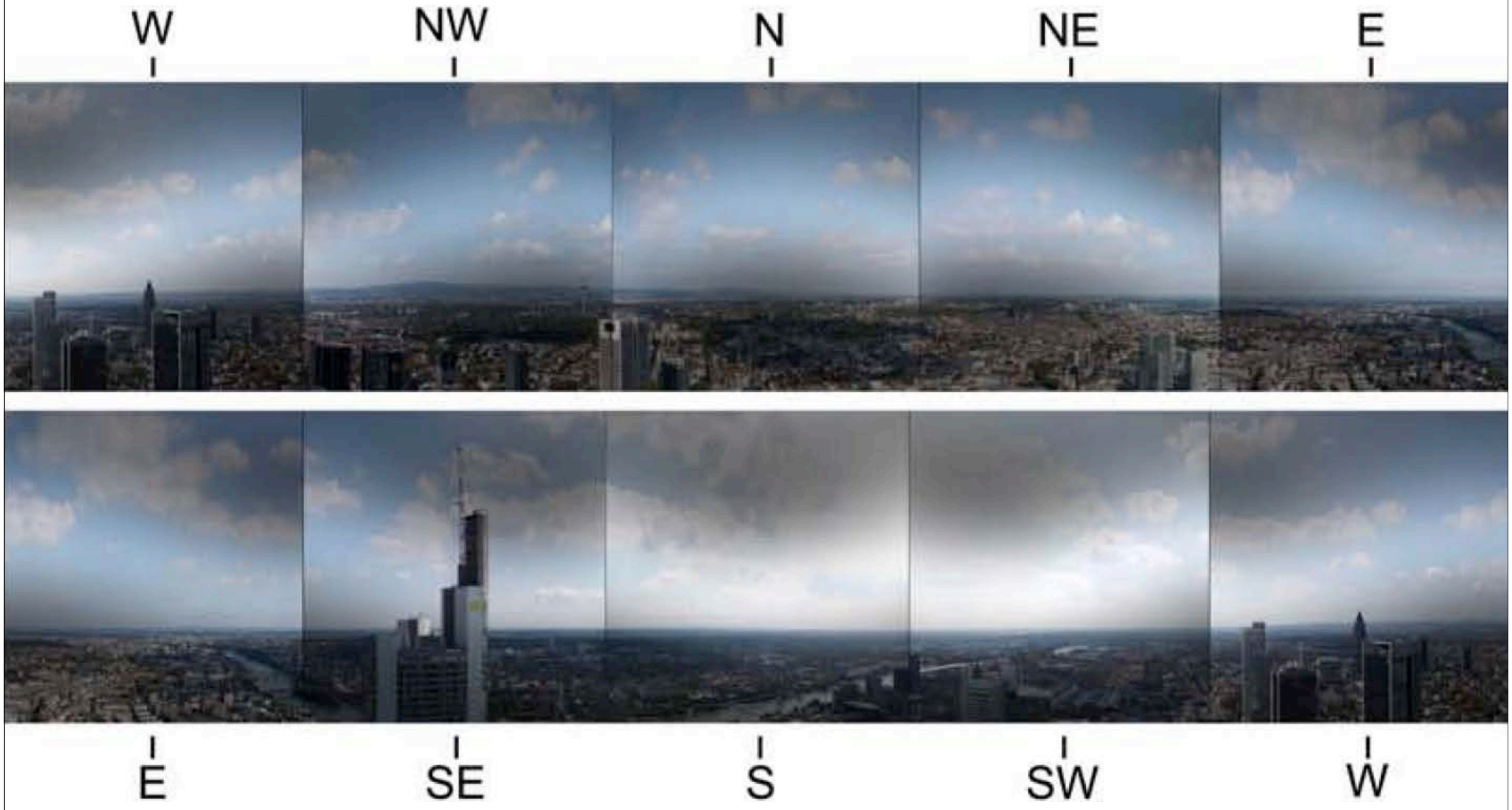
A model for photoreceptor-based magnetoreception in birds. Th. Ritz, S. Adem, and K. Schulten. *Biophysical Journal*, 78:707-718, 2000.

What a Bird May See!

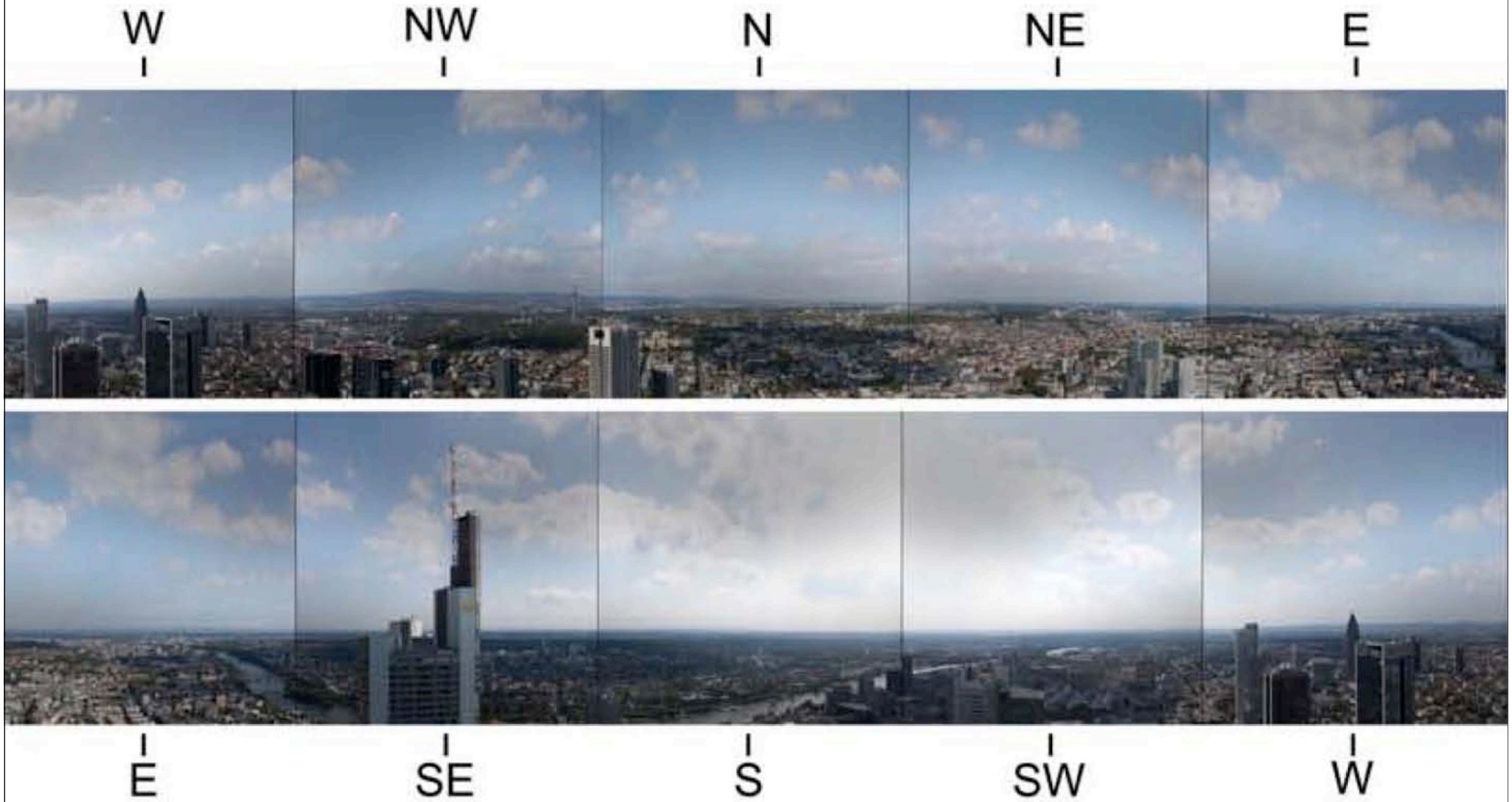
What a Bird May See!

What a Bird May See!

What a Bird May See!



What a Bird May See!



Dependence on Strength of the Geomagnetic Field

Strong argument against a magnetite-based compass!

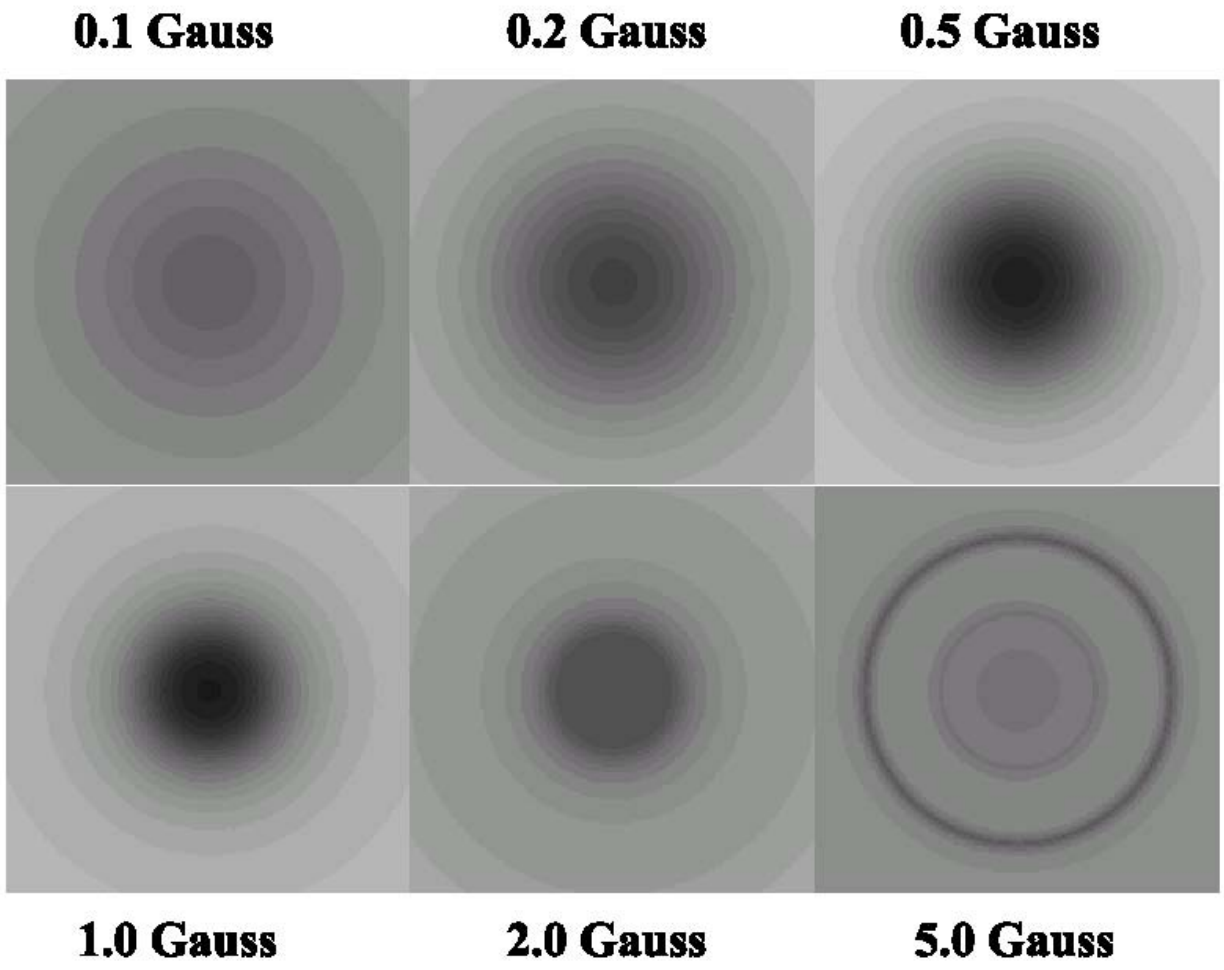


FIGURE 8 Visual modulation patterns through magnetic fields of 0.1, 0.2, 0.5, 1.0, 2.0, and 5.0 G for a bird looking parallel to the magnetic field lines. Changes in the field strength induce changes in the contrast of the modulation pattern, e.g., the central disk feature that is clearly visible for 0.5 and 1.0 G field strengths becomes less visible for lower and higher magnetic fields. In addition, qualitative changes can be observed, such as the occurrence of a new ring feature for higher (5 G) magnetic fields.

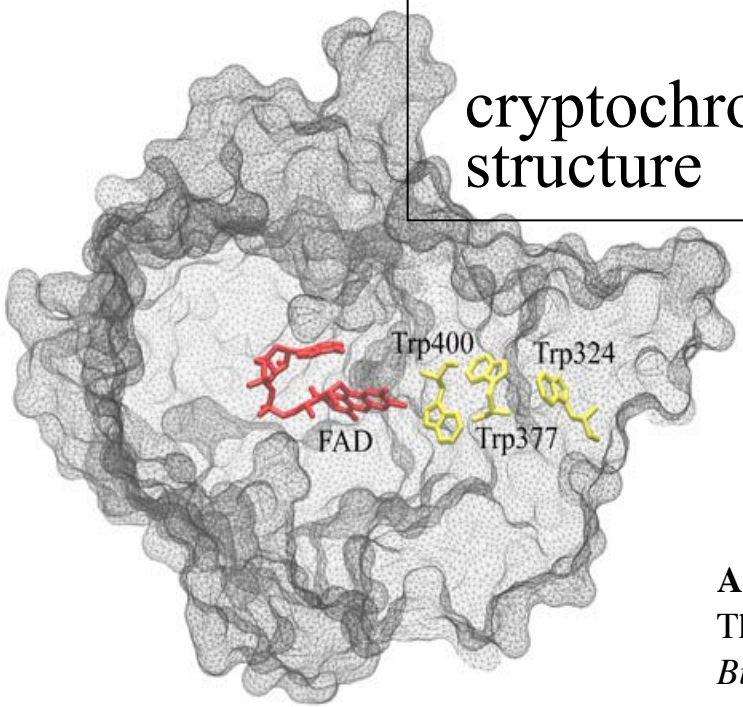
A model for photoreceptor-based magnetoreception in birds. Th. Ritz, S. Adem, and K. Schulten. *Biophysical Journal*, 78:707-718, 2000.

But What is the Actual Photoreceptor ?
It Is Cryptochrome!

- evolved from highly homologous ancestor photolyase

cryptochrome structure

Structure of the photolyase-like domain of cryptochrome 1 from Arabidopsis thaliana. Deisenhofer et al. *PNAS* **101:** 12142-12147 (2004)



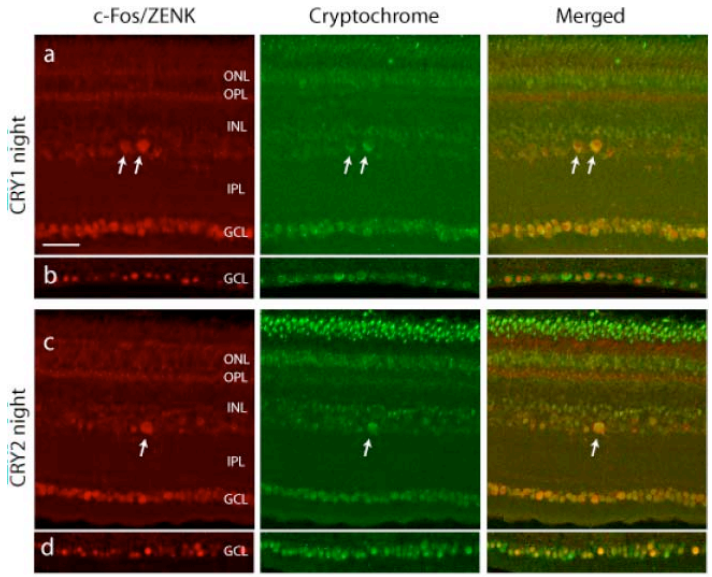
activated through 300-500 nm light

blue-light receptor transfers excitation to flavin (green)

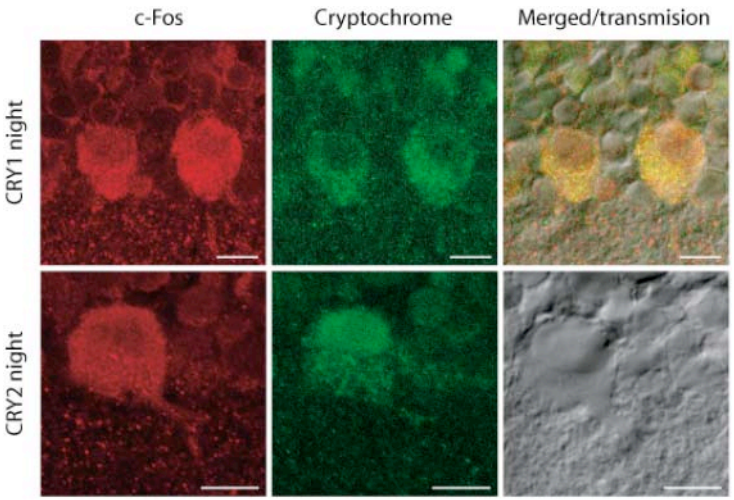
A model for photoreceptor-based magnetoreception in birds.
Th. Ritz, S. Adem, and K. Schulten.
Biophysical Journal, 78:707-718, 2000.

- cryptochromes are expressed in eyes

Colocation of activity spots and cryptochrome expression in the garden warbler retina



side view



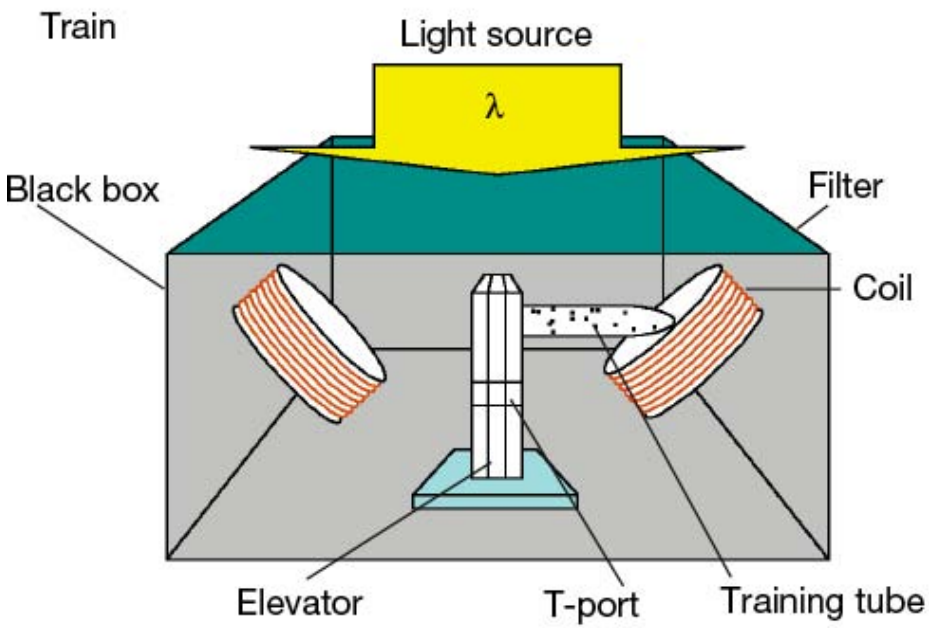
top view

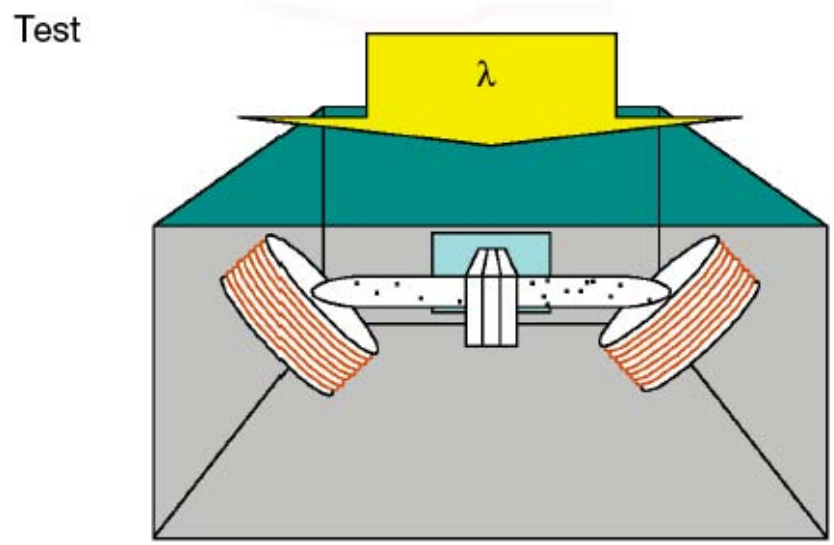
Mouritsen et al , PNAS (2005)

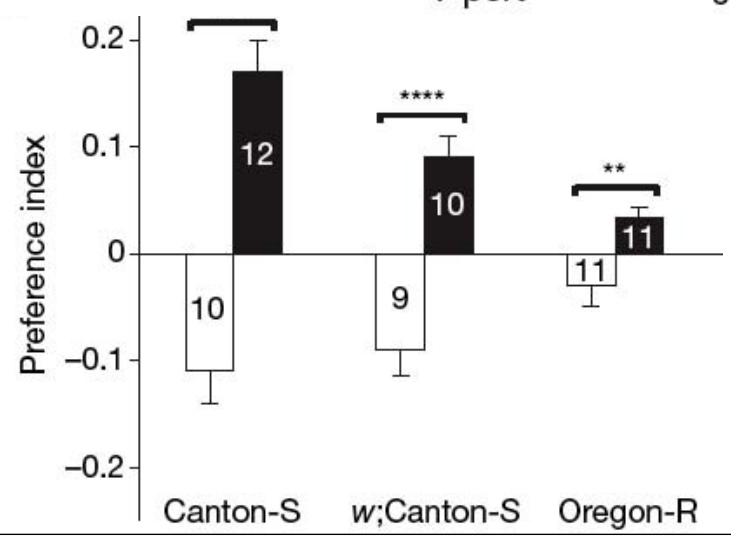
Cryptochrome mediates light-dependent magnetosensitivity in *Drosophila*

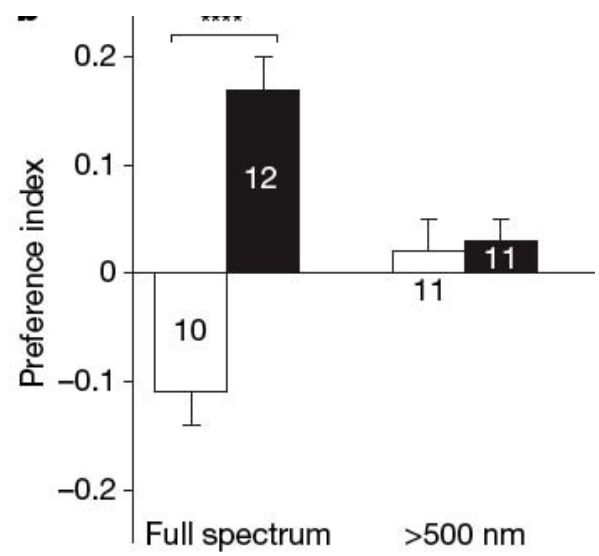
Nature **454**, 1014-1018 (2008)

Robert J. Gegear[1], Amy Casselman[1], Scott Waddell[1] & Steven M. Reppert[1]

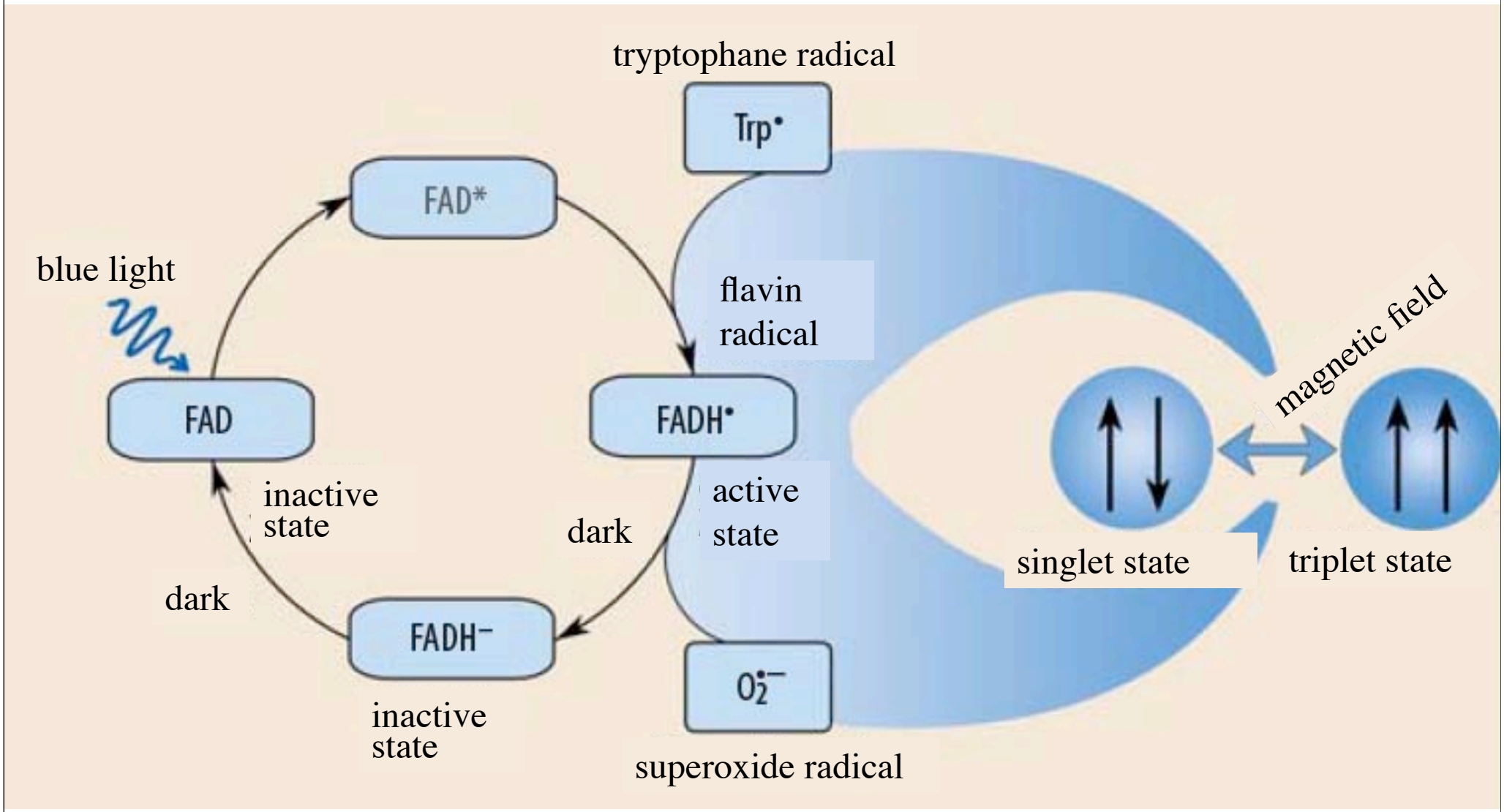








Cryptochrome Signaling

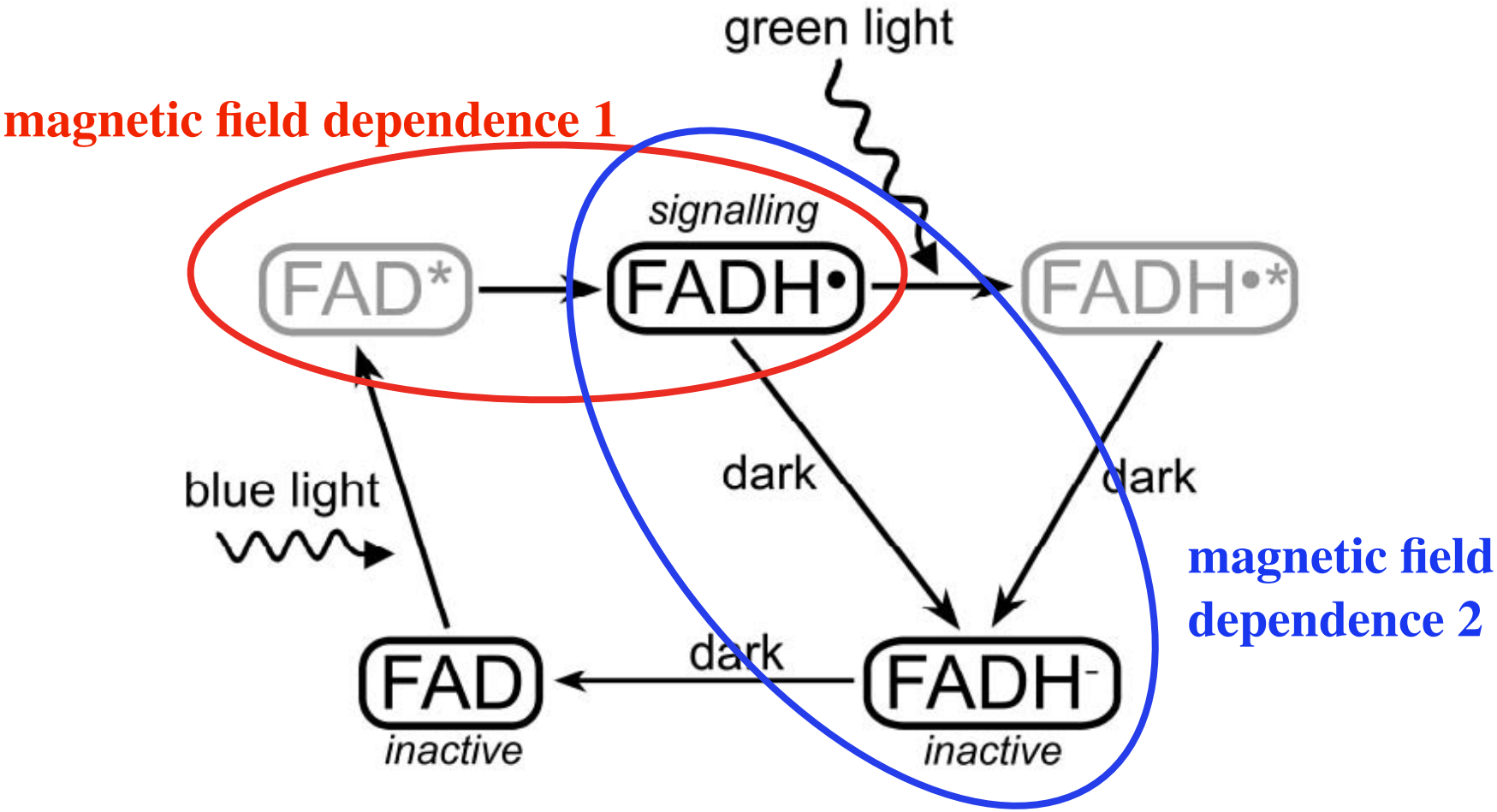


I. Solov'yov, D. Chandler, and K. Schulten, Biophys. J., **92**, 2711-2726 (2007)

I.A. Solov'yov and K. Schulten, Biophysical Journal **96**: 4804-4313 (2009)

Cryptochrome Signaling

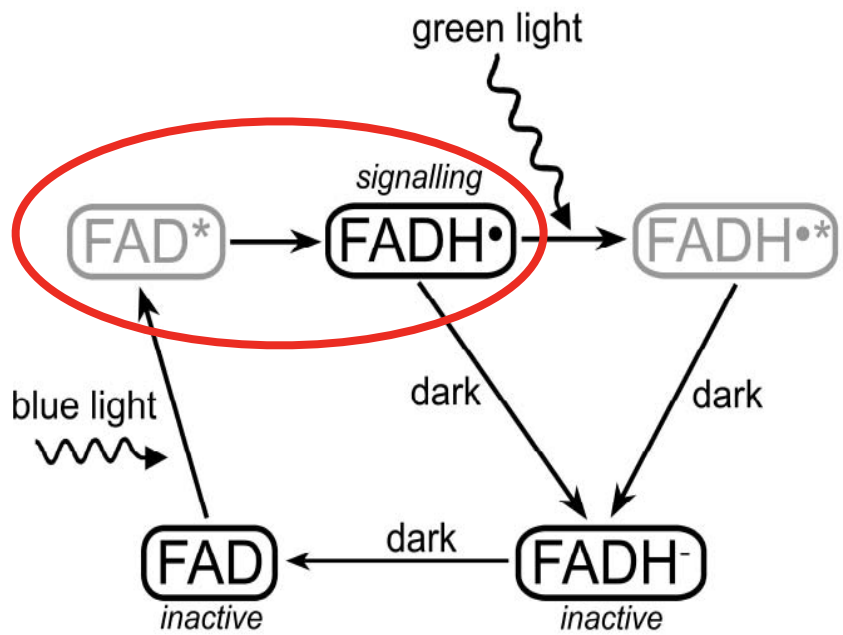
Photoactivation and Dark Deactivation

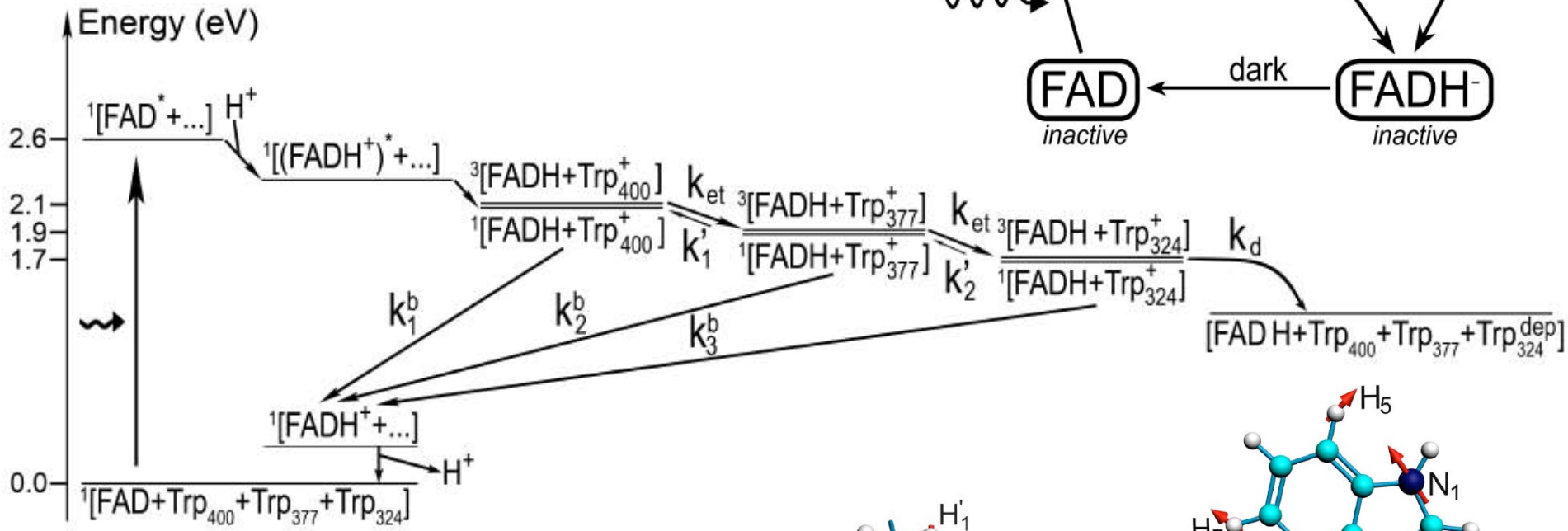


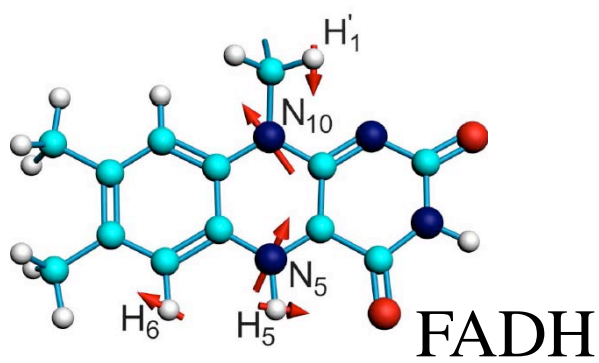
Cryptochrome is observed in three states: FAD, FADH and $FADH^-$

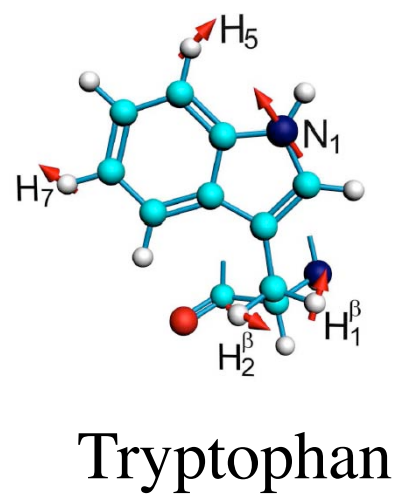
I. Solov'yov, D. Chandler, and K. Schulten, Biophys. J., **92**, 2711-2726 (2007)

Magnetic Field Dependence 1 Affecting Photoactivation of Cryptochrome





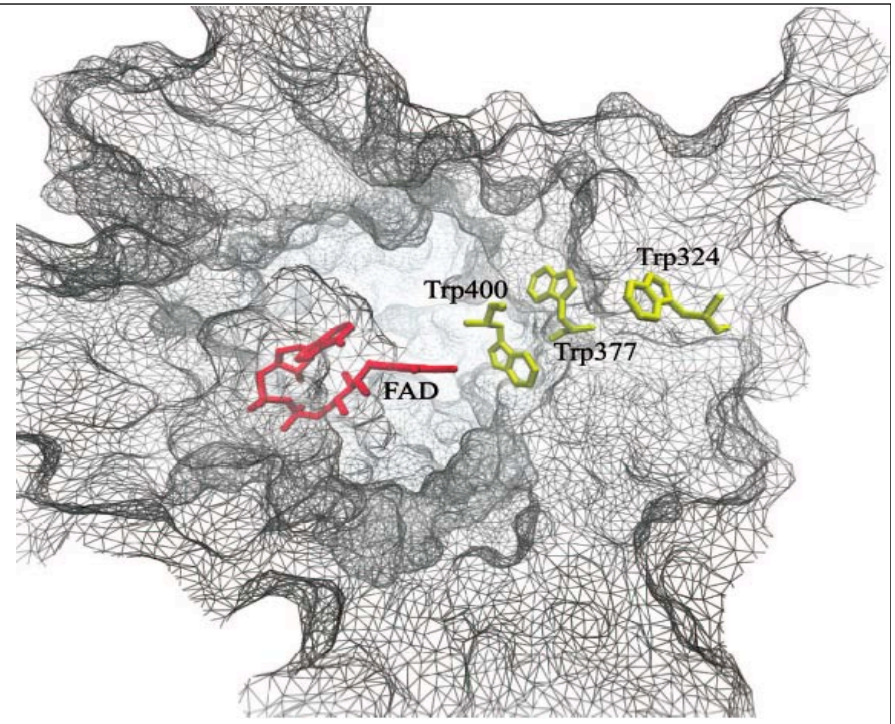


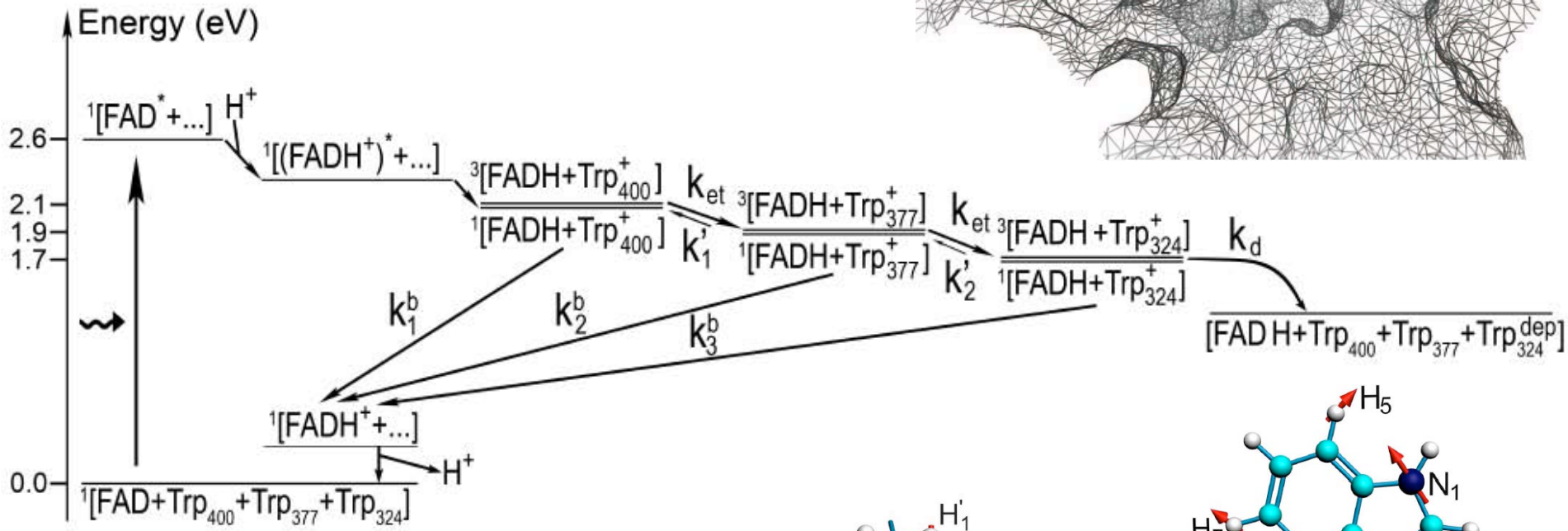


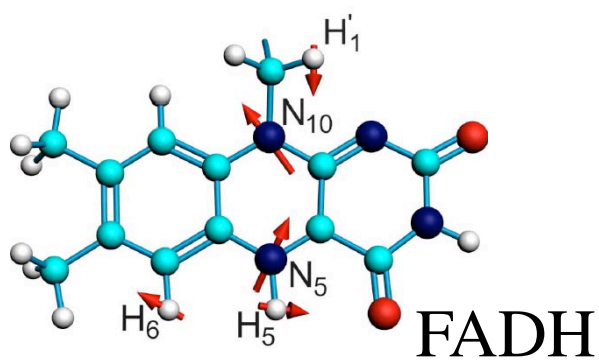
I. Solov'yov, D. Chandler, and K. Schulten, Biophys. J., **92**, 2711-2726 (2007)

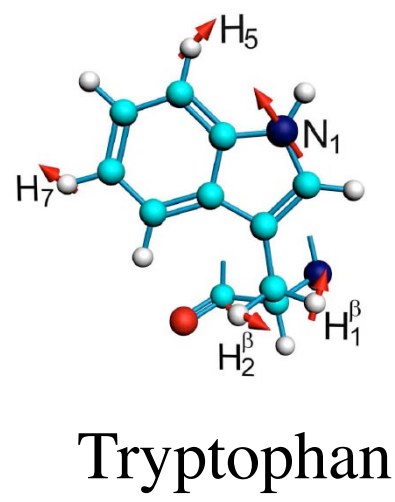
Magnetic Field Dependence 1 Affecting Photoactivation of Cryptochrome

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] - [K\rho + \rho K]$$





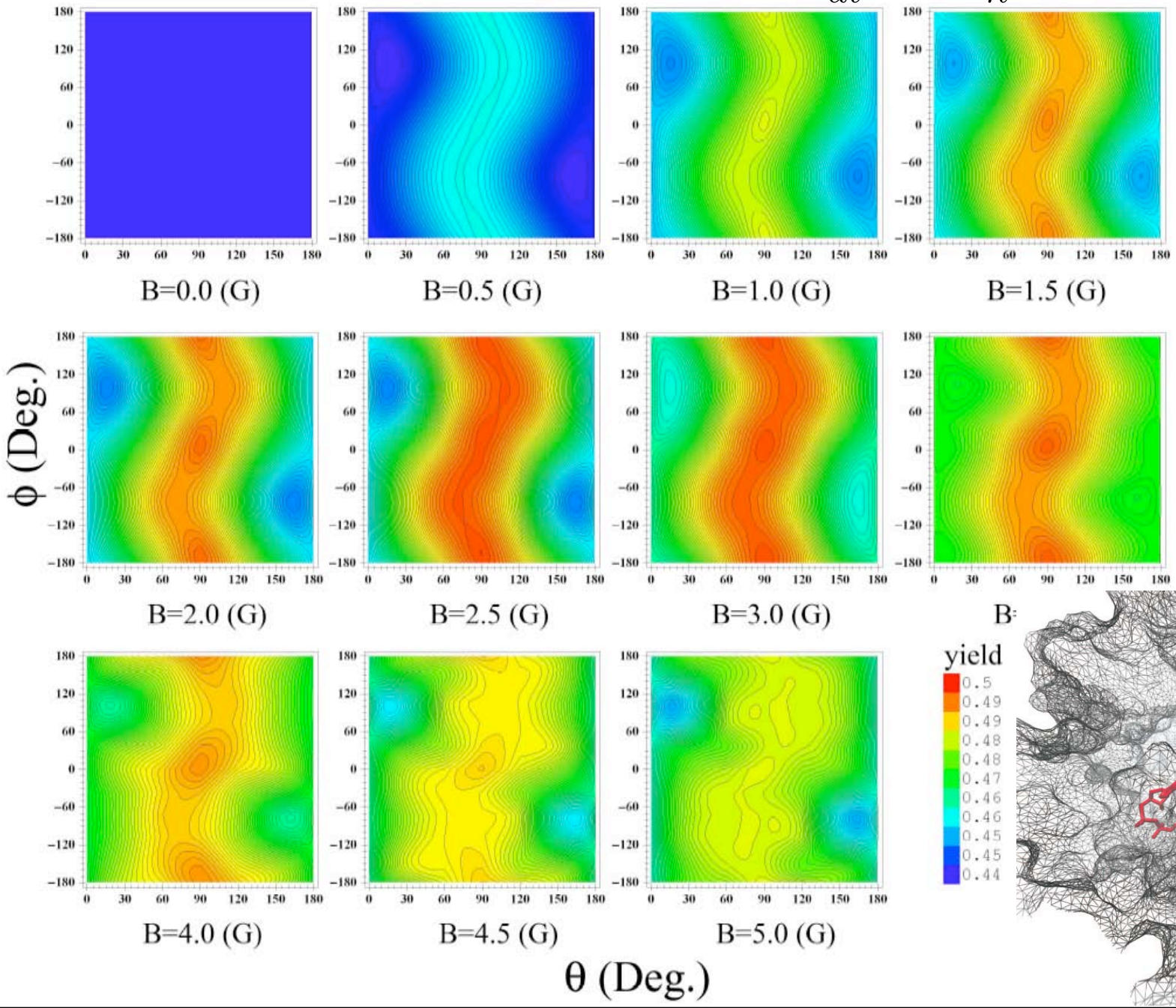


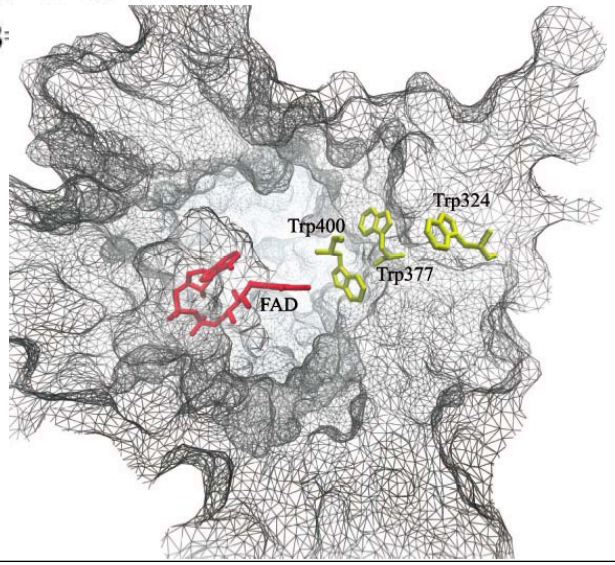


I. Solov'yov, D. Chandler, and K. Schulten, Biophys. J., **92**, 2711-2726 (2007)

Magnetic Field Dependence for Cryptochrome 1 Photoactivation

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] - [K\rho + \rho K]$$

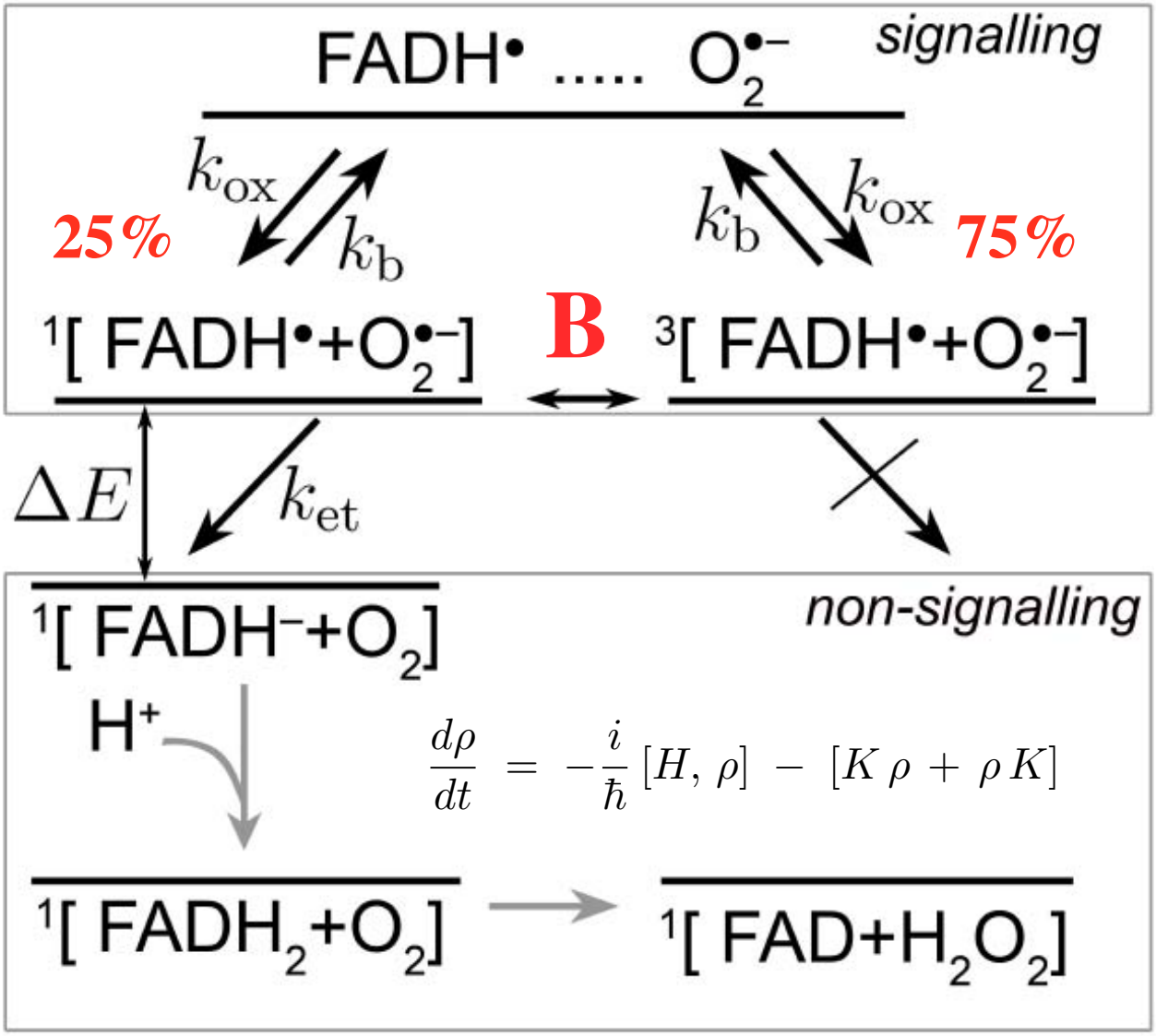




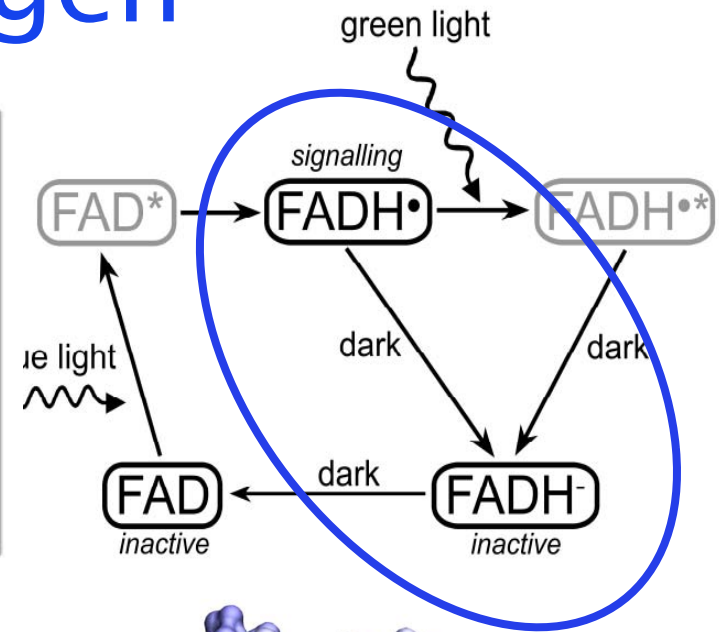
Orientation Dependence of Quantum Yield

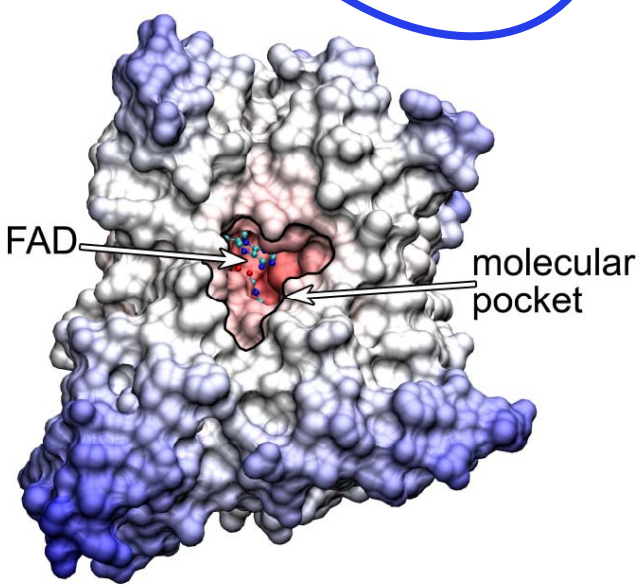
I. Solov'yov, D. Chandler, and K. Schulten, Biophys. J., **92**, 2711-2726 (2007)

Dark Deactivation of Cryptochrome Involving Molecular Oxygen



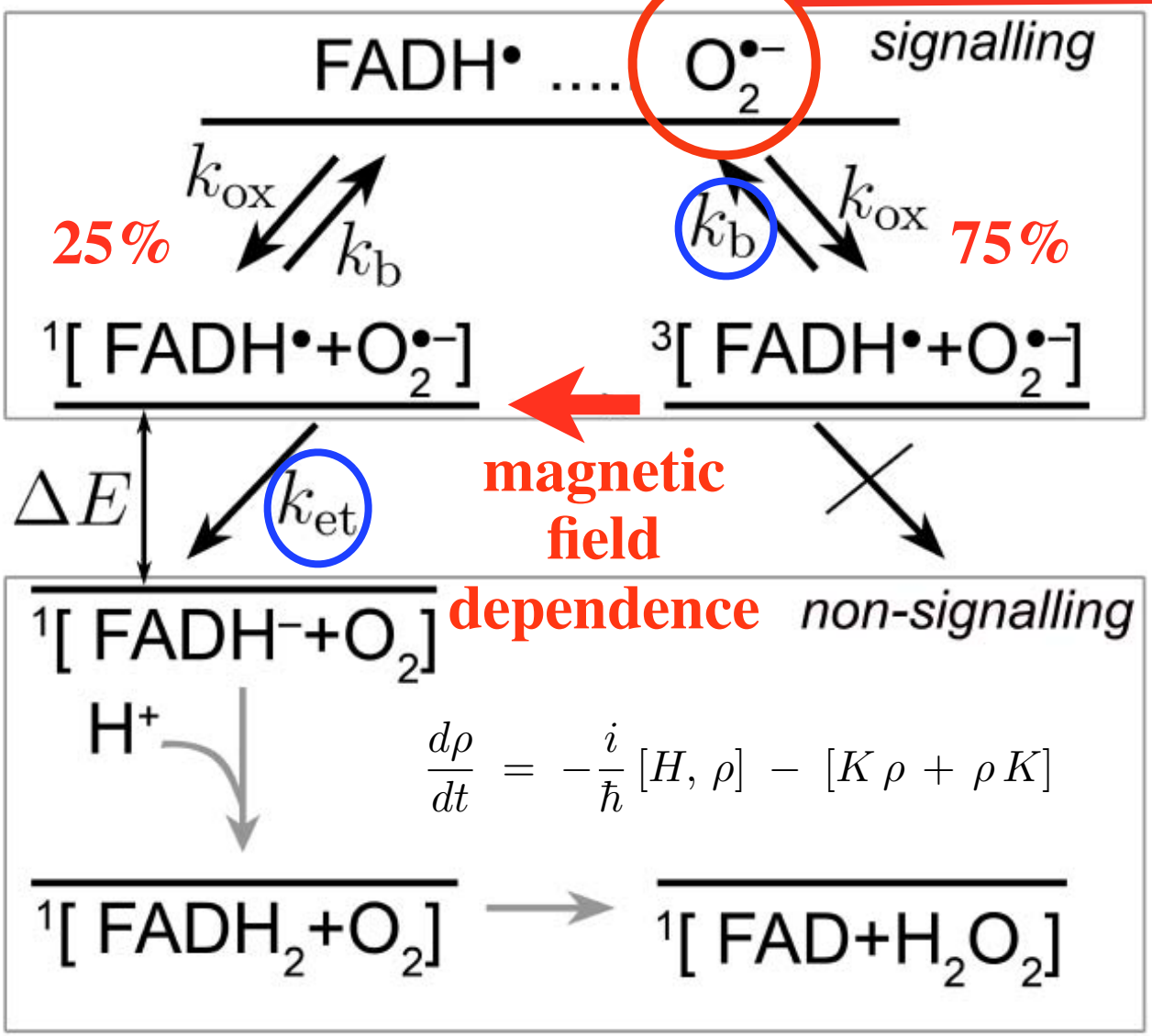
$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] - [K\rho + \rho K]$$





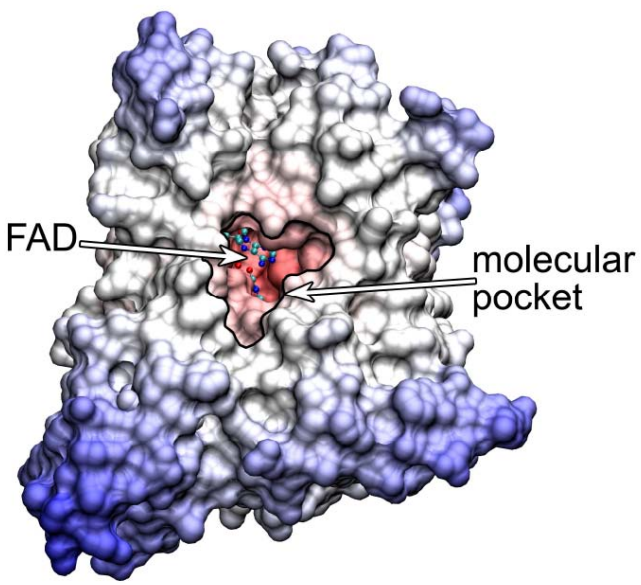
I.A. Solov'yov and K. Schulten, Biophysical Journal **96**, 4804-4313 (2009)

Dark Deactivation of Cryptochrome Actually Involving Superoxide, O_2^-



superxide at low conc. Toxic!

Humans prefer longevity over sense of direction.

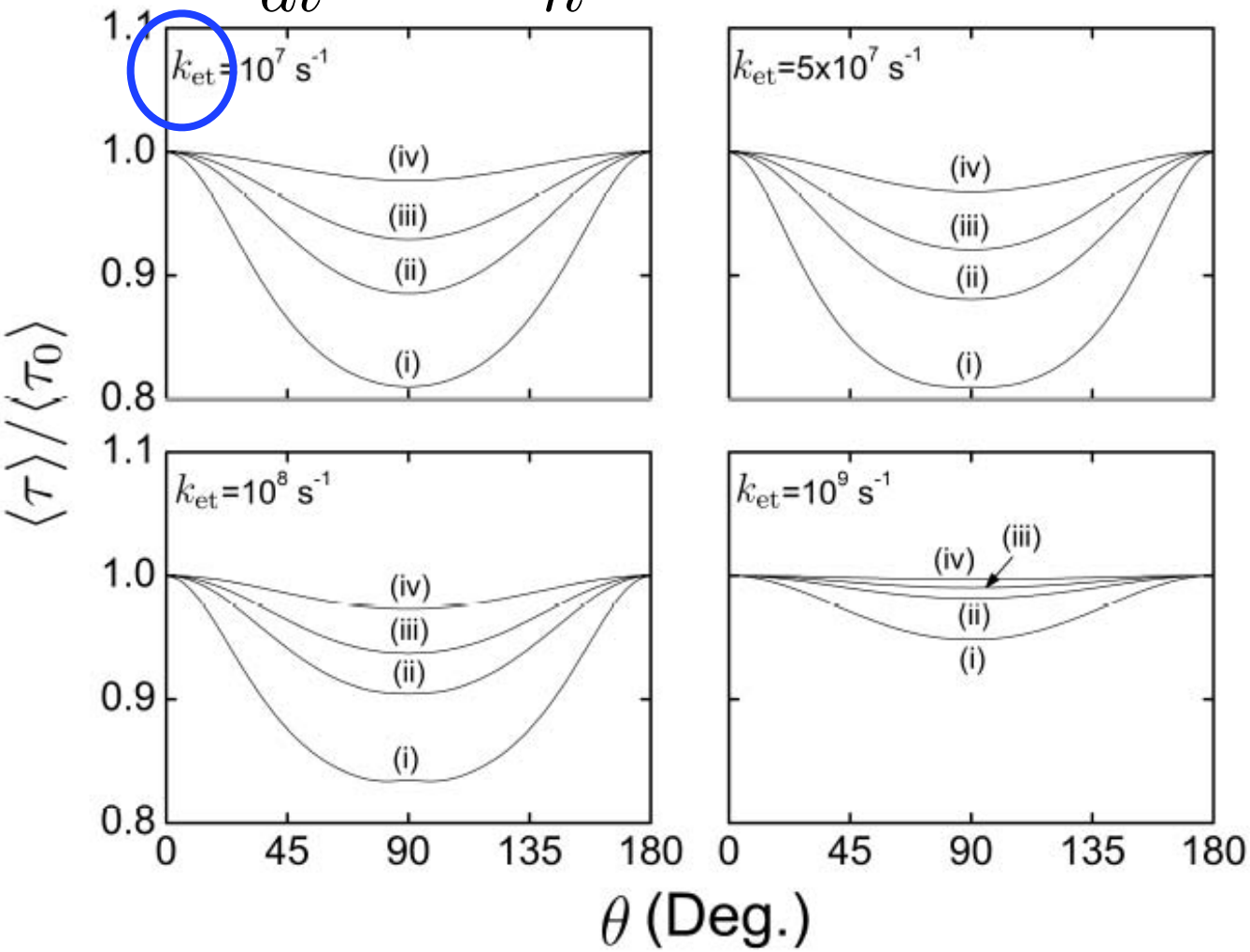


I.A. Solov'yov and K. Schulten, Biophysical Journal **96**: 4804-4313 (2009)

Orientation Dependence of Magnetic Field Effect on Dark Deactivation (Reaction Duration Time)

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] - [K\rho + \rho K]$$

stochastic Liouville Equation



Consider fixed field

$$B_0 = 0.5 \text{ G}$$

(i) $k_b = 10^6 \text{ s}^{-1}$

(ii) $k_b = 3\times10^6 \text{ s}^{-1}$

(iii) $k_b = 5\times10^6 \text{ s}^{-1}$

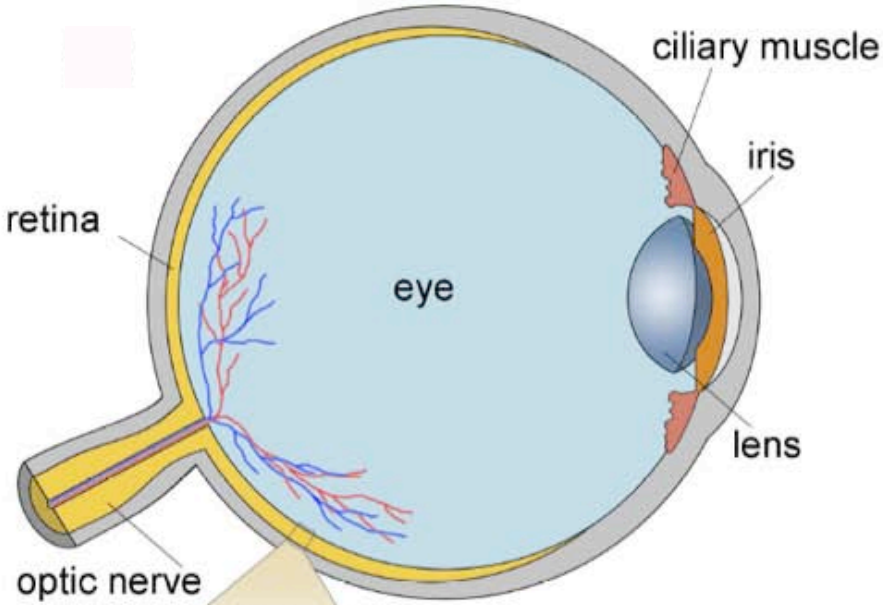
(iv) $k_b = 10^7 \text{ s}^{-1}$

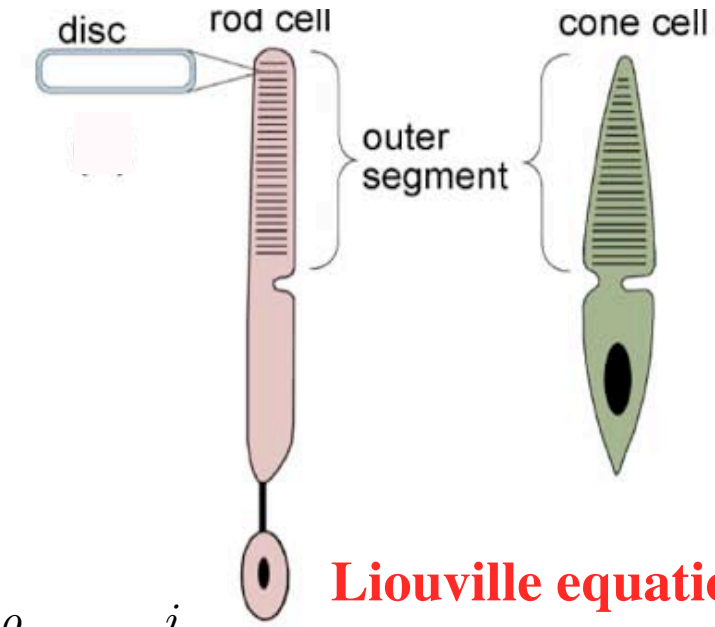
$\langle\tau_0\rangle$ reaction duration at θ=0°

The angular dependence of the reaction duration time corresponds to an inclination compass.
The maximal variation in τ is 18 %.

I.A. Solov'yov and K. Schulten, Biophysical Journal **96**, 4804-4313 (2009)

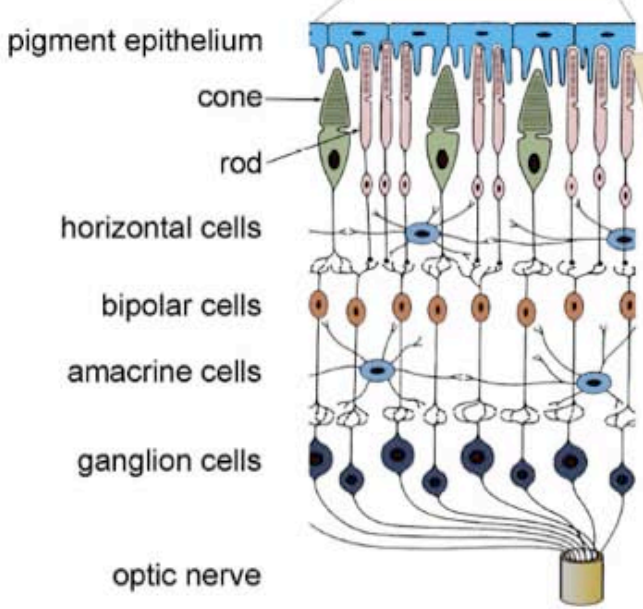
Locating and Orienting Cryptochrome in the Eye

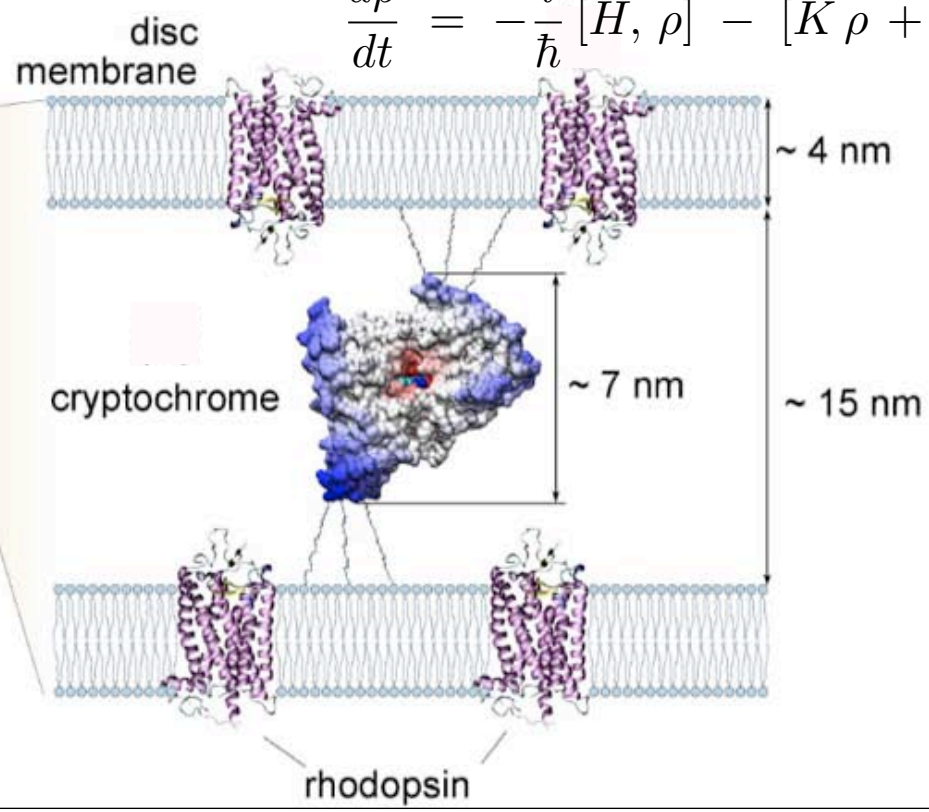




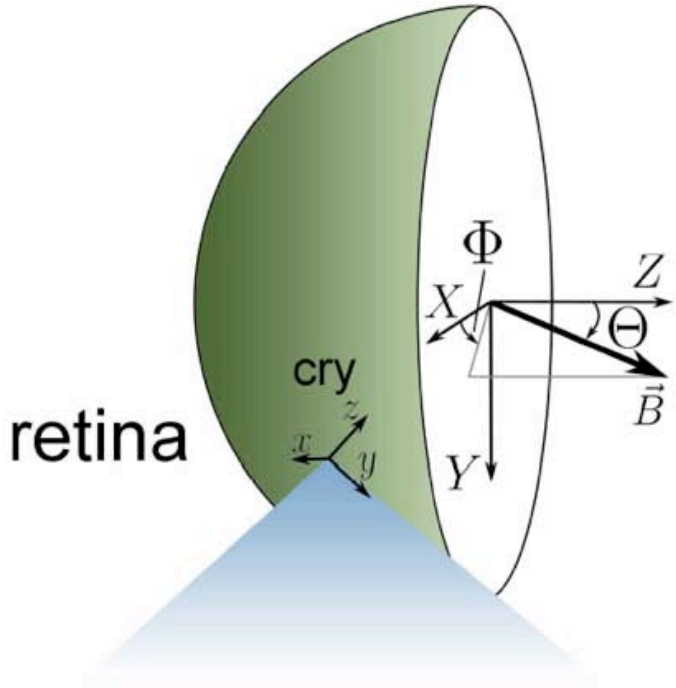
Liouville equation!

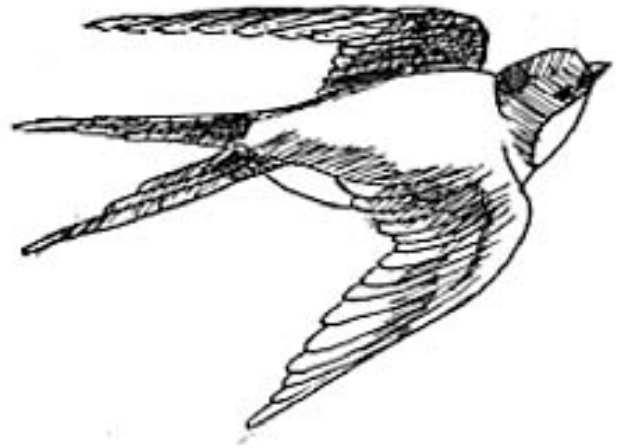
$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] - [K\rho + \rho K]$$

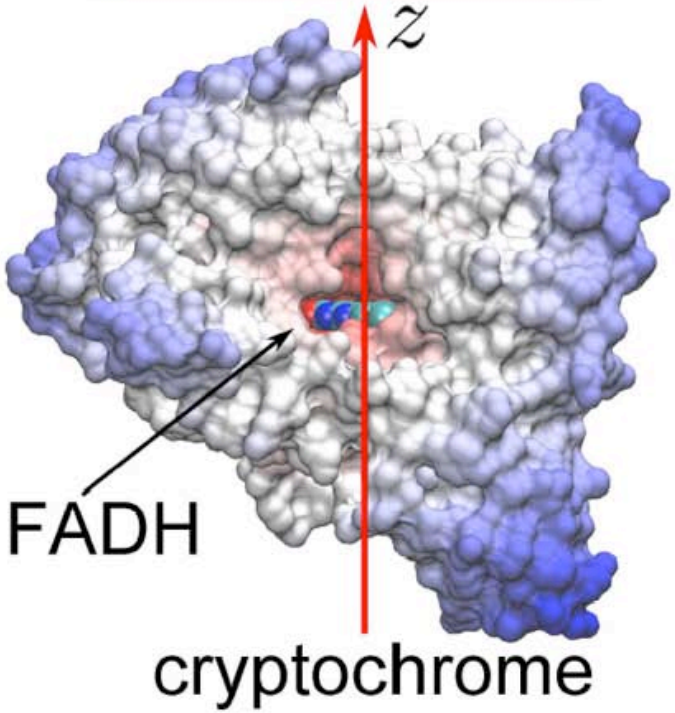


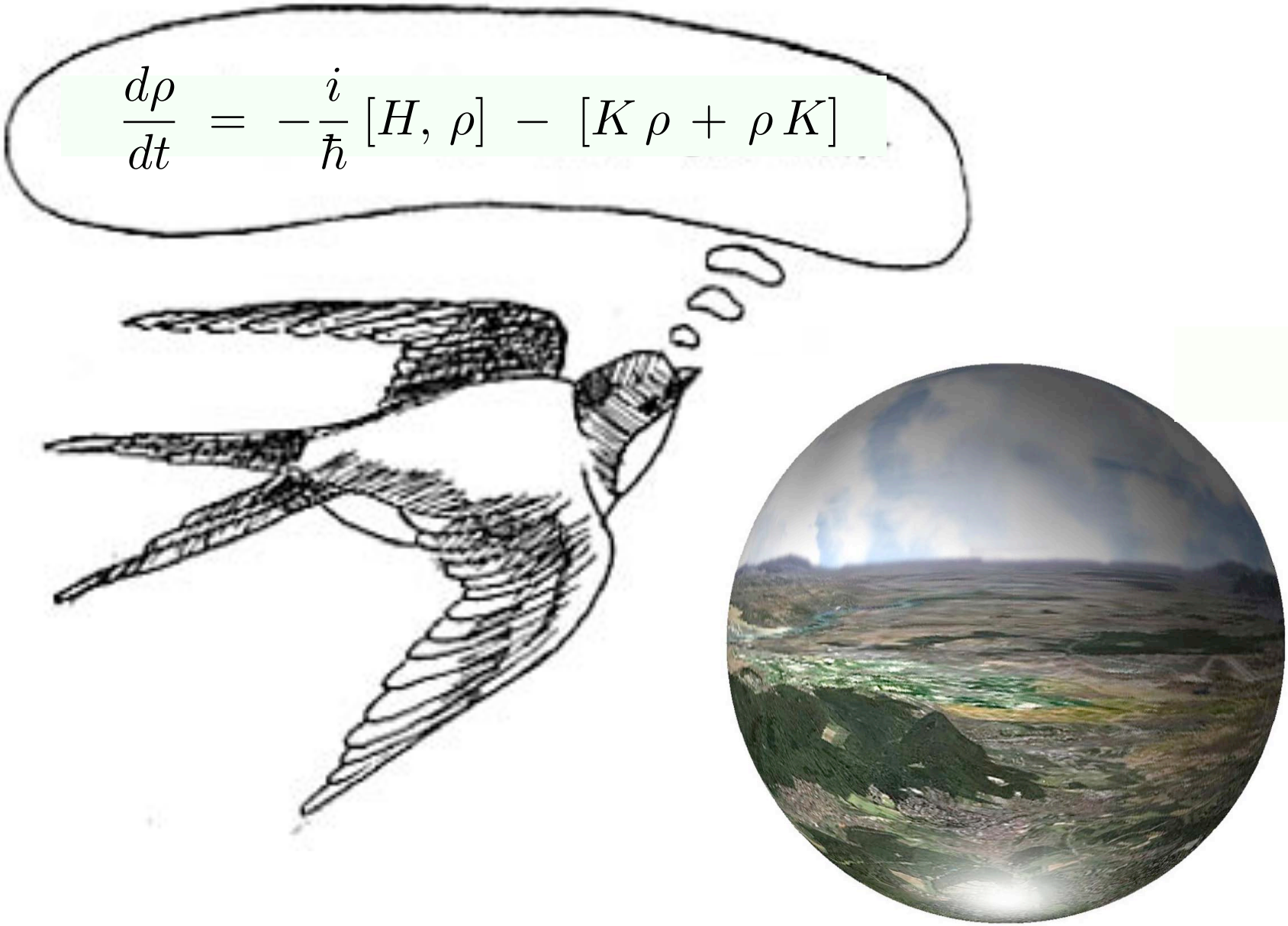


What a bird might see?

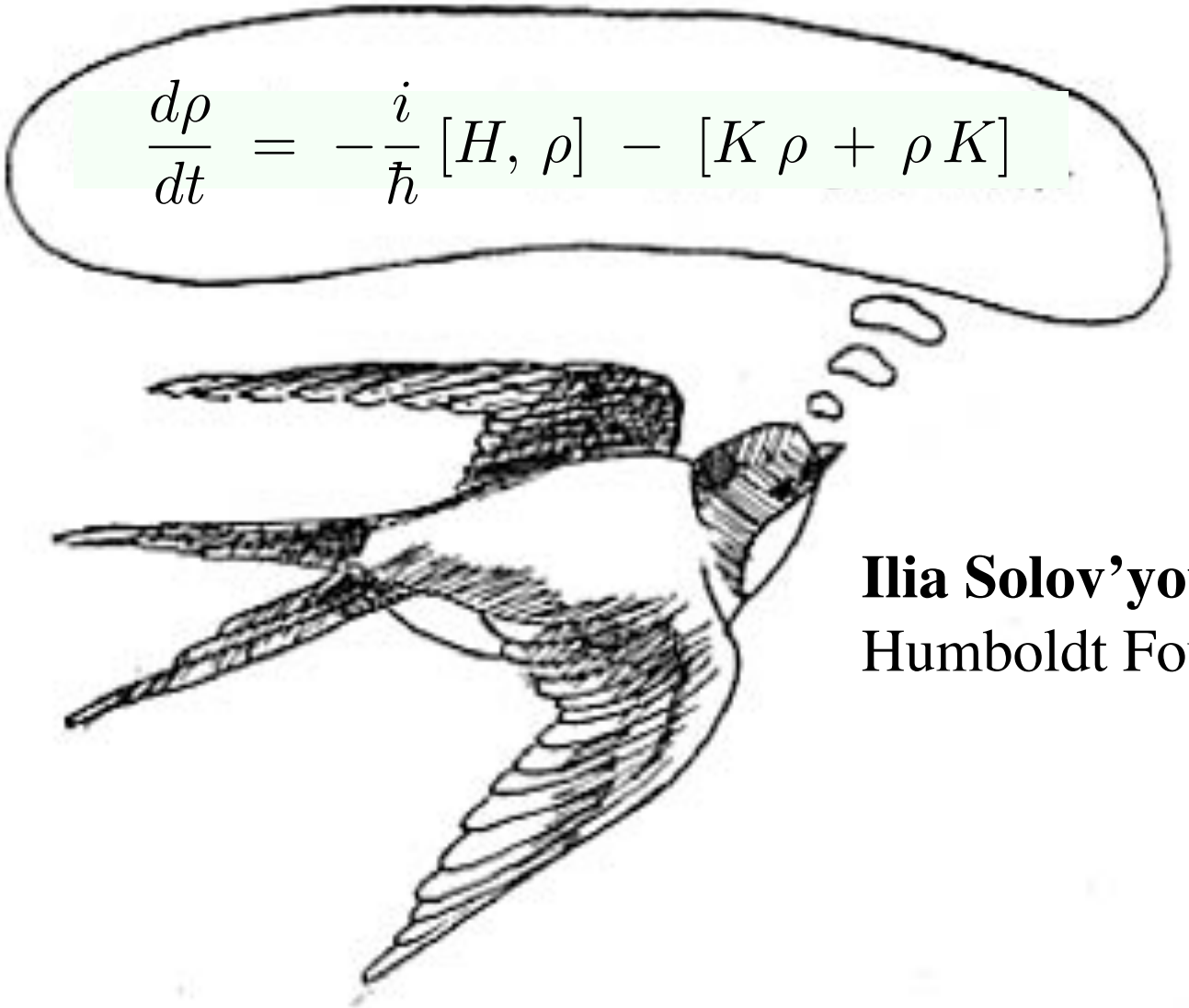







$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] - [K\rho + \rho K]$$

Acknowledgments



Ilia Solov'yov, U. Frankfurt
Humboldt Foundation, NSF

Papers on Quantum Biology of Magnetoreception

Based on: Magnetic Field Dependence of the Geminate Recombination of Radical Ion Pairs in Polar Solvents K. Schulten, H. Staerk, A. Weller, H.-J. Werner, and B. Nickel, *Z. Physik. Chemie* **NF101**: 371-390 (1976)

radical pair-based biochemical compass

Klaus Schulten, Charles E. Swenberg, and Albert Weller. A biomagnetic sensory mechanism based on magnetic field modulated coherent electron spin motion. *Zeitschrift für Physikalische Chemie*, NF111:1-5, 1978.

explains axial compass and narrow field window

Klaus Schulten. Magnetic field effects in chemistry and biology. In J. Treusch, editor, *Festkörperprobleme*, volume 22, pp. 61-83. Vieweg, Braunschweig, 1982.

Klaus Schulten and Andreas Windemuth. Model for a physiological magnetic compass. In G. Maret, N. Boccara, and J. Kiepenheuer, editors, *Biophysical Effects of Steady Magnetic Fields*, volume 11 of *Proceedings in Physics*, pp. 99-106. Springer, Berlin, 1986. suggests that biochemical compass is vision-based

Jeff M. Canfield, R. Linn Belford, Peter G. Debrunner, and Klaus Schulten. A perturbation theory treatment of oscillating magnetic fields in the radical pair mechanism. *Chemical Physics*, 182:1-18, 1994.

these papers suggest radio frequency radiation to probe biochemical compass mechanism

J. M. Canfield, R. L. Belford, P. G. Debrunner, and K. Schulten. A perturbation treatment of oscillating magnetic fields in the radical pair mechanism using the Liouville equation. *Chemical Physics*, 195:59-69, 1995.

Thorsten Ritz, Salih Adem, and Klaus Schulten. A model for photoreceptor-based magnetoreception in birds. *Biophysical Journal*, 78:707-718, 2000. suggests cryptochrome as cause of biochemical compass

Ilia A. Solov'yov, Danielle E. Chandler, and Klaus Schulten. Magnetic field effects in Arabidopsis thaliana cryptochrome-1. *Biophysical Journal*, 92:2711-2726, 2007.

magnetic field dependence of photoactivation

Ilia A. Solov'yov, Danielle Chandler, and Klaus Schulten. Exploring the possibilities for radical pair effects in cryptochrome. *Plant Signaling and Behavior*, 3:676-677, 2008. application to plant cryptochrome

Ilia A. Solov'yov and Klaus Schulten. Magnetoreception through cryptochrome may involve superoxide. *Biophysical Journal*, 96:4804-4813, 2009. magnetic field dependence of dark deactivation

Ilia A. Solov'yov, Henrik Mouritsen, and Klaus Schulten. Acuity of a cryptochrome and vision based magnetoreception system in birds. *Biophysical Journal*, 2010. In press. investigates degree of cryptochrome orientation