Biochemical Mechanisms for Magnetic Orientation in Animals

Physics 498 Biological Physics

Spring 2007, Lecture on March 5

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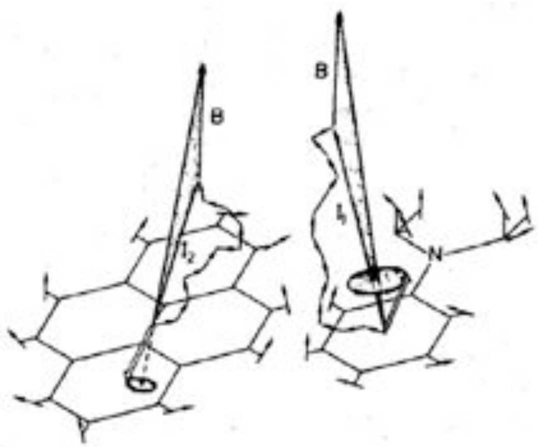
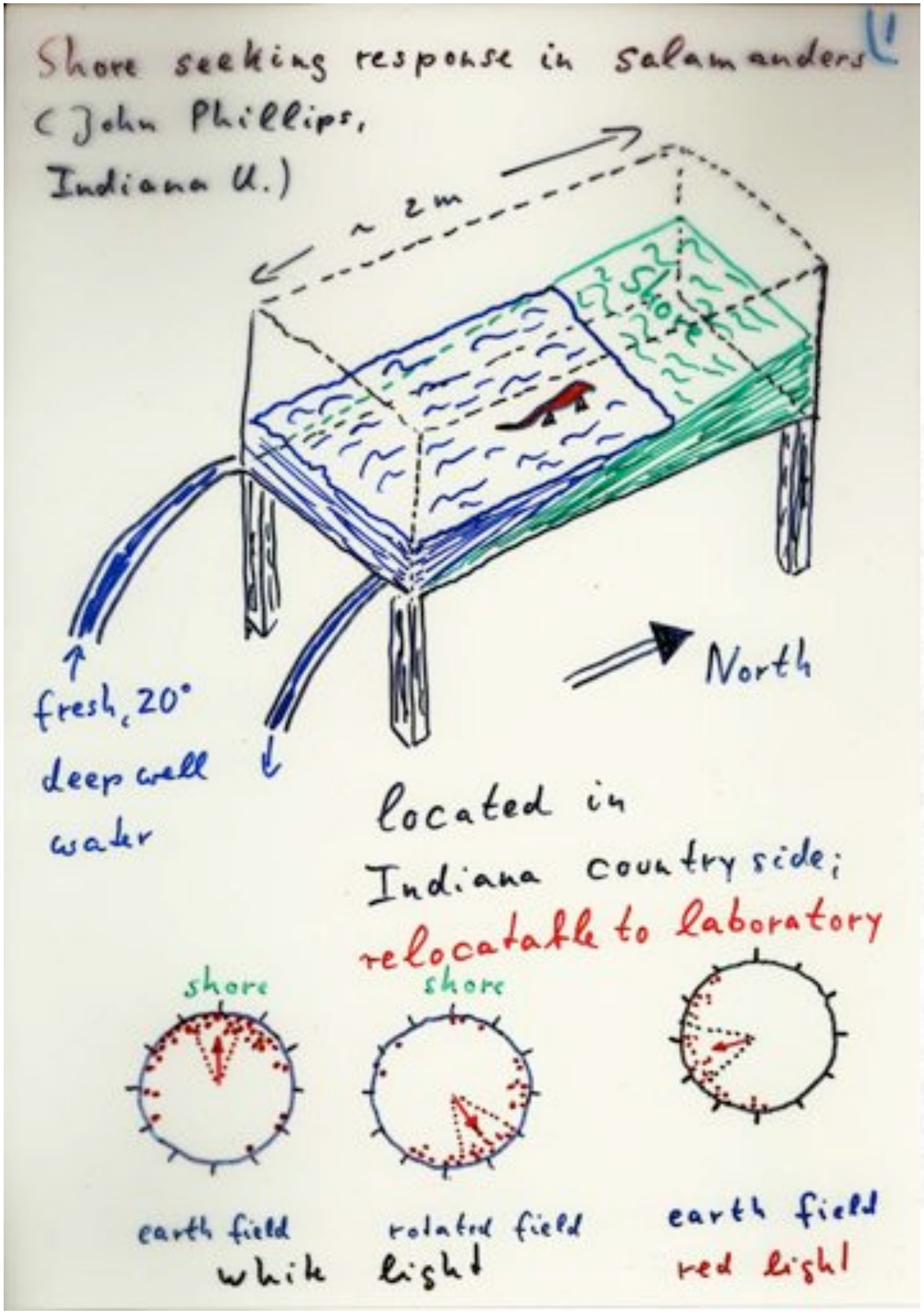


Magnetoreception in Animals

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

First experiments were performed in the 1960s with homing pigeons and migratory birds



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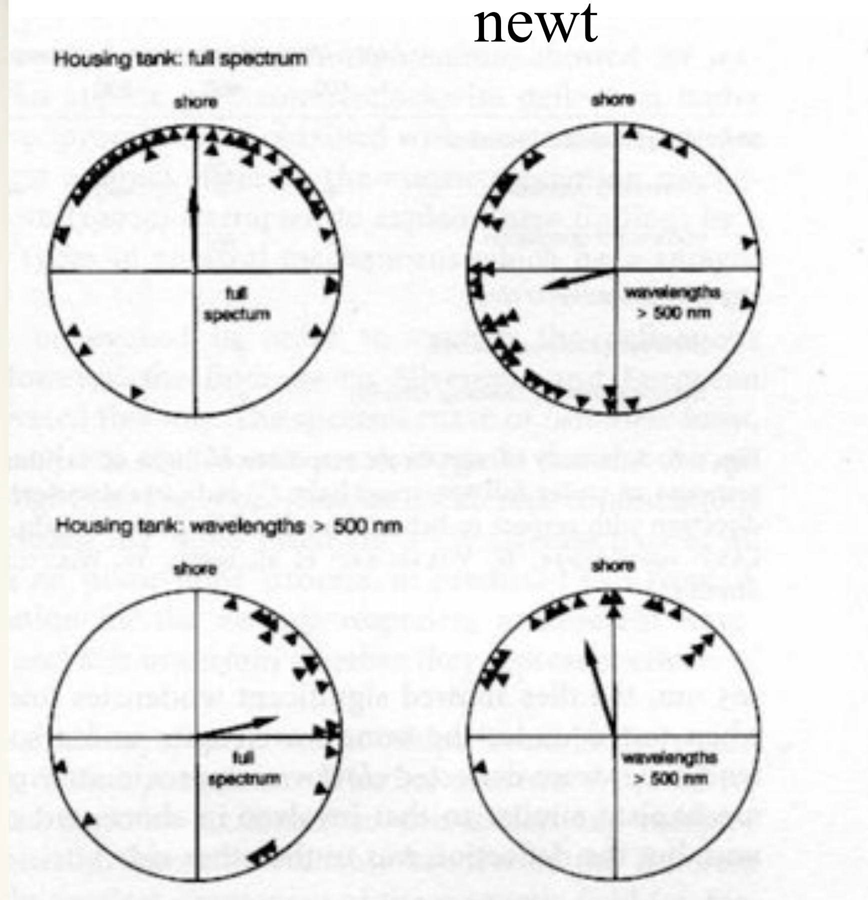
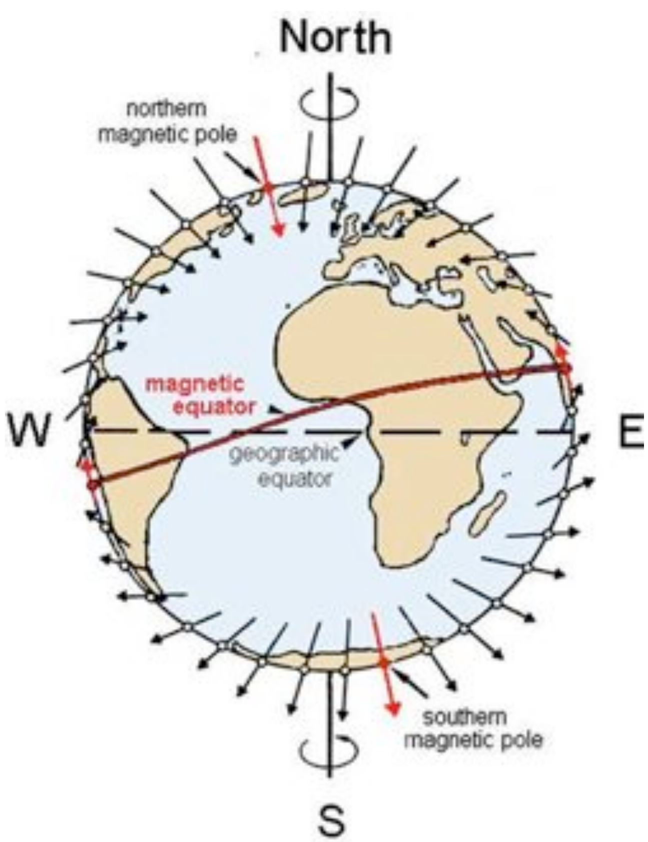


Phillips and Borland, Nature 359: 142 (1992)

Avian Magnetoreception

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

Have both a "map" of small variations in field intensity along migratory path and a "compass" to determine direction



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

Avian Compass

European robin

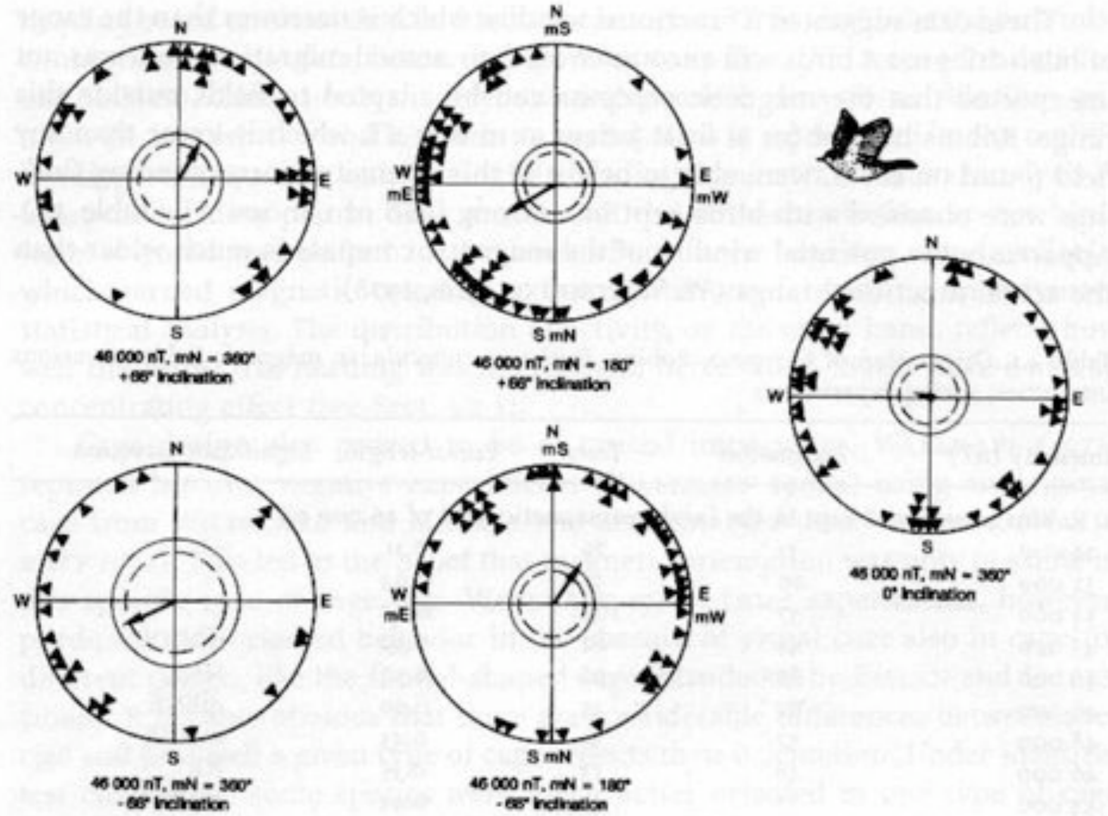


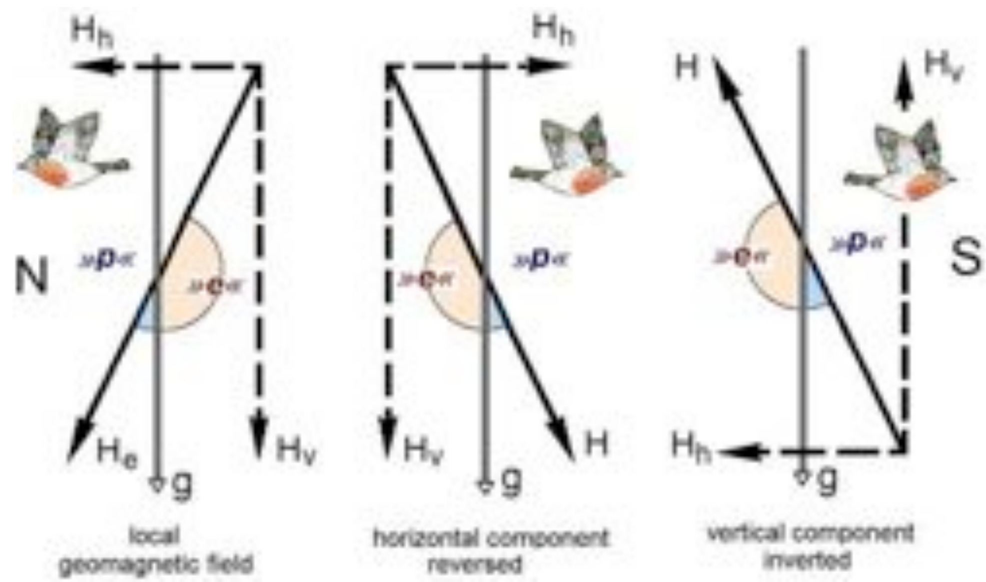
Fig. 4.3. Orientation behavior of European Robins tested in magnetic fields of equal intensity, but with various declinations and inclinations. *Symbols* as in Fig. 4.2. (After W. WILTSCHKO and WILTSCHKO 1972)

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

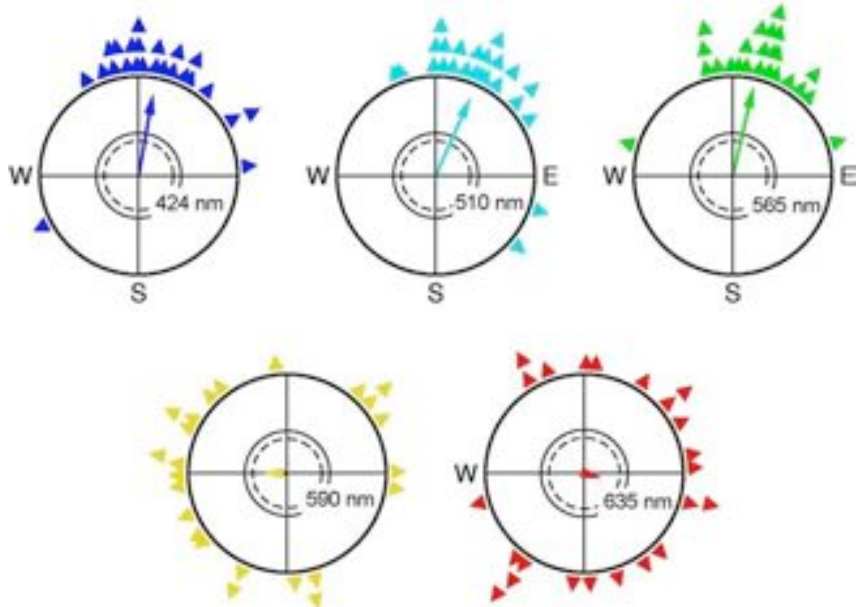


Birds must know the direction of “up” to differentiate North from South

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



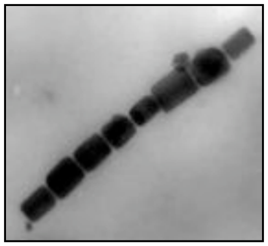
each triangle represents the orientation of one bird

(Wiltschko 2005)

The physical mechanism for magnetoreception for birds is located in the right eye.

Visual Modulation Compass

Two Theories for Avian Magnetoreception



1. Use of Magnetite Particles

small amounts of magnetic materials have been found in some bird species

does not explain :

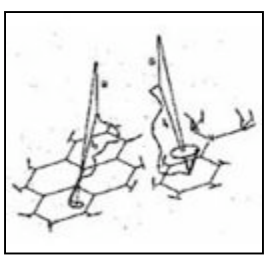
-why the compass is light-dependent

-why the compass is inclination-only

-why the compass works for only a narrow range of field strength

disagrees with experiments using pulsed magnetic field

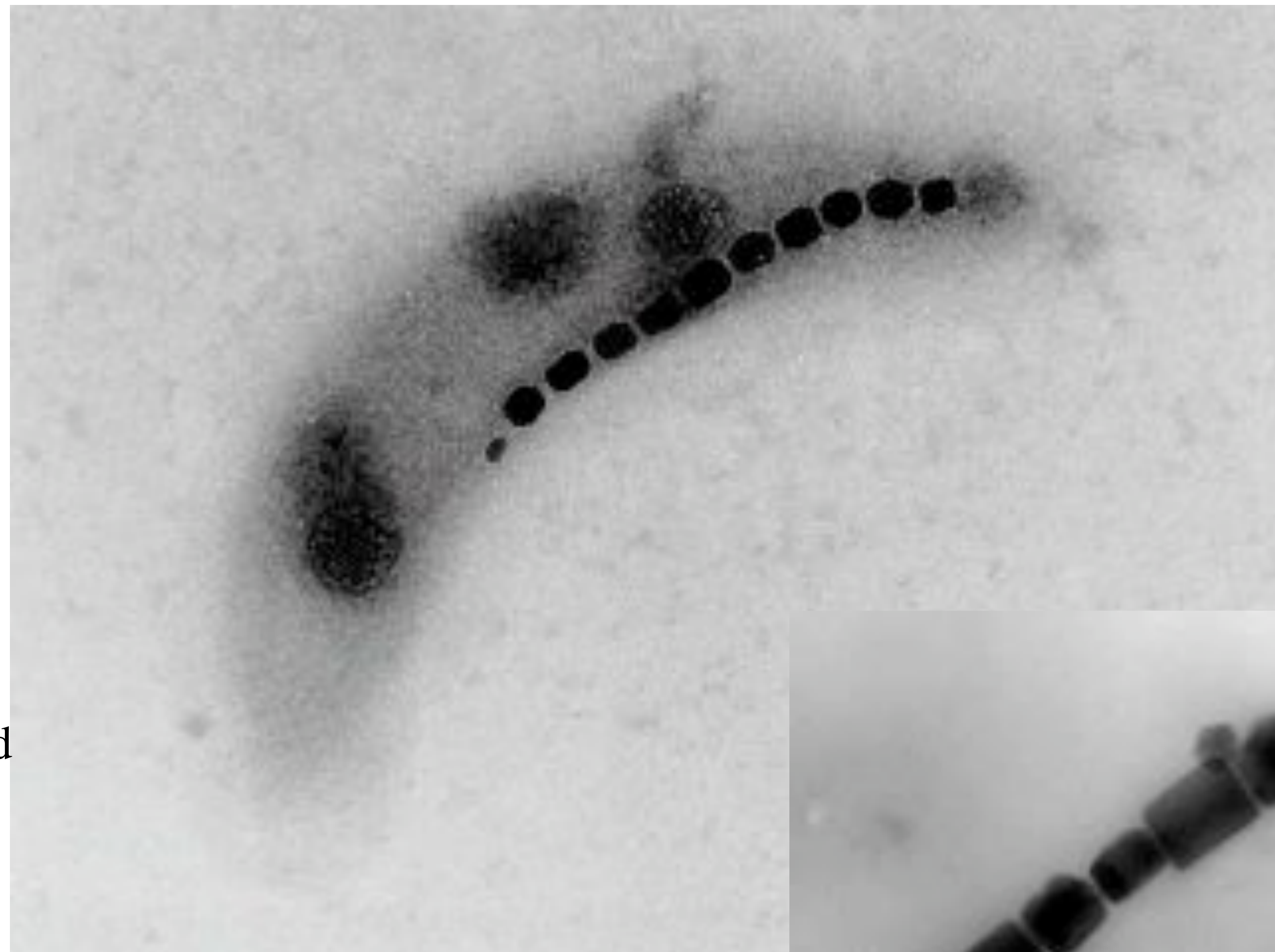
birds may still use magnetite for a “magnetic map”

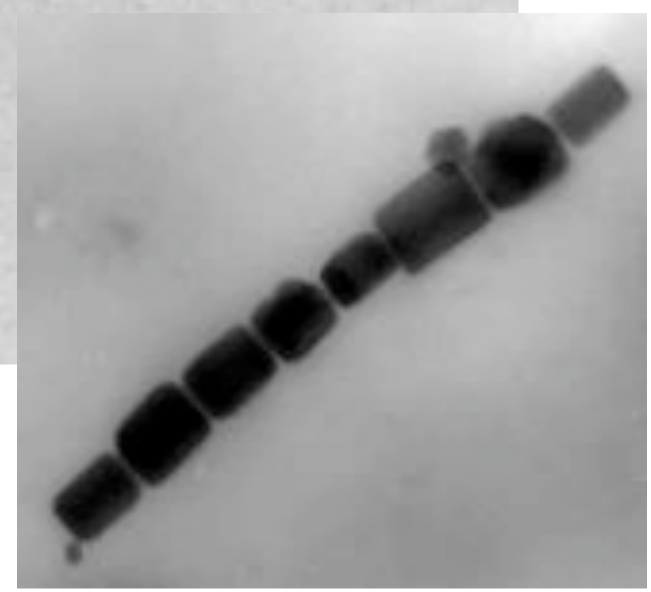


2. Radical Pair Mechanism

Magnetotactic Bacteria Suggest an Obvious Physics-Based Mechanism for Magnetotaxis

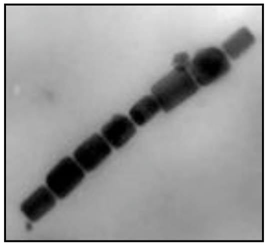
This is definitely one possible mechanism. Research at ***Frankfurt University (Gerda Fleissner et al)*** finally identified magnetic particles in birds' beaks that are likely involved in magnetotaxis. However, it is generally assumed that an alternative magnetic sense exists that is based on a biochemical mechanism. Some evidence is provided below and the respective mechanism is subject of this lecture.





TEM image, T. St Pierre et al, Physics, UWA

Two Theories for Avian Magnetoreception



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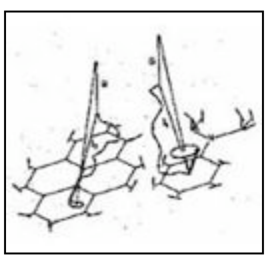
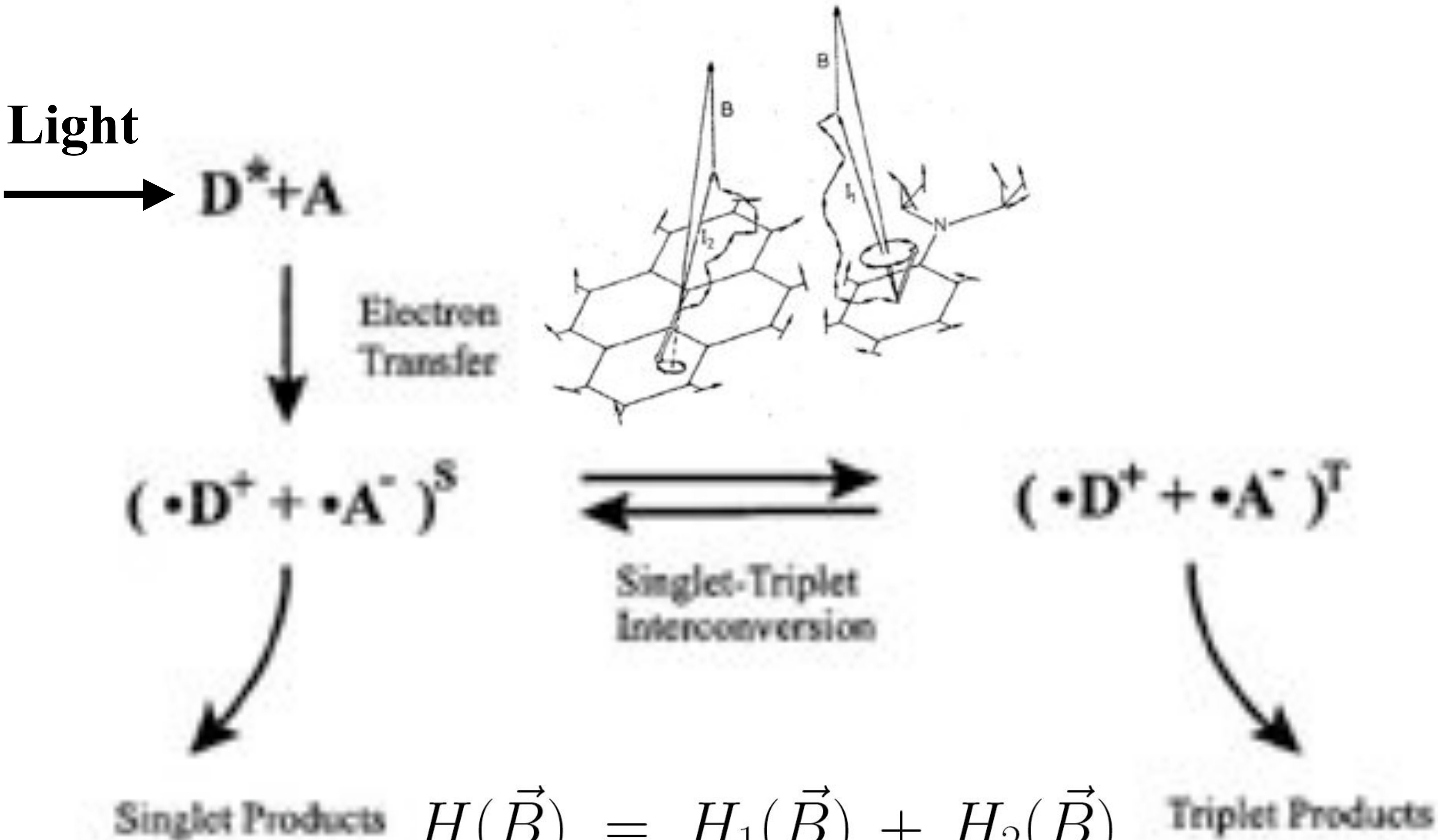


2. Radical Pair Mechanism

The Radical Pair Mechanism

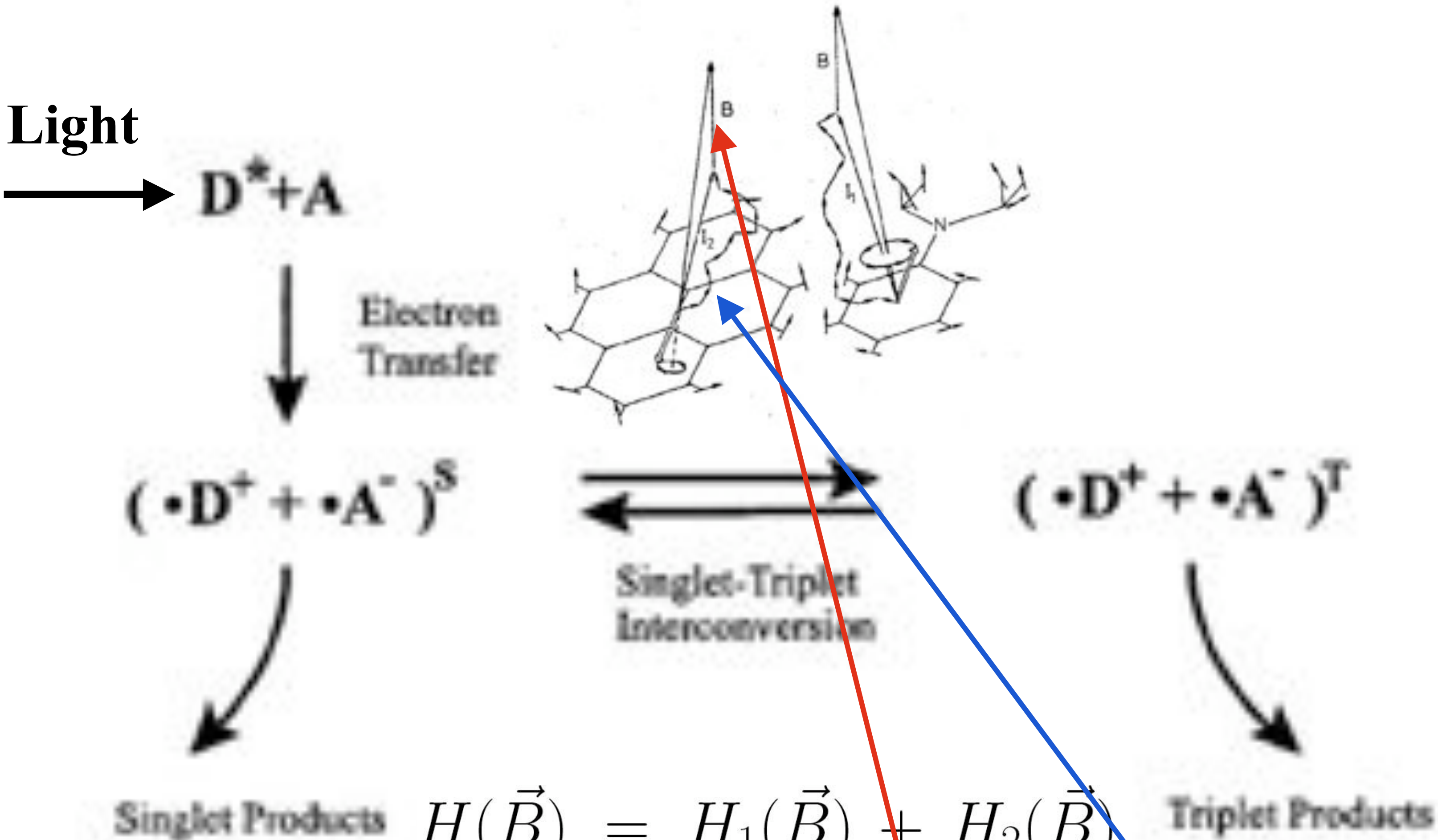


$$H(\vec{B}) \;=\; H_1(\vec{B}) \,+\, H_2(\vec{B})$$

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

(in both radicals)

The Radical Pair Mechanism



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

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

(in both radicals)

$\vec{\mathbf{I}}_{\mathbf{j}} = \vec{\mathbf{B}}_{\mathbf{local}}$

Formulas to Evaluate the Triplet Yield of the Radical Pair Reaction

reaction rate constant in triplet state

$$\Phi^{T} = \int_0^\infty k_T T(t) dt \qquad T(t) = \mathrm{Tr}[Q^T \rho(t)]$$

projection operator on triplets $Q^T = \frac{3}{4} + \vec{S}_1 \cdot \vec{S}_2$

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

$Q^S = \frac{1}{4} - \vec{S}_1 \cdot \vec{S}_2$ initial state

$$\rho(t) = \frac{1}{N} e^{-iHt/\hbar} Q^S e^{iHt/\hbar} e^{-kt}$$

Spin-independent decay kinetics: $k = k_S = k_T$

m-th eigenvalue of H

$$T(t) = \frac{1}{N} e^{-kt} \cdot \sum^{4N} \sum^{4N} Q^T_{mn} Q^S_{mn} \cos[(w_m - w_n)t]$$

$$\Phi^{T} = \frac{1}{N} \cdot \sum_{m=1}^{4N} \sum_{n=1}^{4N} Q^T_{mn} Q^S_{mn} \frac{k^2}{k^2 + (w_m - w_n)^2}$$

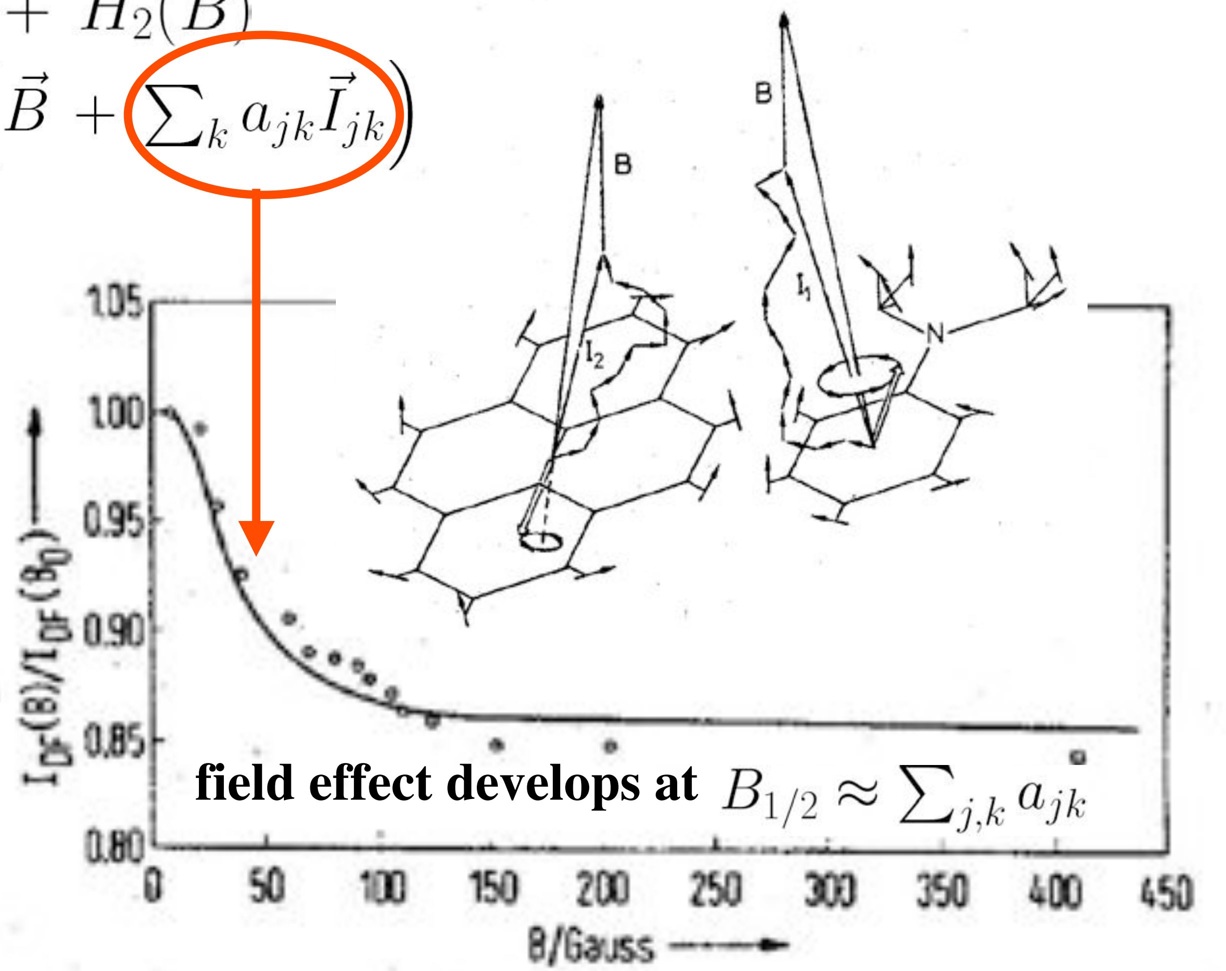
Predicted and Observed Magnetic Field Dependence of Triplet Yield

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

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

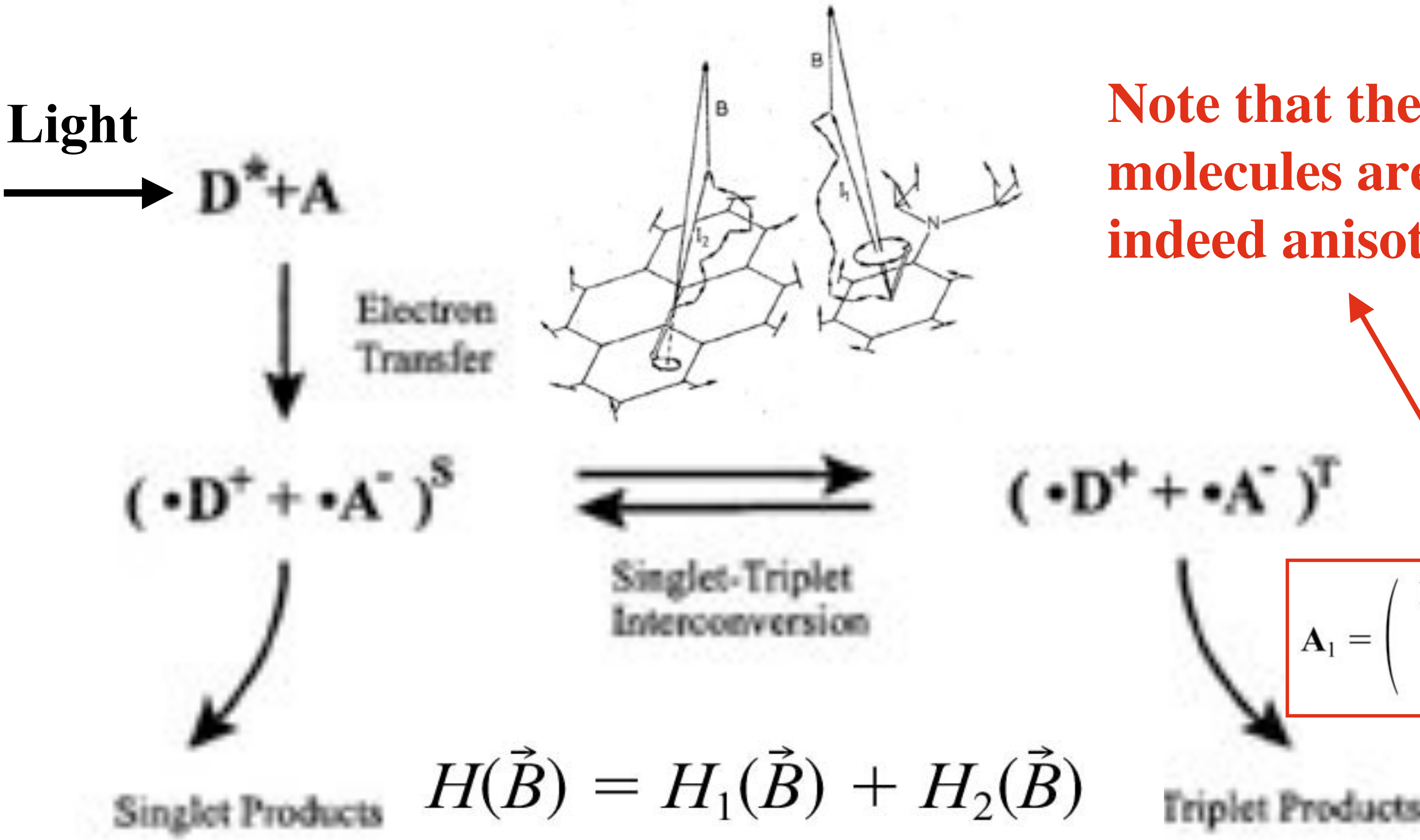
$$H_j(\vec{B}) = g\mu_B \vec{S}_j \cdot \left(\vec{B} + \sum_k a_{jk} \vec{I}_{jk}\right)$$

hyperfine coupling constants determine field strength needed



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

Radical Pair Mechanism as a Compass



Note that the molecules are indeed anisotropic!

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

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

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

(anisotropic hyperfine interaction does not yield a compass)

anisotropic in molecular frame

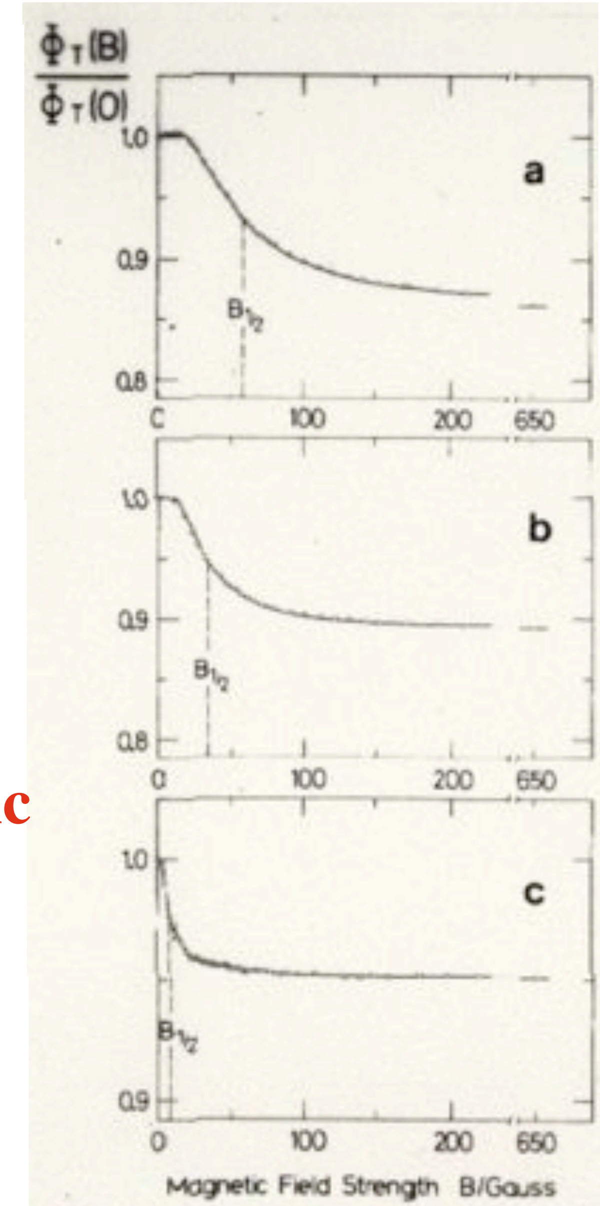
Magnetic Field Effect in Case of Anisotropic Hyperfine Coupling

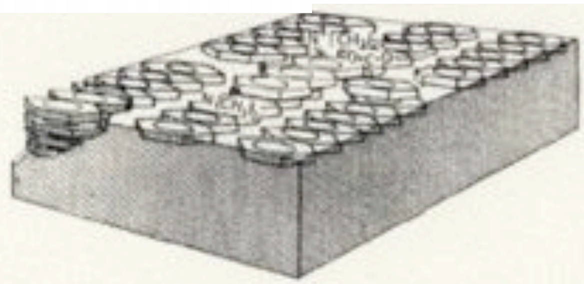
$$H(\vec{B}) = H_1(\vec{B}) + H_2(\vec{B})$$

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

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

Should work in geo-magnetic field!





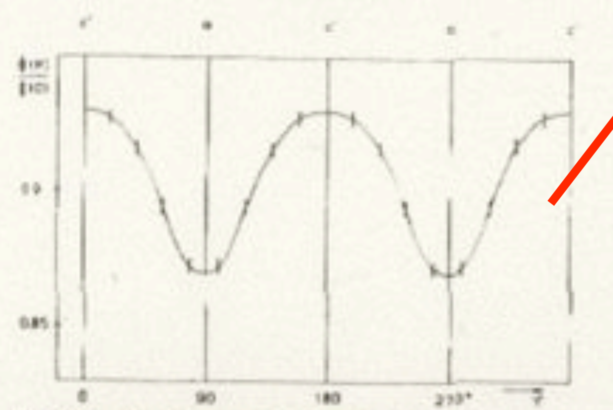
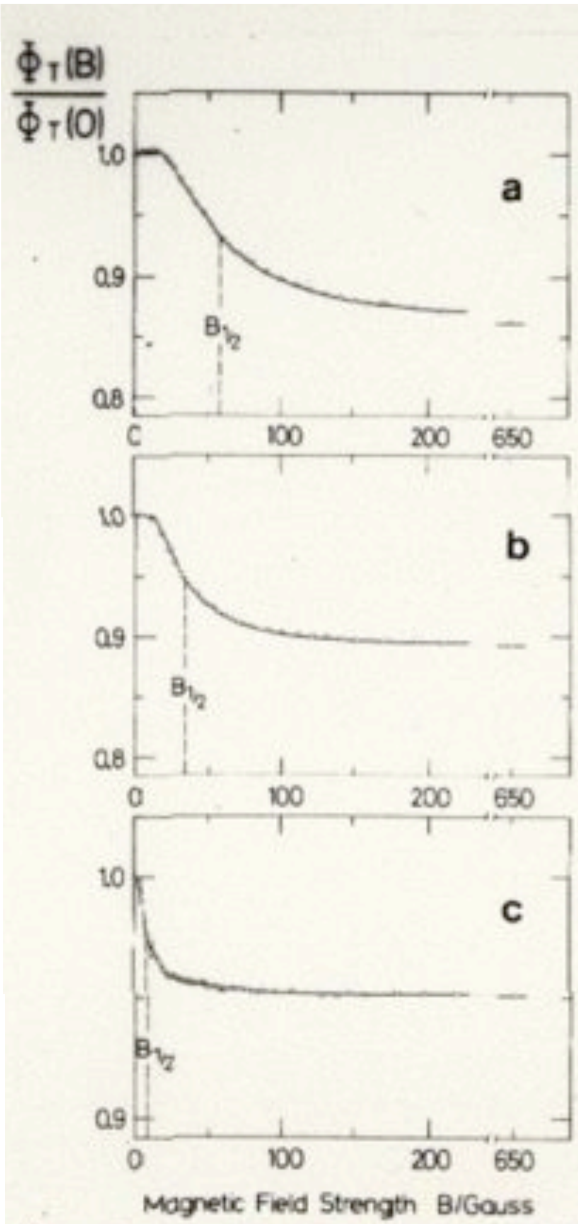
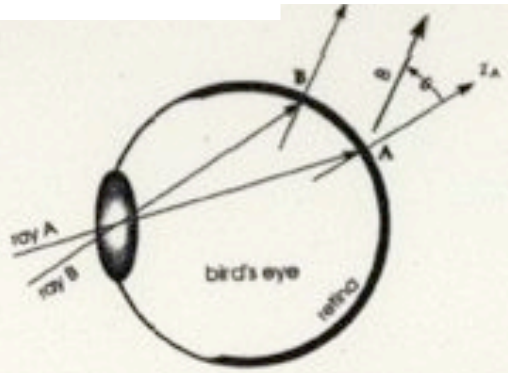


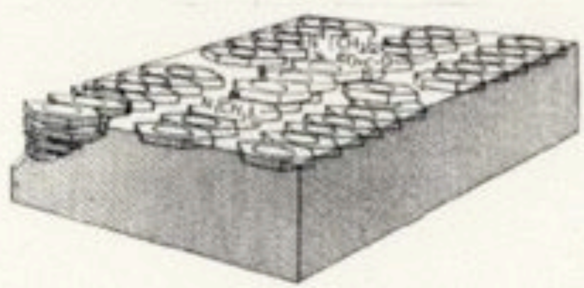
Fig. 3. Normalized magnetic field modulation of the sensitized delayed fluorescence φ as a function of the angle between the direction of the external magnetic field H and the a axis of the anthracene crystal.

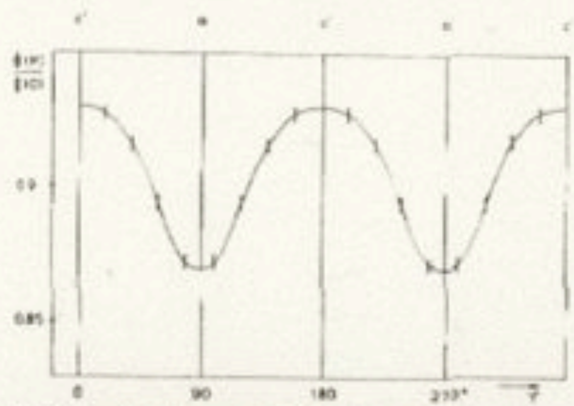
Compass

Applying Anisotropic Hyperfine Coupling to the Visual System









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

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

Model for a physiological magnetic compass. K. Schulten and A. Windemuth. 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.

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

What a Bird Might See

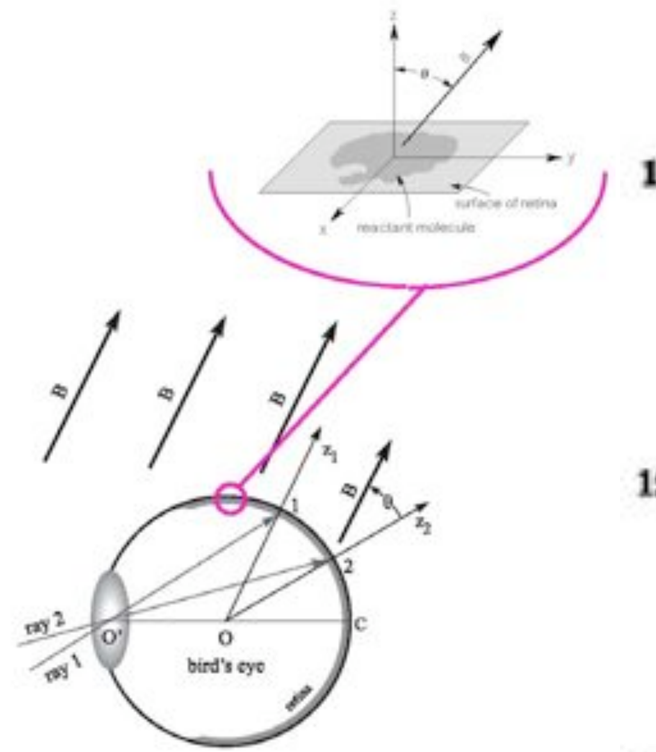
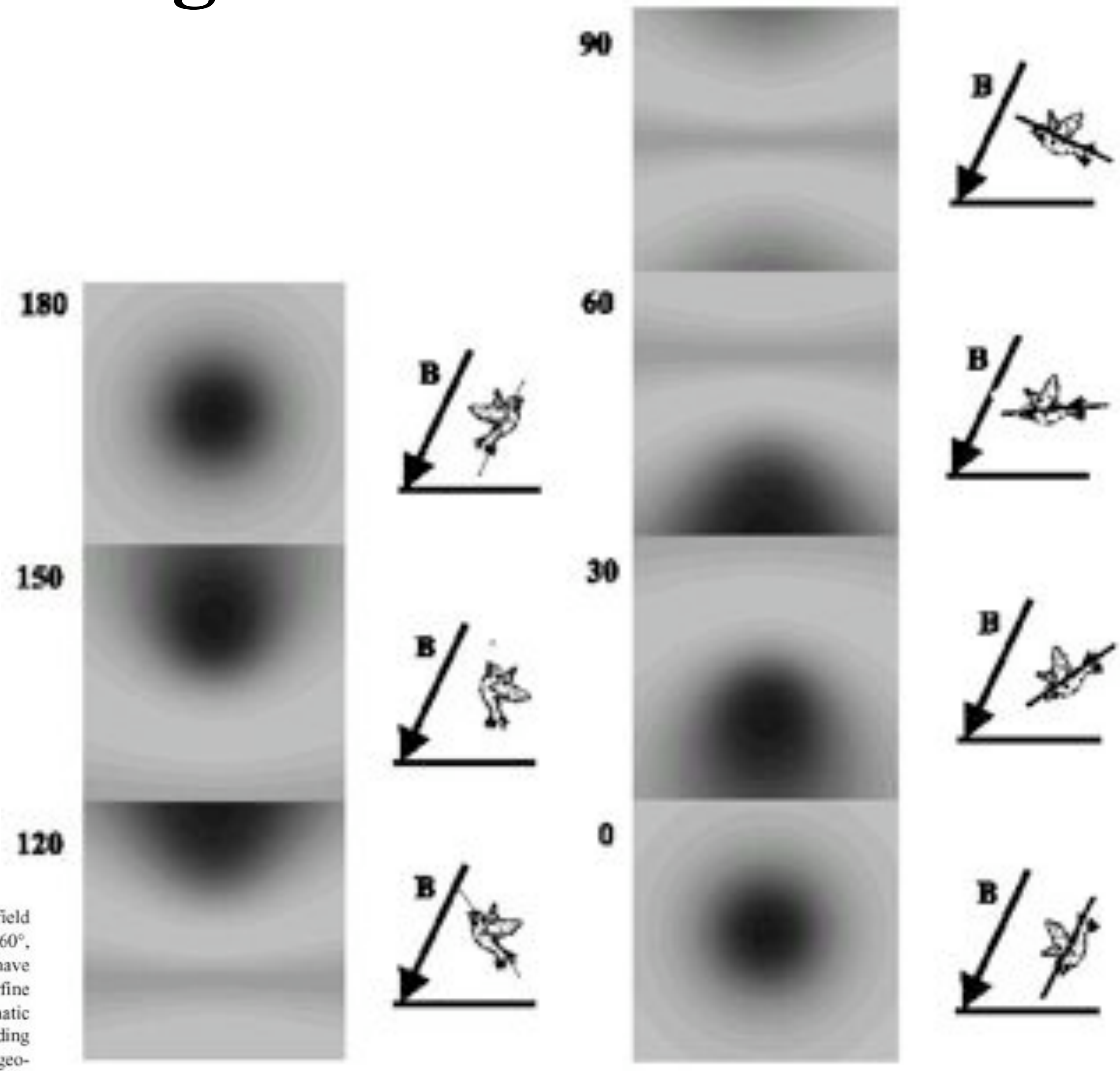


FIGURE 6 Visual modulation patterns through the geomagnetic field (0.5 G) for a bird looking into different directions at angles 0°, 30°, 60°, 90°, 120°, 150°, and 180° with the magnetic field vector. The patterns have been evaluated assuming radical-pair receptors with anisotropic hyperfine couplings 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°).



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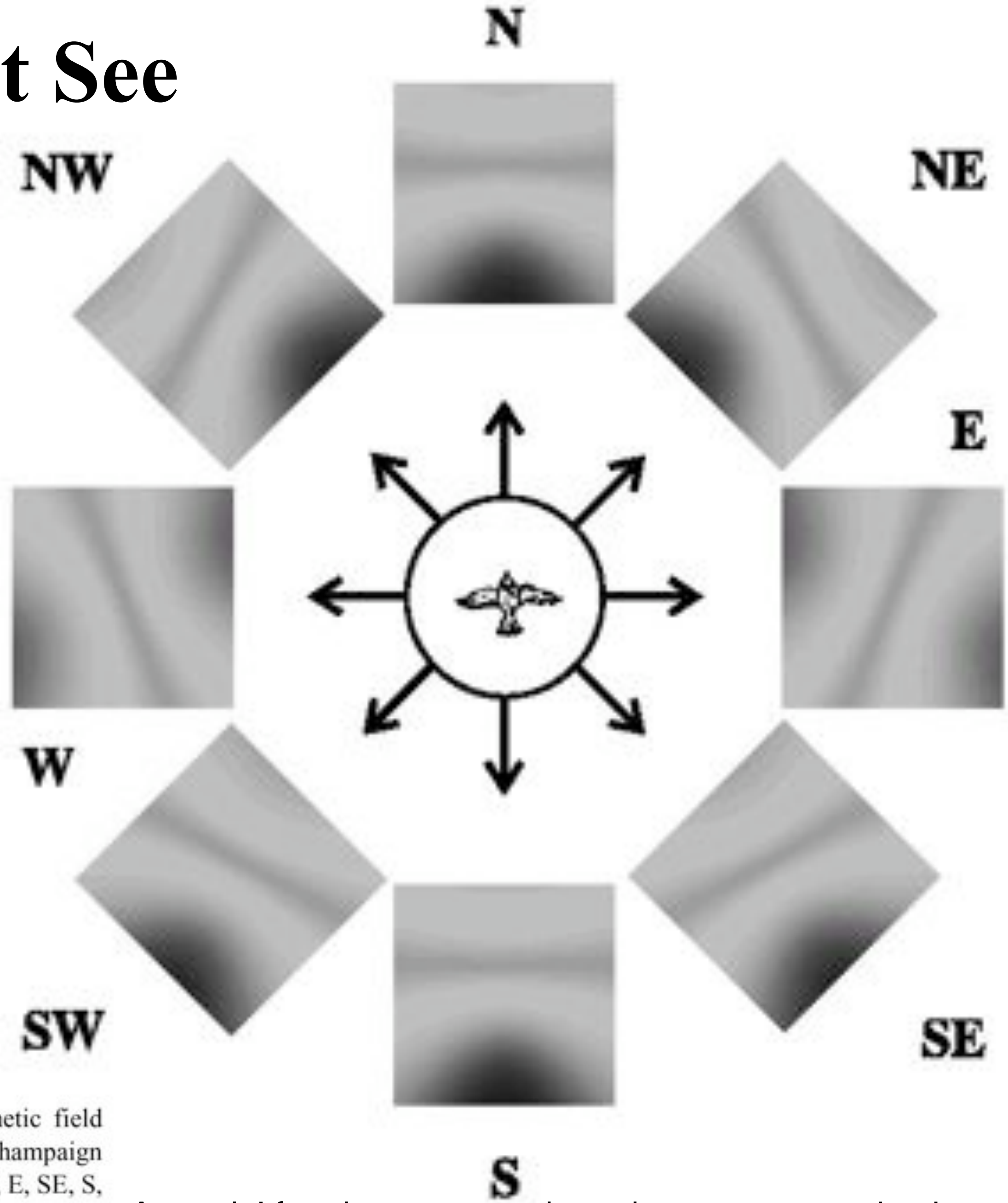


FIGURE 7 Visual modulation patterns through the geomagnetic field (0.5 G) for a bird flying parallel to the horizon at Urbana-Champaign (geomagnetic field inclination of 68°) and looking toward N, NE, E, SE, S, SW, W, and NW. The patterns have been evaluated assuming radical-pair receptors with anisotropic hyperfine couplings arranged in the eye model depicted in Fig. 5.

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

Dependence on Strength of the Geomagnetic Field

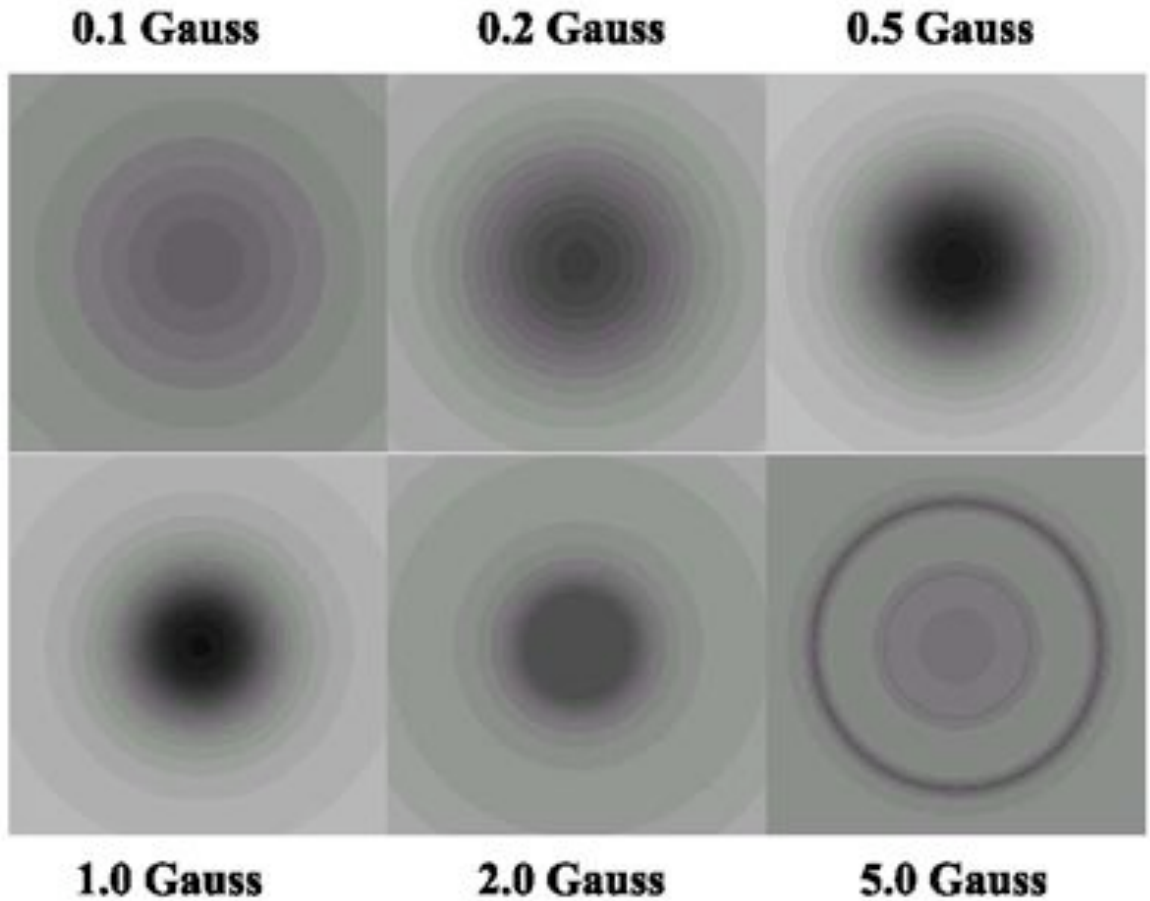
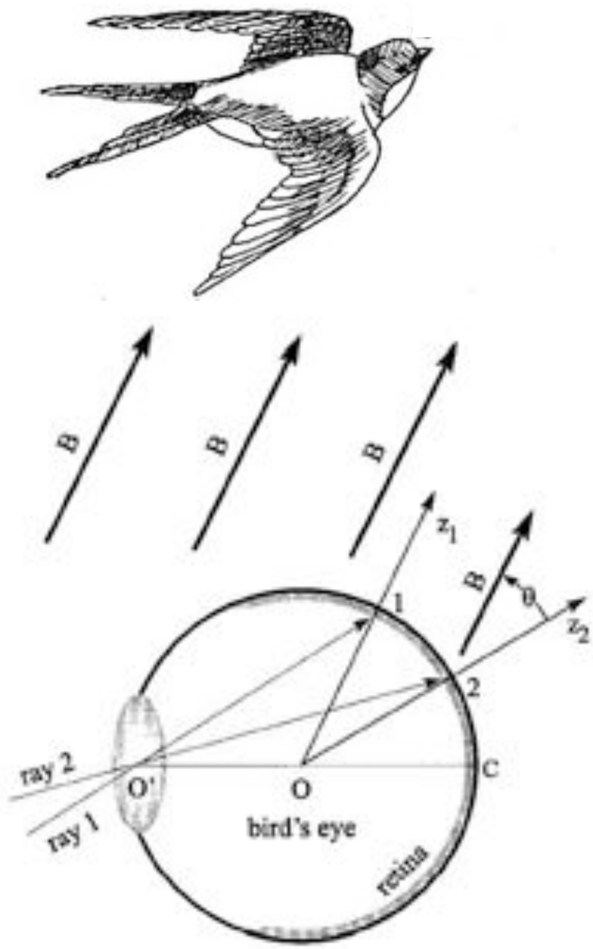


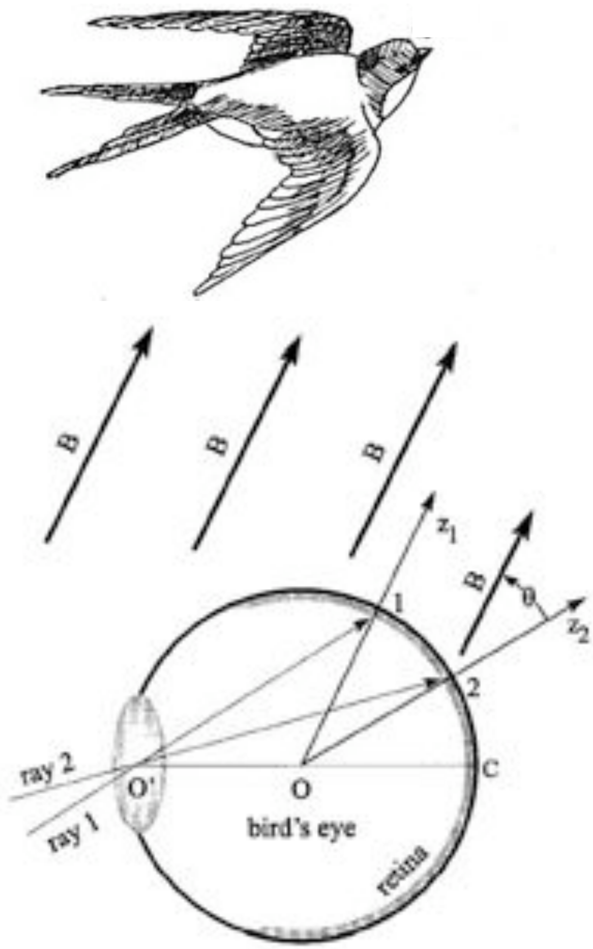
FIGURE 8 Visual modulation patterns through magnetic fields of 0.1, 0.2, 0.5, 1.0, 2.0, and 5.0 G for a bird looking parallel to the magnetic field lines. Changes in the field strength induce changes in the contrast of the modulation pattern, e.g., the central disk feature that is clearly visible for 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.

Visual Modulation Compass



(from BBC)

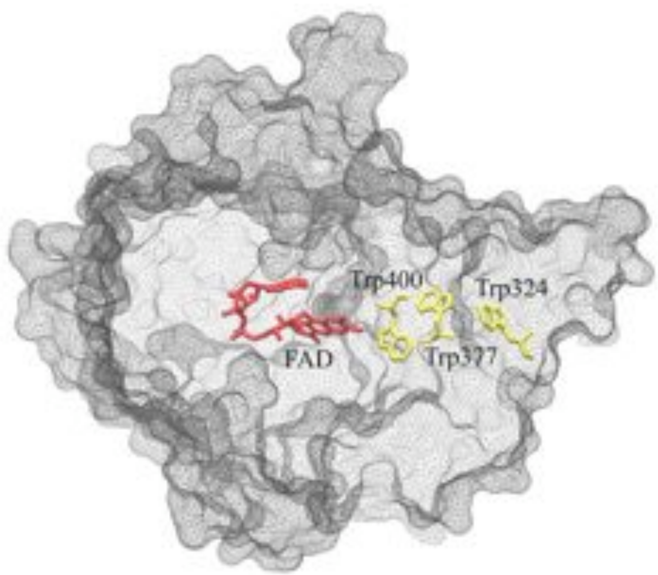
Visual Modulation Compass



(from BBC)

But What is the Actual Photoreceptor ?

- evolved from highly homologous ancestor photolyase



Cryptochrome

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

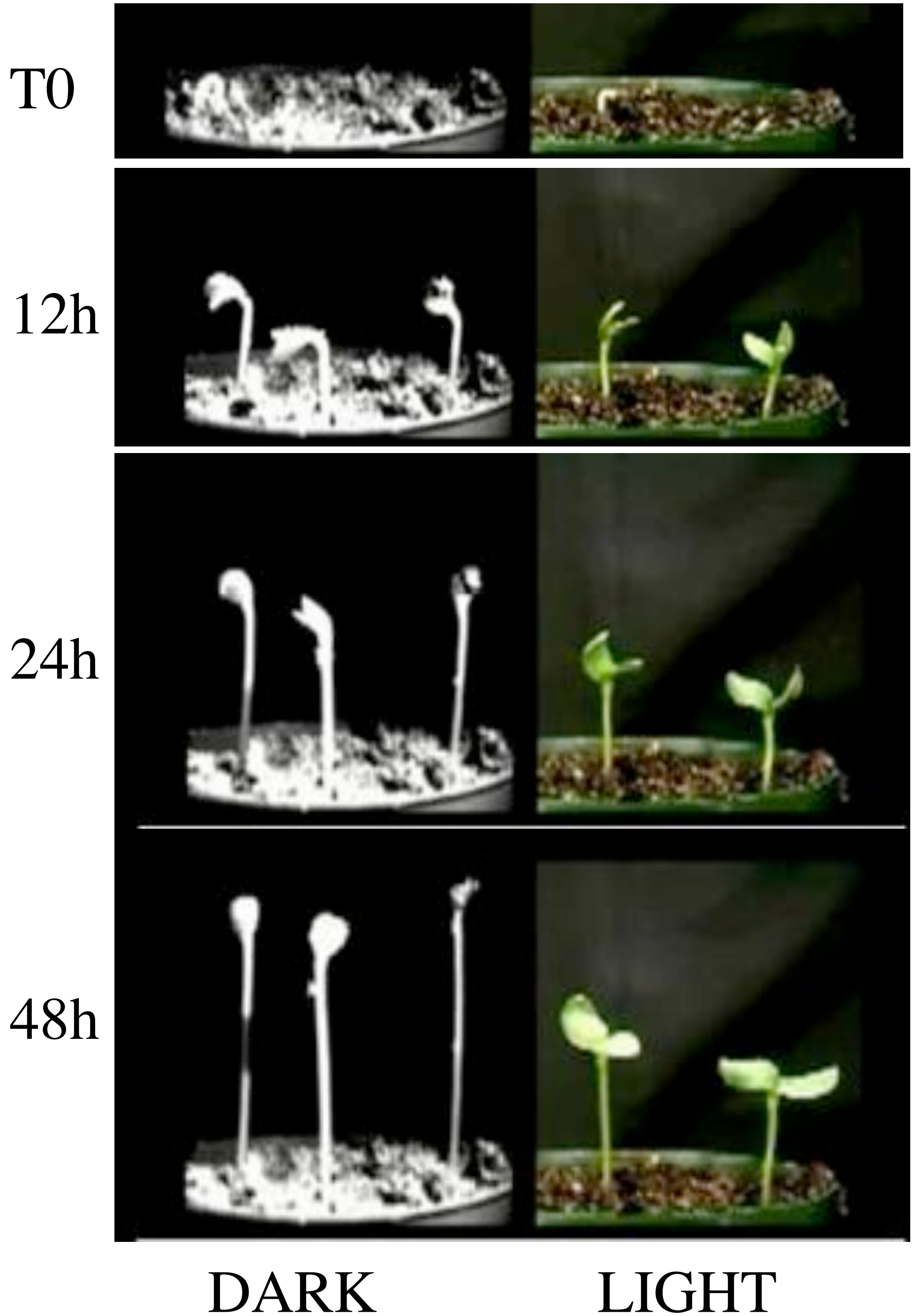
blue-light receptor transfers excitation to flavin (green)

flavin repairs DNA through radical pair reaction

- cryptochromes are expressed in eyes

Hypocotyl Growth Inhibition Response of Sunflower seedlings

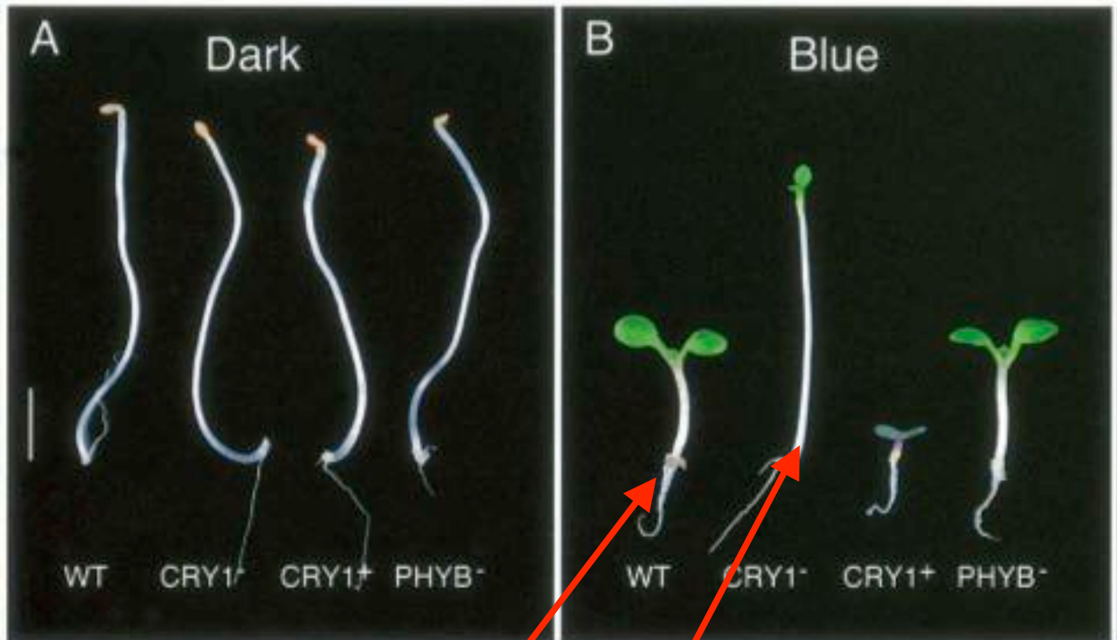
(from Roger Hangarter , U. Indiana, web site)



Effect of light is to shorten the hypocotyl.(stem between root and cotyledon.)

Cryptochrome and *Arabidopsis*

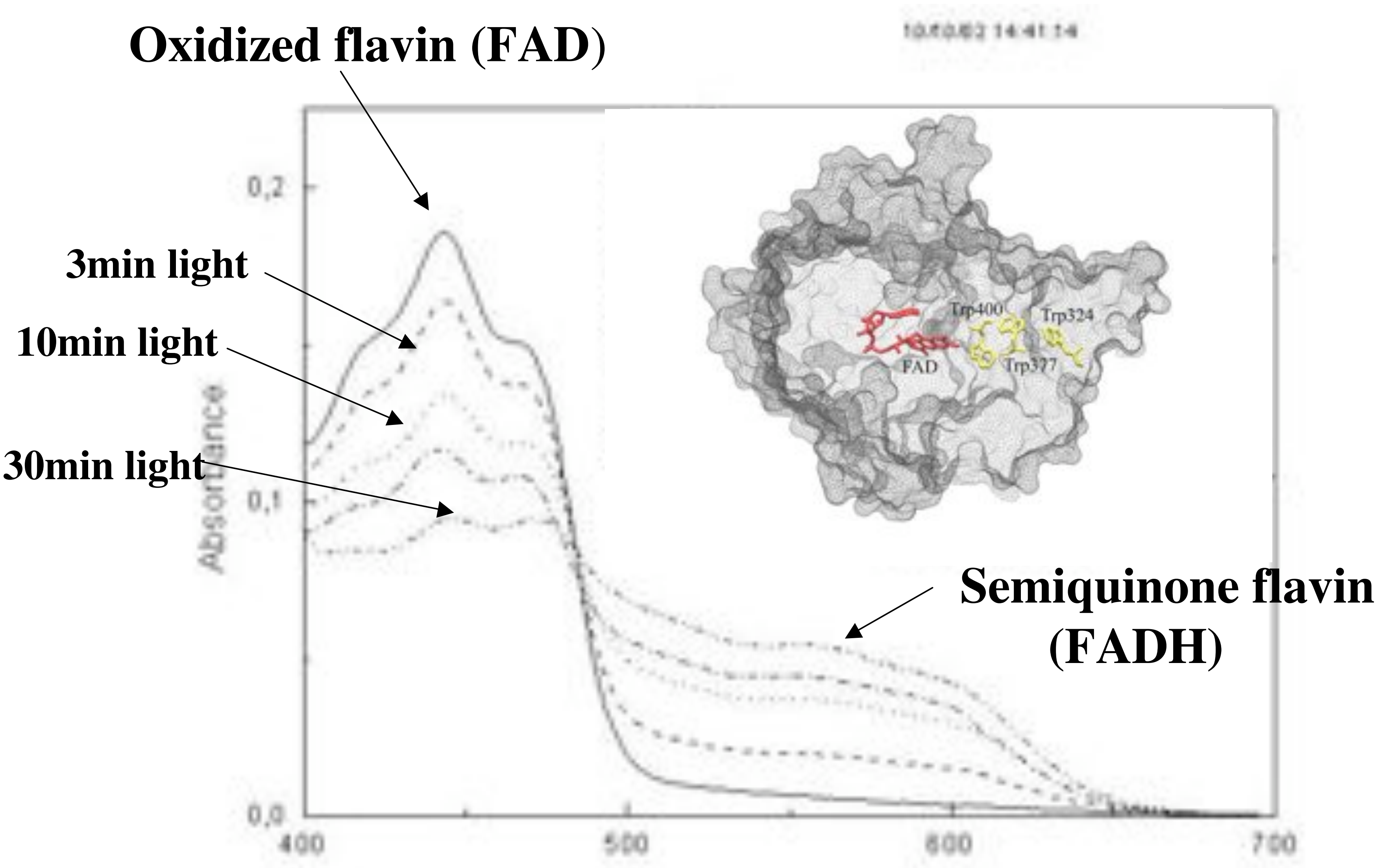
Cryptochrome mediates certain blue-light-dependent responses in plants, such as hypocotyl inhibition and anthocyanin accumulation.



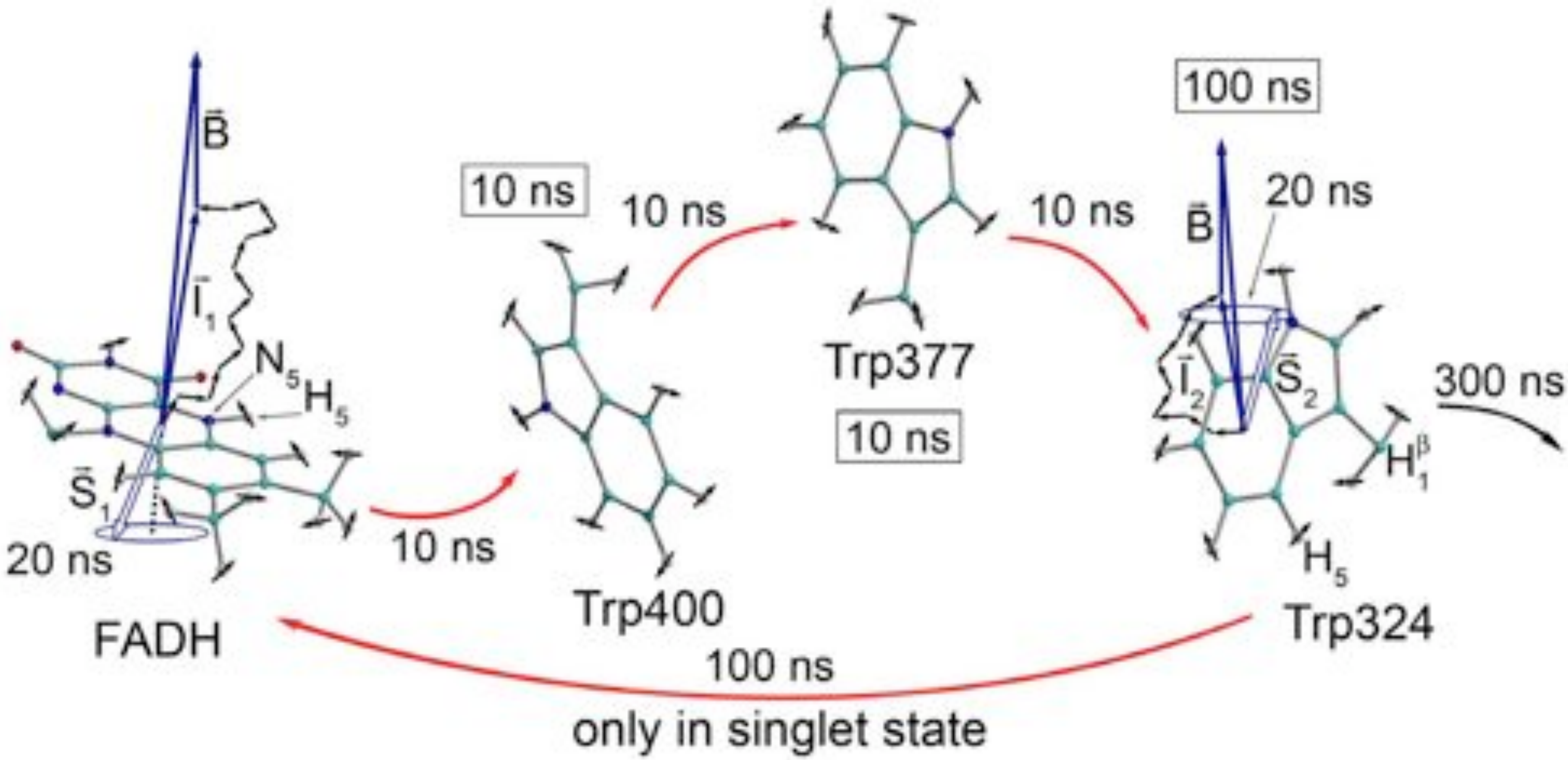
seedling lacking cryptochrome has long hypocotyl

wild-type seedling has shorter hypocotyl

Plant cryptochrome undergoes a light-dependent redox reaction under steady state conditions



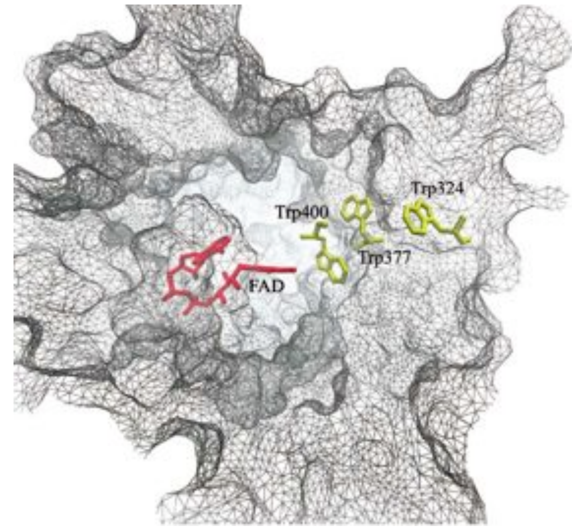
Cryptochrome Signaling and Electron Transfer



- back-transfer can only occur when the unpaired electrons on FADH and Trp are in a singlet state

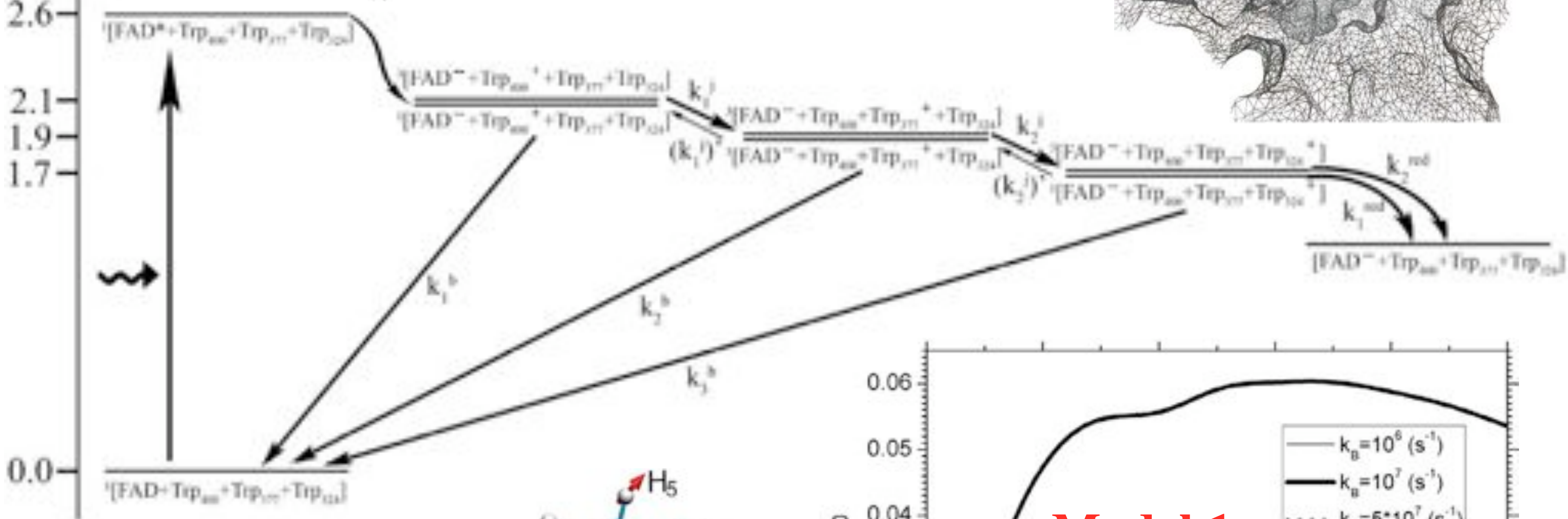
- this back-transfer quenches signaling state

Magnetic Field Dependence of Radical Pair Mechanism for Cryptochrome 1 Photoactivation



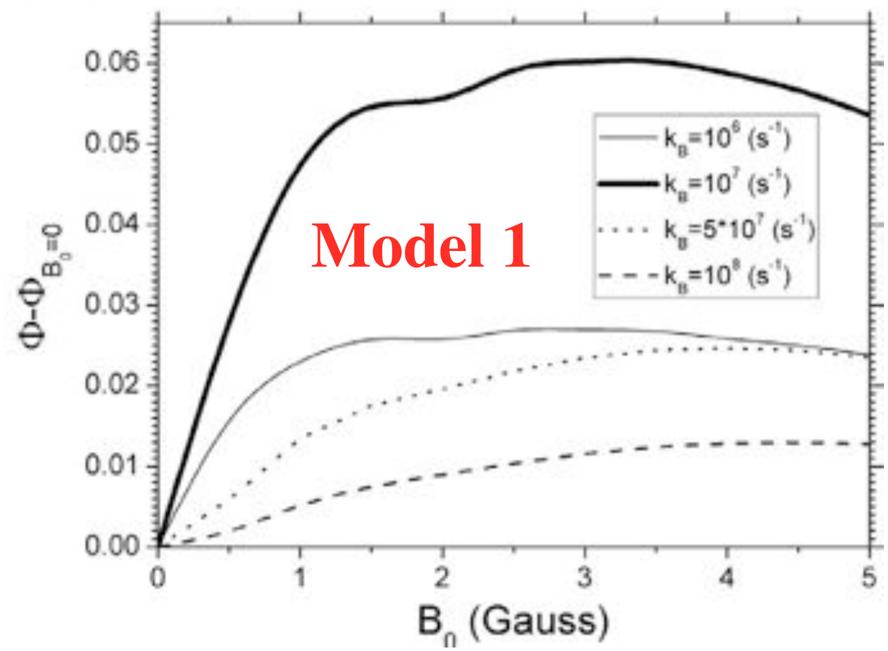
Quantum Yield of Activation

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



FADH

Tryptophan



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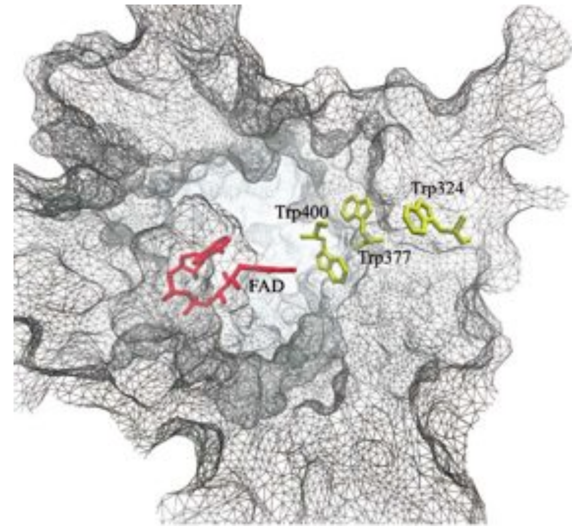
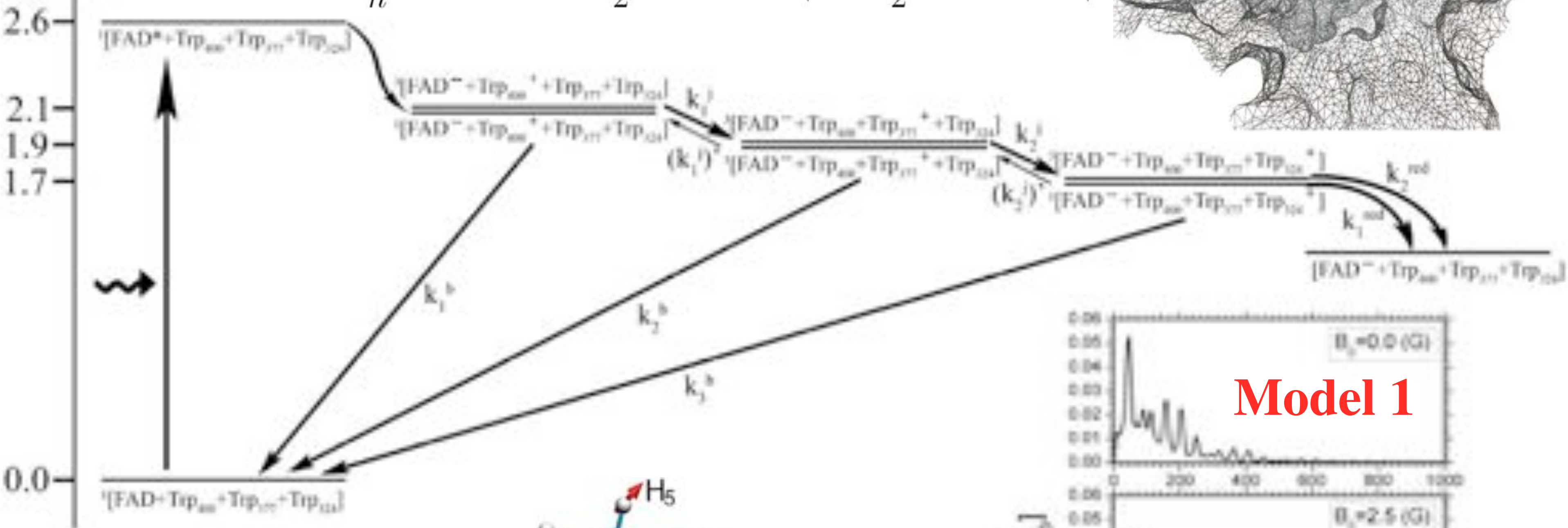
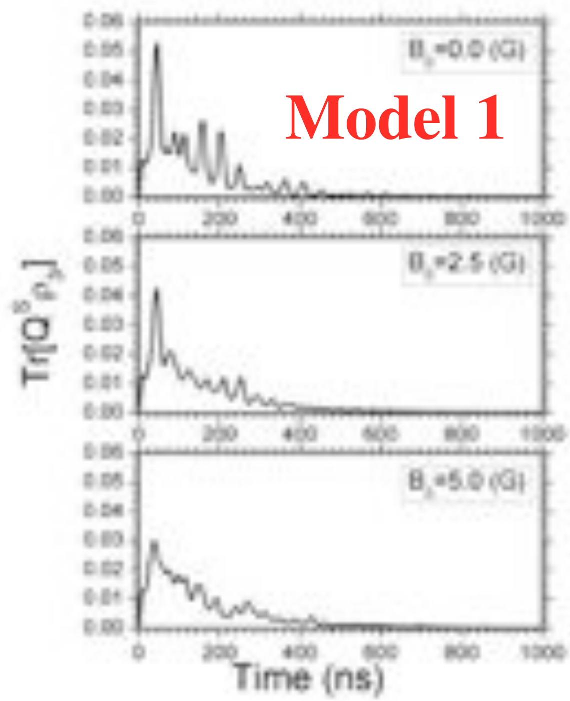


Time Dependence of Product Formation

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





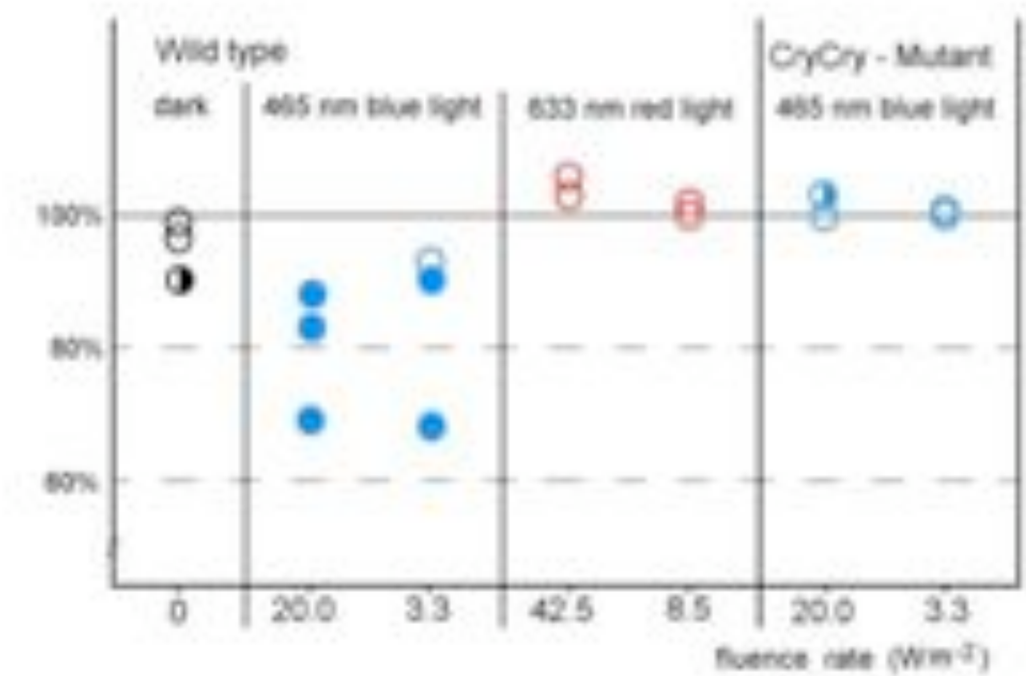
FADH

Tryptophan

Cryptochrome - dependent hypocotyl growth inhibition in plants is sensitive to the geomagnetic field.

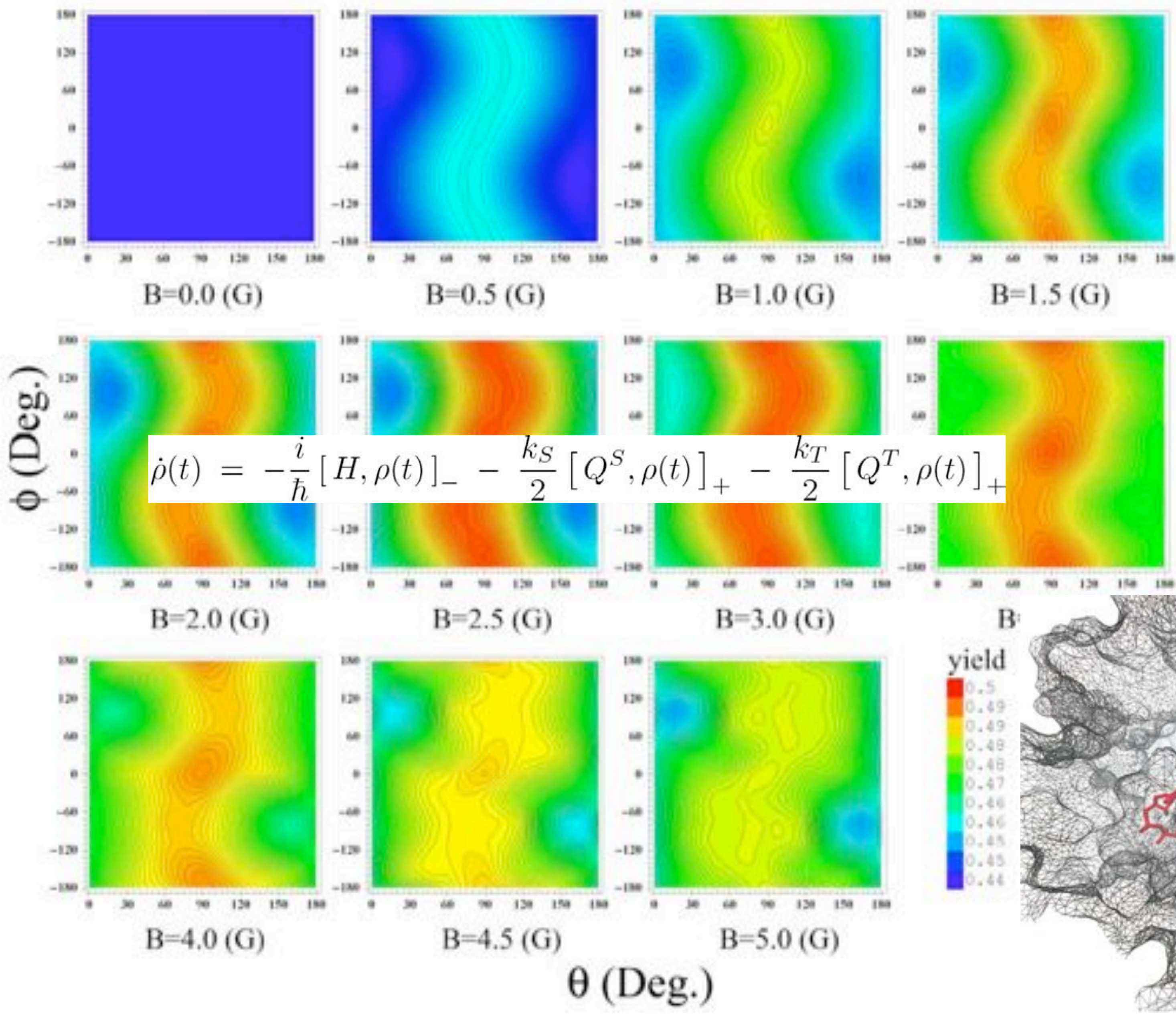
Hypocotyl growth 500µT/

Hypocotyl Growth 44µT



Relative growth of Arabidopsis seedlings in local field and 10 X local field.

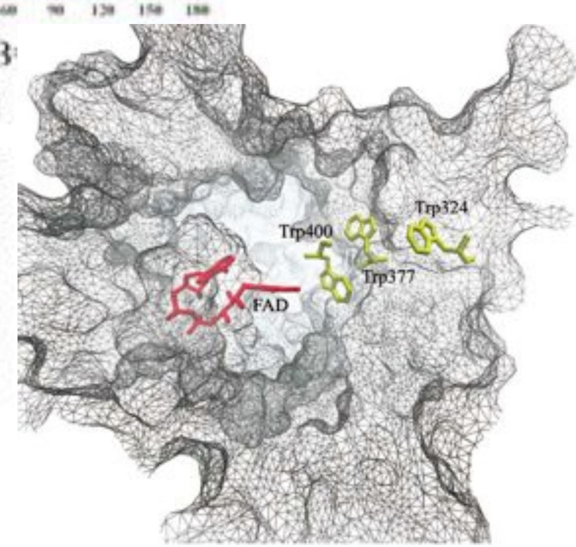
Magnetic Field Dependence of Radical Pair Mechanism for Cryptochrome 1 Photoactivation

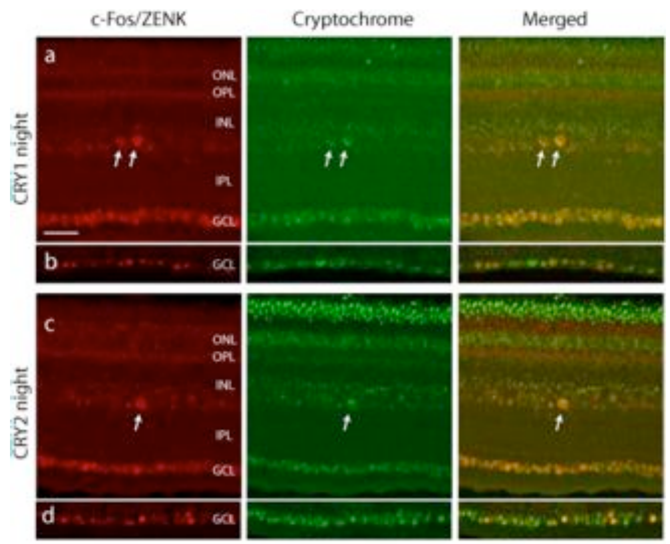


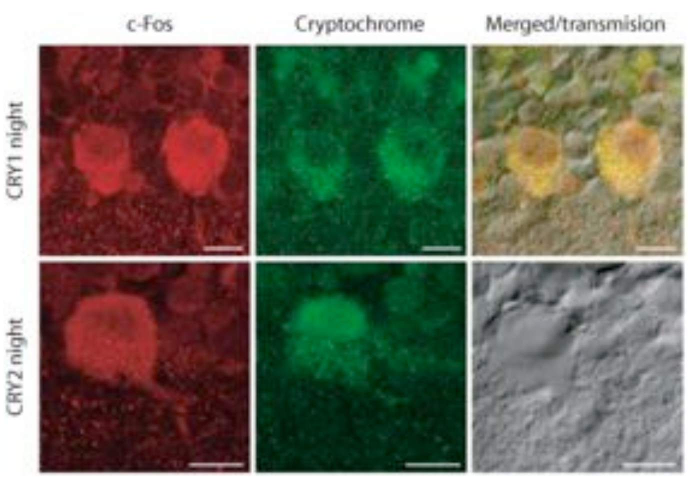
$$\dot{\rho}(t) = -\frac{i}{\hbar}\left[H, \rho(t)\right]_- - \frac{k_S}{2}\left[Q^S, \rho(t)\right]_+ - \frac{k_T}{2}\left[Q^T, \rho(t)\right]_+$$

Orientation Dependence of Quantum Yield

Model 1



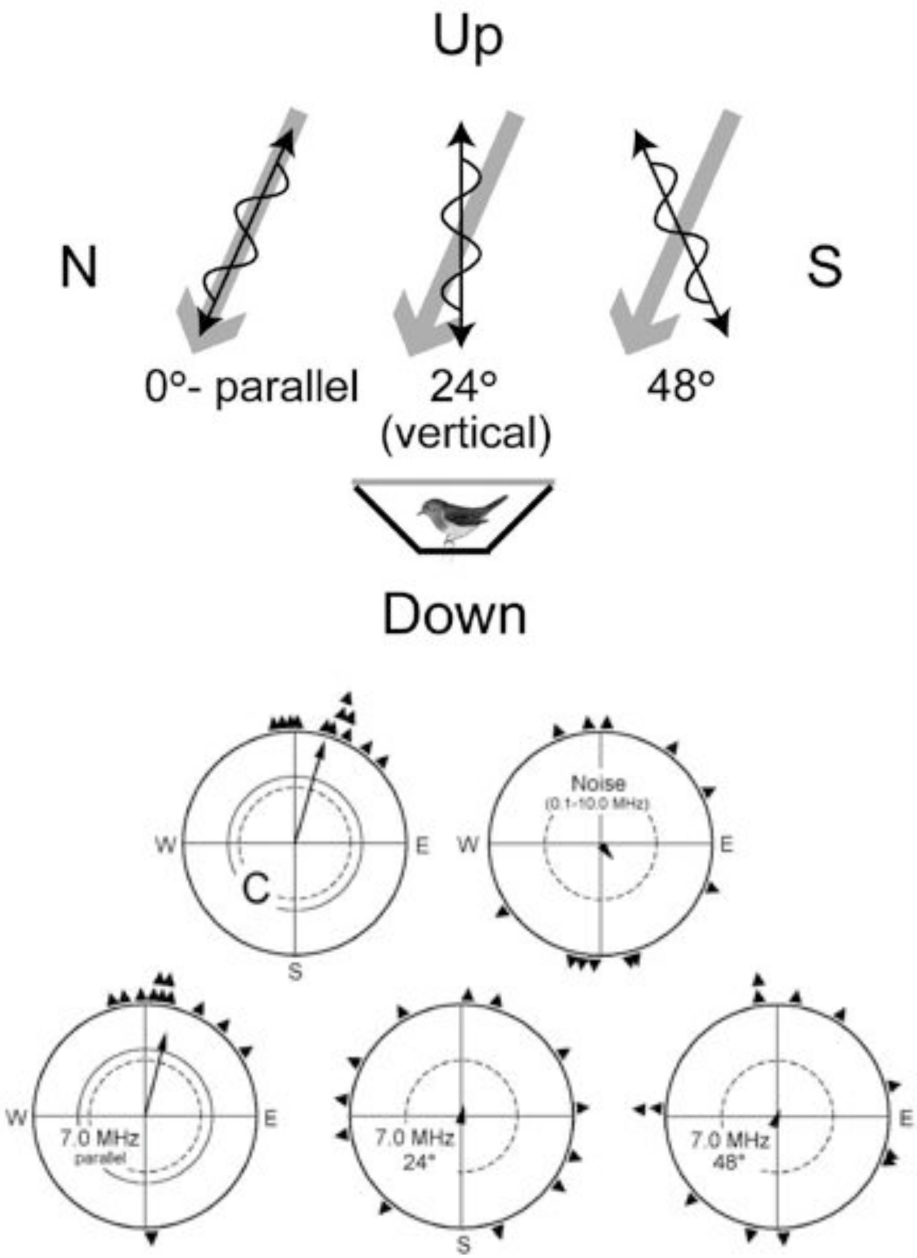




Colocation of activity spots and croptochrome expression in the garden warbler retina

Mouritsen et al , PNAS (2005)

Effect of Radio Frequency Fields on the Orientation Behavior of Robins



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Chemical Physics

A perturbation theory treatment of oscillating magnetic fields in the radical pair mechanism

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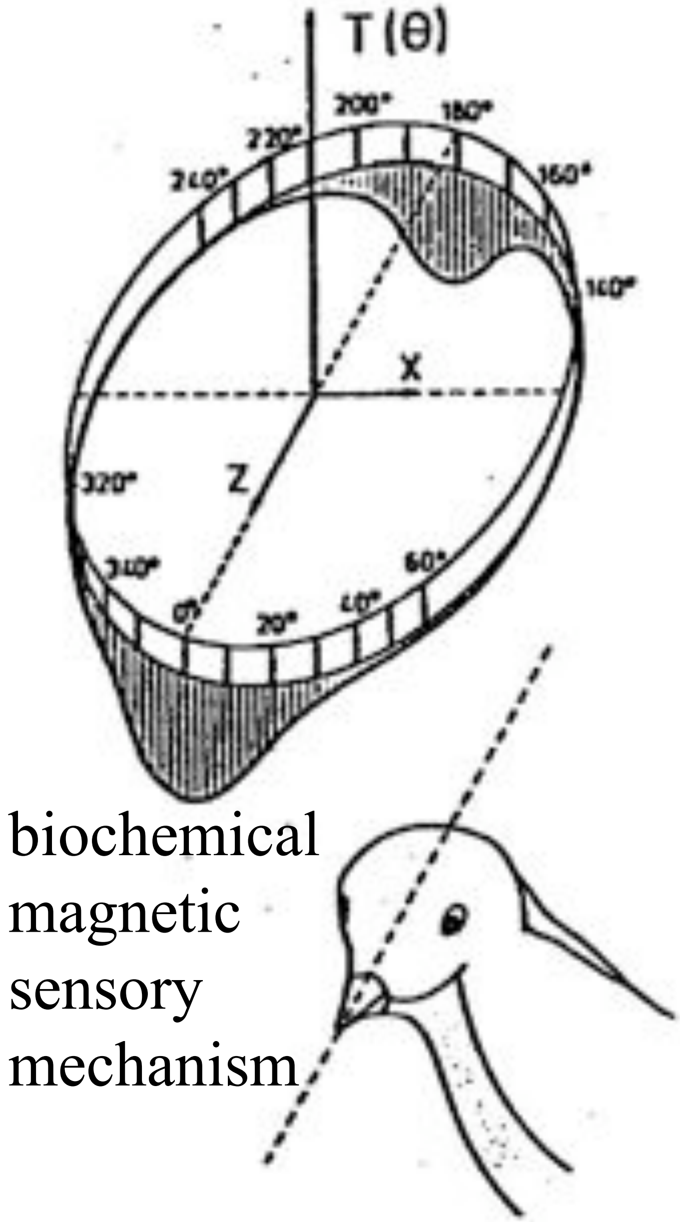
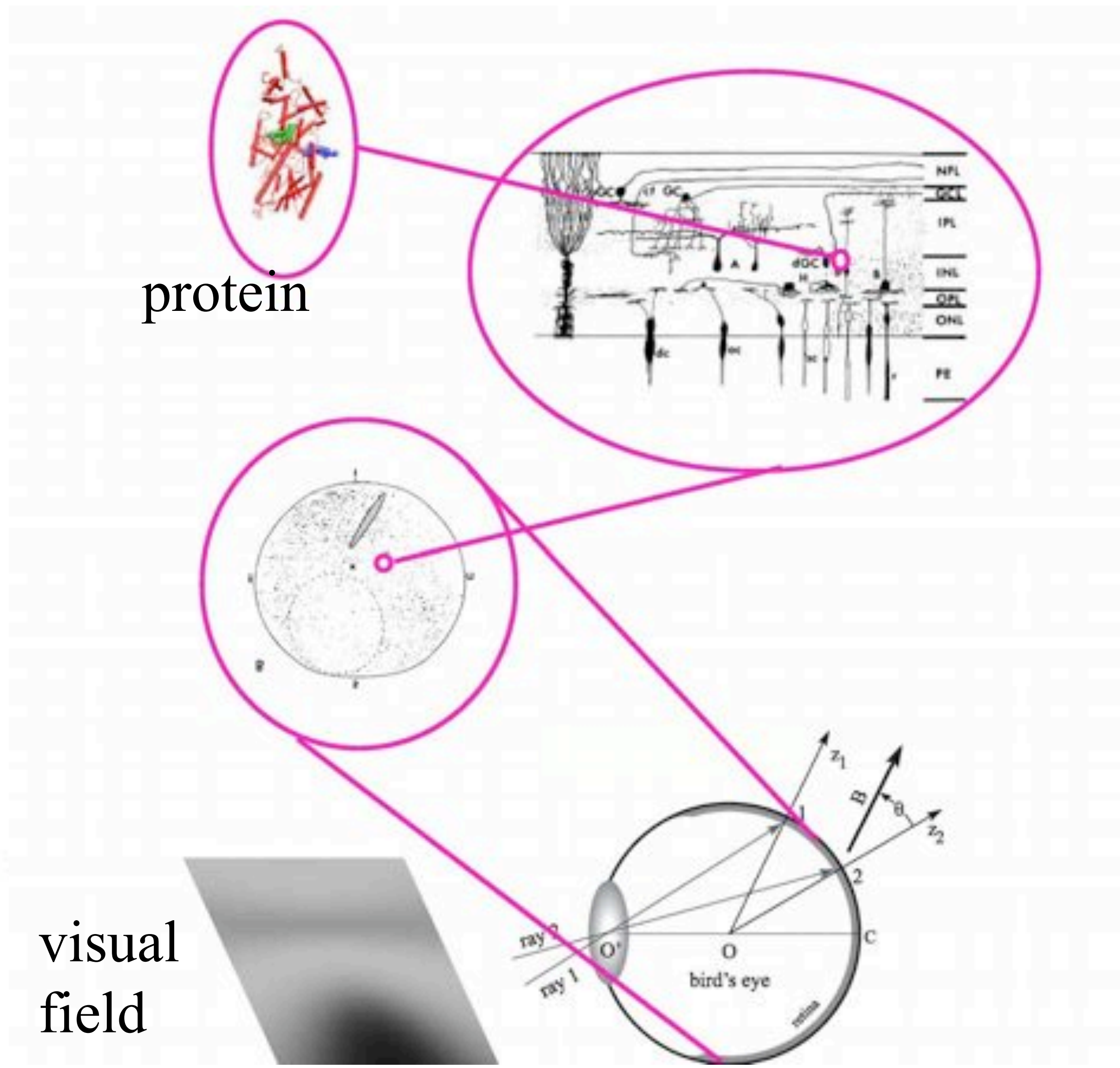
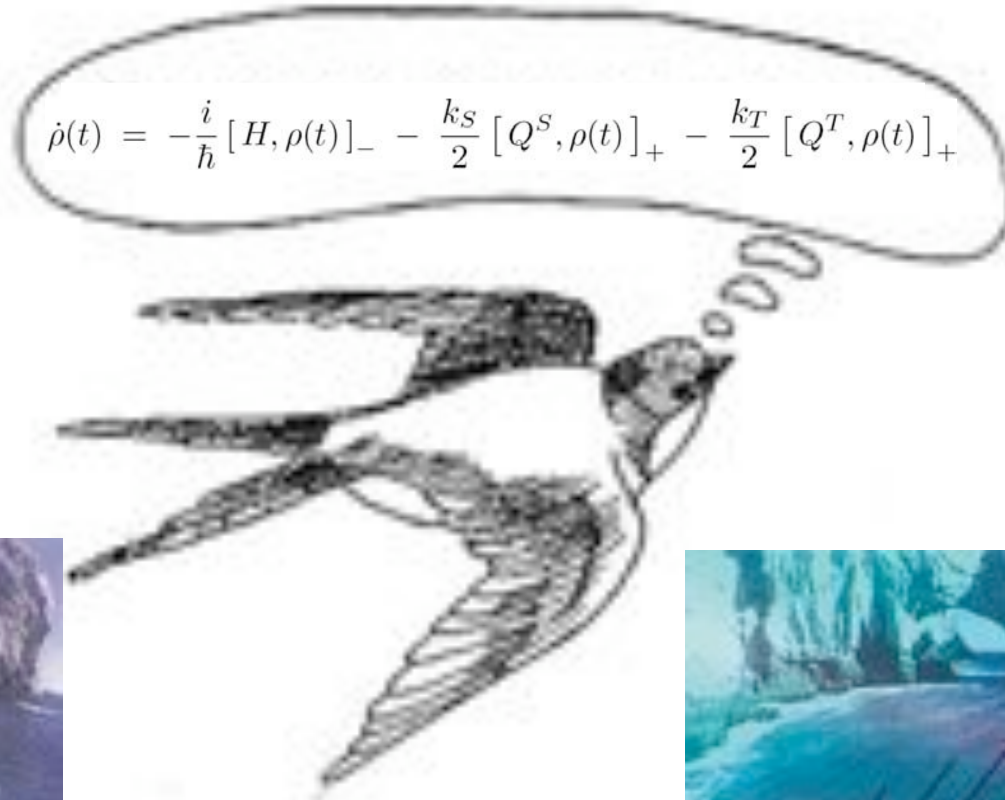
Biochemical Mechanisms for Magnetic Orientation in Animals





Visual Modulation Compass



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