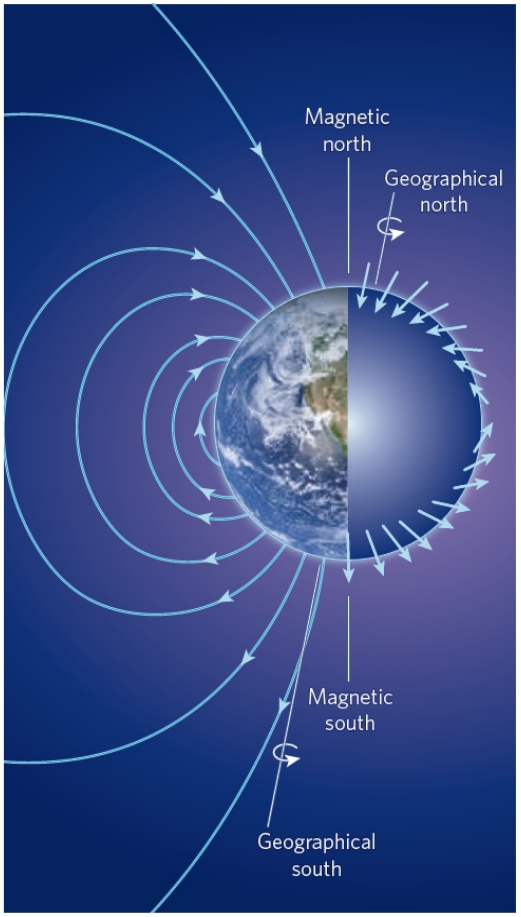
Photo-activated biological processes as quantum measurements

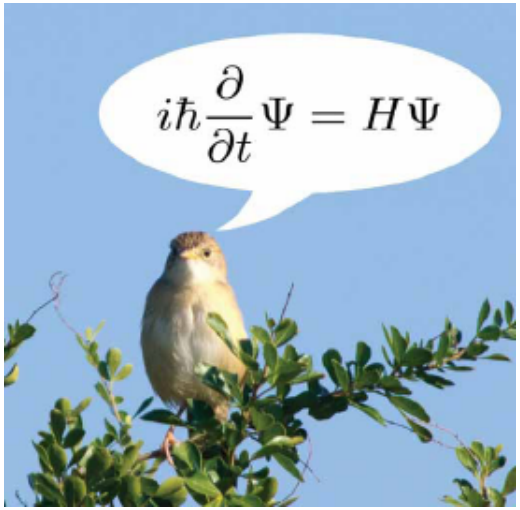
A. Imamoglu ETH

K. B. Whaley UCB

Fellows, Wissenschaftskolleg zu Berlin 2012-2013

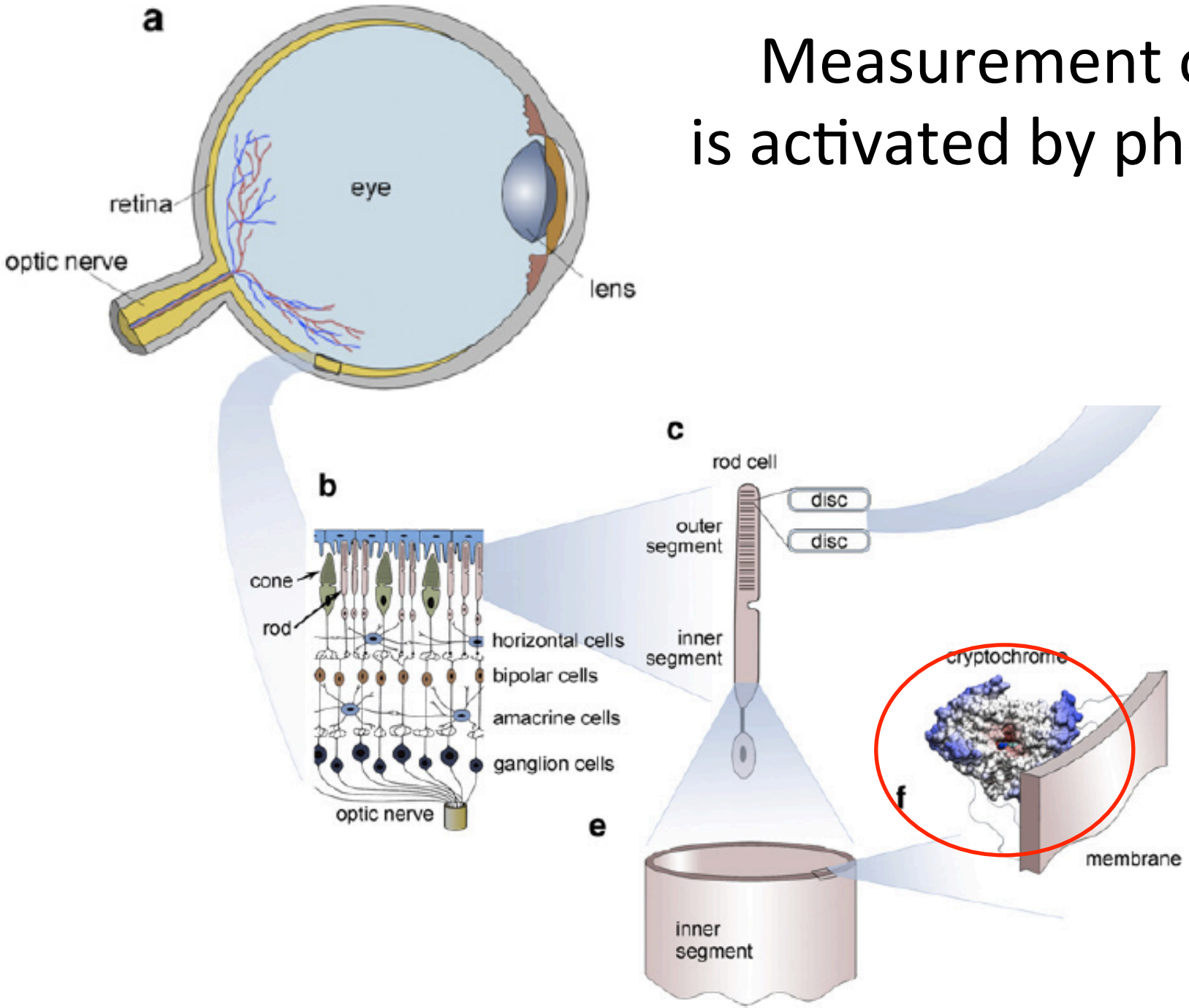
Magnetoreception



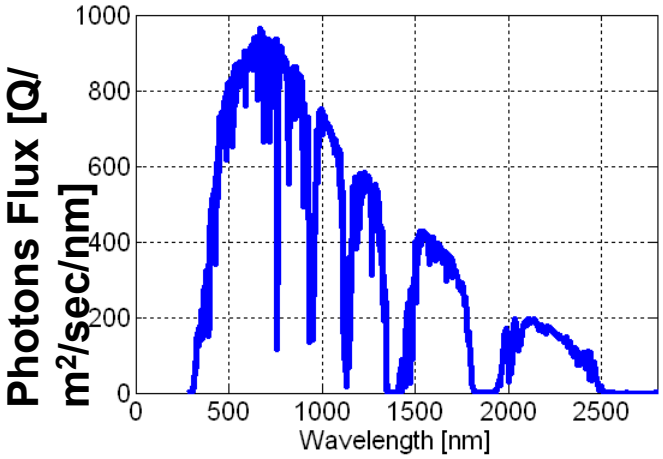


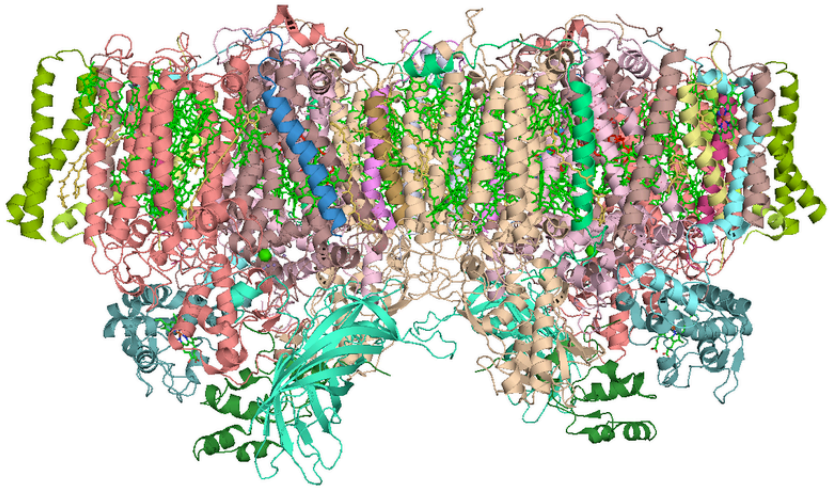
$\vec{B}_{ext}$

Measurement of $\vec{B}_{ext}$ is activated by photons

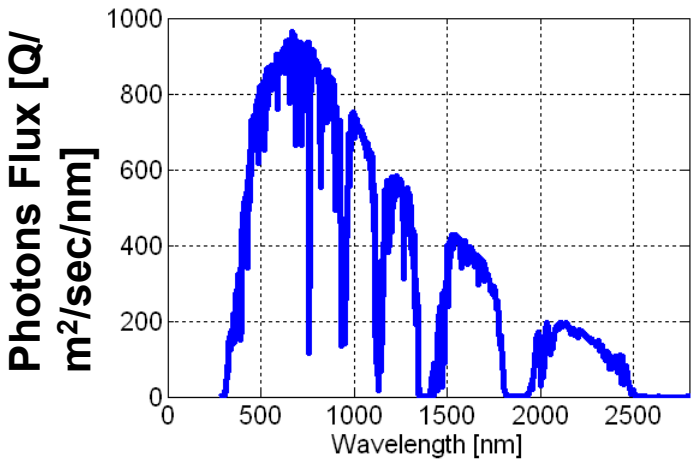


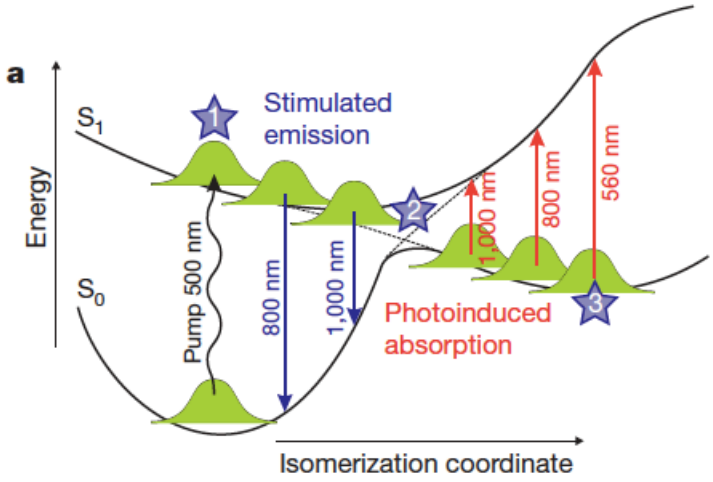
Photosynthesis

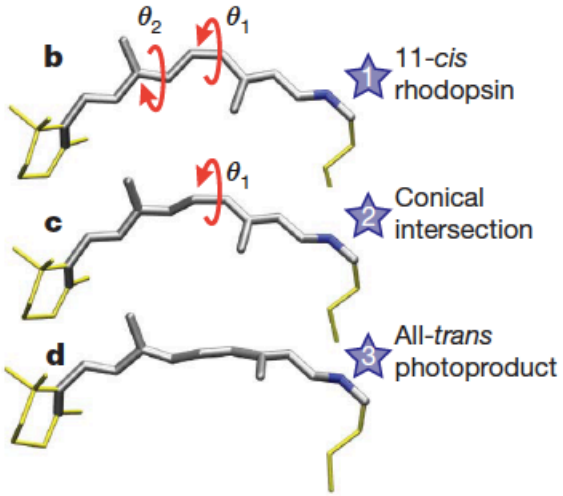




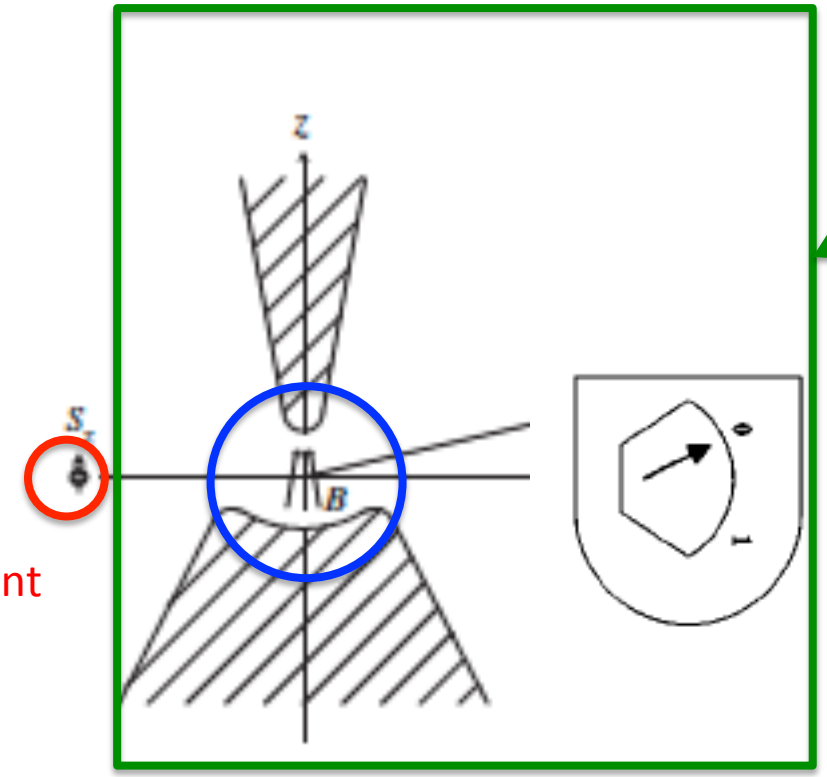
Vision


Photons Flux [Q/m²/sec/nm]
1000
800
600
400
200
0
0
500
1000
1500
2000
2500
Wavelength [nm]


a
Energy
S1
S0
Stimulated emission
Pump 500 nm
800 nm
1,000 nm
1,000 nm
800 nm
560 nm
Photoinduced absorption
Isomerization coordinate


b
θ2
θ1
11-cis rhodopsin
c
θ1
Conical intersection
d
All-trans photoproduct

Measurement



meter + environment

system -
magnetic moment

interaction = magnetic moment x B field

$$H = H_{sys} + H_m + H_{int}$$

Quantum measurement in biology

system meter interaction meter - environment

$$H = H_{sys} + H_m + H_{meas} + H_{m-env}$$

$\overline{n}_{photon}$

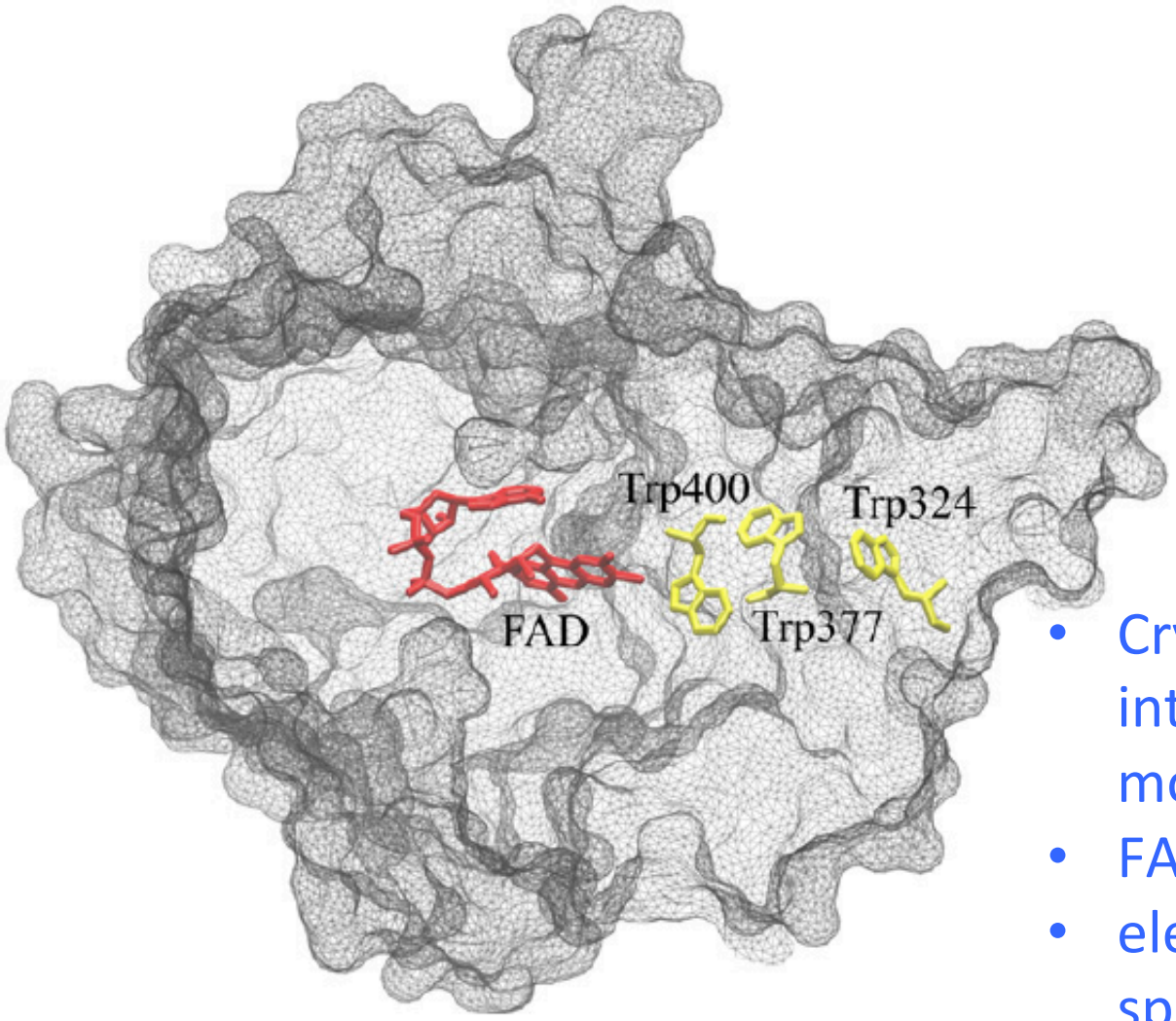
$\vec{B}_{ext}$

Electrons in pigment-protein complex
charge/spin degrees of freedom

$H_{m-rad} + H_{int}$

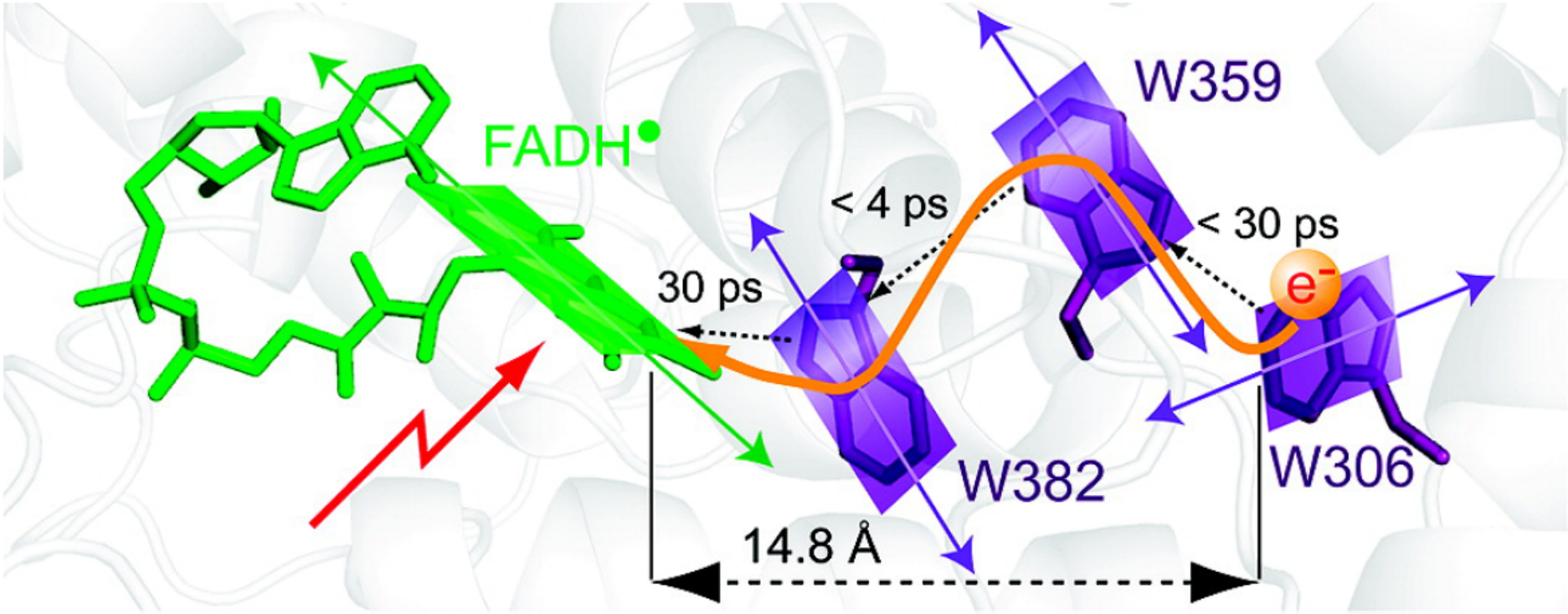
- Correlations between system and meter
- Post-measurement state of meter carries information about system state
- Irreversibility of measurement derives from coupling of meter to environment (protein and beyond)

Cryptochrome – candidate receptor system



- Cryptochrome protein internally binds additional molecules
- FAD absorbs light
- electron transfer via Trp species generates radical pair

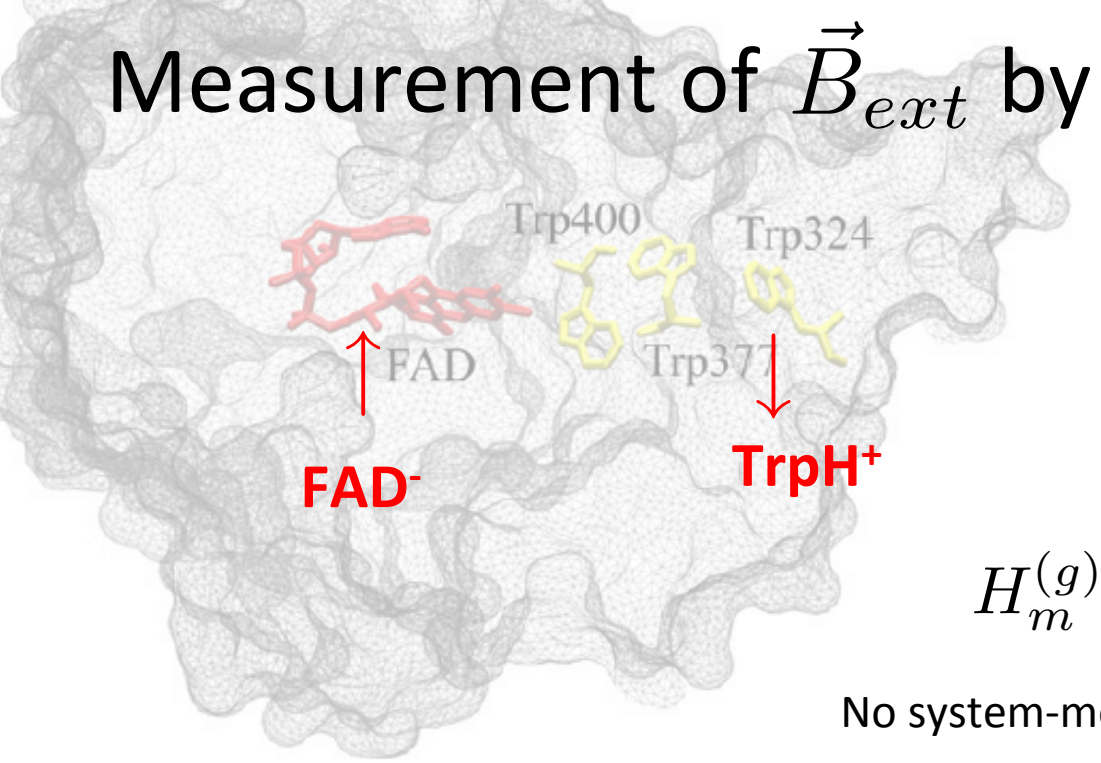
Radical pair = 2 electrons located on different molecules



Radical pair of electrons have quantum correlated, ‘entangled’ spins

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

Measurement of $\vec{B}_{ext}$ by radical pair



$$H_{meas} = H_{int}$$

$$g_e \mu_B \vec{B}_{ext} \cdot \left(\vec{S}_1 + \vec{S}_2 \right)$$

$$H_m^{(g)} = H_0 \simeq J(r) \vec{S}_1 \cdot \vec{S}_2$$

No system-meter correlations in meter ground state

photoactivation forms singlet (S)

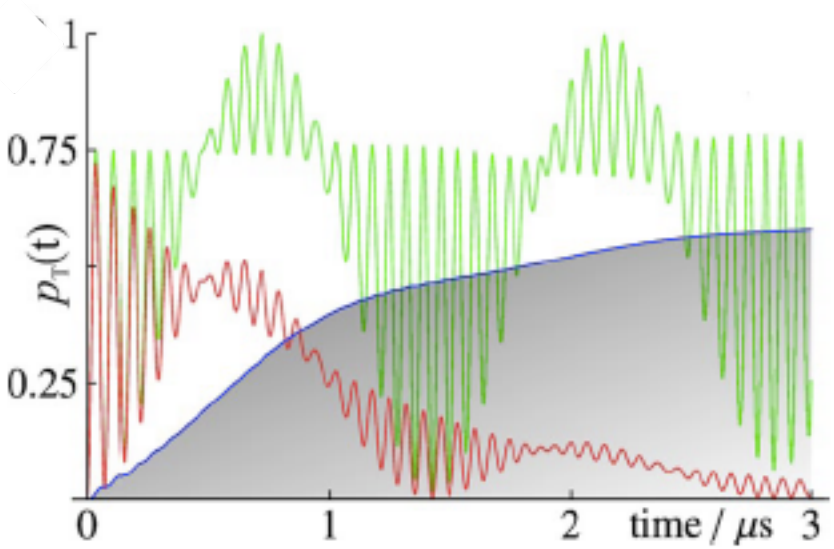
Initialize meter by photoactivation to radical pair (S)

$$H_m^{(ex)} = \sum_{i_1} \mathbf{A}_{i_1} \vec{S}_1 \cdot \vec{I}_{i_1} + \sum_{i_2} \mathbf{A}_{i_2} \vec{S}_2 \cdot \vec{I}_{i_2}$$

meter initial state $\psi_m^{(d)}(\tau_0)$ is not an eigenstate of $H_m^{(ex)}$, results in coherent oscillation of populations S and T

Now we add the external (weak) magnetic field, noting $\left[H_m^{(ex)}, H_{meas} \right] \neq 0$

population of T, no reactions
population of T, with reactions
blue line – triplet product ^{T}P



$$H_{meas} = g_e \mu_B \vec{B}_{ext} \cdot \vec{S}$$

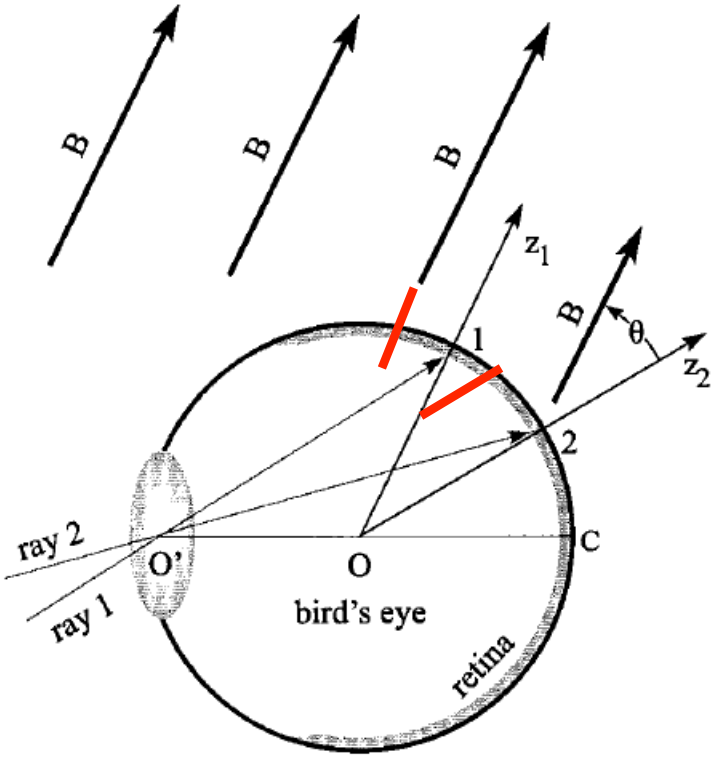
S <--> T interconversion modulated by action of H_{meas}

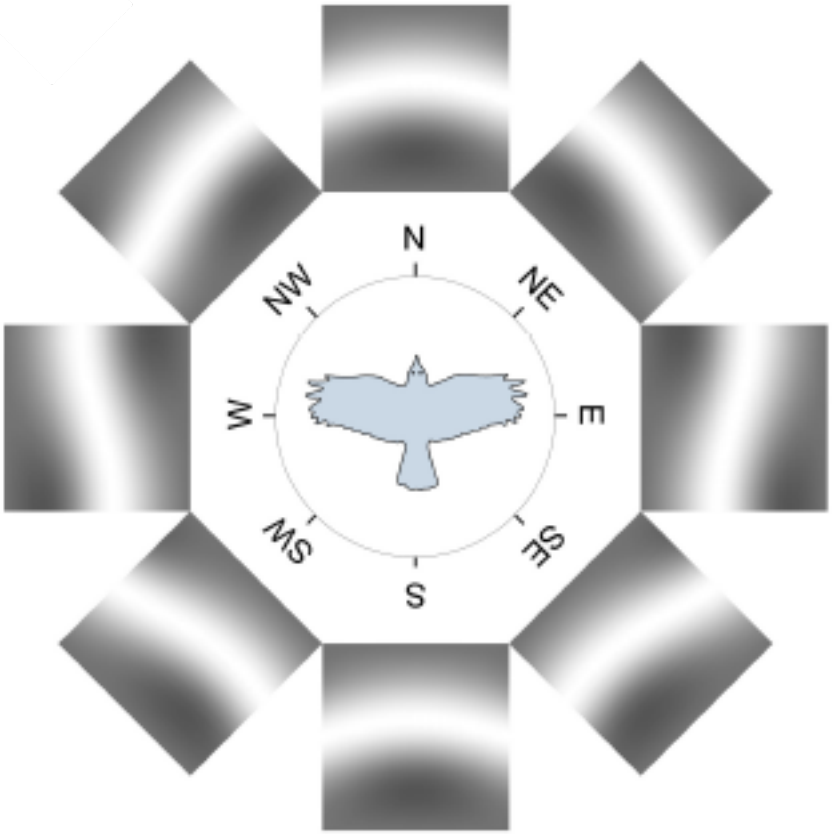
rate is dependent on magnitude and inclination of $\vec{B}_{ext}$

spin-dependent products therefore also dependent on $\vec{B}_{ext}$

Irreversibility from chemical reactions of S and T

Visual modulation pattern resulting from rigidly fixed receptor molecules





Primary requirements for quantum measurement of $\vec{B}_{ext}$ via radical pair dynamics:

i) spin coherence is essential:

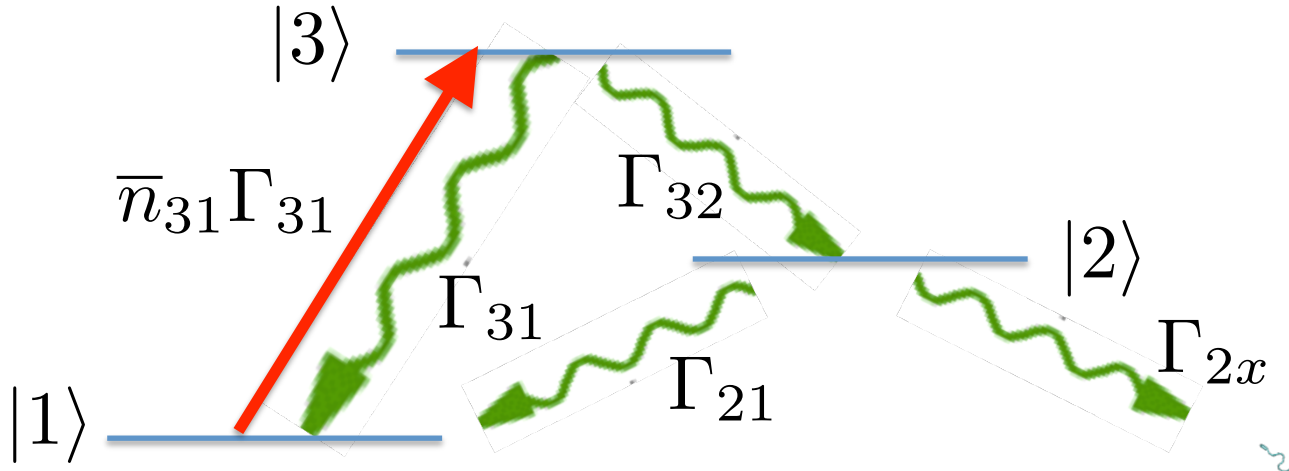
$$|\mathbf{A}| > |\vec{B}_{ext}| > \tau_c$$

pathway interference analysis in energy space shows sensitivity to inclination disappears when the meter is treated classically

ii) Initialization by photoactivation – cf. light harvesting and vision

Measuring photons

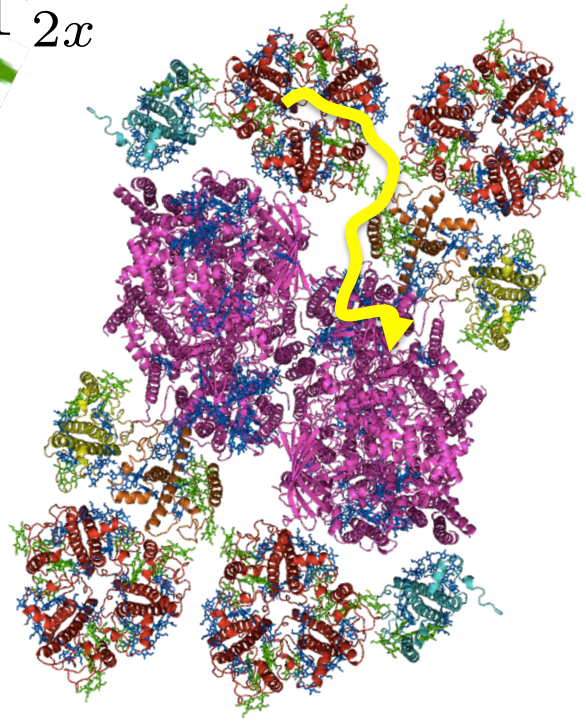
Incoherent Optical Pumping: light harvesting



steady state analysis $\dfrac{\rho_{22}}{\rho_{11}} = C\overline{n}_{31}$

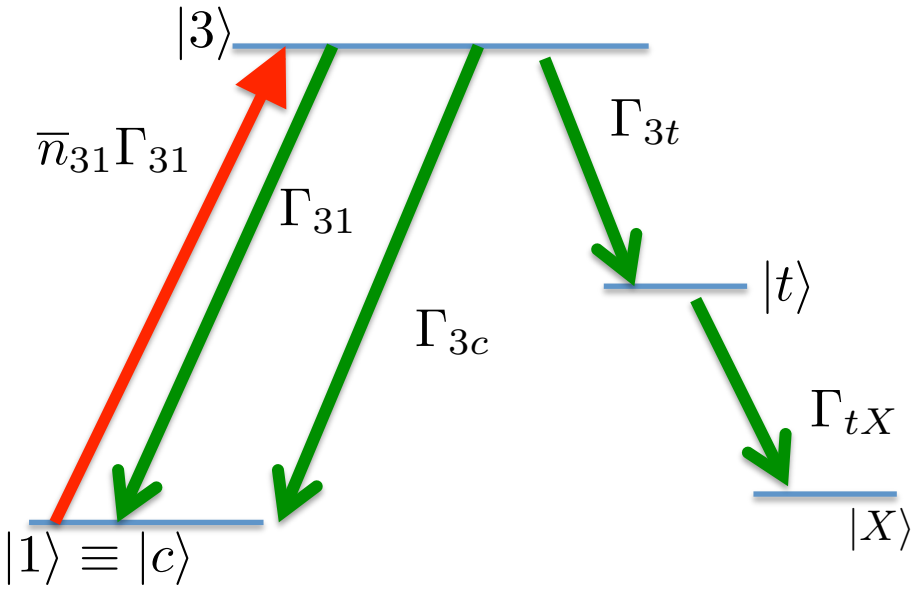
- LH complex measures the incident photon number,
- regardless of whether coherent or incoherent non-radiative dynamics Γ_{32}

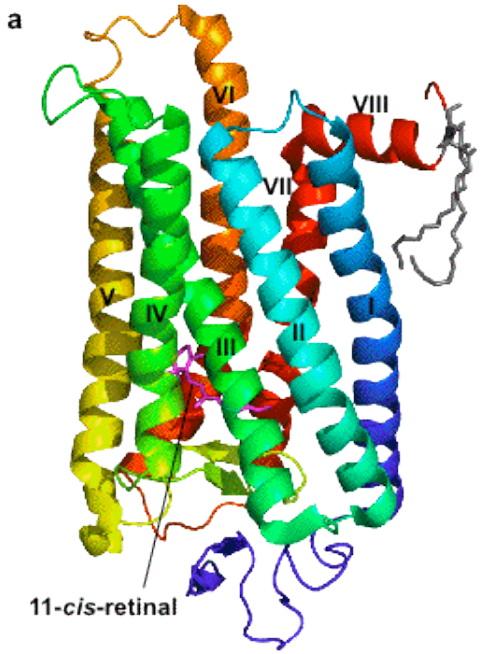
PSII in green plants

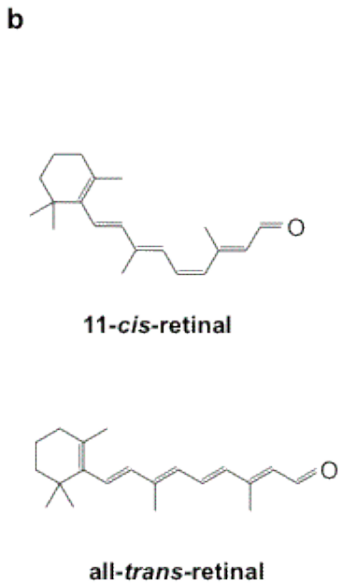


unreferred quantum measurement – measurement event essential for biological function but not the specific information gained from this

Incoherent Optical Pumping: vision



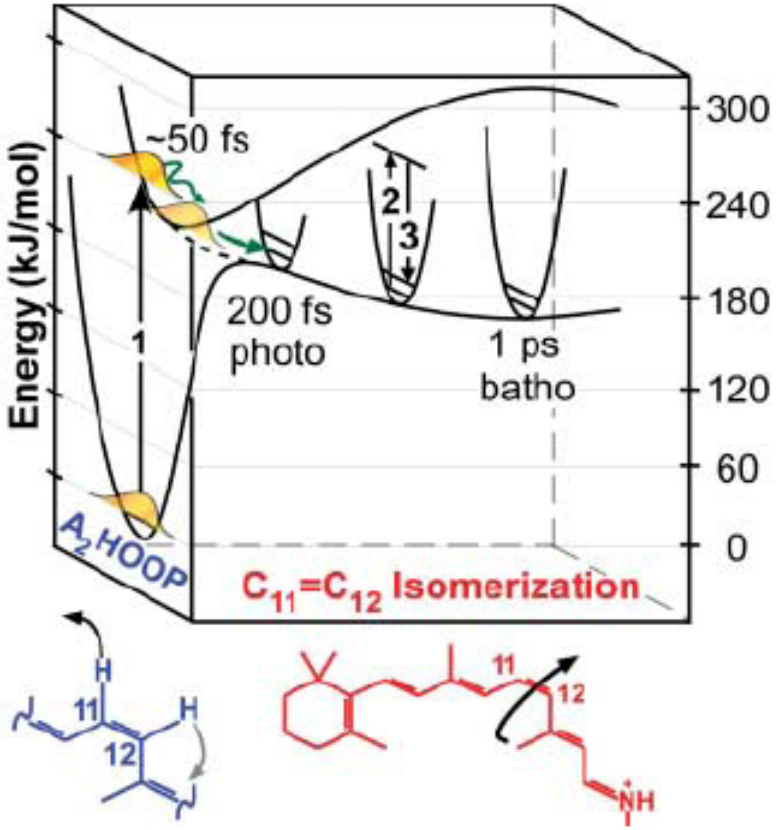




- simplified model, just levels 1, 3, trans and product X
- steady state analysis
- population of trans state measures incident photon number

$$\frac{\rho_{tt}}{\rho_{11}} = B\overline{n}_{31}$$

Isomerization of Retinal in Rhodopsin



very fast coupled electron-nuclear dynamics through conical intersection
→ high quantum efficiency (65%)
50% absorption → 30% probability of detection of single photon
variants sensitive to different wavelengths of light

Questions

- When is coherence essential and when non-essential for biological function?

$$\tau_c > t_{bio}$$

- Photoactivated processes initiate quantum dynamics – other candidates in biology?

- Measurement, information and system response…