Photosynthetic Light Harvesting and Electronic Quantum Coherence Effects

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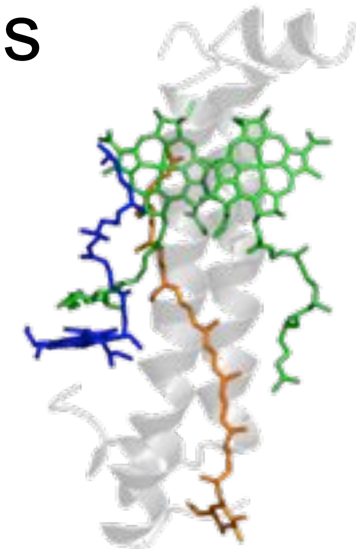
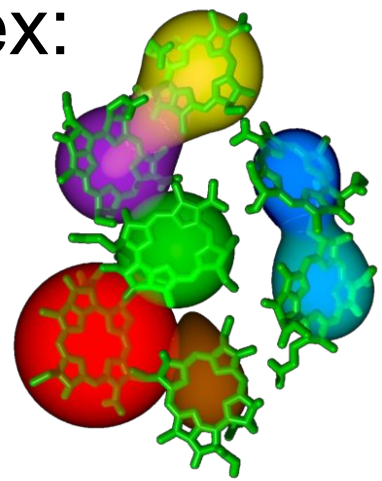
Outline

- Photosynthetic light harvesting systems
- Experimental evidences for quantum coherence effects in photosynthesis
- Theoretical modeling of quantum dynamics & nonlinear spectroscopy of light harvesting complexes



- Coherent dynamics in the FMO complex: coherence assisted excitation energy transfer mechanism
- Concluding remarks



Photosynthesis

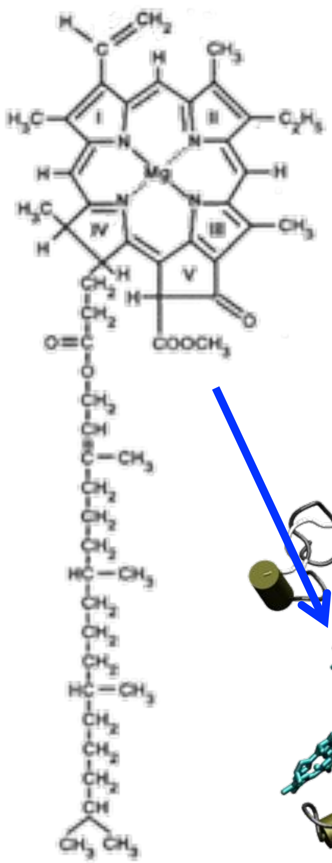
- Might be the most important photochemical process on earth
- Still, there is much unknown and much to be learned & modeled after

$$6CO_2 + 6H_2O \xrightarrow{h\nu} C_6H_{12}O_6 + 6O_2$$

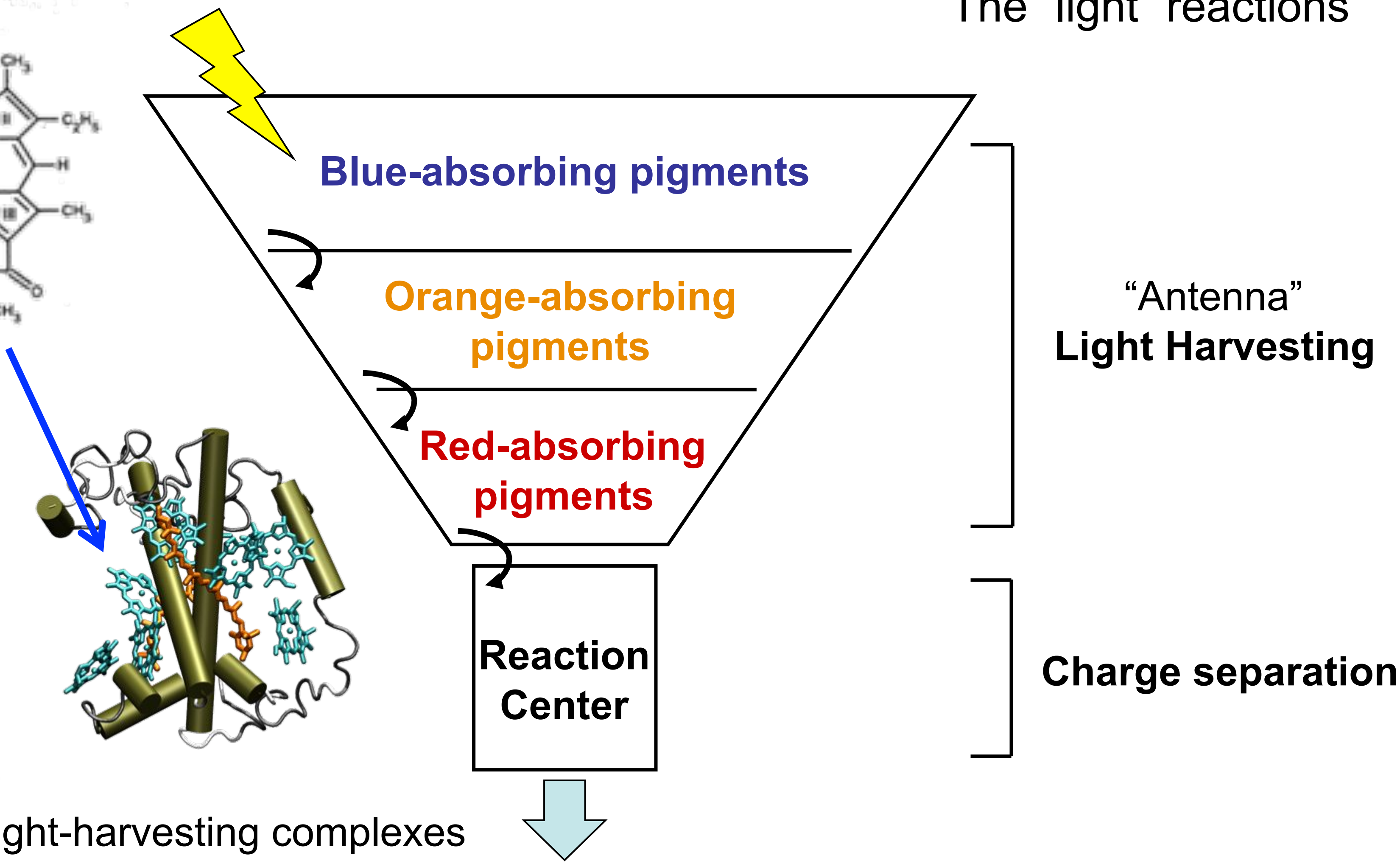
- Collecting sun-light energy with high efficiency is not trivial

Light Harvesting in Photosynthesis

The “light” reactions



Chlorophyll *a*

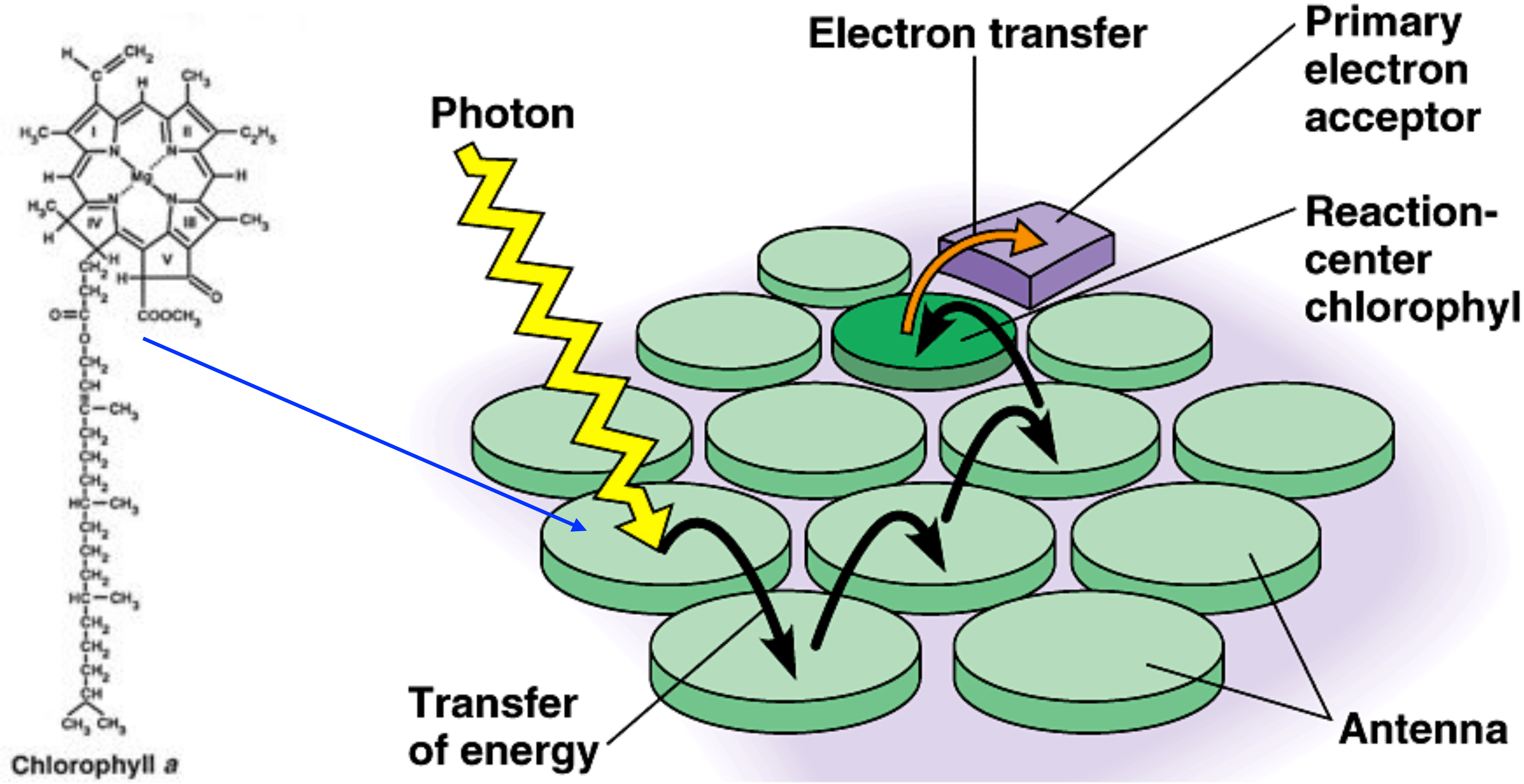


Light-harvesting complexes

…Secondary electron transfer reactions, Water splitting, Proton transport across thylakoid membrane, Reduction of $NADP^+$, ATP synthesis…

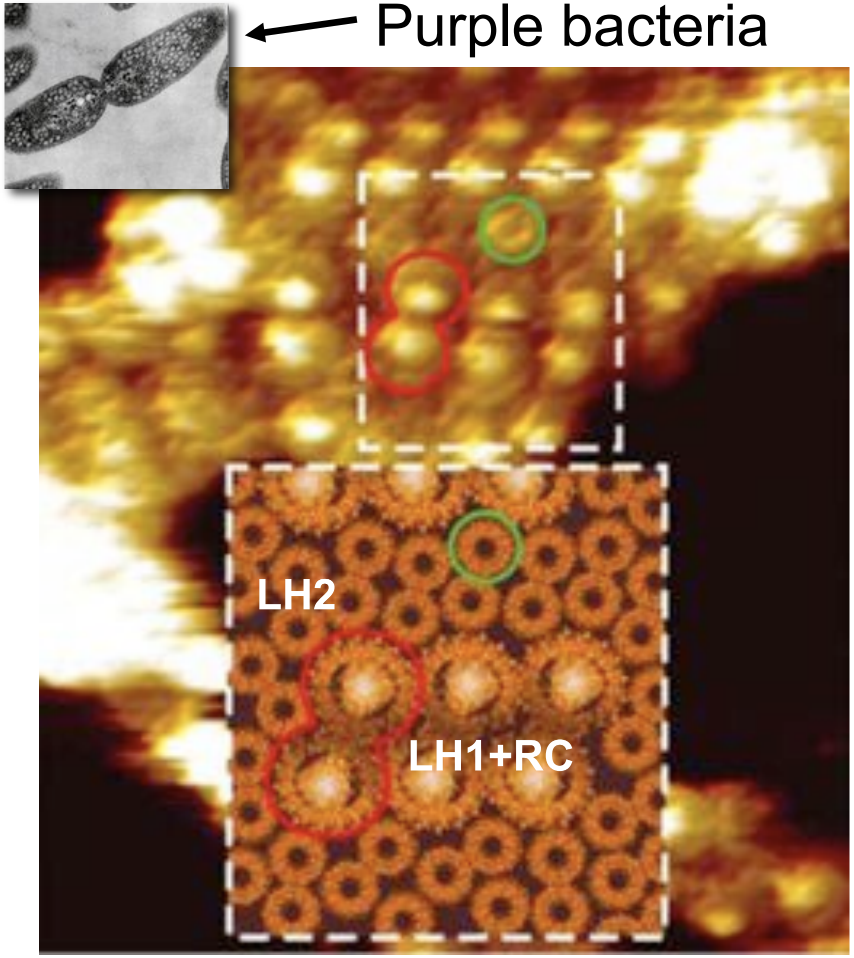
Primary Processes of Photosynthesis

Light harvesting in the antenna & charge separation in the reaction center ➔ remarkable, near unity quantum yield



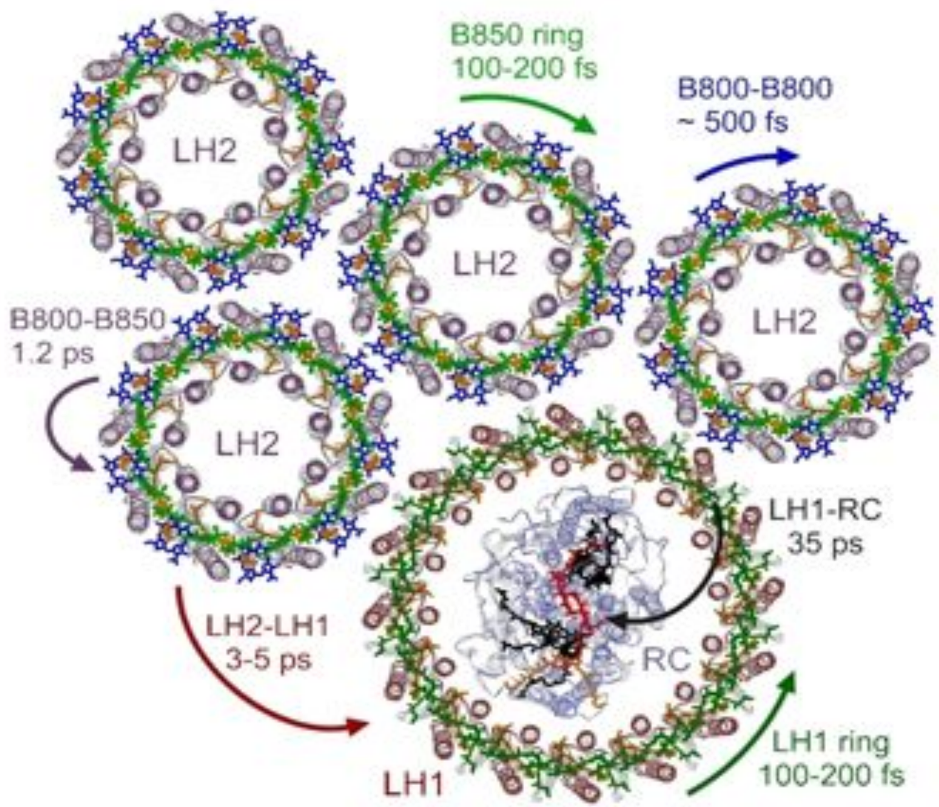
Light-harvesting Apparatus of Purple Bacteria

Purple bacteria



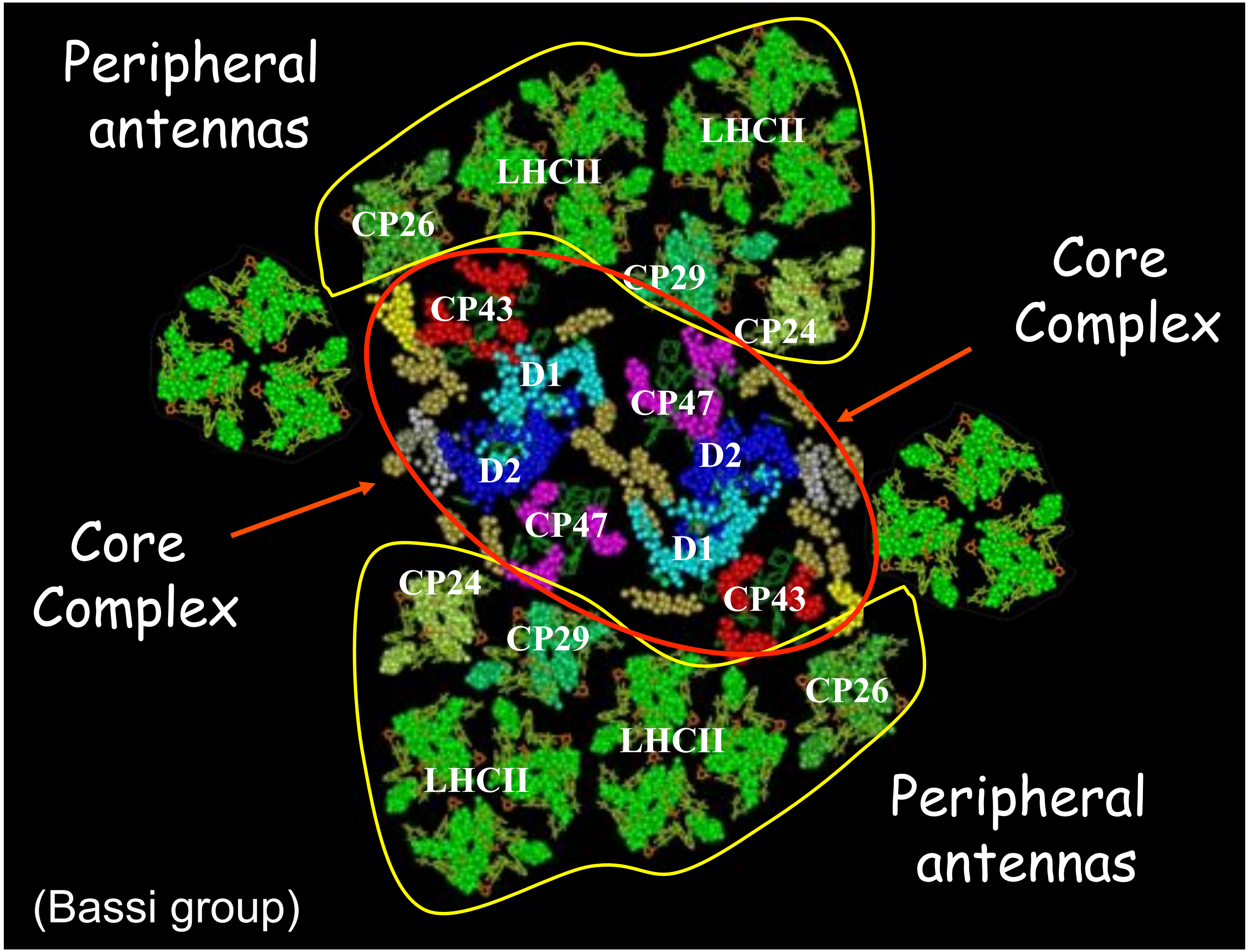
AFM of native photosynthetic membranes of a purple bacterium

Bahatyrova et al., *Nature* **430**, 1058 (2004)

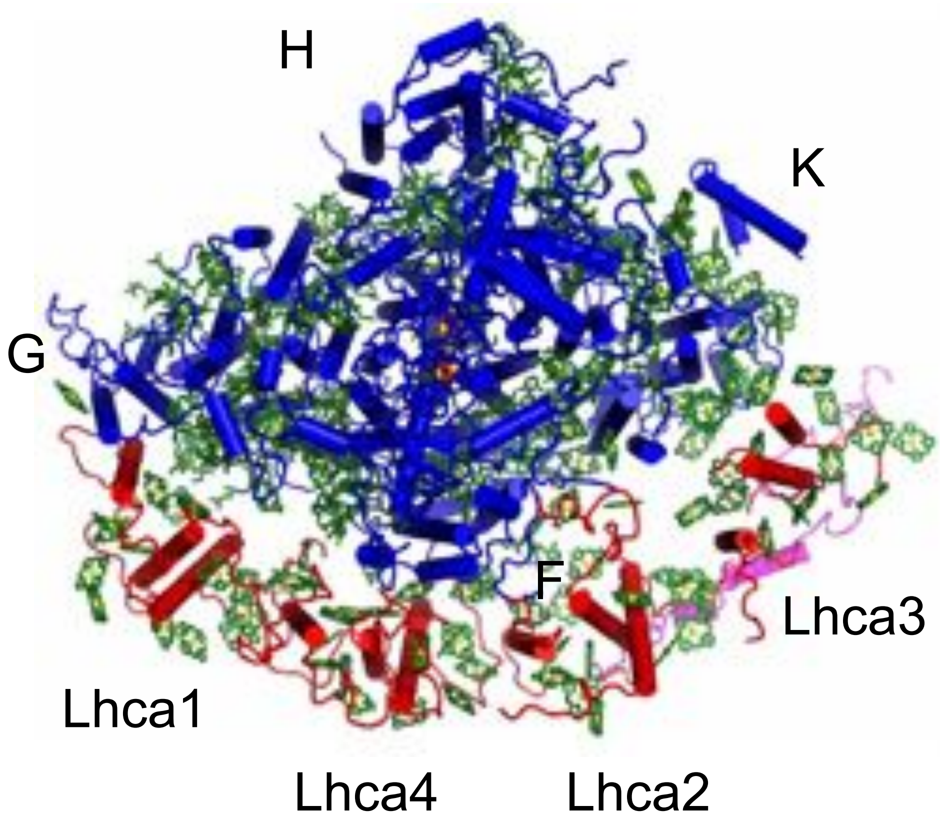


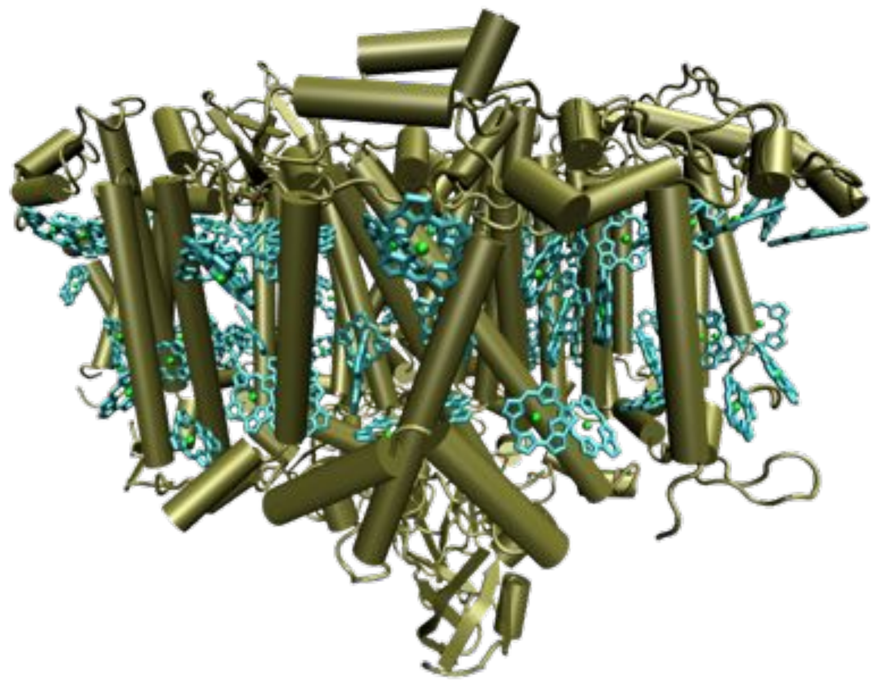
Hu et al., *Q. Rev. Biophys.* **35**, 1 (2002)

Light-harvesting Apparatus of Higher Plants



Photosystem I Supercomplex of Plants

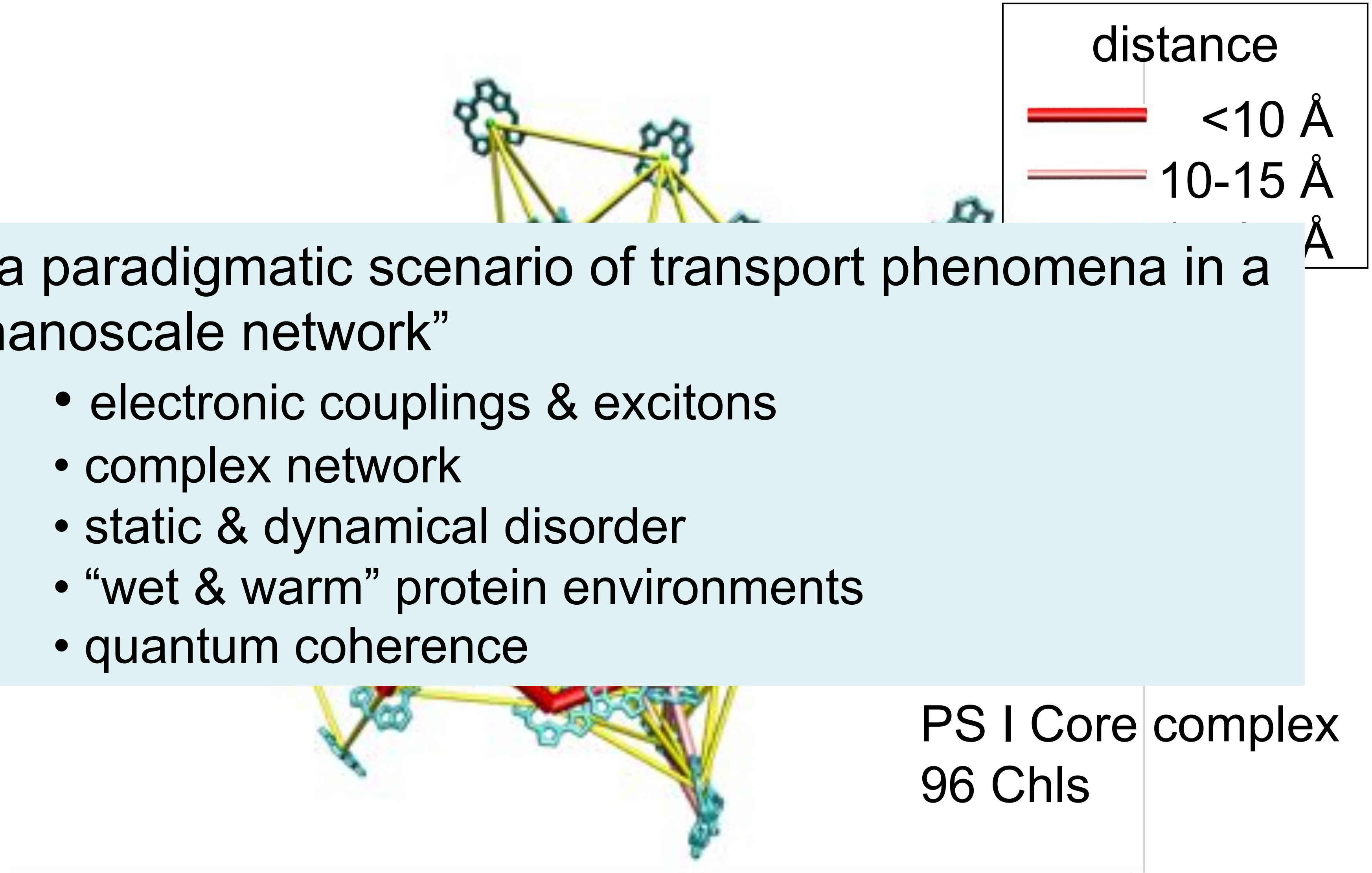




PS I Core complex
96 Chls

A. Ben Shem, F. Frolow & N. Nelson, Nature, 426, 630-5 (2003).

Chlorophyll Arrangement in the PS I Core



"a paradigmatic scenario of transport phenomena in a nanoscale network"

- electronic couplings & excitons
- complex network
- static & dynamical disorder
- "wet & warm" protein environments
- quantum coherence

PS I Core complex
96 Chls

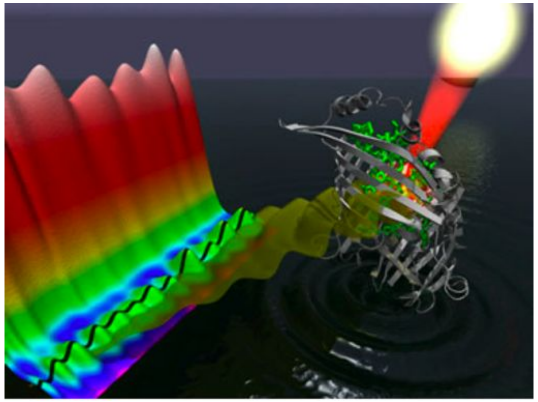
Pdb id: 1JB0

A complex chlorophyll network for light harvesting

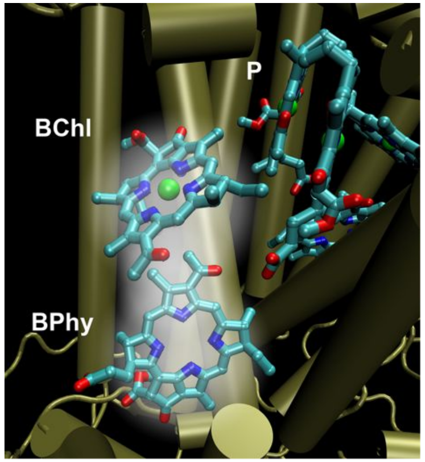
New Insights into Photosynthetic Light Harvesting

- Recent experiments indicate that **quantum coherence** can play a role in light harvesting

- **Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems**, G.S. Engel, T.R. Calhoun, E.L. Read, T. Ahn, T. Mancal, Y.-C. Cheng, R.E. Blankenship & G.R. Fleming, *Nature* **446**, 782 (2007).



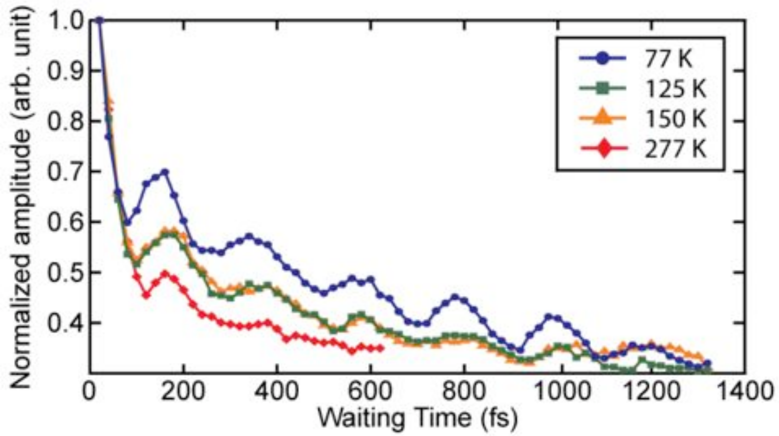
- **Coherence Dynamics in Photosynthesis: Protein Protection of Excitonic Coherence**, H. Lee, Y.-C. Cheng & G.R. Fleming, *Science* **316**, 1462 (2007).



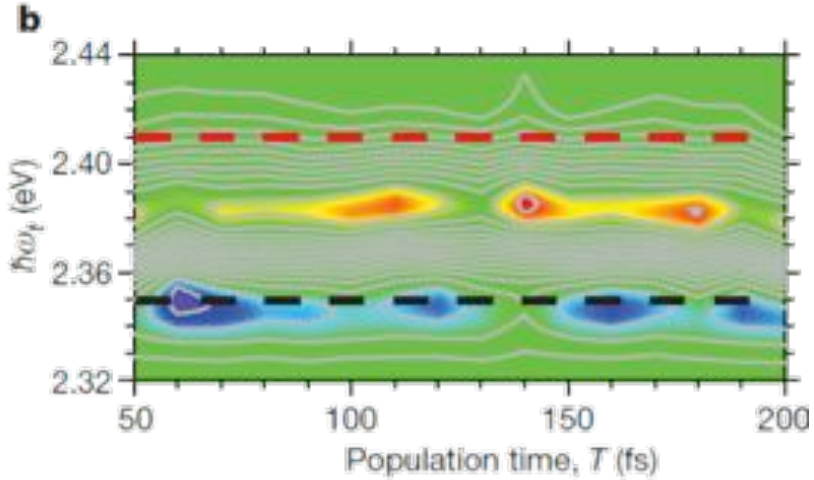
New Insights into Photosynthetic Light Harvesting

- Recent experiments indicate that quantum coherence can play a role in light harvesting – **even at ambient temperature**

- **Long-lived quantum coherence in photosynthetic complexes at physiological temperature**, Gregory S. Engel and coworkers, *arXiv*:1001.5108v1 (2010).



- **Coherently wired light-harvesting in photosynthetic marine algae at ambient temperature**, G. D. Scholes and coworkers, *Nature,* **463**, 644 (2010).

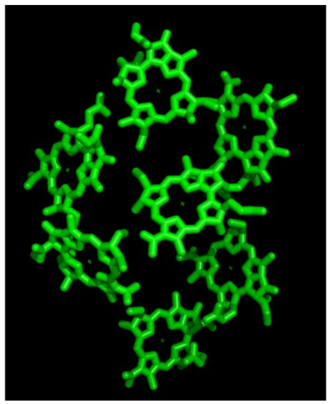


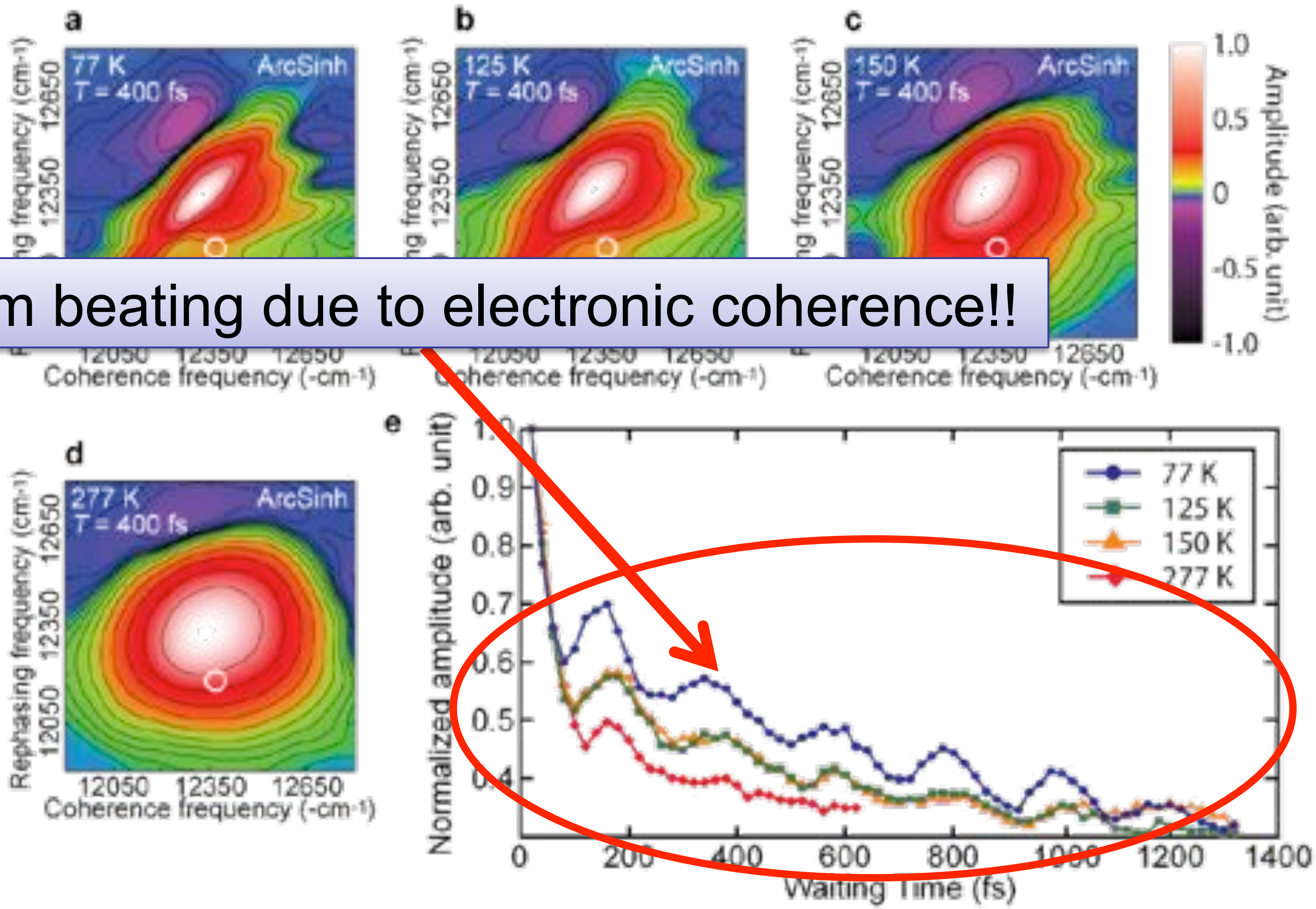
Quantum Coherence in FMO at Physiological Temperature

FMO

2DES

Sp





Quantum beating due to electronic coherence!!

Gregory S. Engel and coworkers, *arXiv*:1001.5108v1 (2010)
http://arxiv.org/abs/1001.5108

Coherent Evolution of Density Matrix

- Time-evolution of a superposition of

stationary

$$|\Psi(t)\rangle = ae^{-i\omega_1 t}|e_1\rangle + be^{-i\omega_2 t}|e_2\rangle$$

- Density matrix with ***excitonic coherence***

$$|\Psi(t)\rangle\langle\Psi(t)| = |a|^2|e_1\rangle\langle e_1| + |b|^2|e_2\rangle\langle e_2|$$

$$+ab^* e^{-i(\omega_1-\omega_2)t}|e_1\rangle\langle e_2| + a^* b e^{i(\omega_1-\omega_2)t}|e_2\rangle\langle e_1|$$

- Coherence oscillation results in energy population moving rever … ophores
- Cohe … ence … sing 2-D photon echo spectroscopy: quantum beats in 2-D signals

phase oscillation

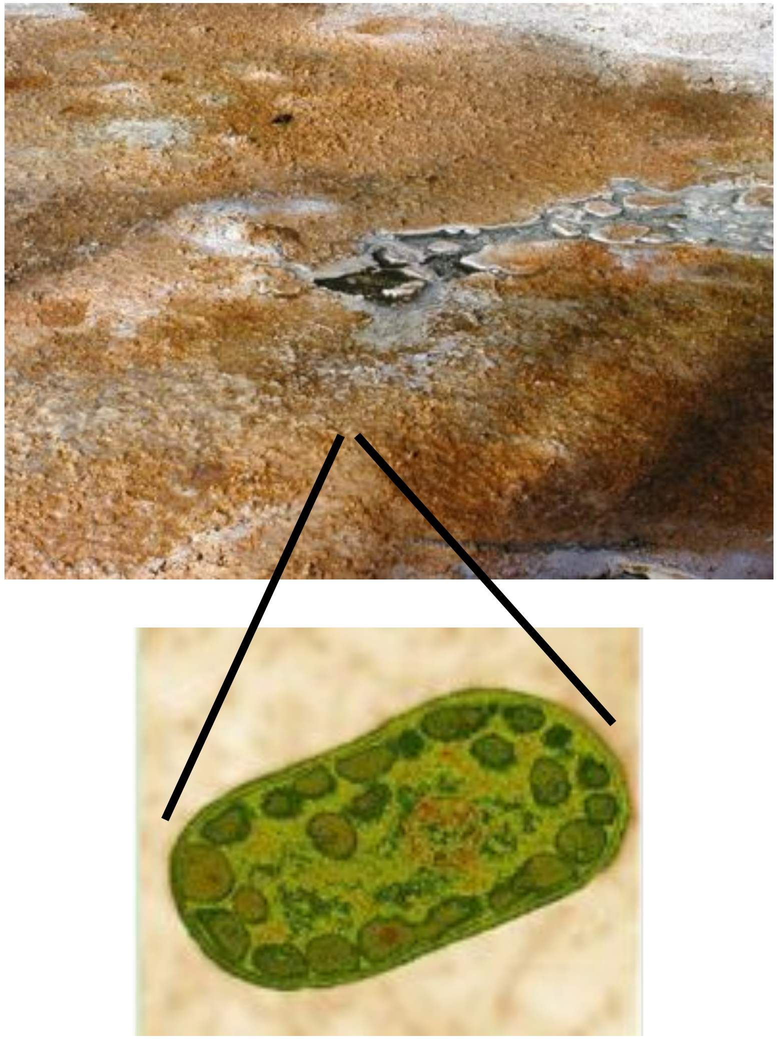
How does such long-lasting electronic coherence affect light harvesting?

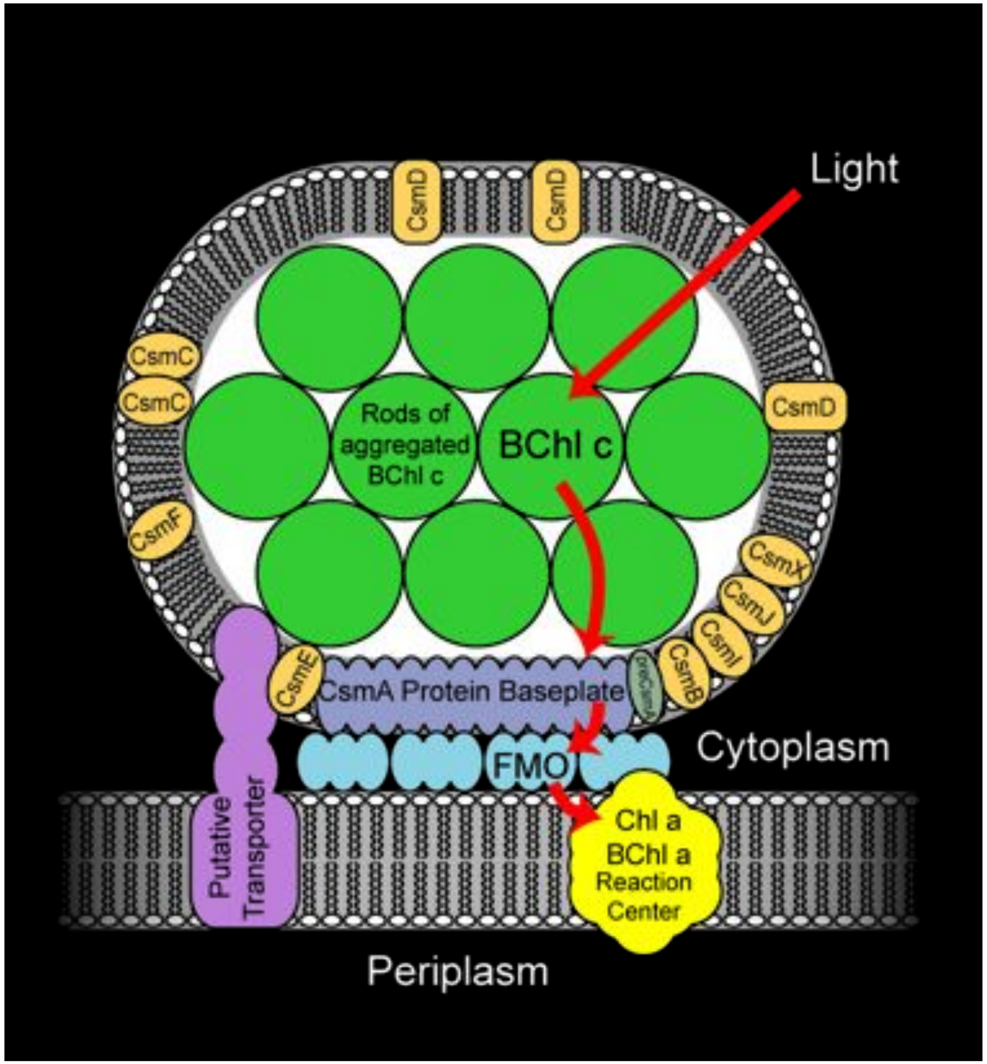
Combine experimental results & theoretical modeling to find out!

Strategy for Theoretical Investigations

- In order to elucidate how quantum coherence affects excitation energy transfer in the FMO complex, we
  - Build an effective model for FMO excitations & dynamics of excitation energy transfer
  - Refine the theoretical model by comparing to experimental two-dimensional optical spectra
  - Simulate the dynamics of energy trapping both **with** and **without** quantum coherence
  - Compare the results to determine the role of electronic quantum coherence

Light-harvesting Apparatus of Green Sulfur Bacteria

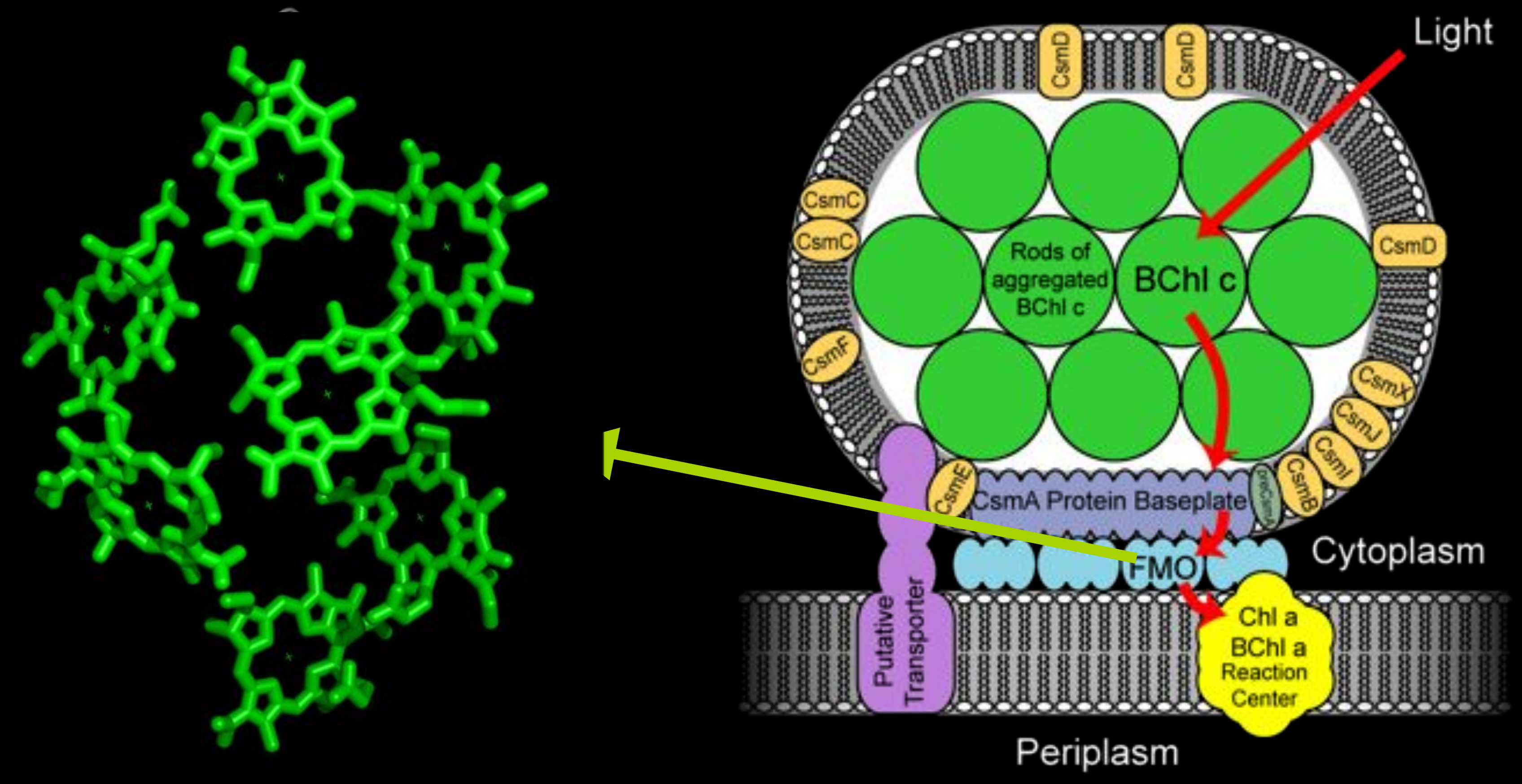




James Allen & coworkers, Photosynth. Res., 75:49 2003

Fenna-Matthews-Olson Complex from Green Sulfur Bacteria

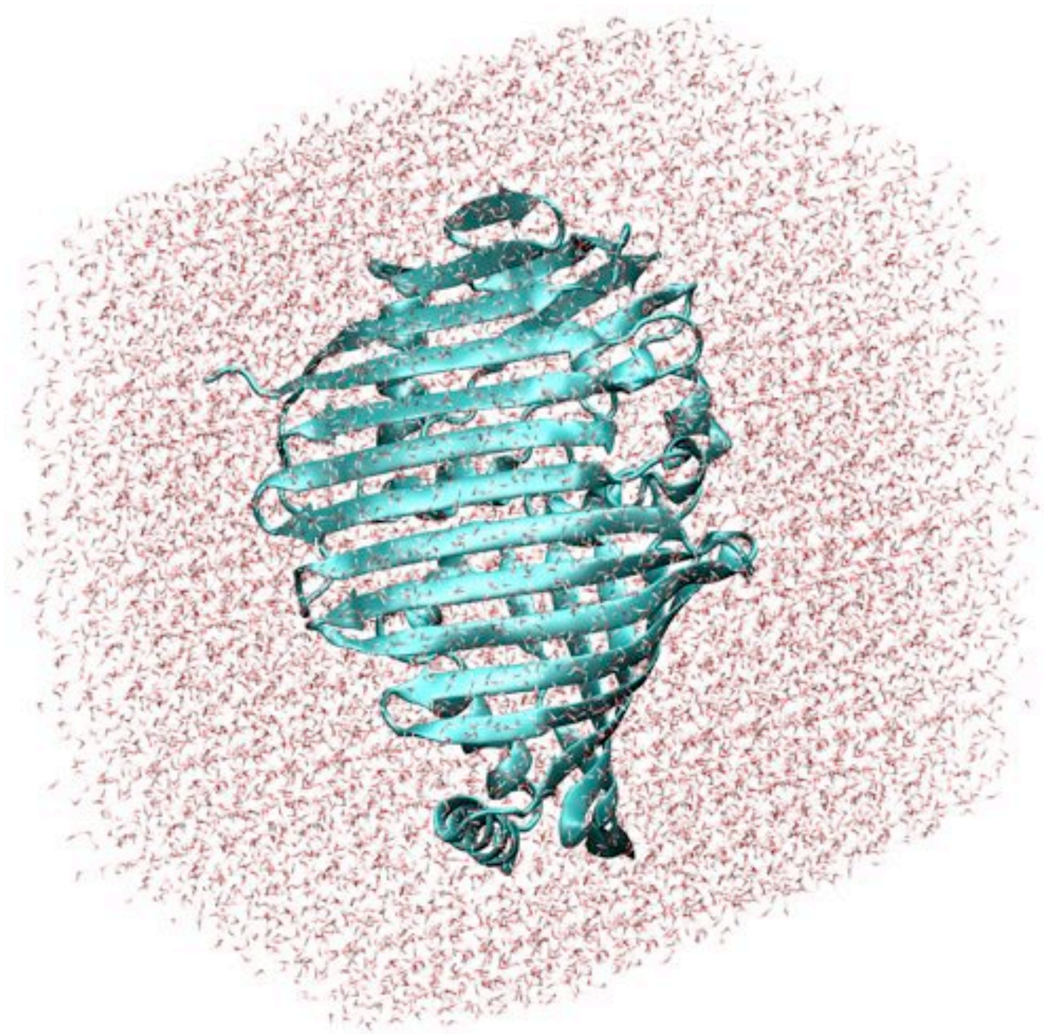
well characterized model



PDB ID: 4bcl, 1m50

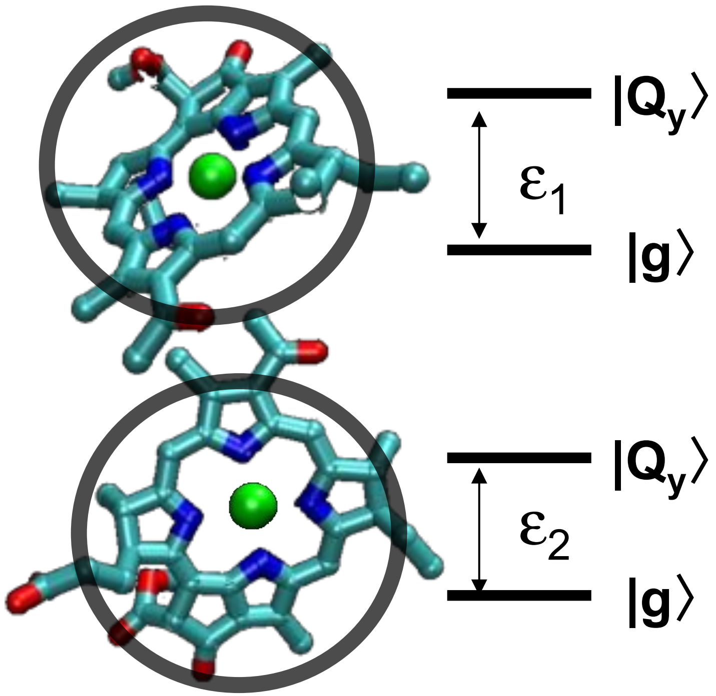
James Allen & coworkers, Photosynth. Res., 75:49 2003

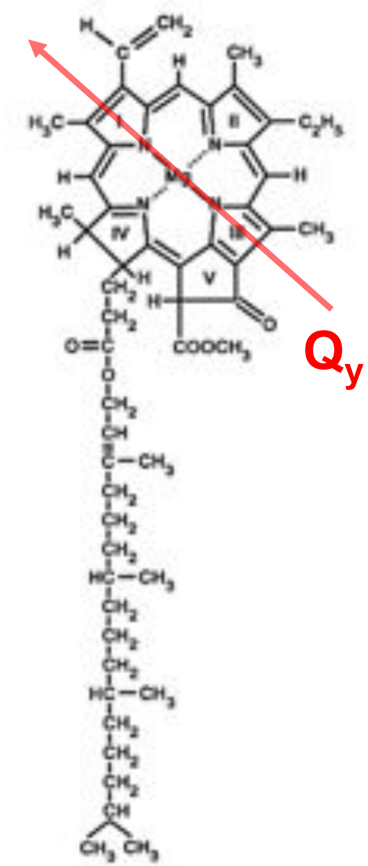
Modeling Excitation Energy Transfer in the FMO?



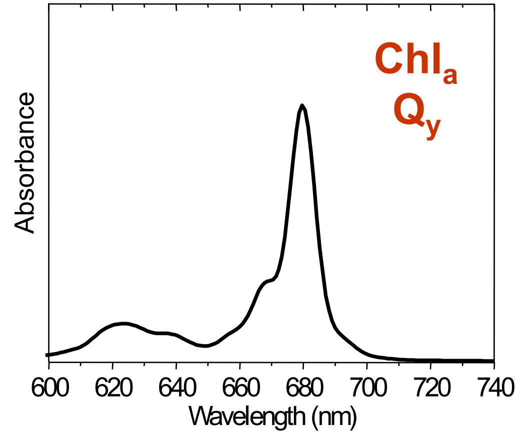
Full quantum dynamics of such a system is infeasible!

Frenkel Exciton Model





Chlorophyll *a*



ε_1, ε_2: site energy, transition energy modified by proteins

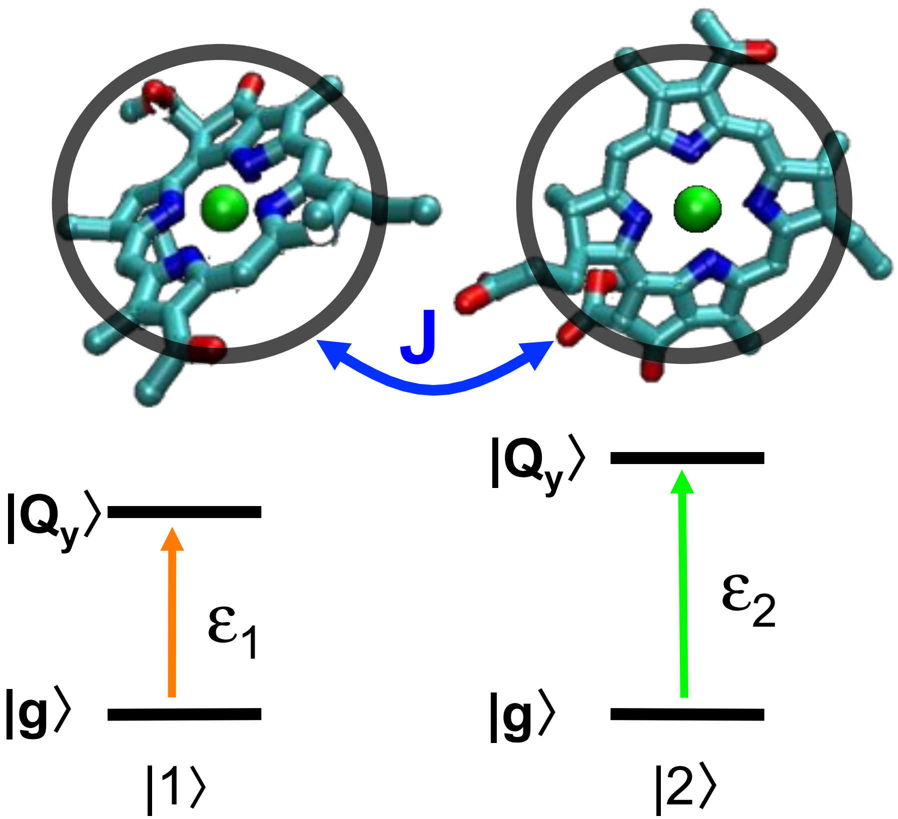
Exciton Hamiltonian and Excitonic Coupling

- Excitations interact with each other through excitonic coupling J
- H_e ➔ transition energies and excitonic couplings in multichromophoric systems!!

site energy coupling

$$H_e = \begin{bmatrix} \varepsilon_1 & J_{12} & \cdots & J_{1N} \\ J_{12} & \varepsilon_2 & \cdots & J_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ J_{1N} & J_{2N} & \cdots & \varepsilon_N \end{bmatrix}$$

"site basis"



- Excitation energy transfer induced by excitonic coupling J

FMO Complex: Electronic Interactions

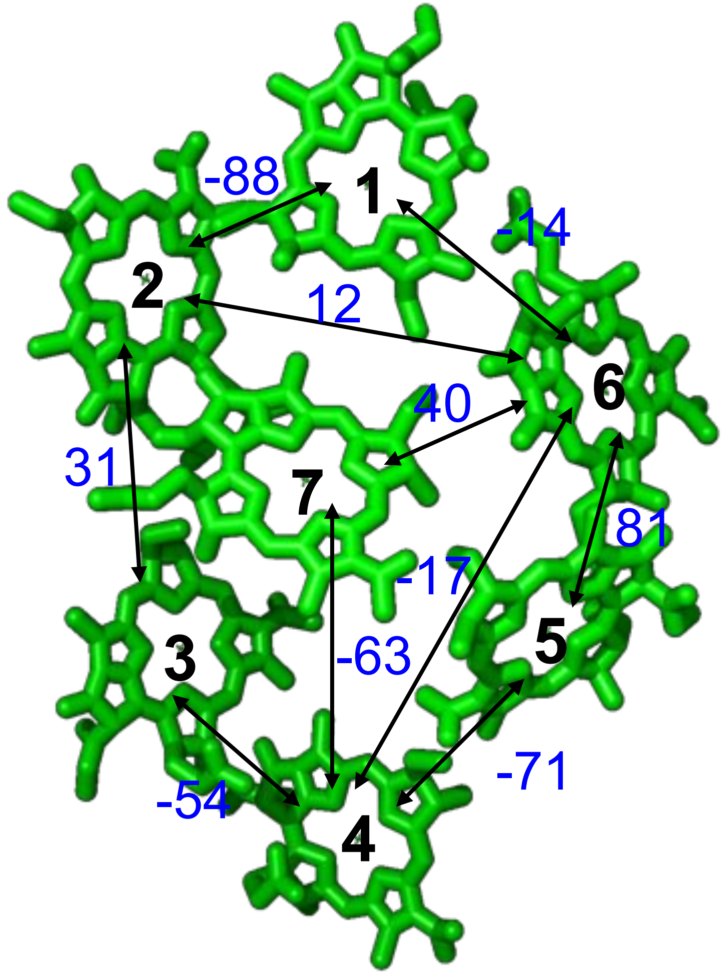
• There is a good starting point for the model of FMO Hamiltonian
• Couplings from **quantum chemistry** + transition density cube calculations
• Site energies from fitting to optical spectra

<u>Site energies</u>

BChl	Monomer	Trimer
1	12,445	12,410
2	12,520	12,530
3	12,205	12,210
4	12,335	12,320
5	12,490	12,480
6	12,640	12,630
7	12,450	12,440

J. Adolphs & T. Renger, Biophys. J. 91, 2778 (2006).

Excitonic couplings



* For C. Tep. FMO, unit in cm^{-1}

Quantum Dynamics of Excitation Energy Transfer

When system-bath coupling is weak, we can use Redfield equation to describe energy transfer:

exciton Hamiltonian

dissipation determined by system-bath couplings

$$\partial_t \rho(t) = -i[H_e, \rho(t)] - \Re[\rho(t)]$$

population

coherence

$$\rho = \begin{bmatrix} \rho_{11} & \rho_{12} & \cdots & \rho_{1N} \\ \rho_{12} & \rho_{22} & \cdots & \rho_{2N} \\ \vdots & \vdots & & \vdots \\ \rho_{1N} & \rho_{2N} & \cdots & \rho_{NN} \end{bmatrix}$$

ρ: reduced-system density matrix

N: number of chromophores

$$\Re[\,]: \quad \begin{array}{l} \rho_{nn} \rightarrow \rho_{mm} : \text{ population dynamics (incoherent)} \\ \rho_{nm} \rightarrow \rho_{n'm'} : \text{ coherence dynamics} \end{array}$$

Calculate Nonlinear Spectrum

Also consider light-matter interactions with laser pulses to simulate nonlinear spectrum using dynamical propagation

exciton Hamiltonian

dissipation

$$\partial_t \rho(t) = -i[H_e + H_{\text{int}}(t), \rho(t)] - \Re[\rho(t)]$$

light-matter interactions

$$H_{\text{int}}(t) = -\hat{V} \cdot \sum_{a=1}^{3} \mathbf{E}_a(t)$$

➔ Extract photon-echo signal at the phase-matching direction by selective combinations of light-matter interactions in calculations (non-trivial)

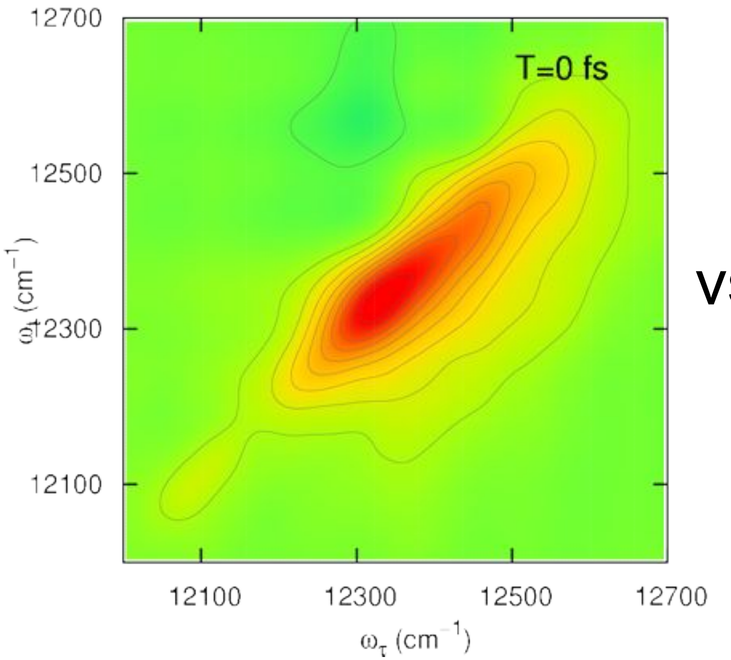
M. F. Gelin, D. Egorova, W. Domcke, JCP **123**, 164112 (2005);
Y.-C. Cheng, H. Lee, G. R. Fleming, JPCA **111**, 9499 (2007).

QDAS Code

- Quantum Dynamics And Spectroscopy
- Simulates excitation energy transfer dynamics and various linear & nonlinear spectra (Absorption, 2D, 3PEPS…)
- Treats an array of bath spectra densities and bath memory effects
- Includes doubly excited states and average over a Gaussian distribution of disordered energies
- MPI capability for parallel computing

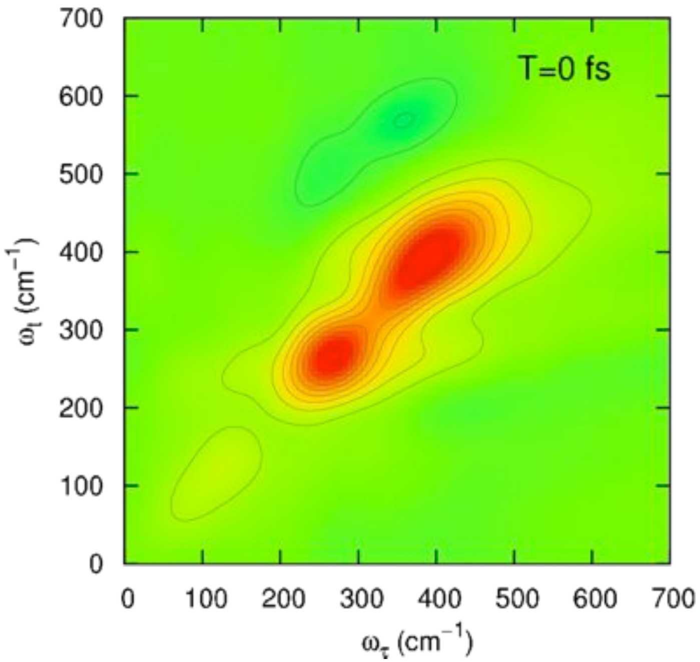
Simulated 2D Spectrum for FMO

Experiment



vs.

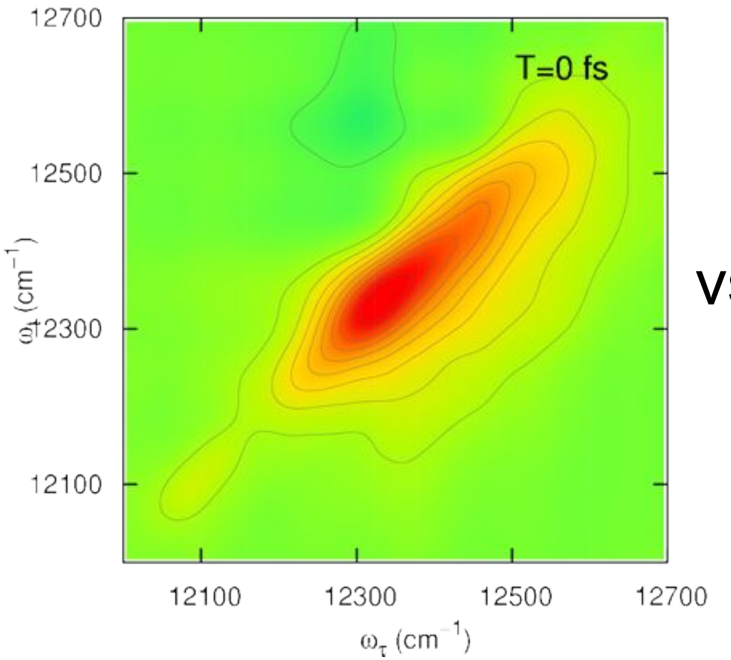
Renger's model



- Renger's model does not provide adequate 2D electronic spectra
- Parallel computing is necessary for seeking a better model:
  - each spectrum needs ~ 12 hrs using 128 CPUs on NERSC' Franklin cluster due to extensive Monte-Carlo ensemble averaging procedure
  - > 30 parameters to adjust/optimize

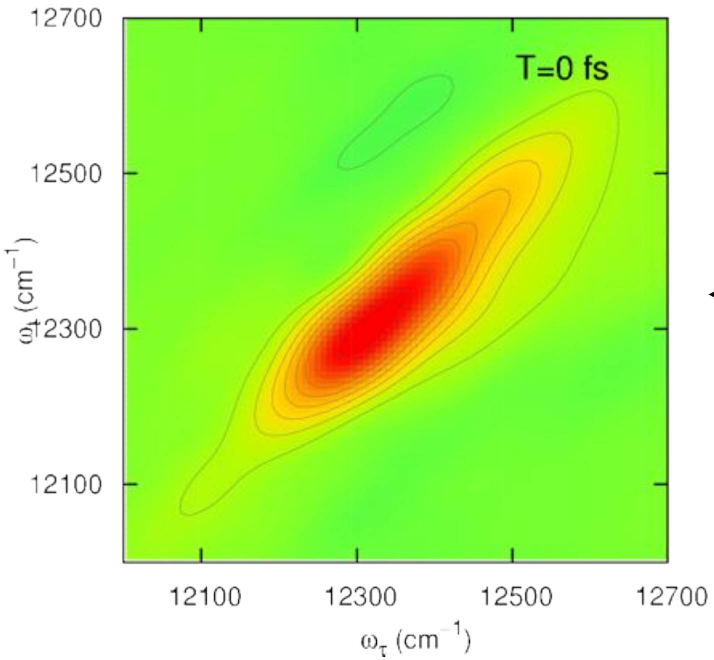
Simulated 2D Spectrum for FMO

Experiment



vs.

Optimal Model



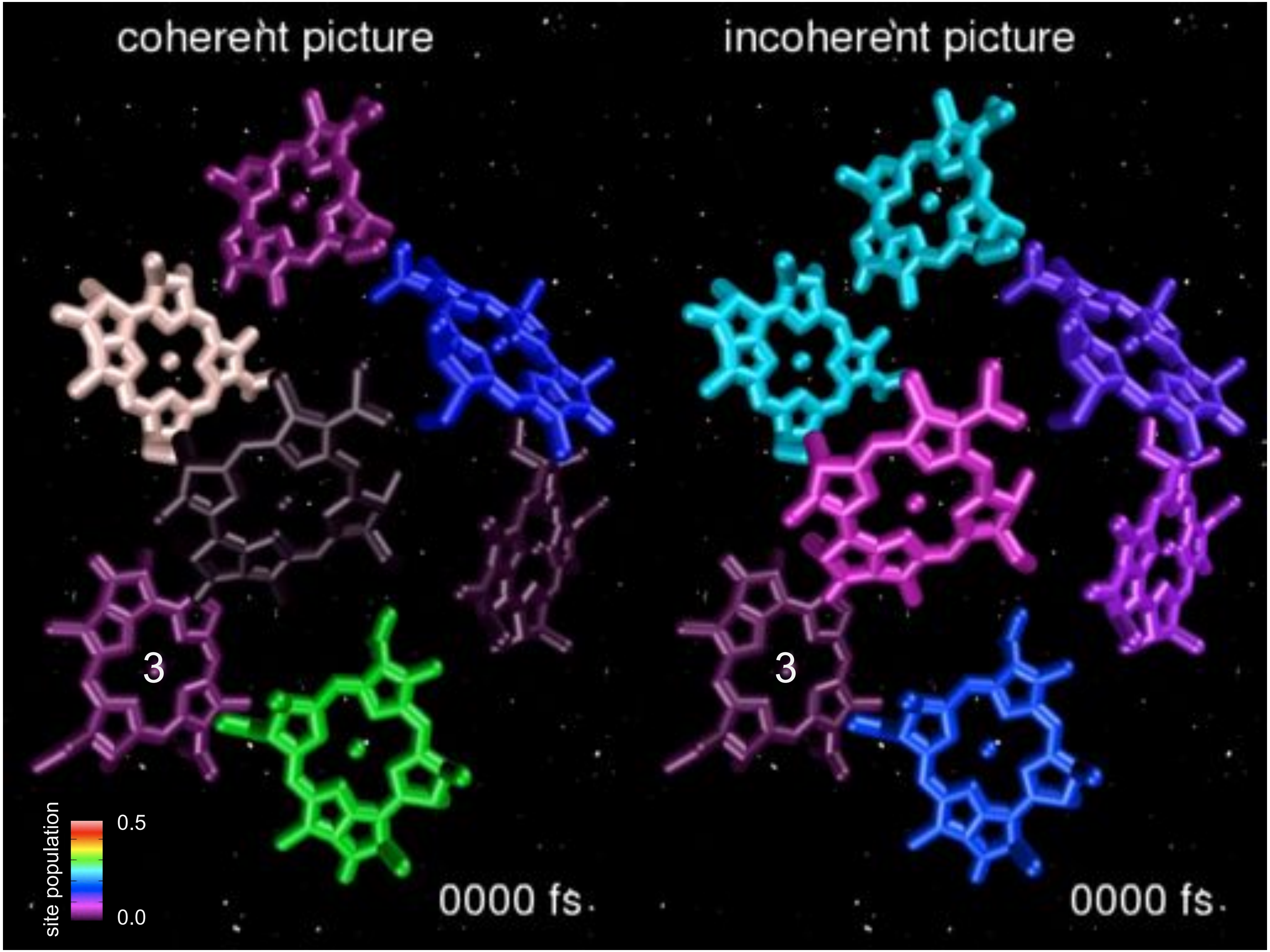
Model

⟷ $H_e + \Omega(\omega)$

- Iterate to reach good agreement between experiment & theory starting from Renger's model
- Require inclusion of doubly excited states and average over a Gaussian distribution of disordered energies
- Provide refined model ➔ basis for studying coherence effects

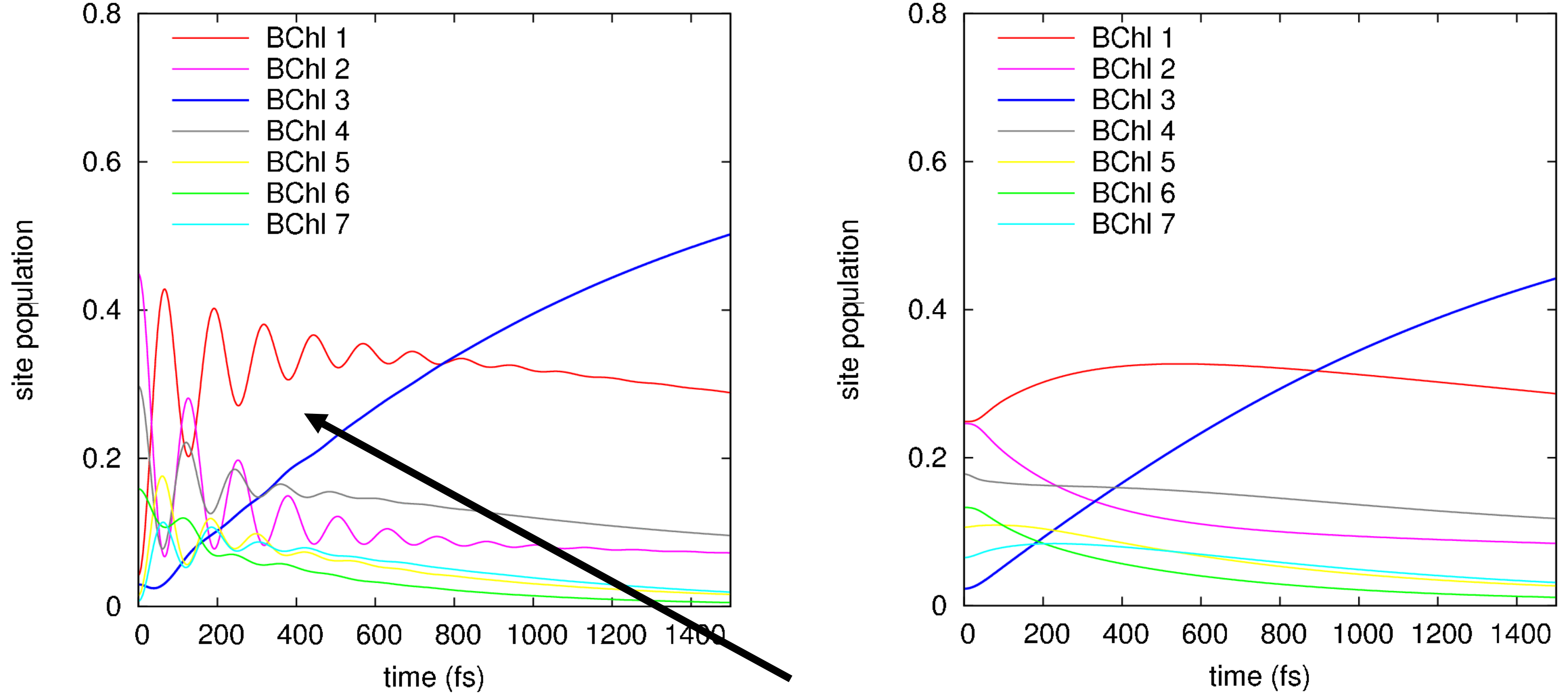
Coherent vs. Incoherent Model

- Use the refined theoretical model to investigate the effects of quantum coherence on excitation energy transfer
- Two theories for energy transfer dynamics:
  - Coherent: full quantum master equation
  - Incoherent: population dynamics only
    ➔ conventional excitation hopping view
- Initial conditions: coherent superposition for the coherent picture, and population-only for the incoherent picture


coherent picture
incoherent picture
3
3
site population
0.5
0.0
0000 fs
0000 fs

Dynamics in the Site Basis

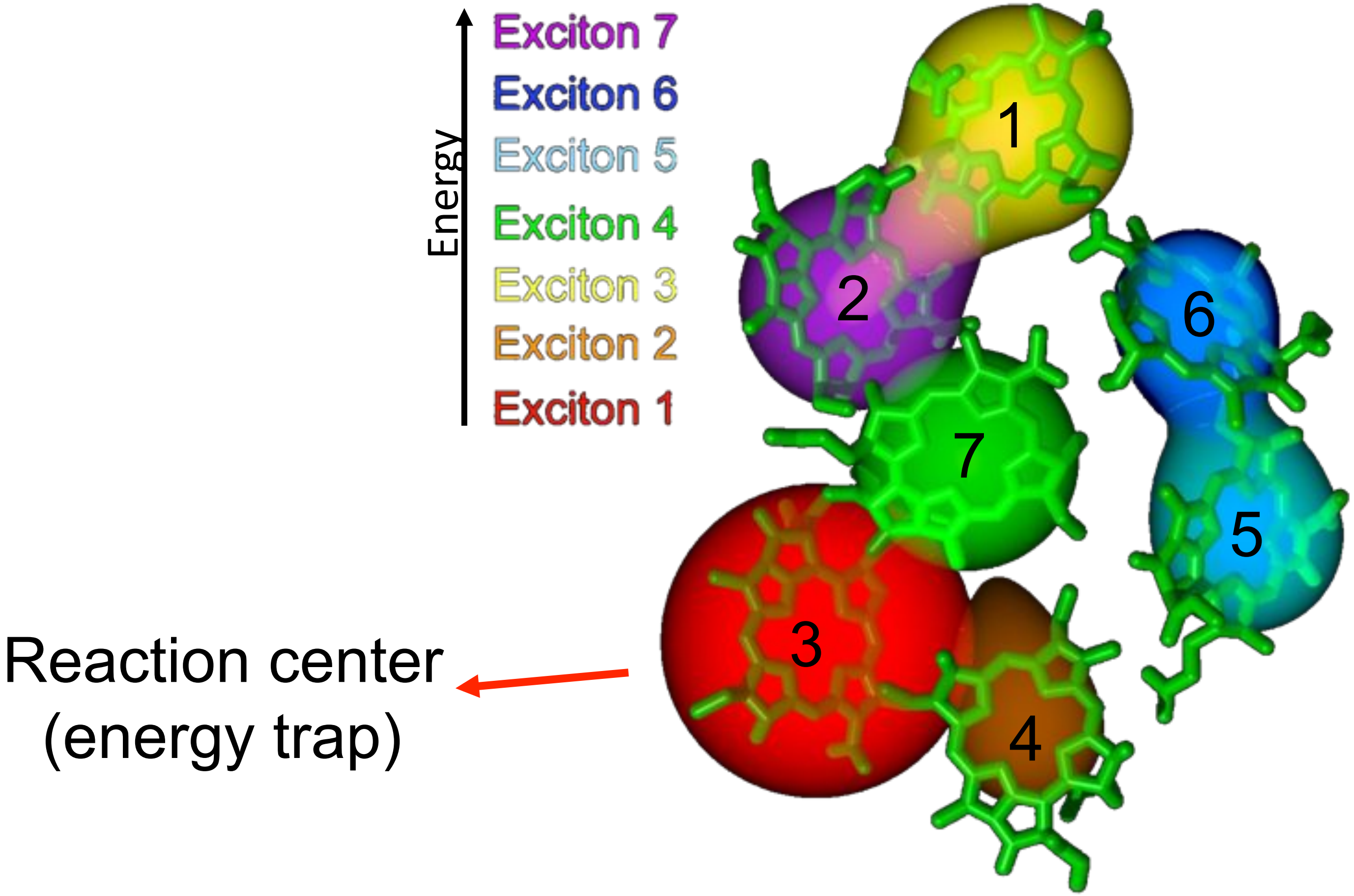
Coherent Picture | Incoherent Picture



- Reversible population redistribution in space showing interference effects due to quantum coherence
- Efficiencies of reaching BChl 3 only marginally different.

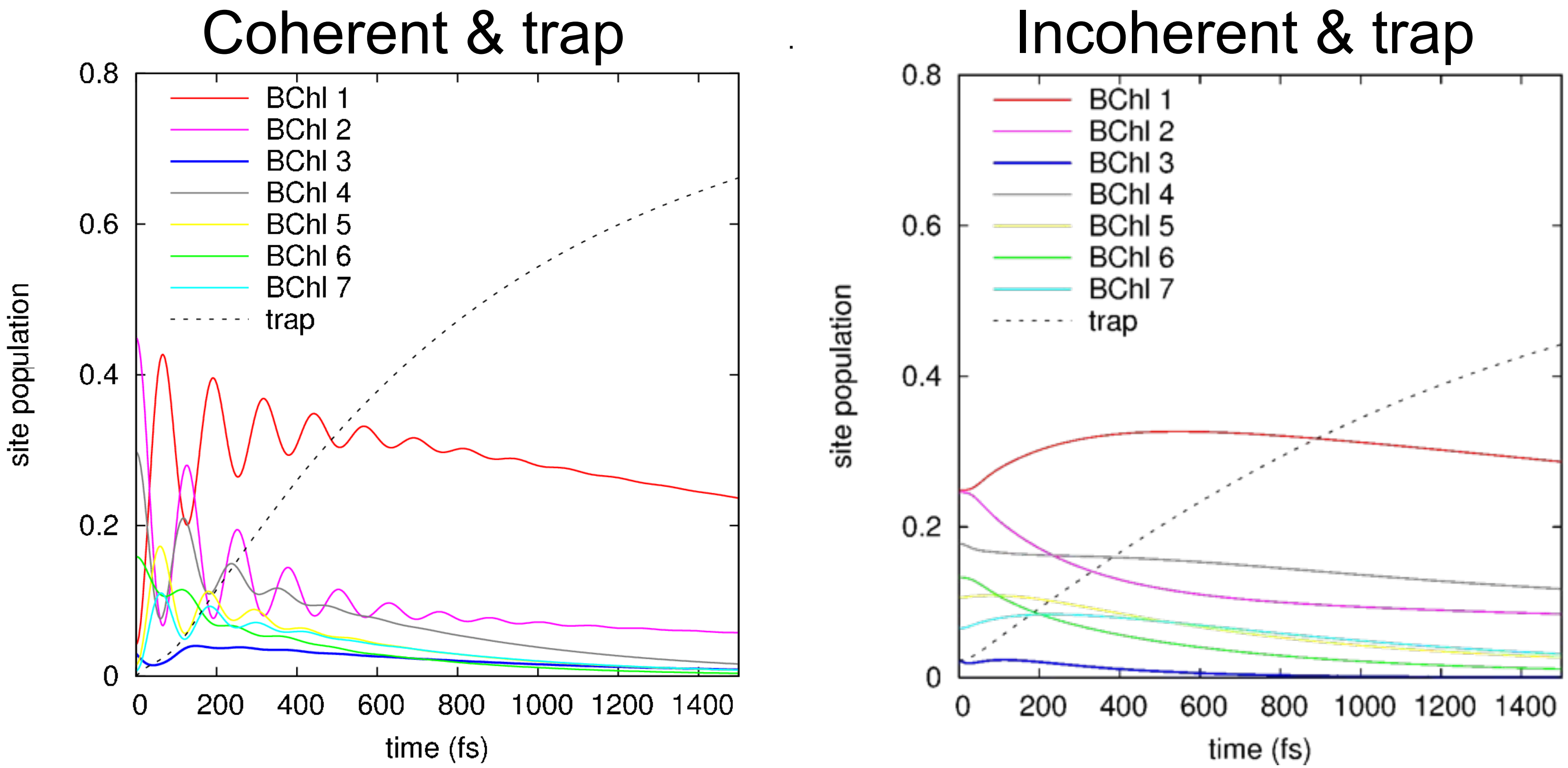
Energy Trapping from BChl 3

FMO complex is a energy wire connected to RC through BChl 3



What if an efficient energy trap is attached to BChl 3?

Coherence Assisted Energy Trapping



- Rapid trapping (50 fs) from BChl 3 enhances efficiency for the coherent case because of the suppression of back transfer
- Quantum coherence may enable excitation to find RC rapidly through reversible sampling in space ➔ *Coherence assisted energy trapping*

Coherence Assisted Energy Trapping

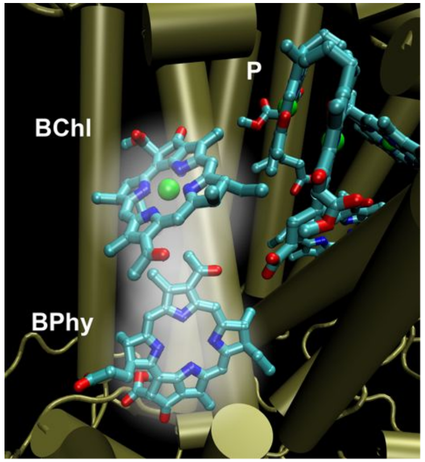
- Long-lived electronic coherence enables the system to perform rapid and reversible sampling in space to search for the trap site
- Efficient trapping process dissipates the energy and localizes the excitation
- The scheme can be more efficient than incoherent hopping and is likely to be more robust on energetically disordered landscape
- This proposal is currently being actively studied by many groups: Aspuru-Guzik (Harvard), Lloyd (MIT), Whaley (Berkeley), Plenio (Imperial College, UK)…

How is the long-lasting quantum coherence achieved?

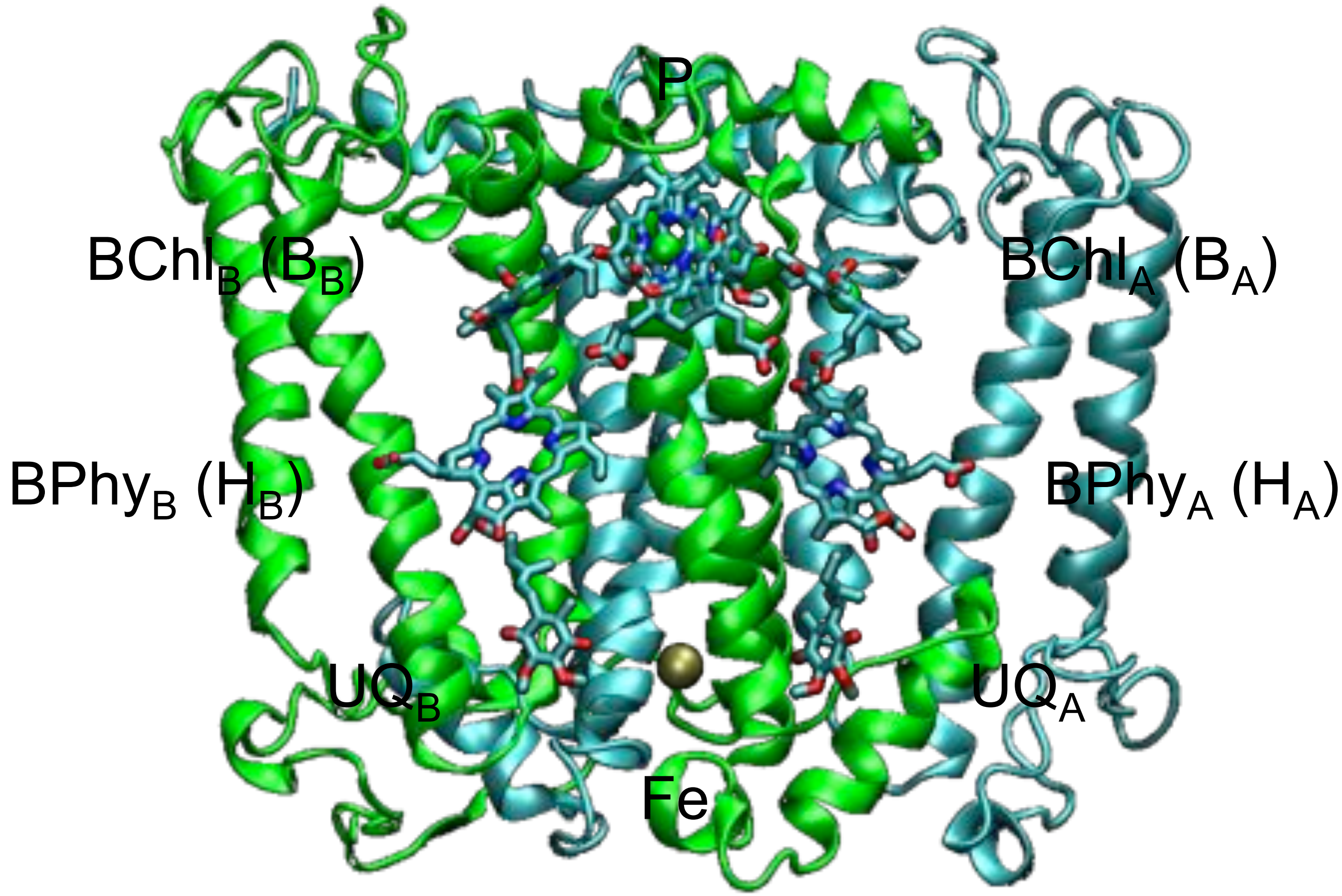
1. Protein environment & correlated motions
2. Non-equilibrium effects in energy transfer

Coherence Photon Echo of Bacterial Reaction Center

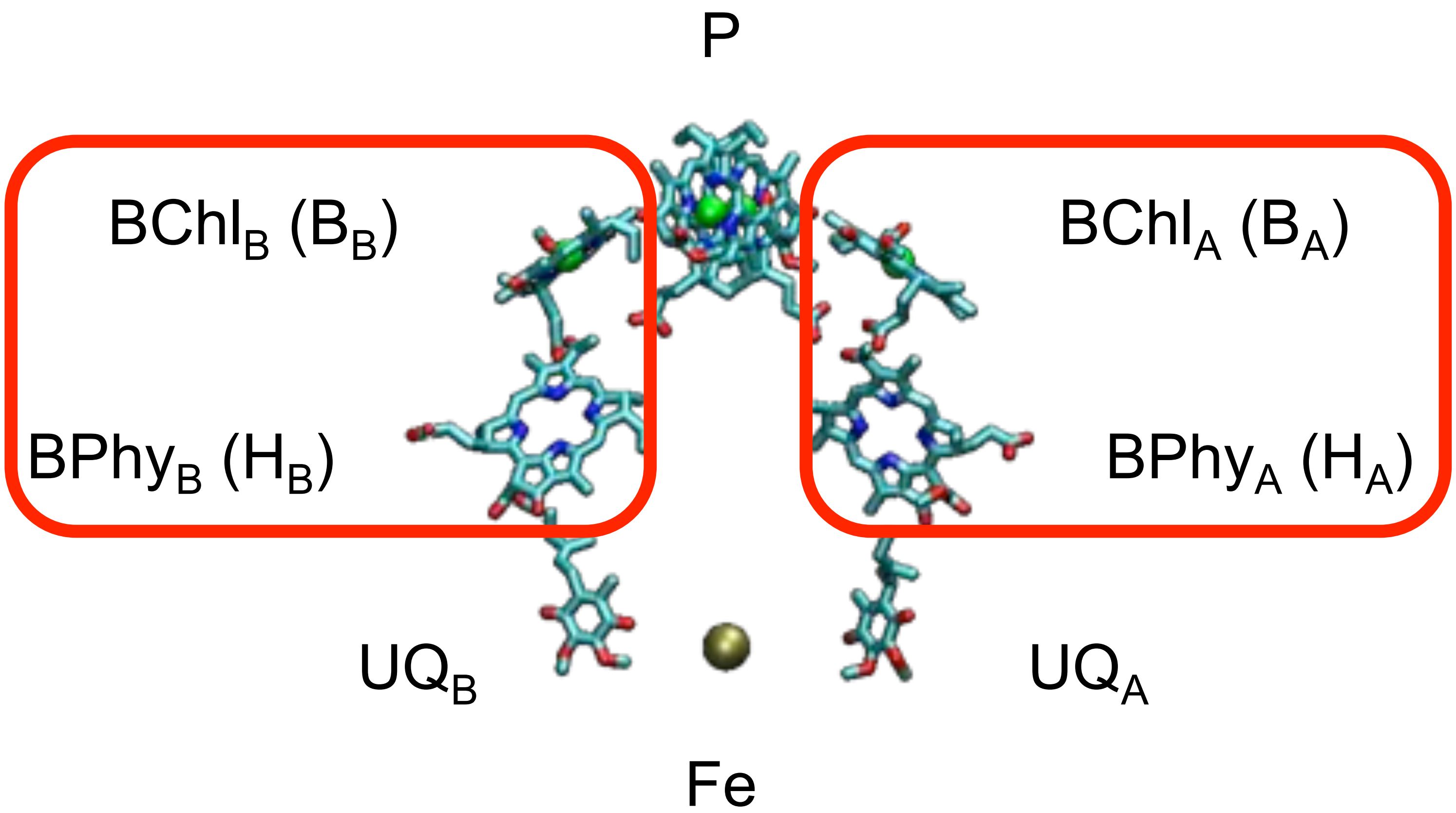
- Protein protection of electronic quantum coherence:
  - H. Lee, Y.-C. Cheng & G.R. Fleming, *Science* **316**, 1462 (2007).



The Reaction Center of Purple Bacteria

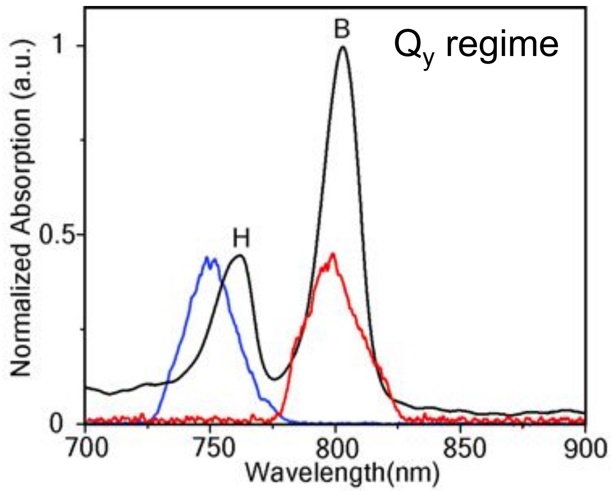


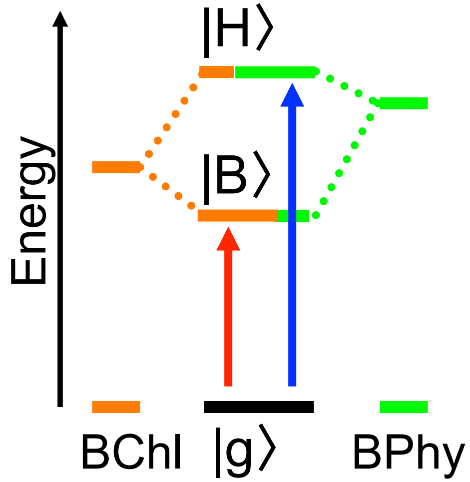
The Reaction Center of Purple Bacteria

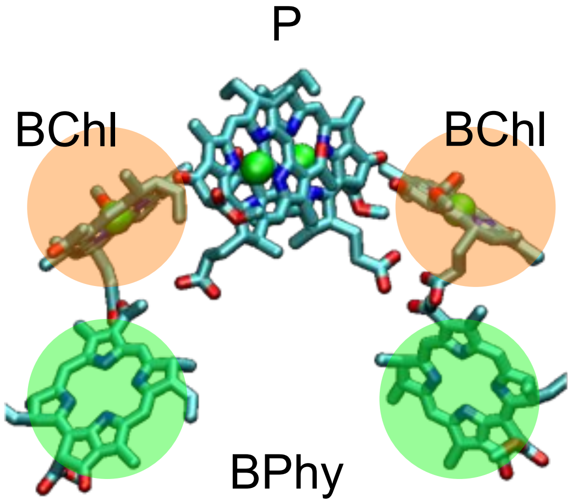


Probing H/B Coherence Dynamics: Two-color Electronic Coherence Photon Echo

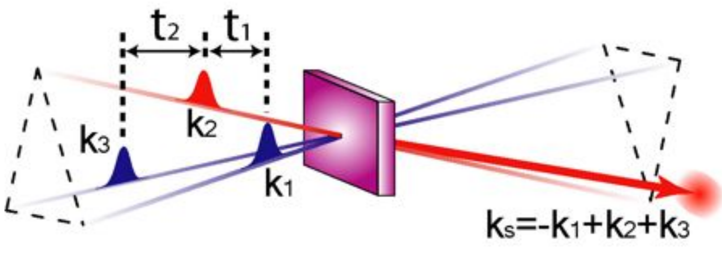
Spectrum of the RC



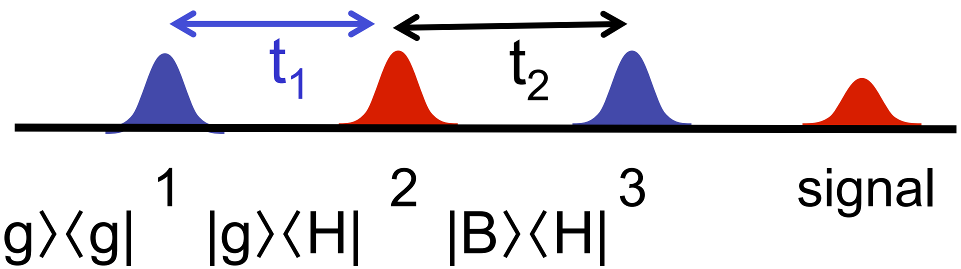




- |H⟩ and |B⟩ selectively excited
- Design to probe coherence specifically |g⟩⟨H| in t_1, |B⟩⟨H| in t_2

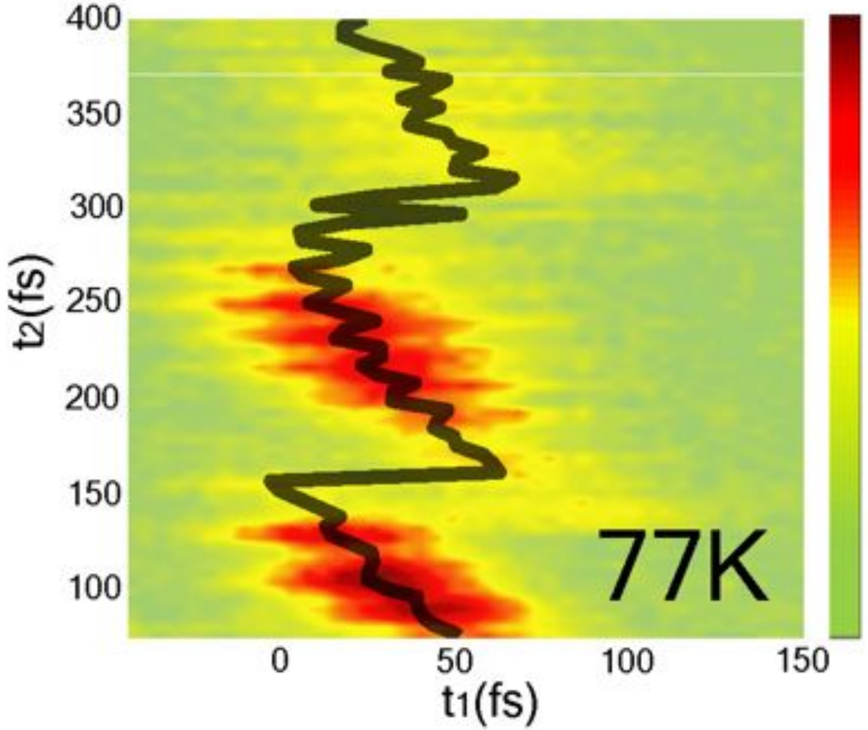


Ordering: 750-800-750 (nm)



Experimental Data @ 77K

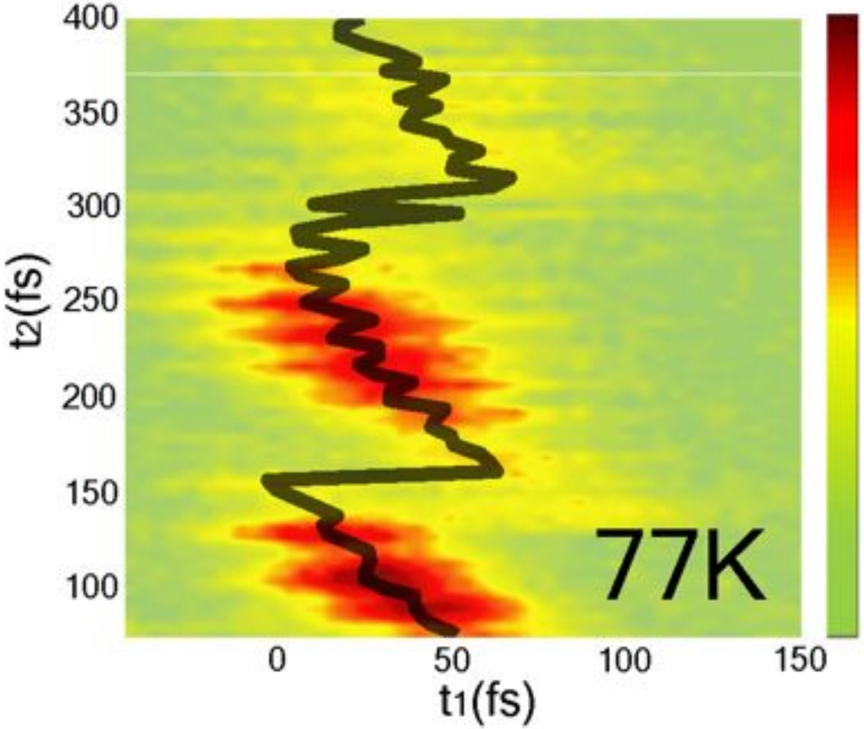
Photon-echo Intensity



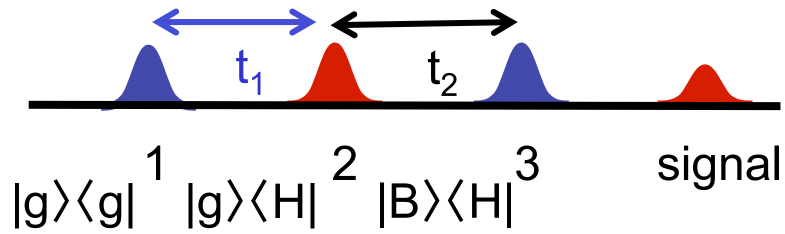
Mapping Coherence Dynamics in the RC

Photon-echo Intensity

|B⟩⟨H| dephasing



|g⟩⟨H| dephasing



- Photon-echo intensity measured in this two-color experiment follows coherence dynamics.
- Along t_1: |g⟩⟨H| dephasing
- Along t_2: |B⟩⟨H| dephasing

H. Lee, Y.-C. Cheng, G.R. Fleming, *Science* **316**, 1462 (2007).

Dephasing of Electronic Coherence

- Phase associated with the time evolution of coherences (off-diagonal density matrix elements):

$$\phi_{ij}(t) = e^{-i(w_i - w_j)t}$$

➔ Randomness in the energy gap $\delta\omega_{ij}(t)$ results in dephasing

➔ Fluctuations of the energy gap are induced by dynamics of the protein environment

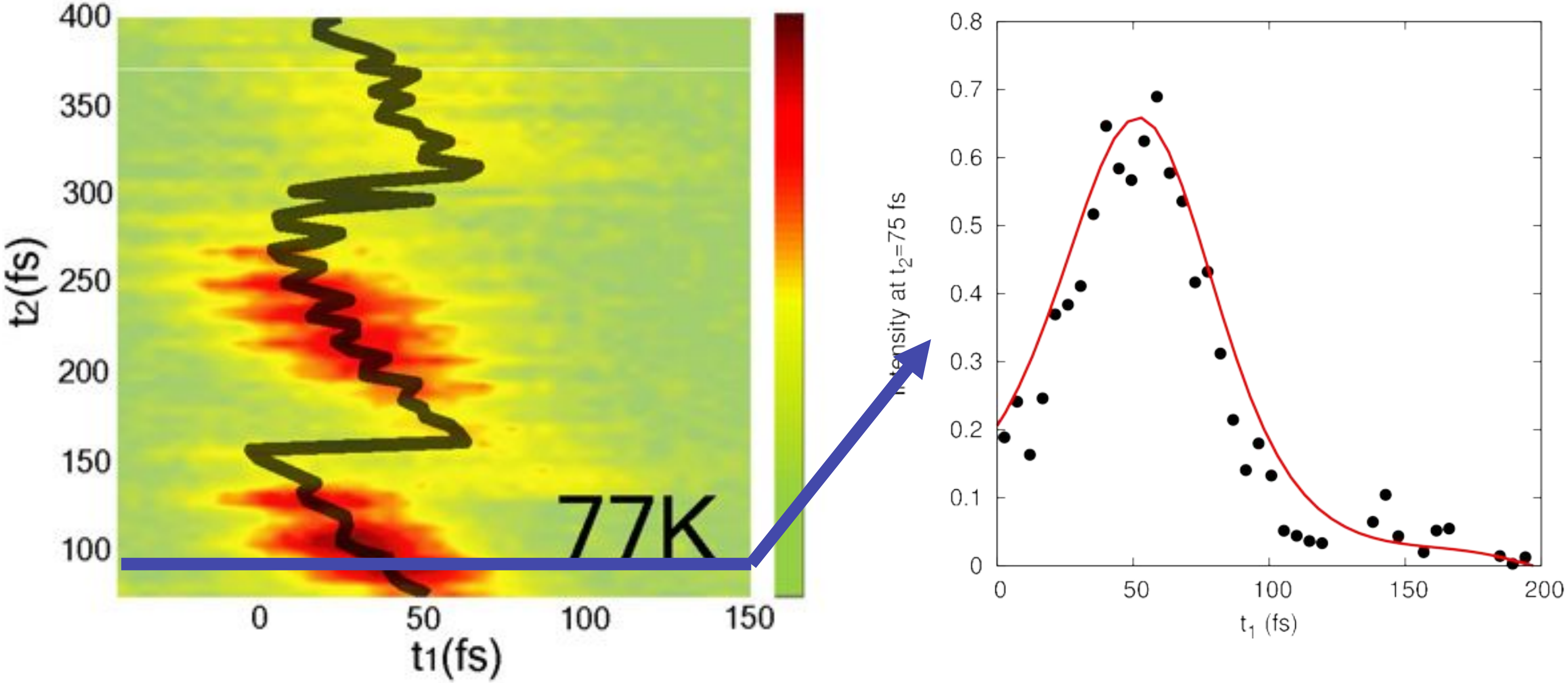
- Stronger fluctuation ➔ faster dephasing

Mapping Coherence Dynamics

Photon-echo Intensity

- Rapid |g⟩⟨H| dephasing (t_1)

|B⟩⟨H| dephasing

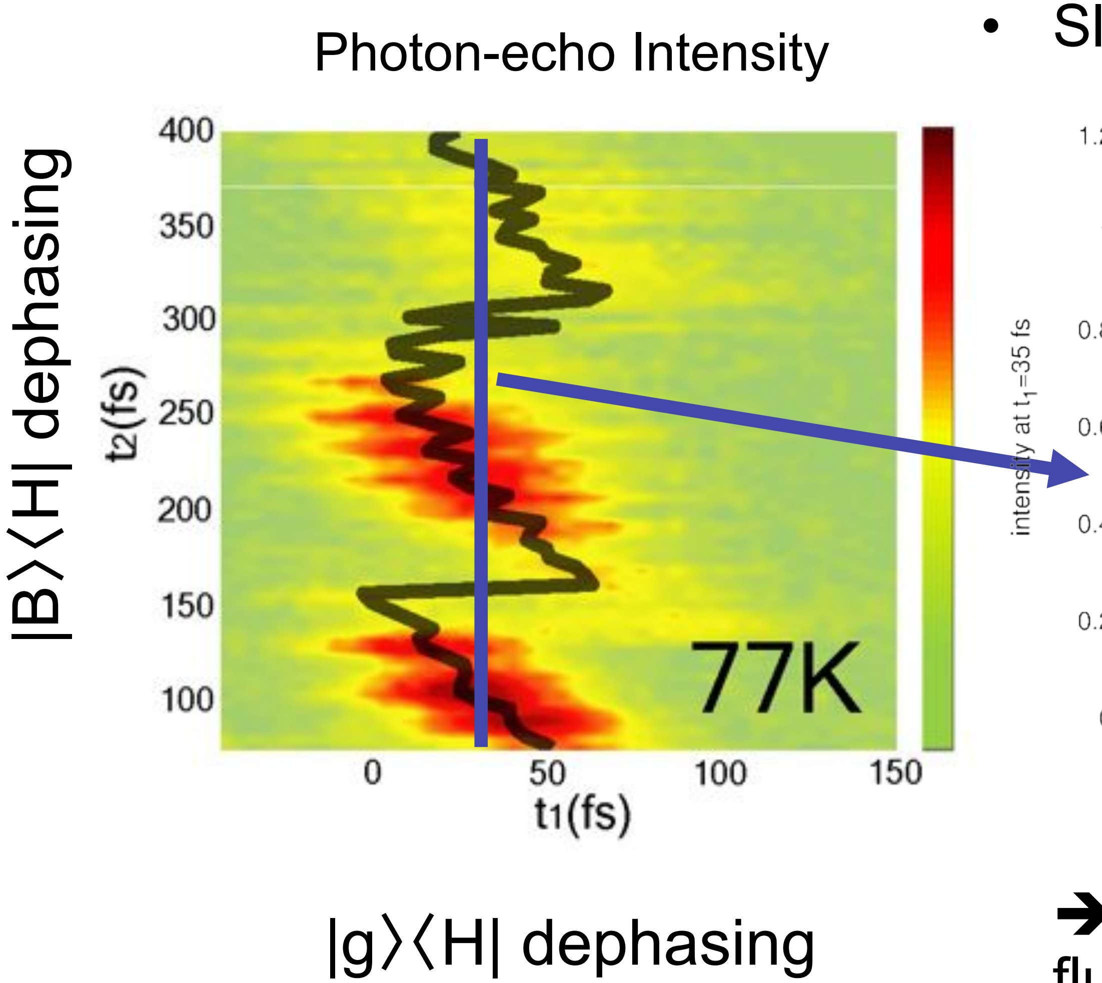


|g⟩⟨H| dephasing

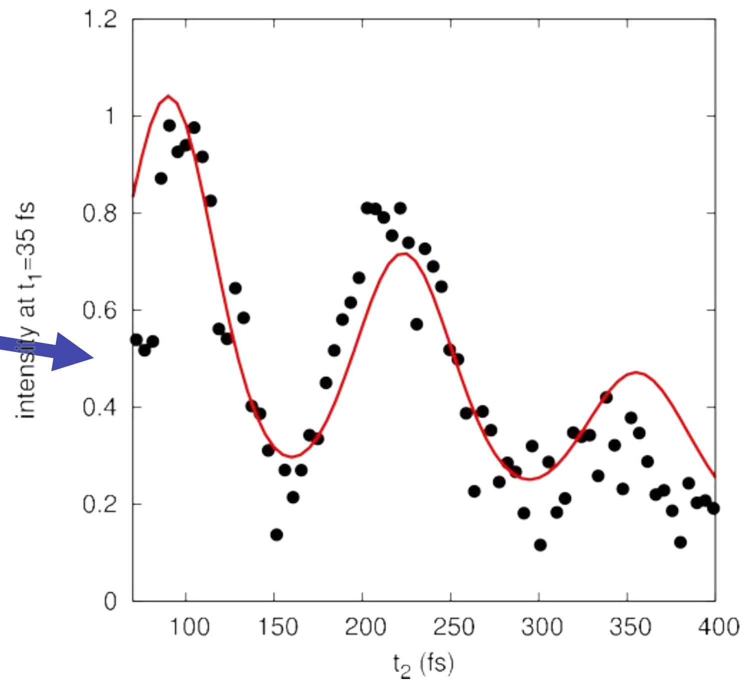
➔ Large E_H fluctuations.

H. Lee, Y.-C. Cheng, G.R. Fleming, *Science* **316**, 1462 (2007).

Mapping Coherence Dynamics



- Slow |B⟩⟨H| dephasing (t_2)

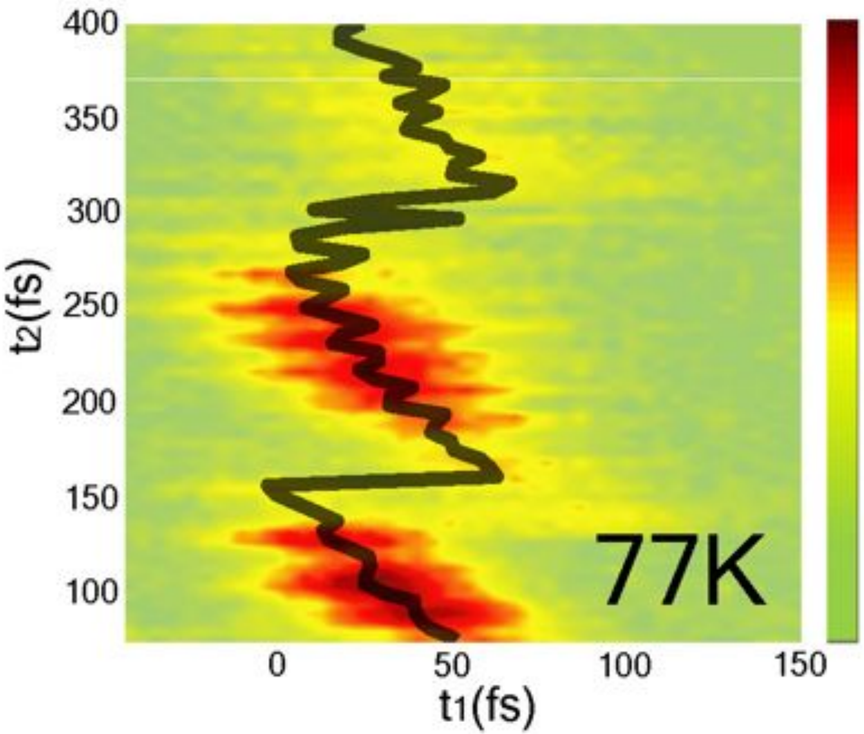


➔ Smaller E_H- E_B energy gap fluctuations.

H. Lee, Y.-C. Cheng, G.R. Fleming, *Science* **316**, 1462 (2007).

Mapping Coherence Dynamics

|B⟩⟨H| dephasing

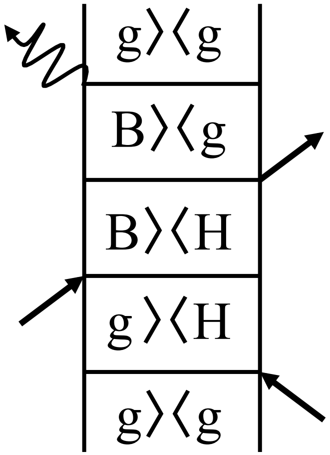


|g⟩⟨H| dephasing

- Rapid |g⟩⟨H| dephasing (t_1) ➔ Large E_H fluctuations.
- Slow |B⟩⟨H| dephasing (t_2) ➔ Smaller E_H-E_B energy gap fluctuations.
- Energy fluctuations on B and H are highly correlated.
- Evidence for correlated protein environments!

H. Lee, Y.-C. Cheng, G.R. Fleming, *Science* **316**, 1462 (2007).

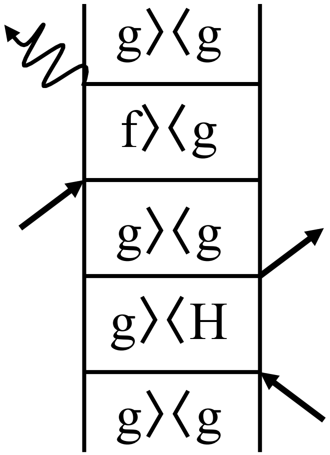
Theoretical Modeling



Impulsive response function formalism.
BPhy-BChl electronic coupling ~ 220 cm^{-1}.
Transition energy fluctuations on Bphy/BChl:

$$C_{BPhy}(t) = \lambda_{BPhy} \exp(-t^2 / \tau_0^2) + \Delta_0^2,$$

$$C_{BChl}(t) = \lambda_{BChl} \exp(-t^2 / \tau_0^2) + \Delta_0^2.$$

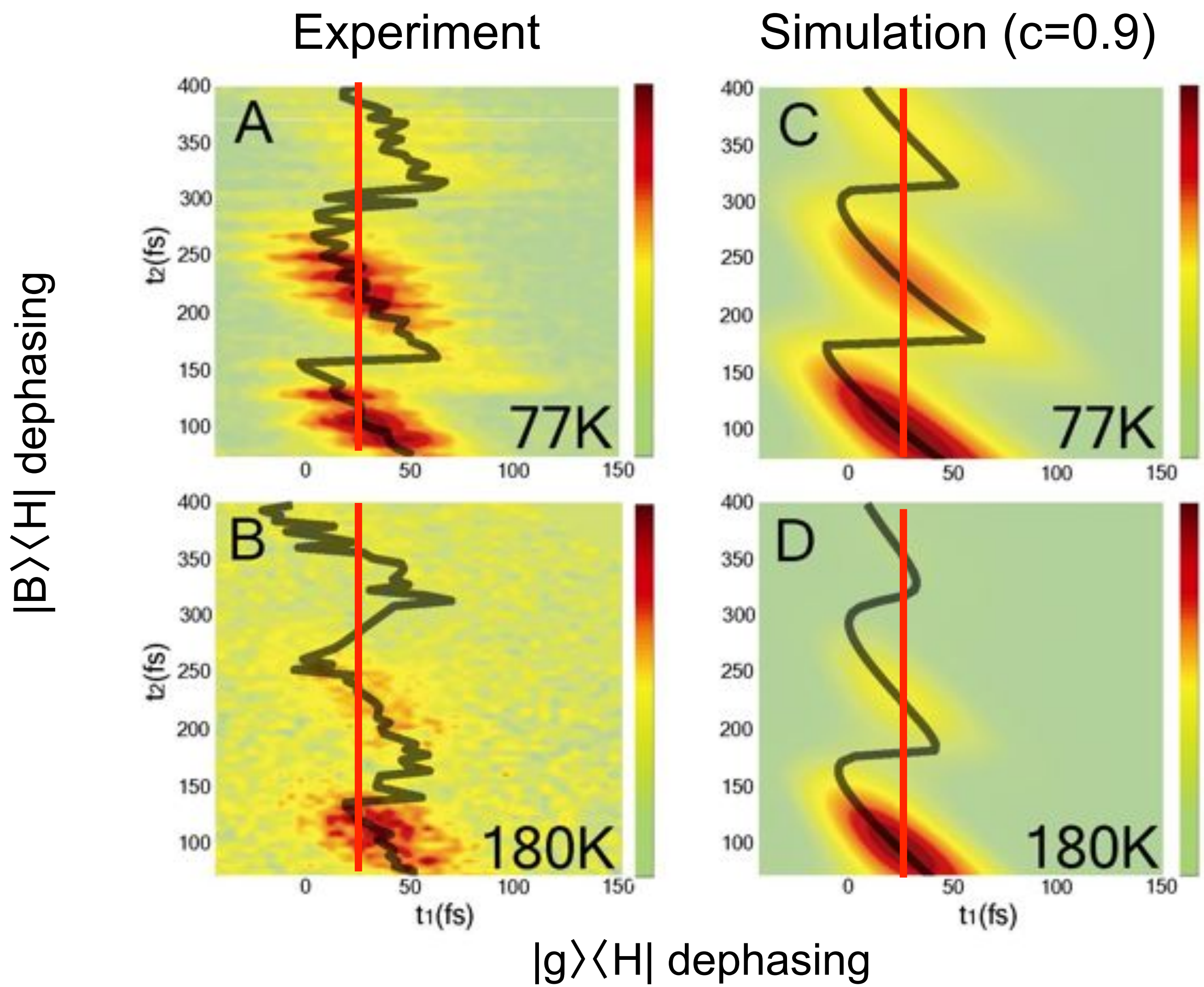


Cross-correlation between BPhy and BChl fluctuations (described by c):

$$C_{hb}(t) = \lambda_{hb} \exp(-t^2 / \tau_0^2) + \Delta_0^2; \ \lambda_{hb} = c\sqrt{\lambda_h \lambda_b}\,.$$

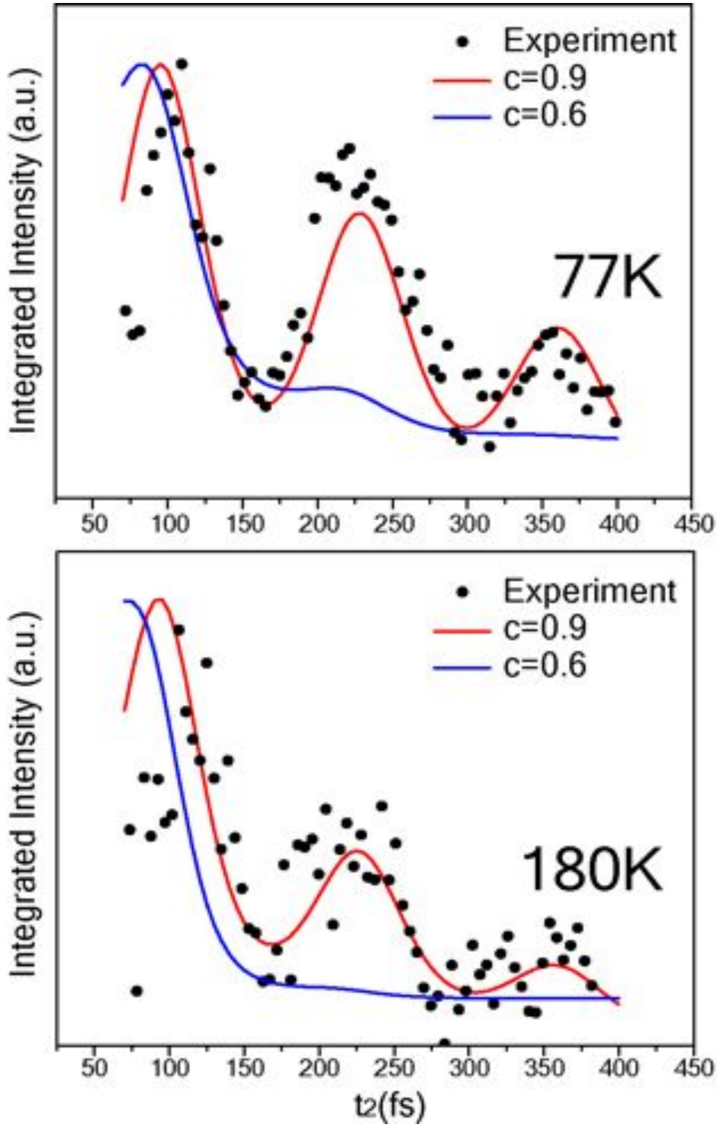
250 cm^{-1} vibrational mode coupled to BPhy (sawtooth pattern).

Experiment vs. Theory



H. Lee, Y.-C. Cheng, G.R. Fleming, *Science* **316**, 1462 (2007).

Protein Protection of Electronic Coherence



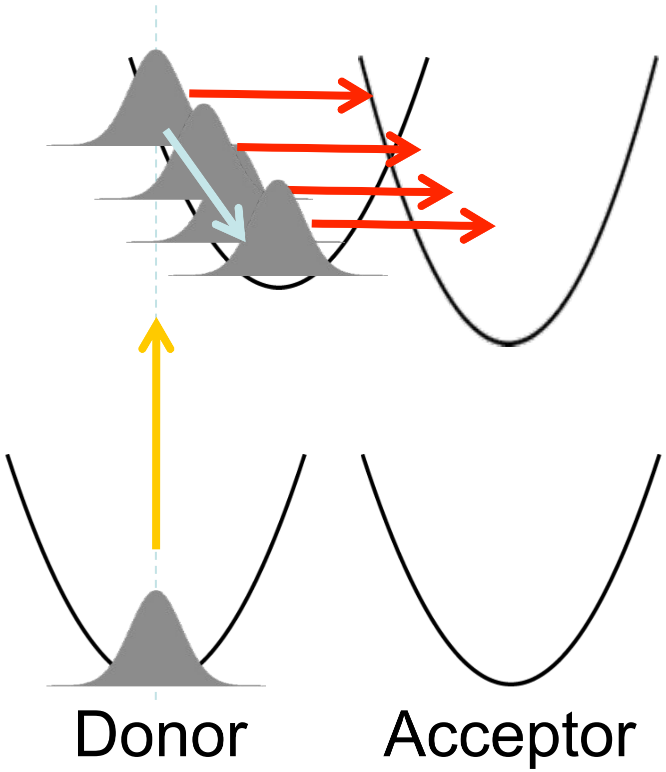
- Electronic coupling alone (c=0.6) cannot explain the long dephasing time
- Strong cross-correlations (c~0.9) between protein environments responsible for long-lived |B⟩⟨H| coherence
- ➔ "*Protein protection of excitonic coherence*"

|B⟩⟨H| dephasing times: $t_{g,77K}$ =440fs, $t_{g,180K}$=310fs

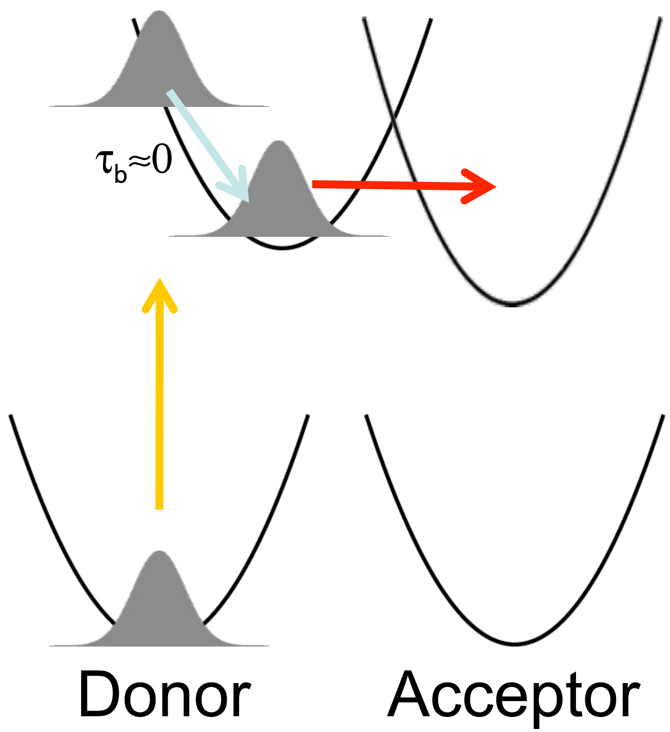
Non-equilibrium Effects in Excitation Energy transfer

- Non-equilibrium effects could be important in ultrafast dynamics
- Conventional theories assume that baths are always in equilibrium ➔ over-estimate of coherence dephasing rate!

Photon-induced dynamics

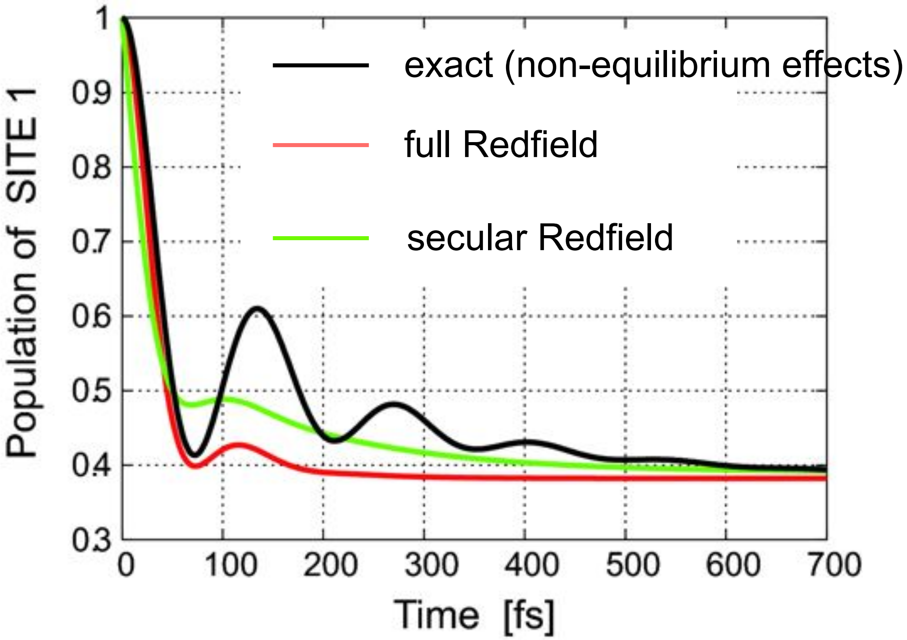


Redfield/Forster picture



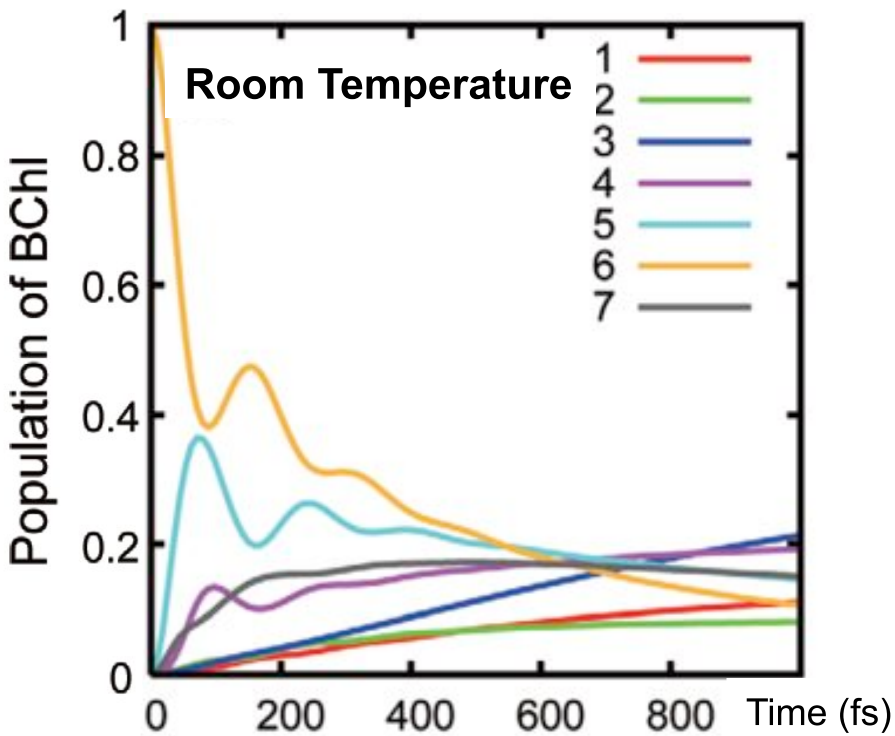
Non-equilibrium Effects Lead to Longer Decoherence Time

- Calculations based on new theoretical formalism including non-equilibrium bath effects show longer decoherence time
- New theory predicts quantum coherence lasting in the FMO complex at physiological temperature (Ishizaki &Fleming, PNAS 2000)

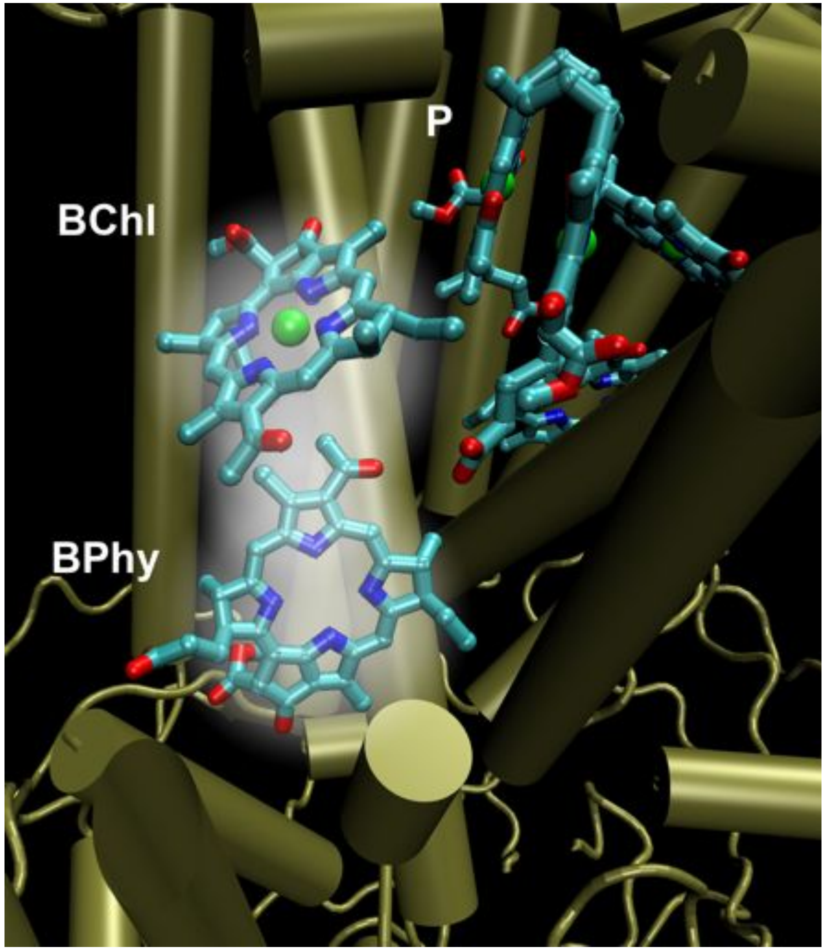


Benchmark calculations on a spin-boson model.
Ishizaki &Fleming, JCP 2009.

Coherent EET Dynamics the FMO



Concluding Remarks



Pigments and proteins in the reaction center of a purple bacteria

- Energy transfer through quantum coherence has been revealed in photosynthesis
- Coherent dynamics may promote energy trapping in light harvesting
- Correlations in protein dynamics & non-equilibrium bath effects contribute to the preservation of coherence
- High-performance computing crucial for studies of quantum dynamics, spectra, molecular quantum chemistry, protein dynamics, complex organization …etc.

Acknowledgements

- Graham Fleming (UC Berkeley)
- Seogjoo Jang (Queens College, CUNY)
- The Fleming Group (UC Berkeley)

- National Science Council of Taiwan

Thank You!

Propagating Dynamics with Bath Memory

- We use a time-nonlocal approach to retain memory effects:

$$\frac{d}{dt}\rho(t) = -i[H_e + H_{\text{int}}(t), \rho(t)] - \int_0^t K(t,\tau)\rho(\tau)d\tau$$

- Important for the description of peak shape
- $K(t,\tau)$ 🡐 memory kernel, can be calculated from $\Omega(\omega)$ using perturbation theory
- Decompose $K(t,\tau)$ into exponentials to facilitate efficient propagation of time-nonlocal dynamics

Meier & Tannor, *J. Chem. Phys.* **111**, 3365 (1999); Cheng, Lee & Fleming, JPCA (2007).

Propagating Dynamics with Bath Memory

- Redfield theory ➔ does not describe full $\langle \delta\omega(t)\delta\omega(0) \rangle$

$$\frac{d}{dt}\rho(t) = -i[H_e + H_{\text{int}}(t), \rho(t)] - \Re(t) \cdot \rho(t)$$

- We use a time-nonlocal approach to retain memory effects:

$$\frac{d}{dt}\rho(t) = -i[H_e + H_{\text{int}}(t), \rho(t)] - \int_0^t K(t,\tau)\rho(\tau)d\tau$$

- $K(t,\tau)$ 🡐 memory kernel, can be calculated from C(t) using perturbation theory

Meier & Tannor, *J. Chem. Phys.* **111**, 3365 (1999); Cheng, Lee & Fleming, JPCA (2007).

Theoretical Background

Photosynthetic Excitons & Quantum Dynamics

Exciton Hamiltonian and Excitonic Coupling

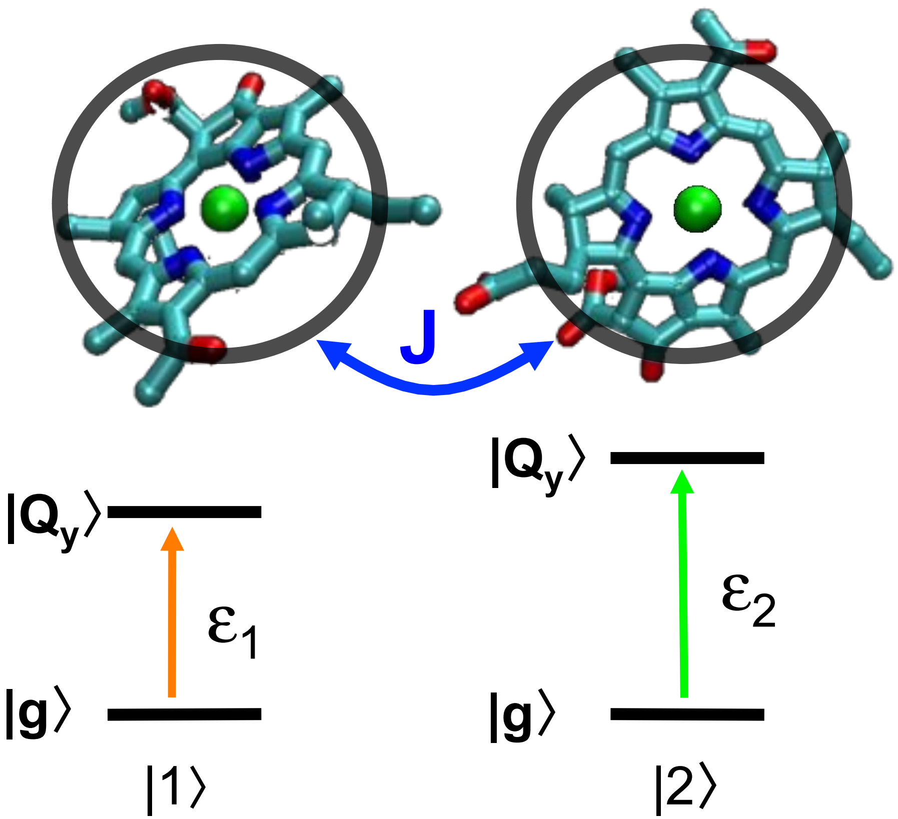
• Excitations interact with each other through excitonic coupling J

• H_e ➔ transition energies and excitonic couplings in multichromophoric systems!!

site energy   coupling

$$H_e = \begin{bmatrix} \varepsilon_1 & J_{12} & \dots & J_{1N} \\ J_{12} & \varepsilon_2 & \dots & J_{2N} \\ \vdots & \vdots & & \vdots \\ J_{1N} & J_{2N} & \dots & \varepsilon_N \end{bmatrix}$$

"site basis"

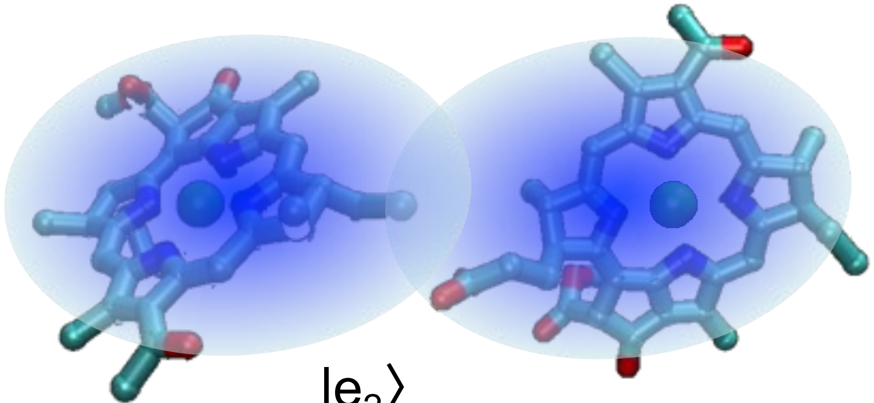


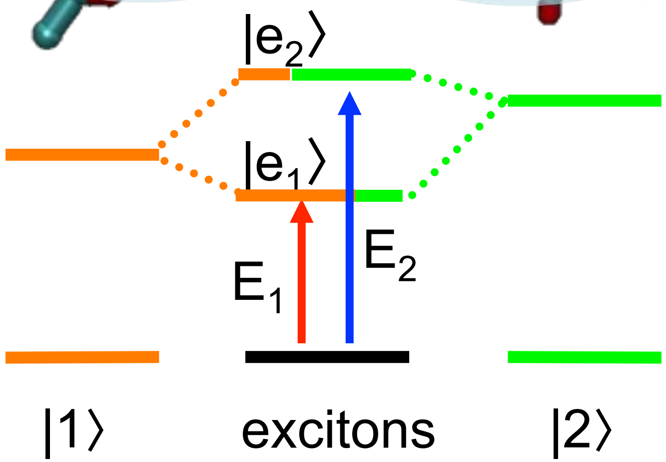
• Excitation energy transfer induced by excitonic coupling J

• When J is significant, the eigenstates of H_e has to be considered ➔ excitons

Excitonic Coupling and Photosynthetic Excitons

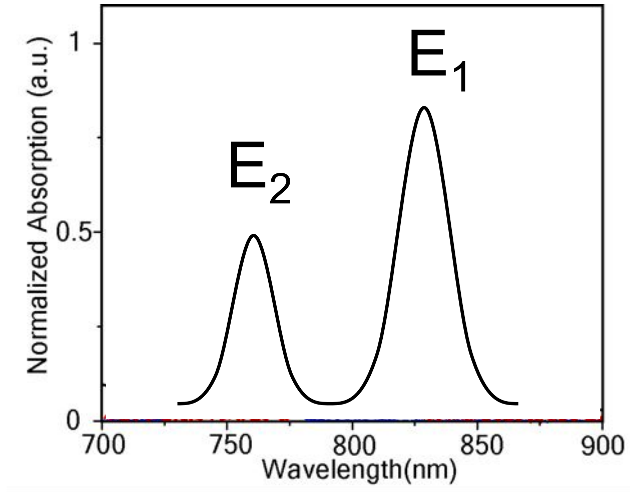
- Excitonic coupling J can result in delocalized excitations ➔ excitons
- Optical transitions correspond to excitonic transitions



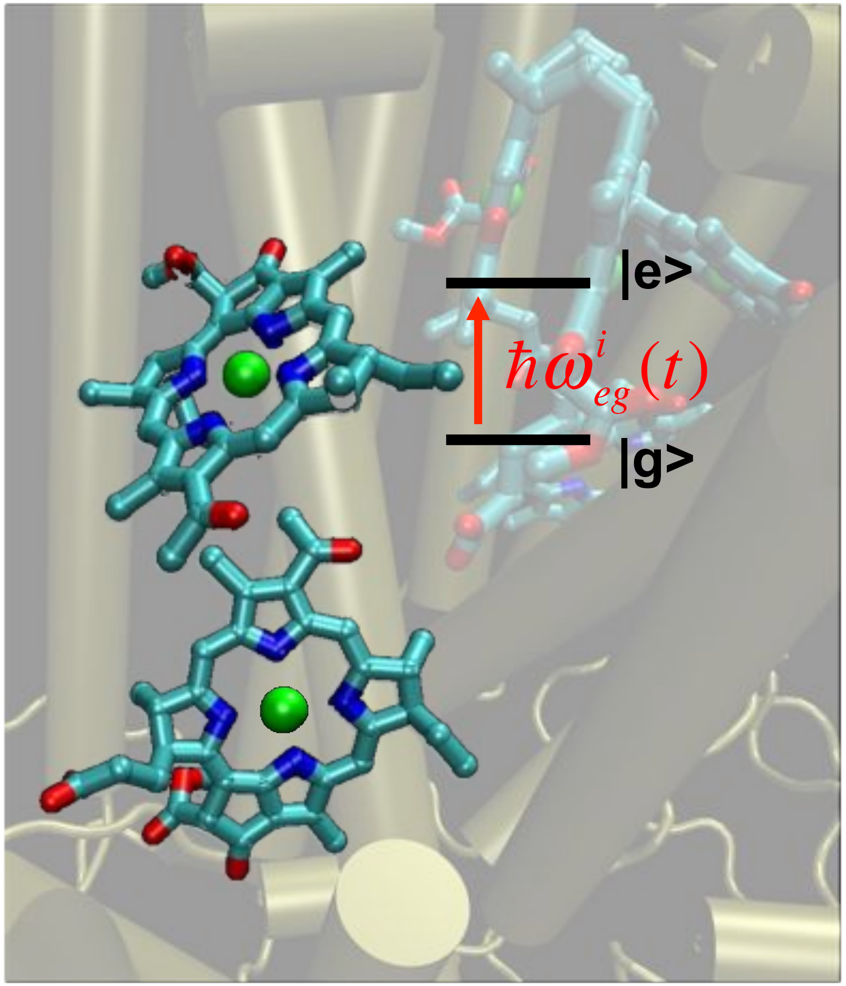


$$H_e = \begin{bmatrix} E_1 & 0 & \cdots & 0 \\ 0 & E_2 & \cdots & 0 \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \cdots & E_N \end{bmatrix}$$

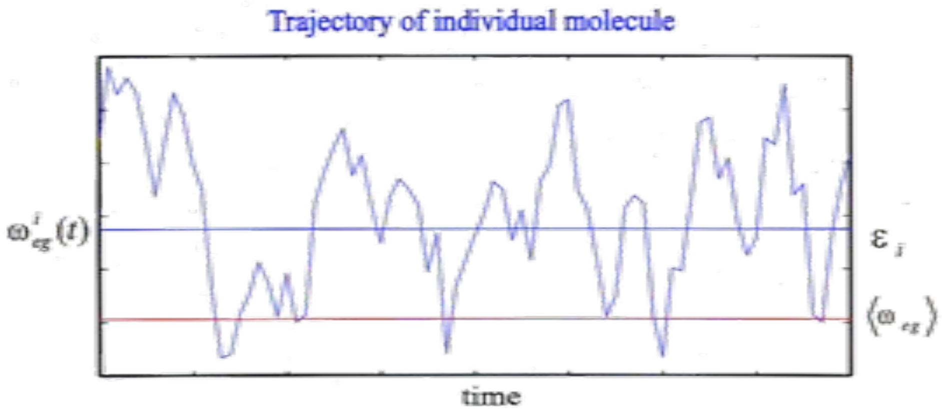
"exciton basis"



Dynamics in the Condensed Phase



Energy of an individual chromophore *i* modulated by its protein environment:



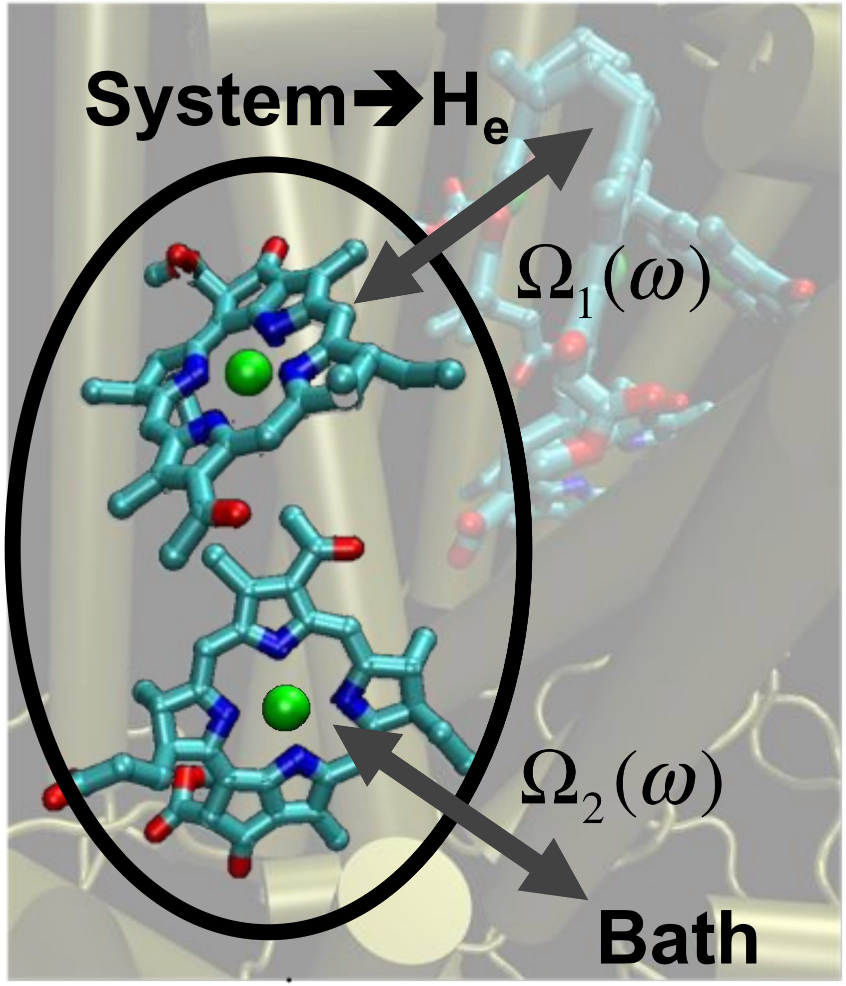
$$\omega^i_{eg}(t) = \langle\omega_{eg}\rangle + \delta\omega_i(t) + \varepsilon_i$$

$\delta\omega_i(t)$ ➔ fast, dynamical changes

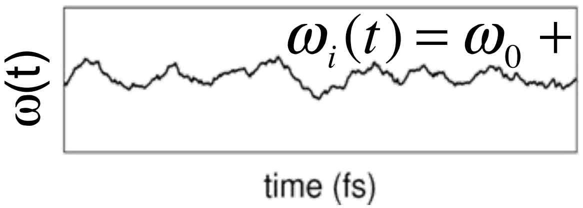
ε_i ➔ slow, static changes

f(ε_i): inhomogeneous broadening

Modeling Excitation Energy Transfer: System-Bath Model



$$\omega_i(t) = \omega_0 + \delta\omega_i(t) + \varepsilon_i$$



- Environments (baths)
  ➔ harmonic oscillators
- System-bath couplings
  ➔ correlation function:

$$C(t) = \langle \delta\omega(t)\delta\omega(0) \rangle$$

or spectral densities:

$$\Omega(\omega) = \sum_{\alpha} \frac{c_{\alpha}^{2}}{2m_{\alpha}\omega_{\alpha}} \delta(\omega - \omega_{\alpha})$$

- Reduced density matrix:

$$\rho = \sum_{n} P_n |\psi_n\rangle\langle\psi_n|$$

➔ H_e and Ω(ω) determine the dynamics, ρ(t).

Redfield Picture of Excitation Energy Transfer

When system-bath coupling is weak, we can use Redfield equation to describe energy transfer:

exciton Hamiltonian

dissipation determined by $\Omega(\omega)$

$$\partial_t \rho(t) = -i[H_e, \rho(t)] - \Re[\rho(t)]$$

population

coherence

$$\rho = \begin{bmatrix} \rho_{11} & \rho_{12} & \cdots & \rho_{1N} \\ \rho_{12} & \rho_{22} & \cdots & \rho_{2N} \\ \vdots & \vdots & & \vdots \\ \rho_{1N} & \rho_{2N} & \cdots & \rho_{NN} \end{bmatrix}$$

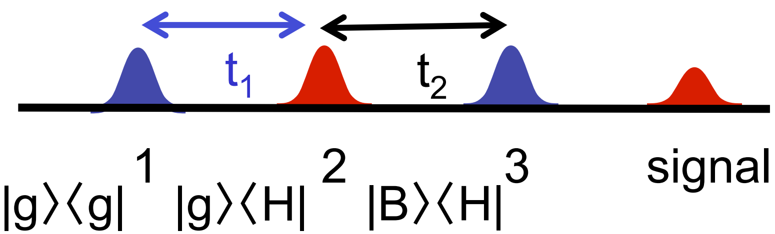
ρ: reduced-system density matrix

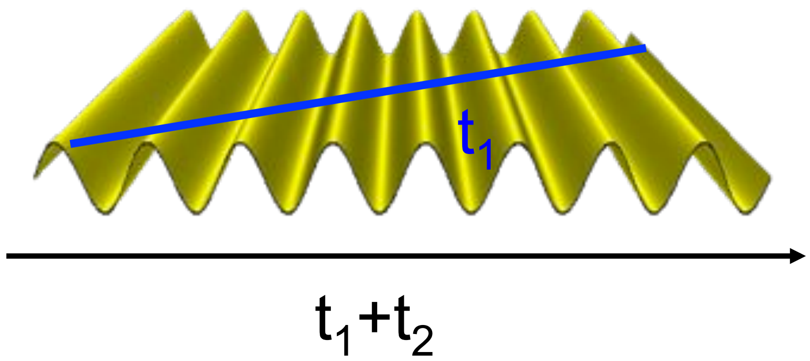
N: number of chromophores

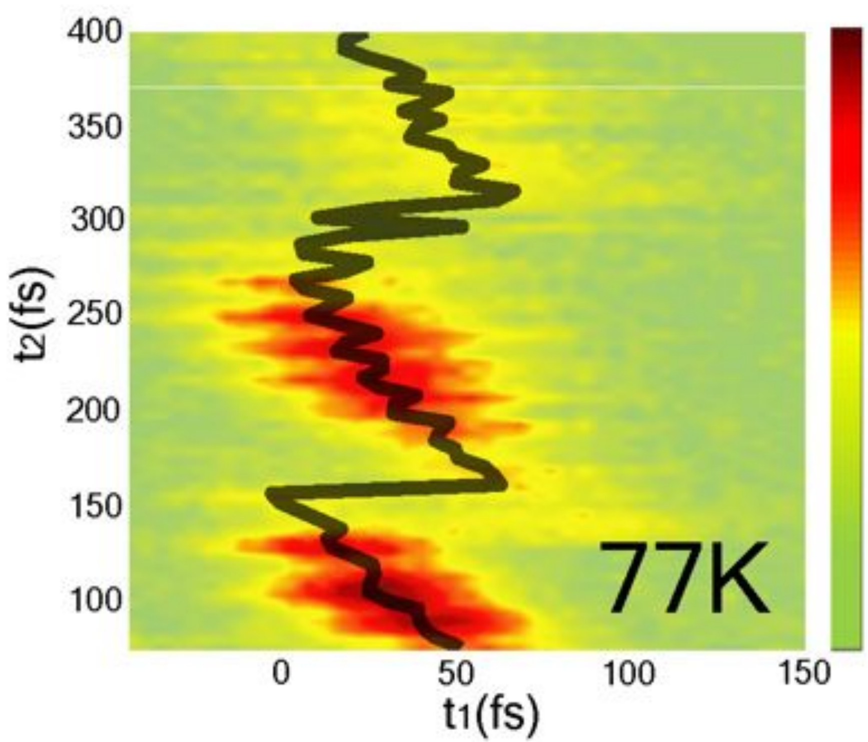
$$\Re[\,]: \quad \begin{array}{l} \rho_{nn} \to \rho_{mm} : \text{ population dynamics (incoherent)} \\ \rho_{nm} \to \rho_{n'm'} : \text{ coherence dynamics} \end{array}$$

Sawtooth Pattern from Vibrational Coherence

Vibrational coherence induced by pulse 1 explains the sawtooth pattern:



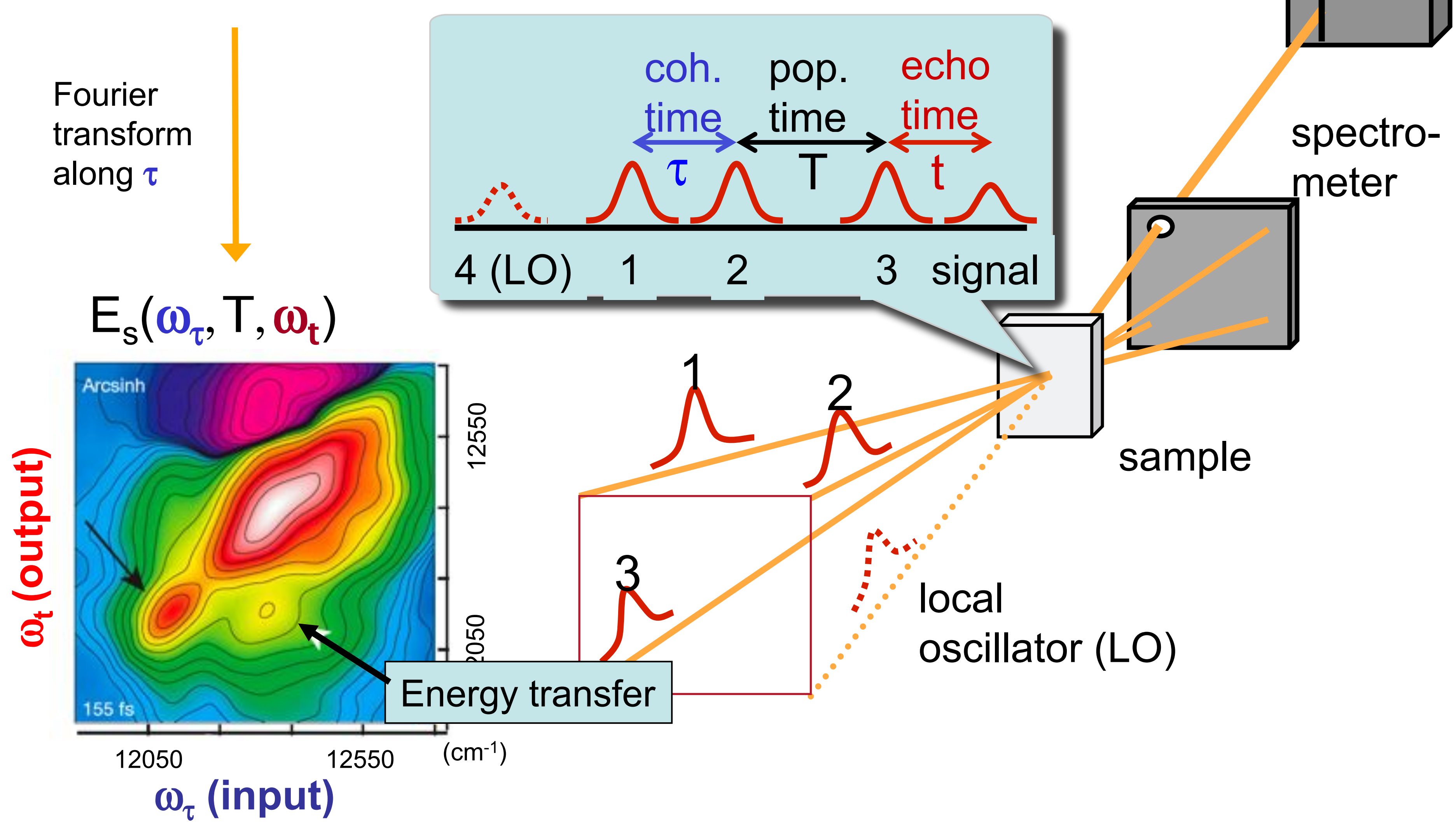




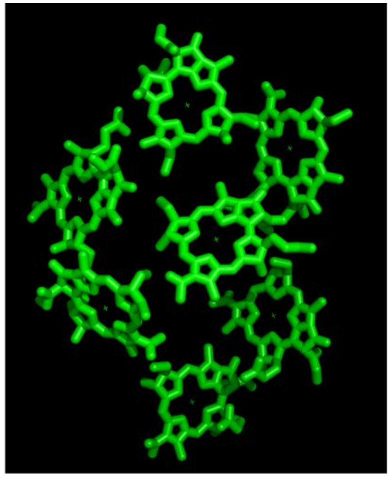
A non-orthogonal cut (t_1) leads to the sawtooth pattern

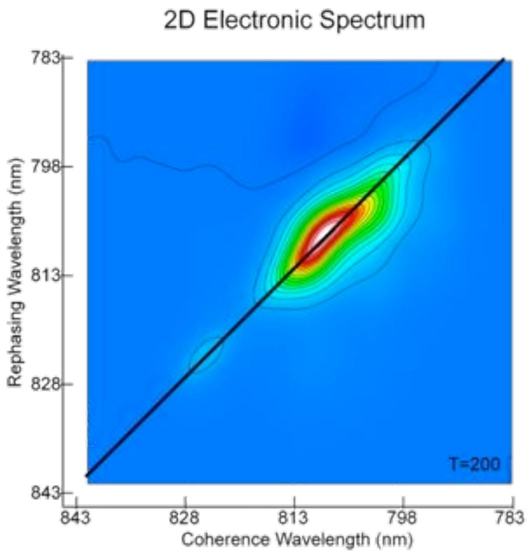
Two-dimensional Electronic Spectroscopy

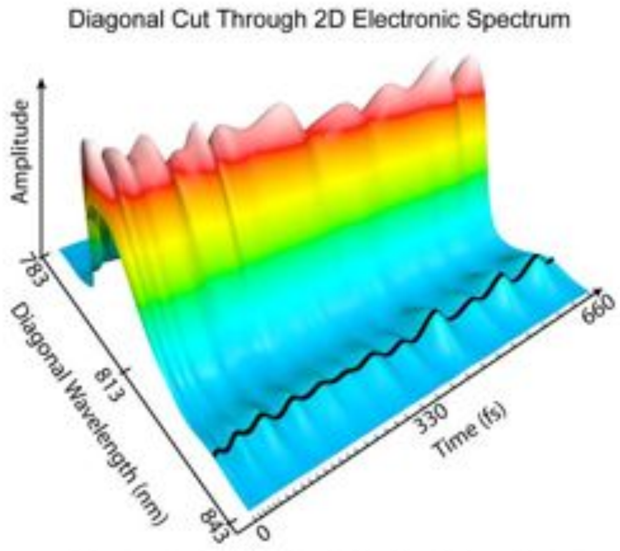
$$E_s(\tau, T, \omega_t) \quad \sim \quad iP^{(3)}(\tau, T, \omega_t)$$



Electronic Coherence in FMO (77K)





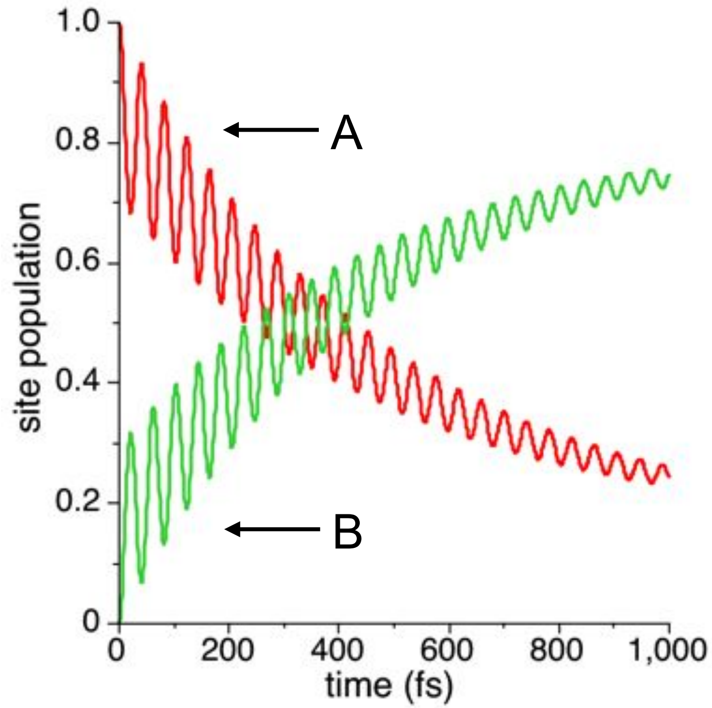


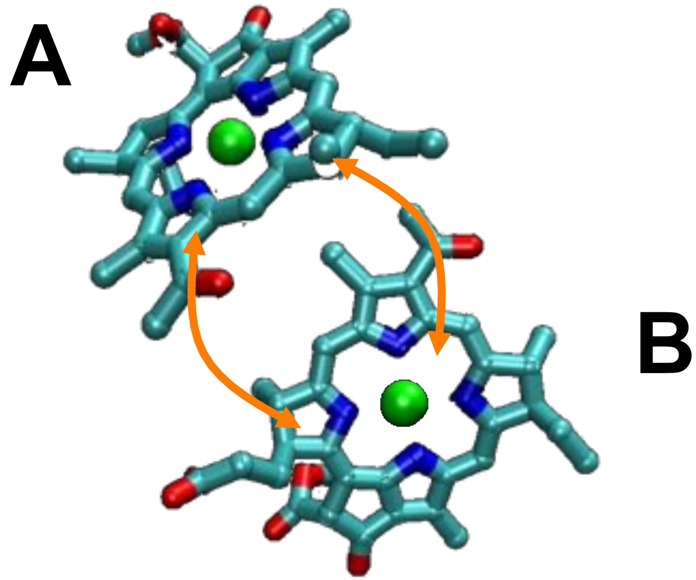
- 2D electronic spectra show quantum beats on the diagonal cuts
- Strong evidence for long-lasting excitonic coherence (> 600 fs) in the Fenna-Matthews-Olson Complex
  ➔ coherent wavelike energy transfer
- True electronic quantum effect may play a role in energy transfer

G.S. Engel, T.R. Calhoun, E.L. Read, T. Ahn, T. Mancal, **Y.-C. Cheng**, R.E. Blankenship & G.R. Fleming, *Nature* **446**, 782 (2007)

Simple Model for Coherence Assisted Energy Trapping

Consider energy transfer within a dimer of two coherently coupled sites:



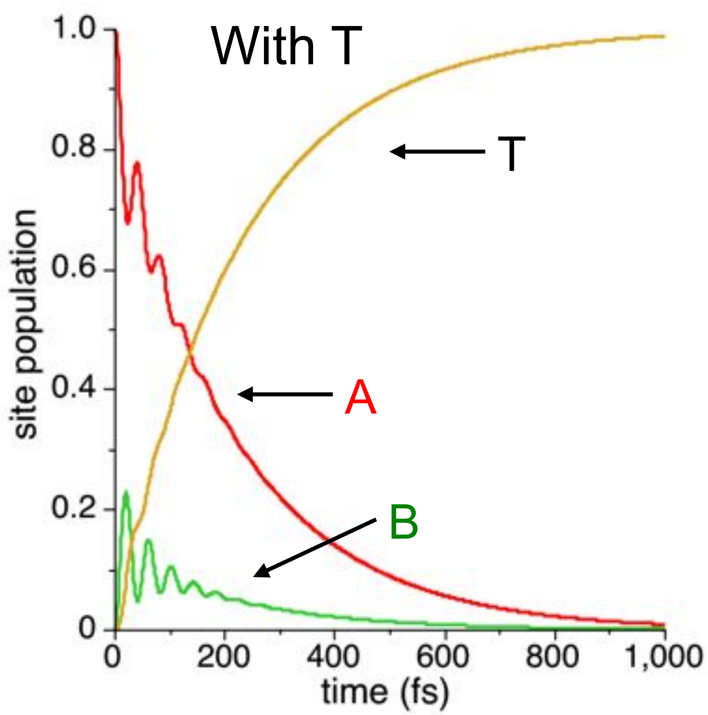


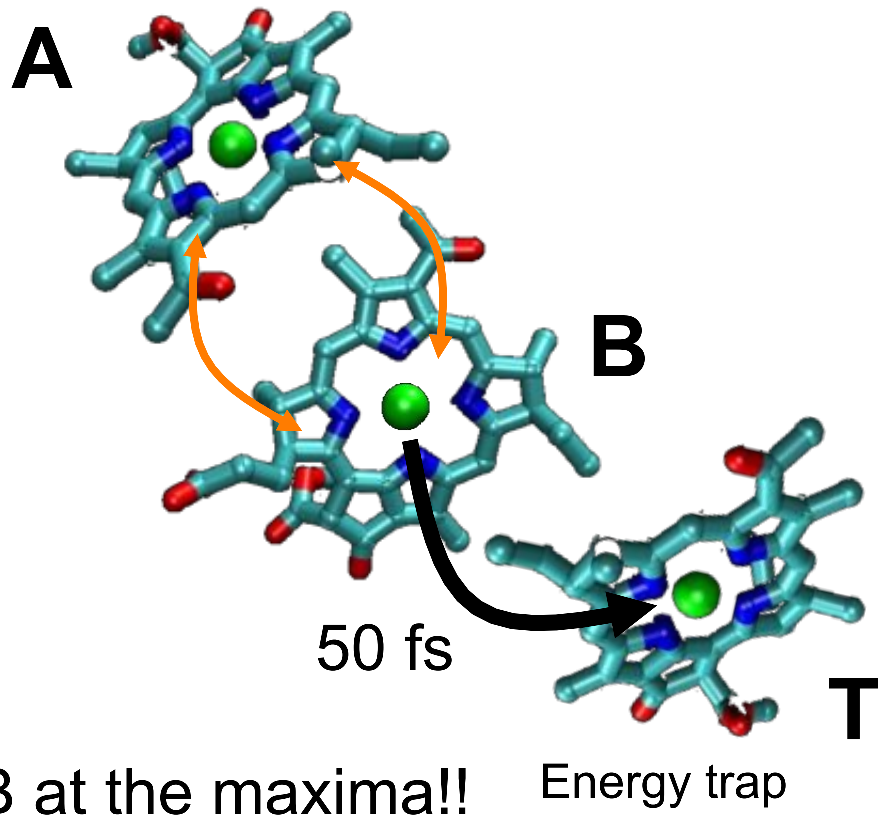
Effective A➔B time: 500 fs

Bloch dynamics using 450 fs A/B dephasing time, 500 fs intrinsic A➔B transfer time; actually modeled based on parameters suitable for a photosynthetic reaction center

Simple Model for Coherence Assisted Energy Trapping

Adding rapid trapping by T results in rapid A population decay
➔ only possible because of coherent oscillation



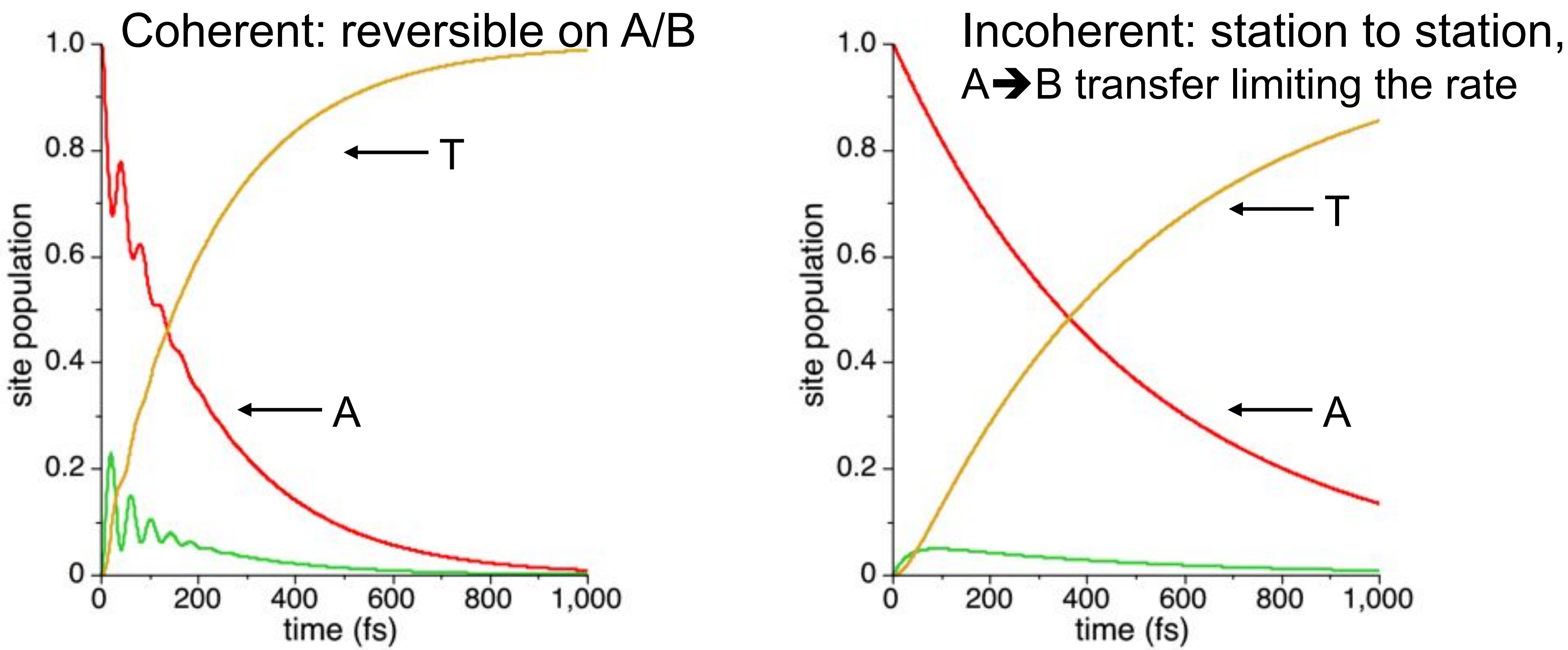


T efficiently captures energy on B at the maxima!!

450 fs A/B dephasing time, 500 fs A➔B transfer time, 50 fs B➔T time.

Simple Model for Coherence Assisted Energy Trapping

Quantum coherence promotes the efficiency of light capture



This model explains efficient excitation energy trapping in the photosynthetic reaction center of purple bacteria

Lee, Cheng & Fleming, UP2008