Unlocking the quantum design of photosynthesis for bio-inspired solar technologies

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NSTF Discussion Forum: Quantum Science and Technology, 19 Nov. 2025

105 billion tons per year

of biomass is produced by photosynthesis


= two great pyramids of Giza
per hour… every hour

~50% of global photosynthesis occurs in water

Photosynthesis: inspiration for solar tech

$CO_2 + H_2O + \text{photons} \rightarrow [CH_2O] + O_2$ (oxygenic photosynthesis)

cheap molecules + light → fuels

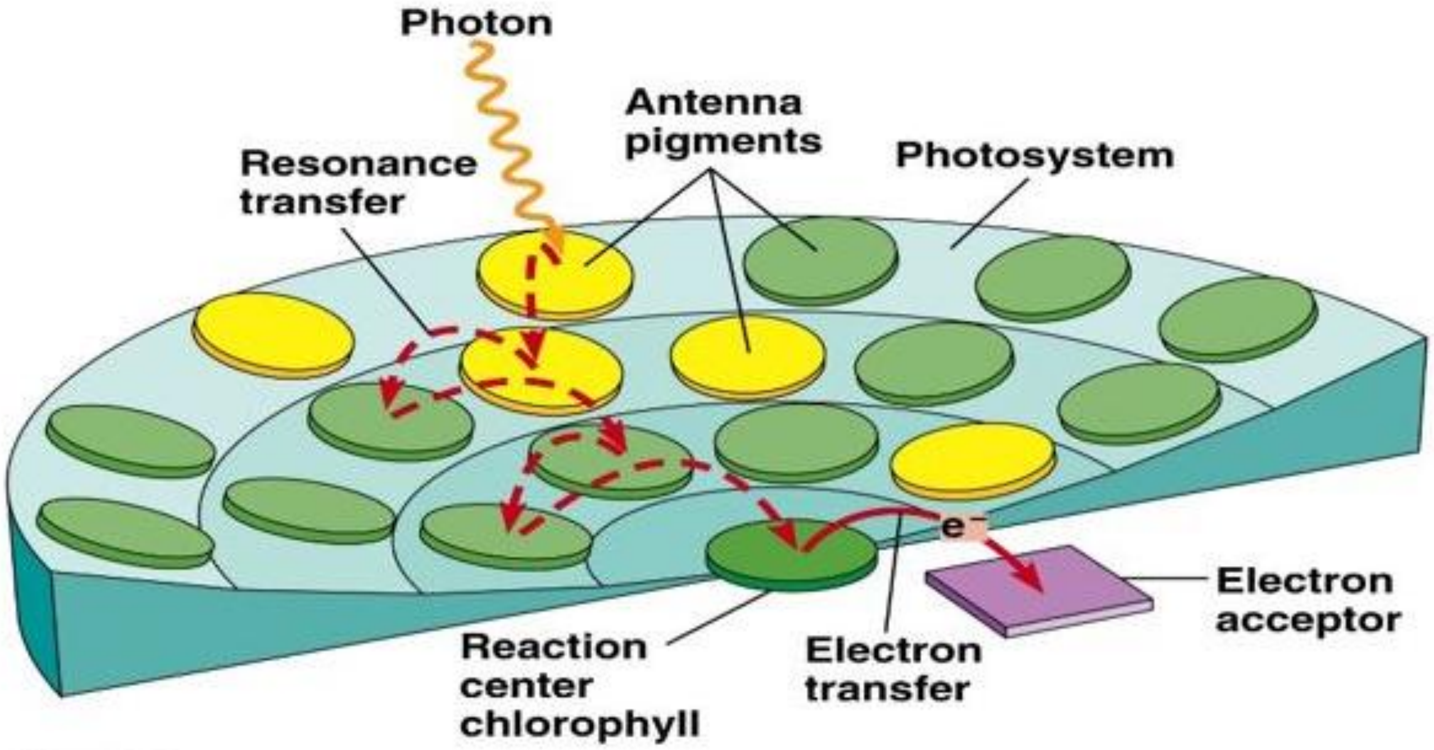
carbohydrates → liquid fuels

electrons → electricity

protons → H_2

NITheCS minischool on Energy Materials: https://www.youtube.com/watch?v=J7pb-yRV4zs

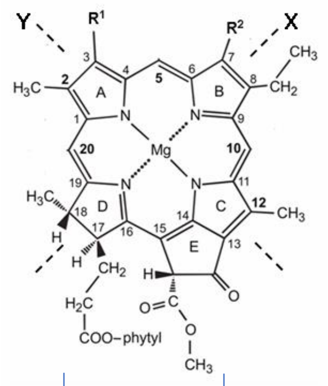
"Natural" solar cells



100% quantum efficiency

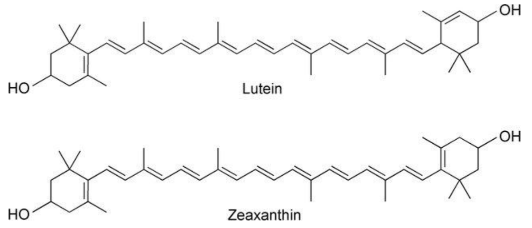
Design principle: high pigment density

Chlorophyll

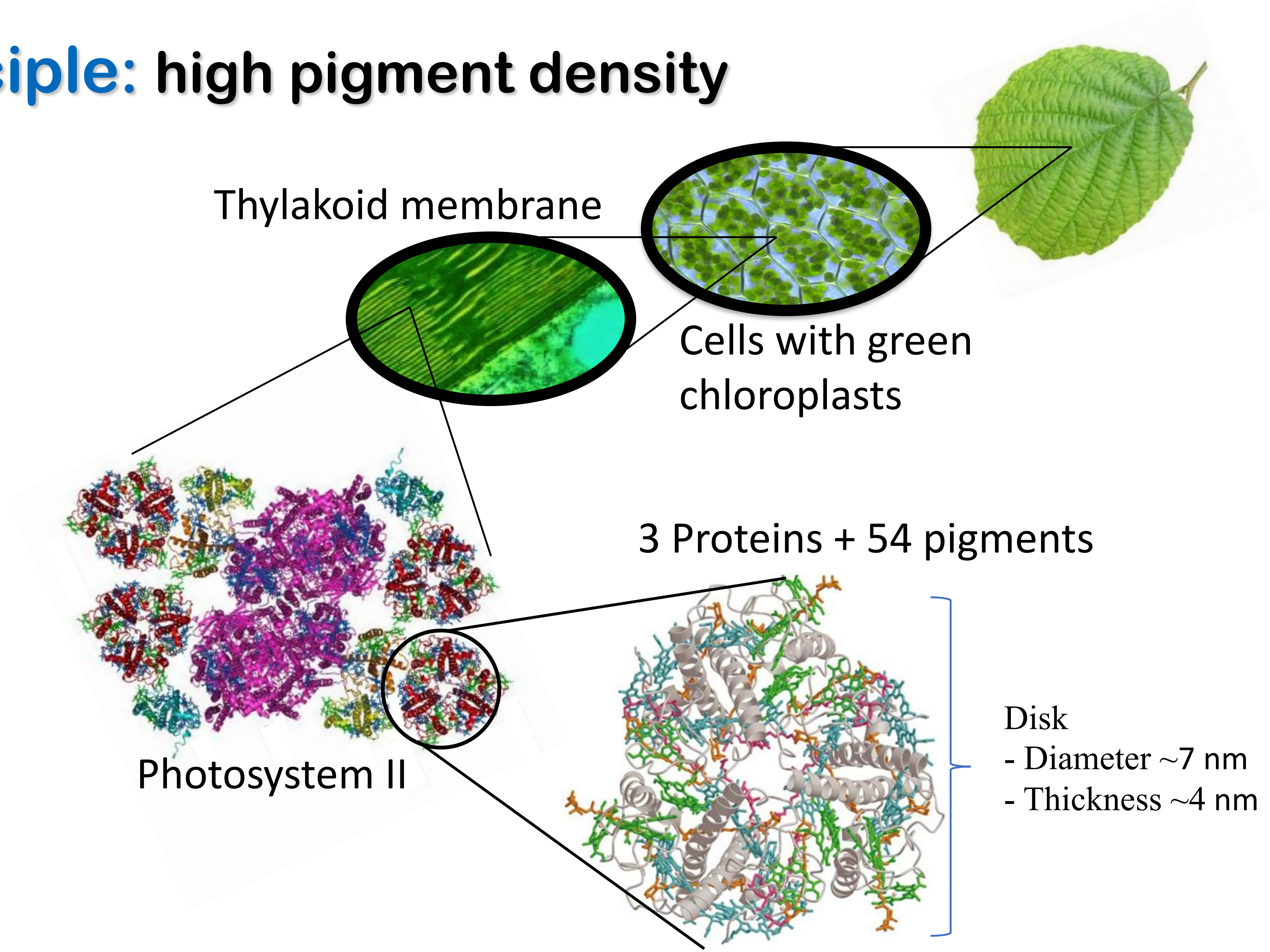


1 nm

Carotenoids



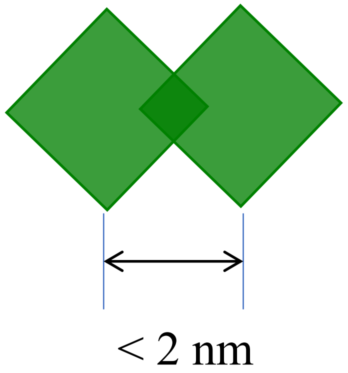
>3 nm



Molecular excitons: quantum coherence

$$\Psi_{1,2} = \frac{1}{\sqrt{2}}\left(\varphi_1^1\varphi_2^0 \pm \varphi_1^0\varphi_2^1\right)$$

The chlorophyll dimer



Physiological benefits:
1. Enhanced light absorption
2. Enhanced energy funnelling
3. Enhanced energy transfer: >10x
4. Less trapping and energy loss in antennas
5. Faster charge separation in reaction centres

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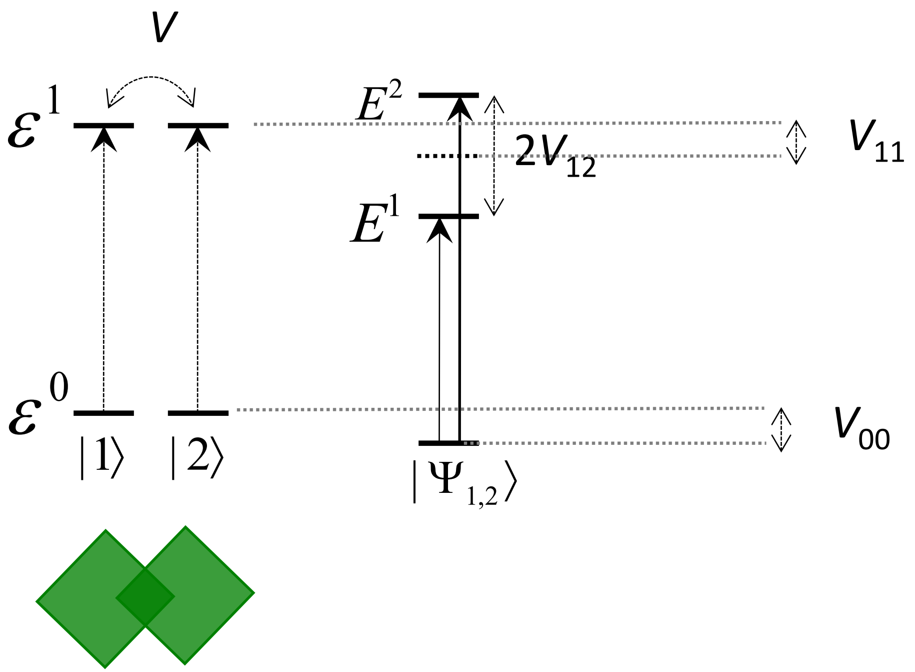

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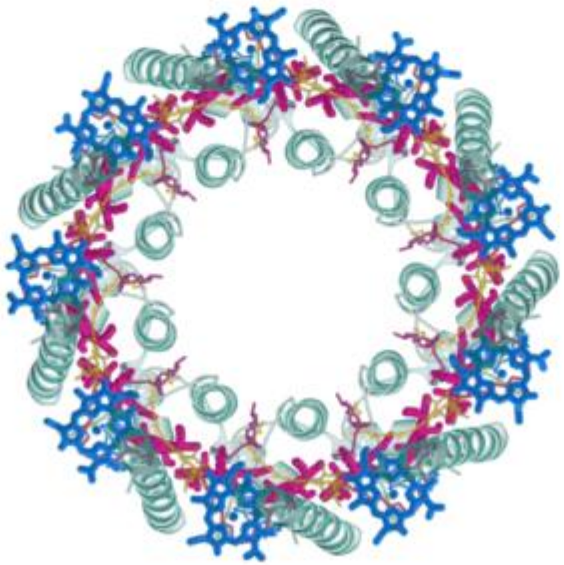
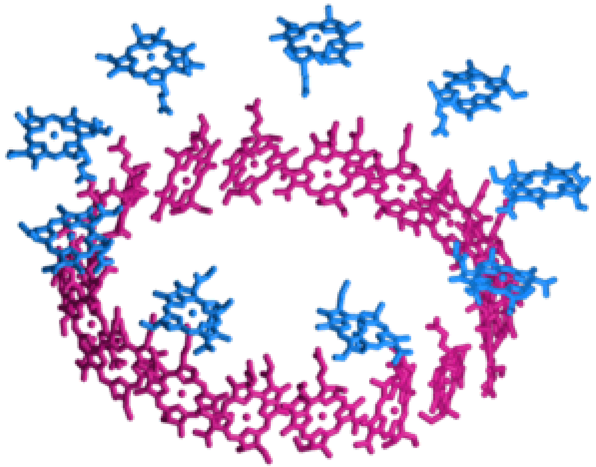
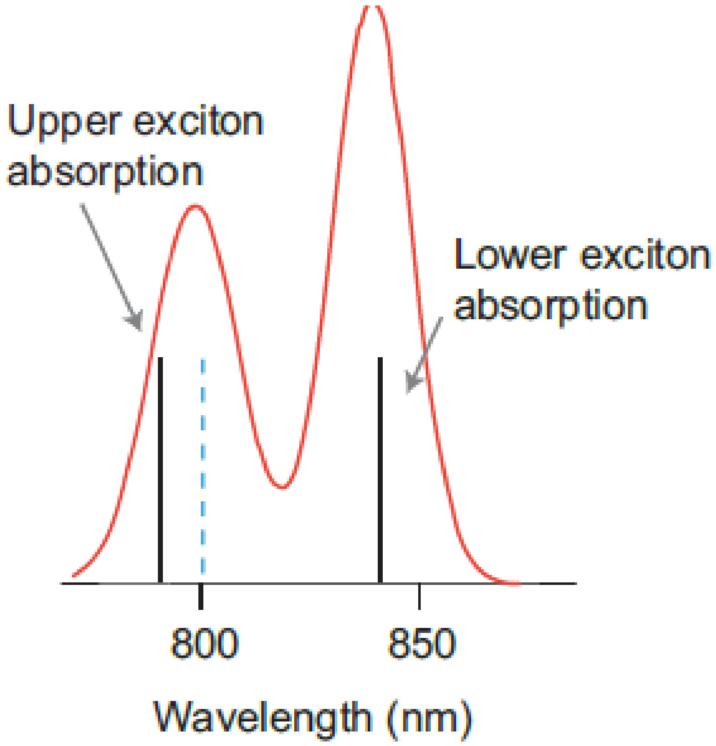
1. Electronic coherence “creates” pigments

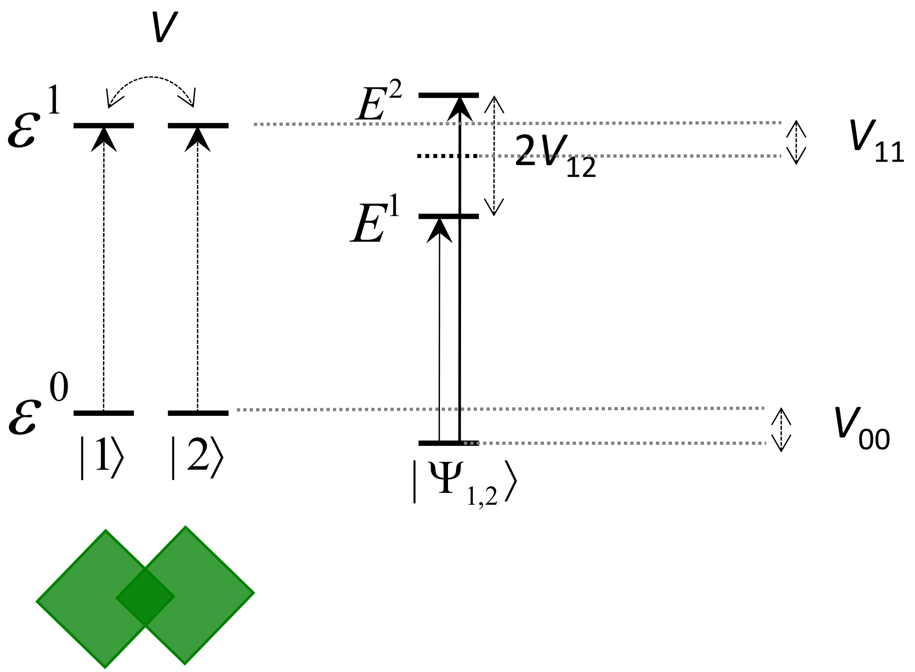






Purple bacteria

Molecular excitons: quantum coherence



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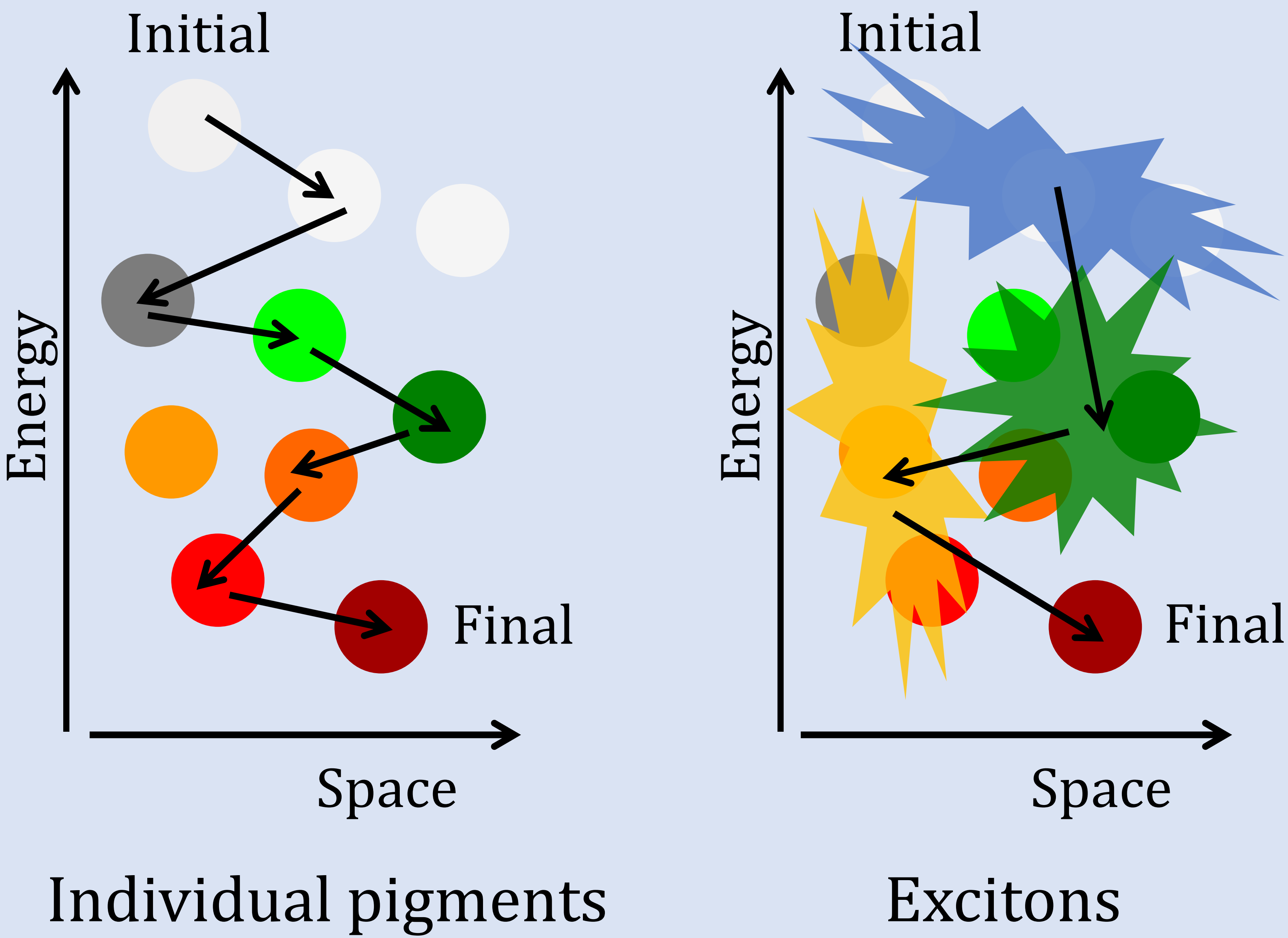
2. Molecular excitons enhance energy funnelling



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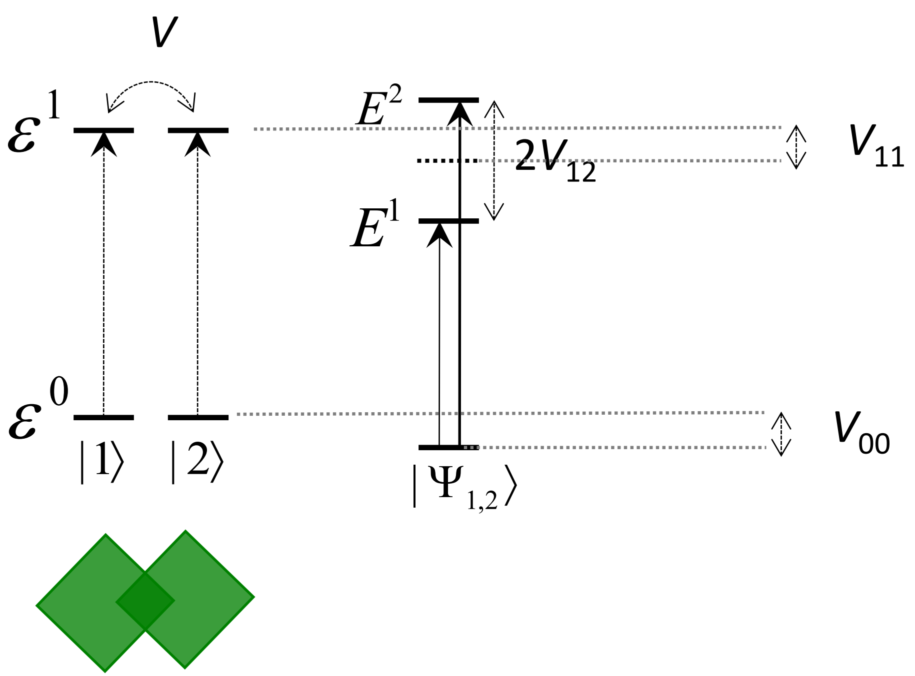

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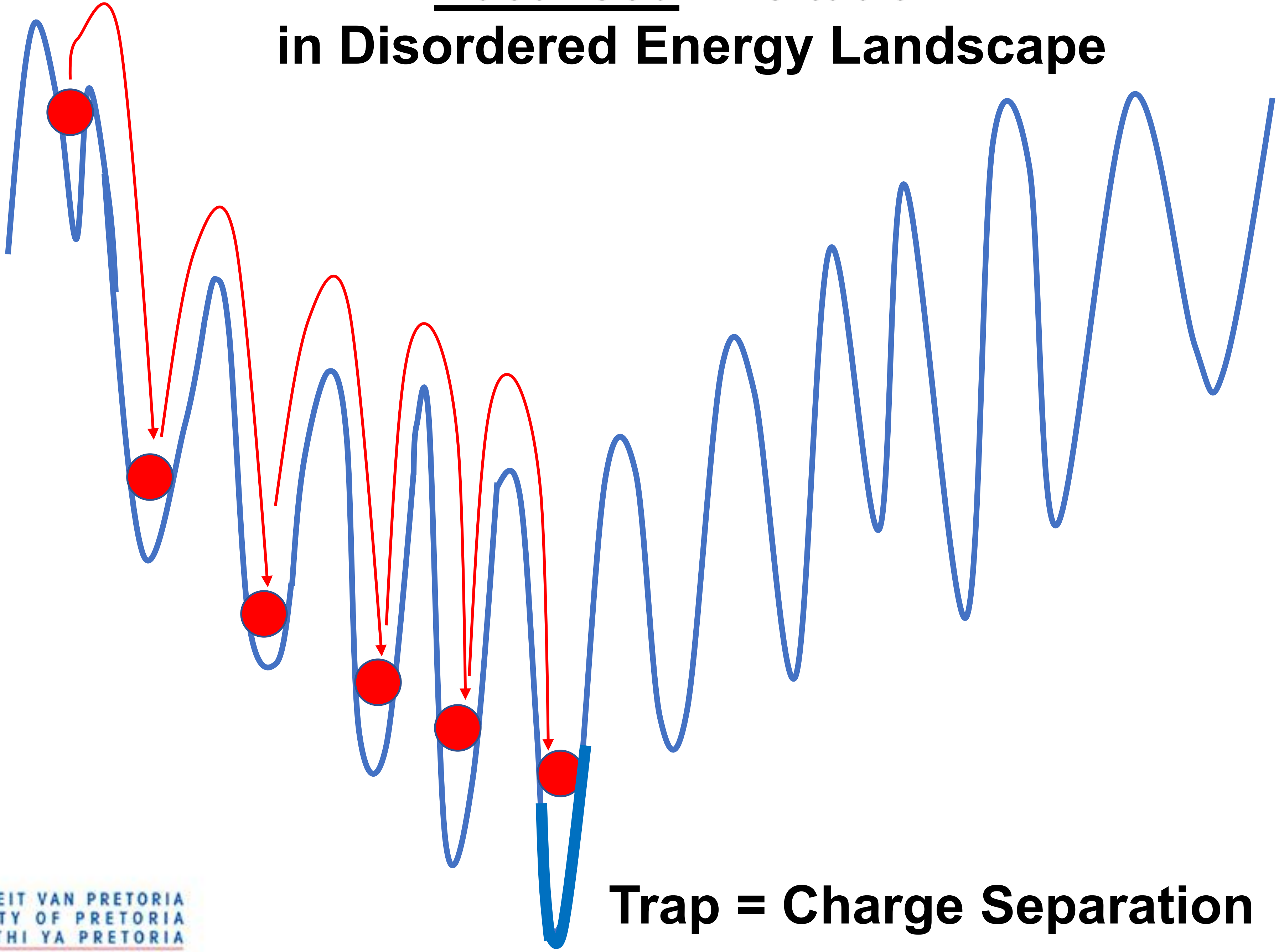
<u>Localised</u> Excitation in Disordered Energy Landscape



Trap = Charge Separation

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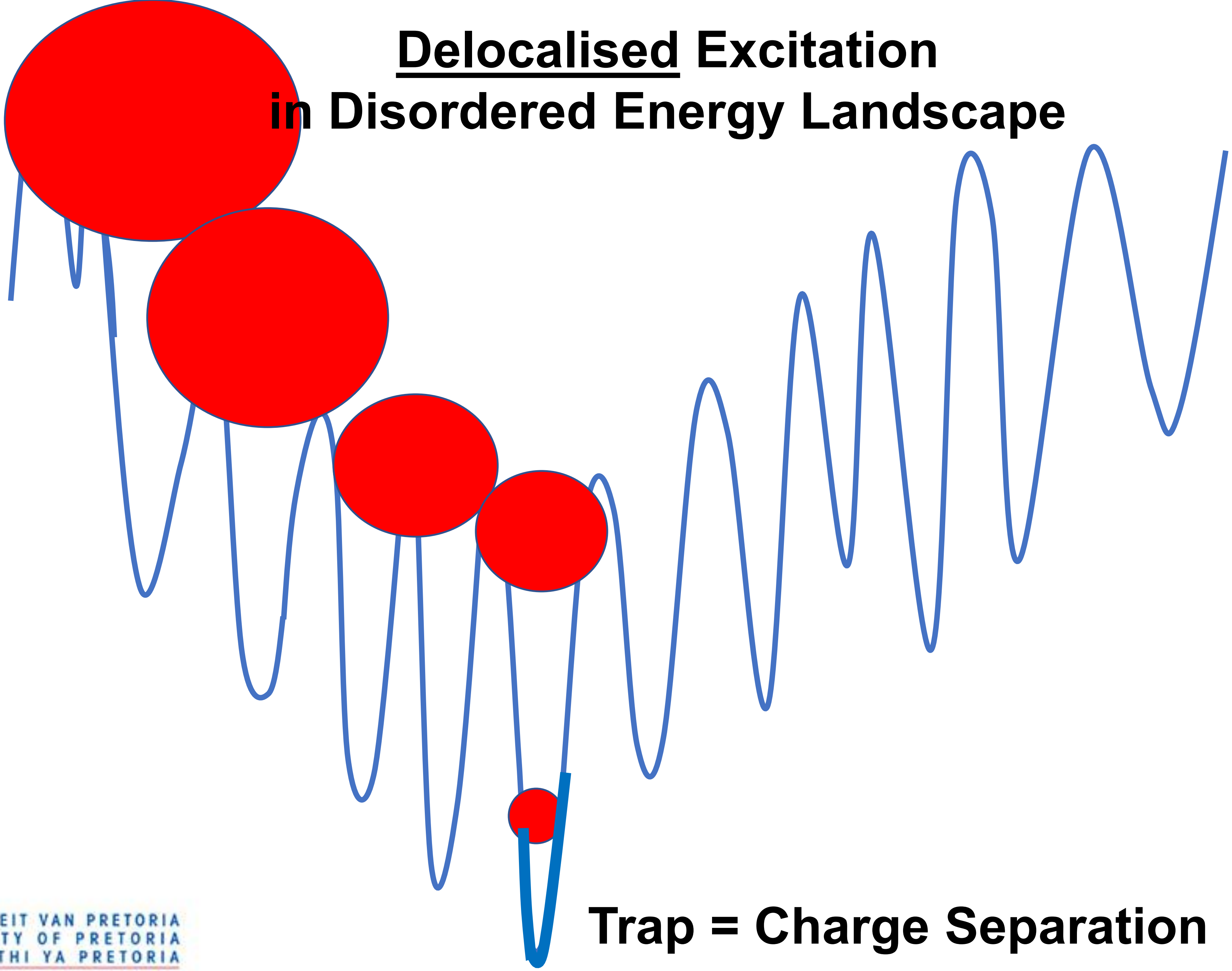
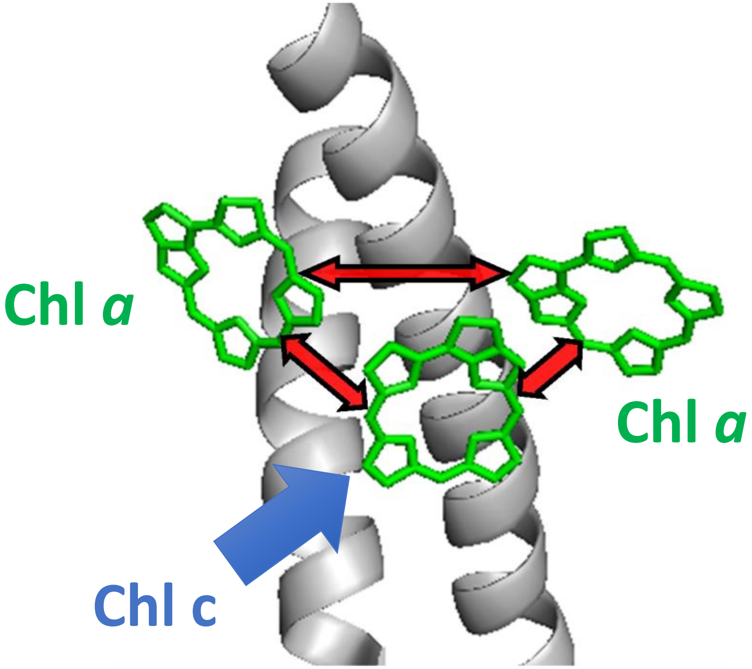
Delocalised Excitation in Disordered Energy Landscape



Trap = Charge Separation

Example: How diatoms tune their quantumness



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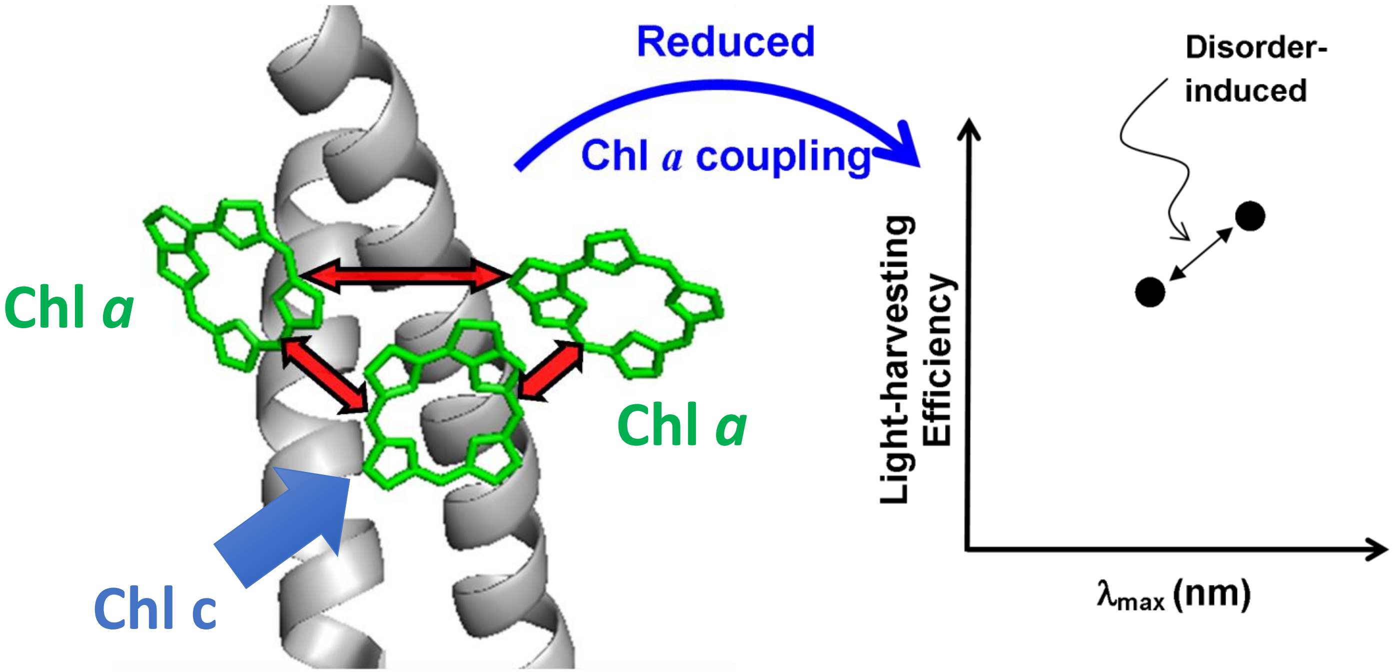

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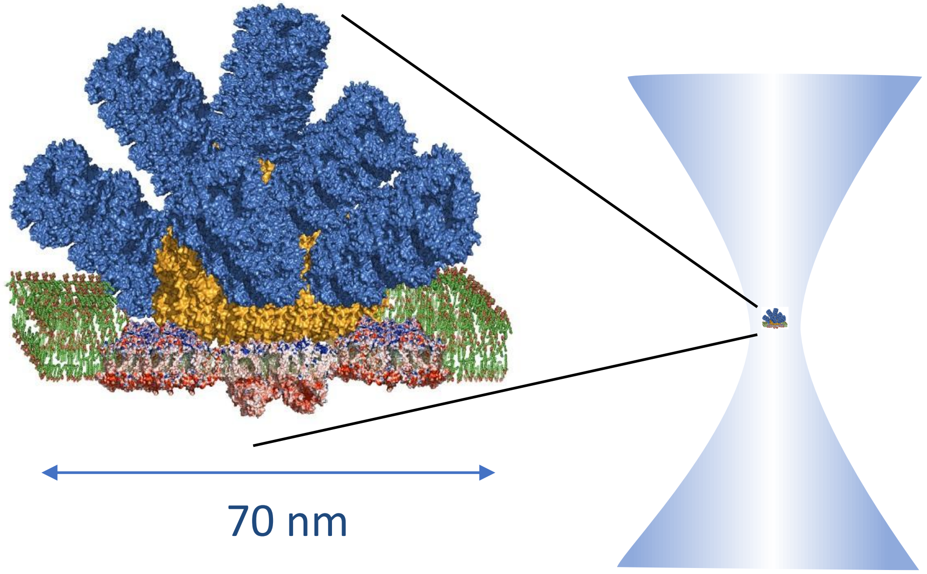
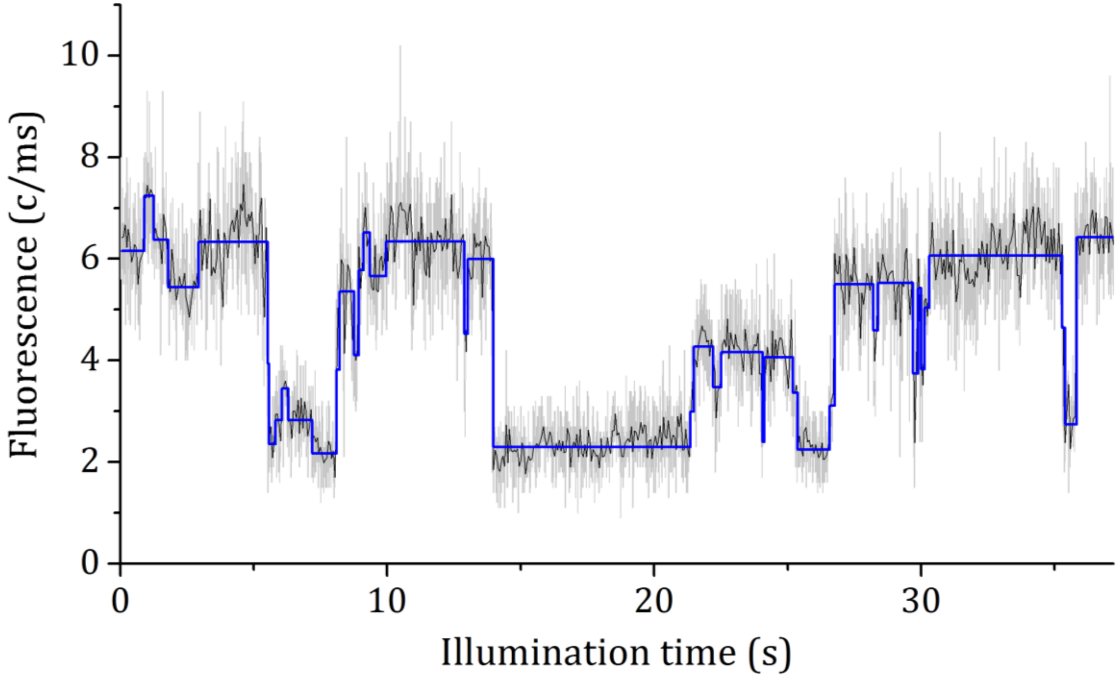
TPJ Krüger *et al.* *PNAS* 114: E11063-E11071 (2017)

Example: How cyanobacteria tune their quantumness

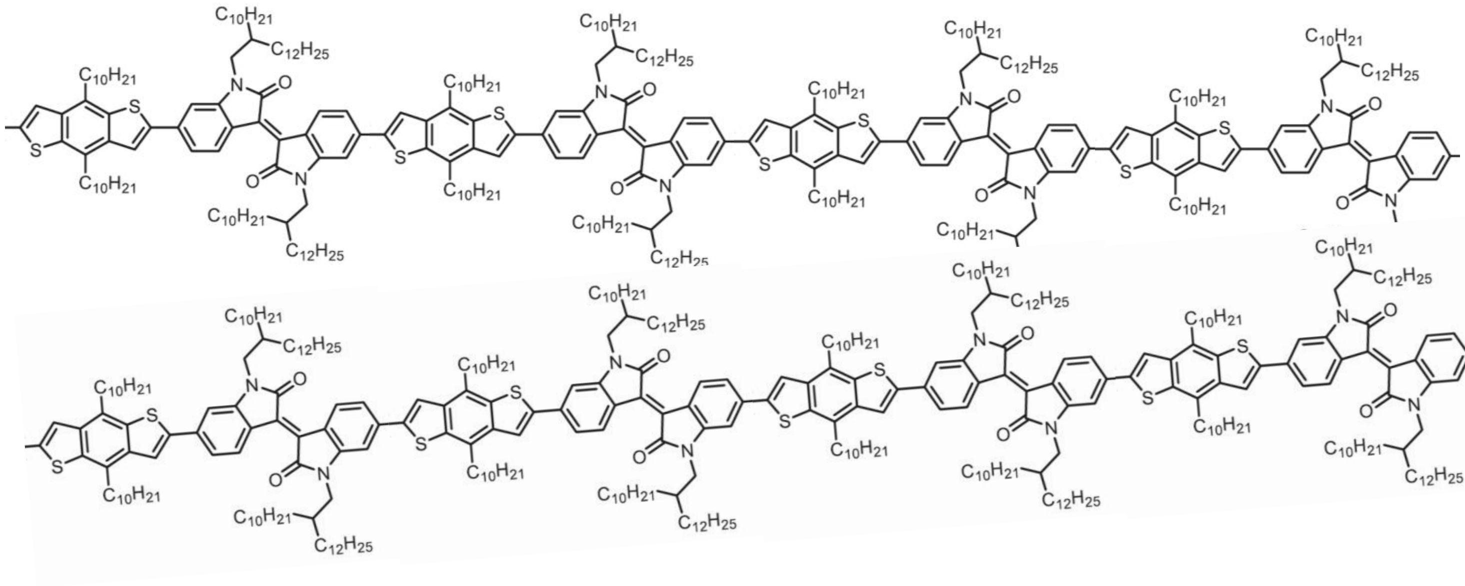




The photosynthetic activity is rapidly switched on and off!

Gwizdala, Berera, Kirilovsky, van Grondelle & Krüger *J. Am. Chem. Soc.* 138:11616−11622 (2016)

Application to organic solar cells



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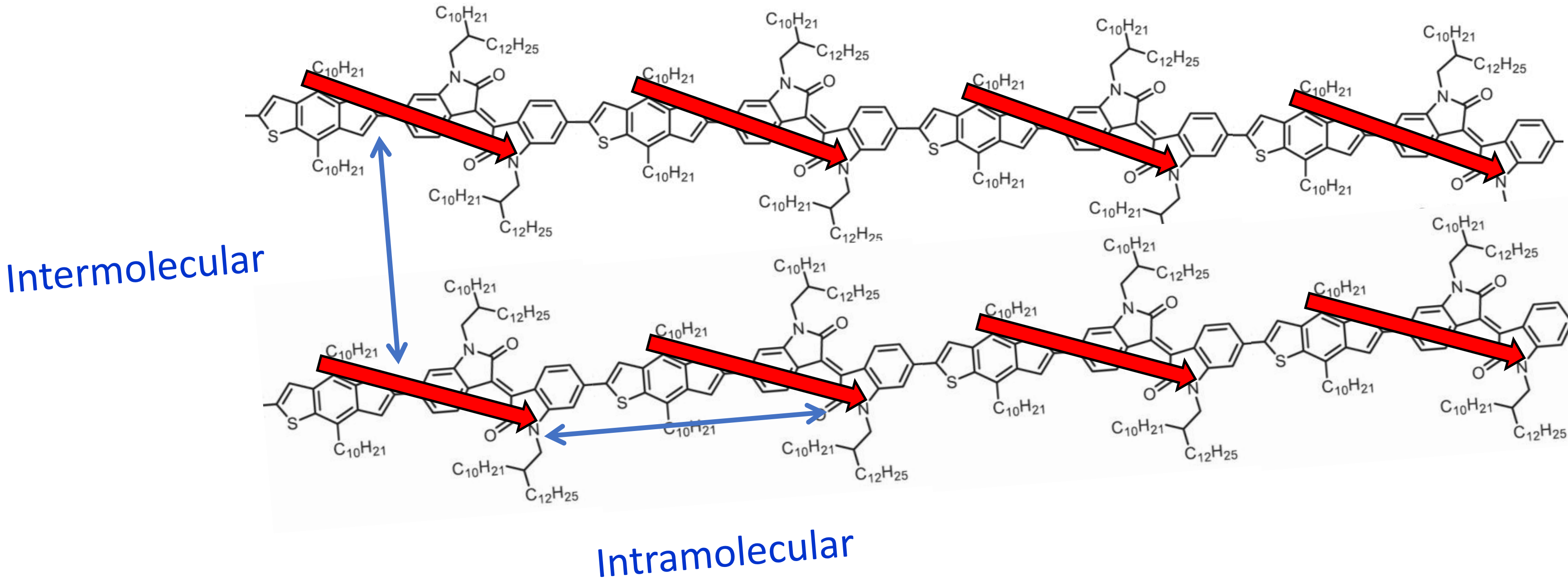
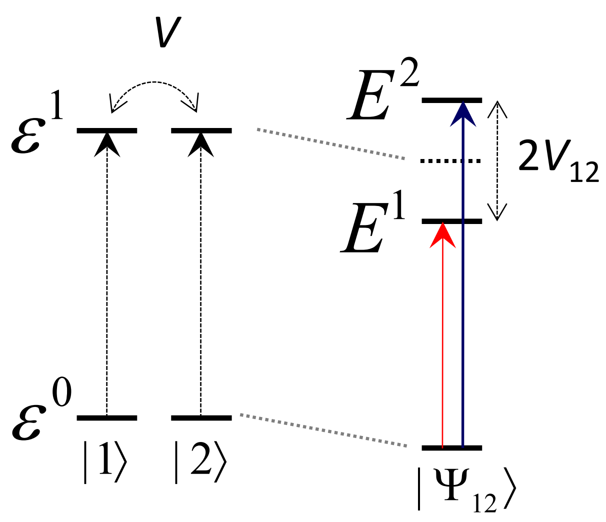
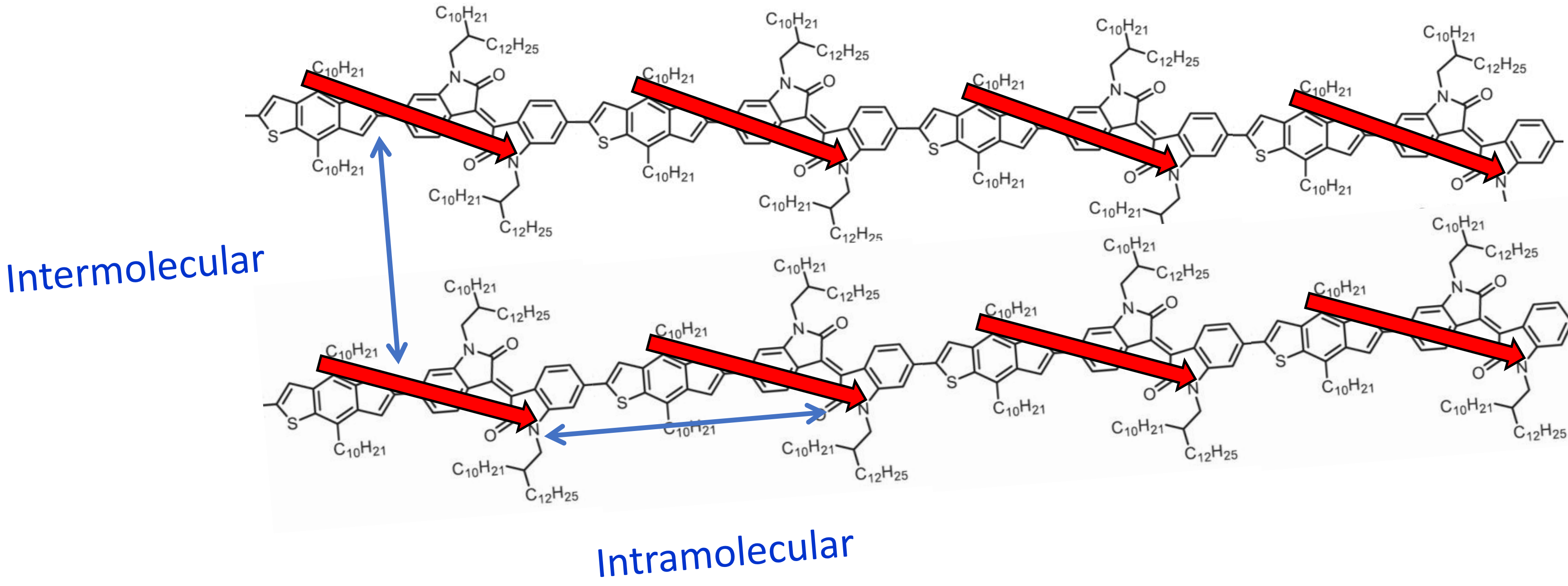


Molecular excitons: quantum coherence



monomers dimer



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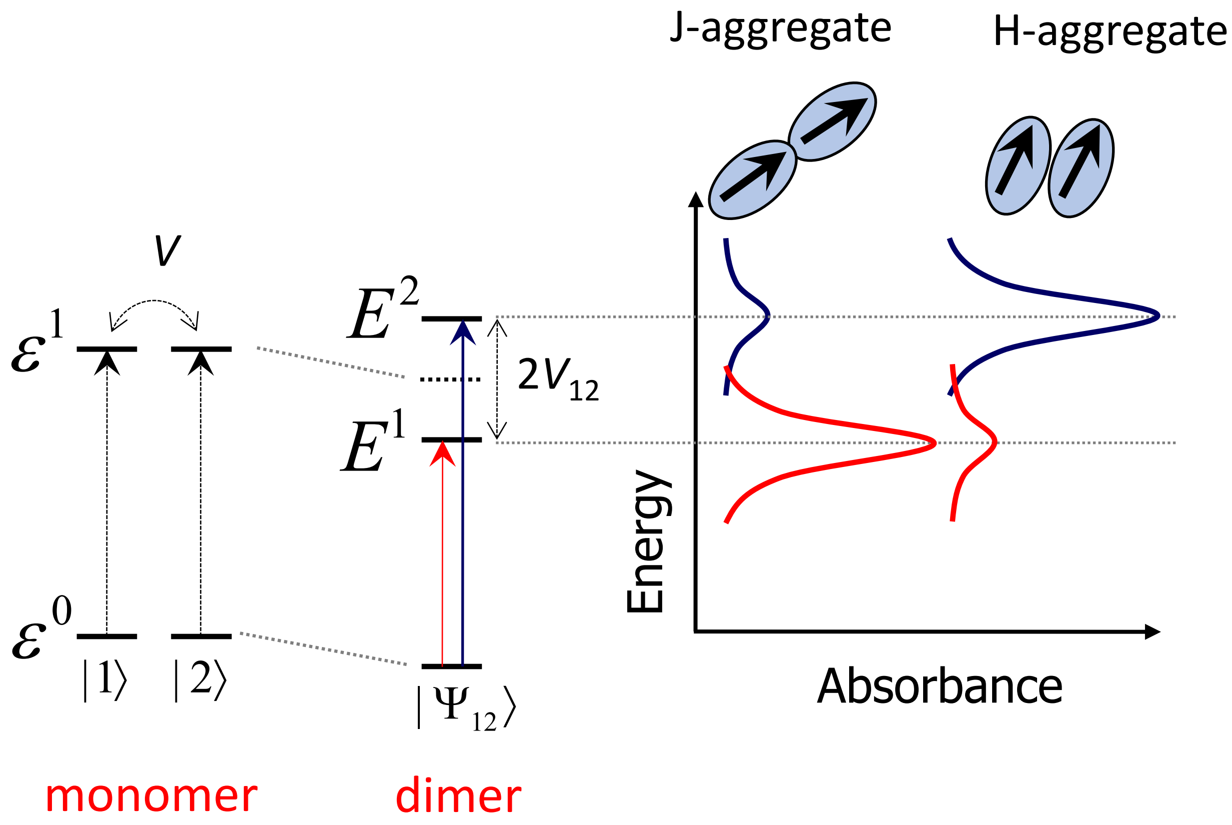
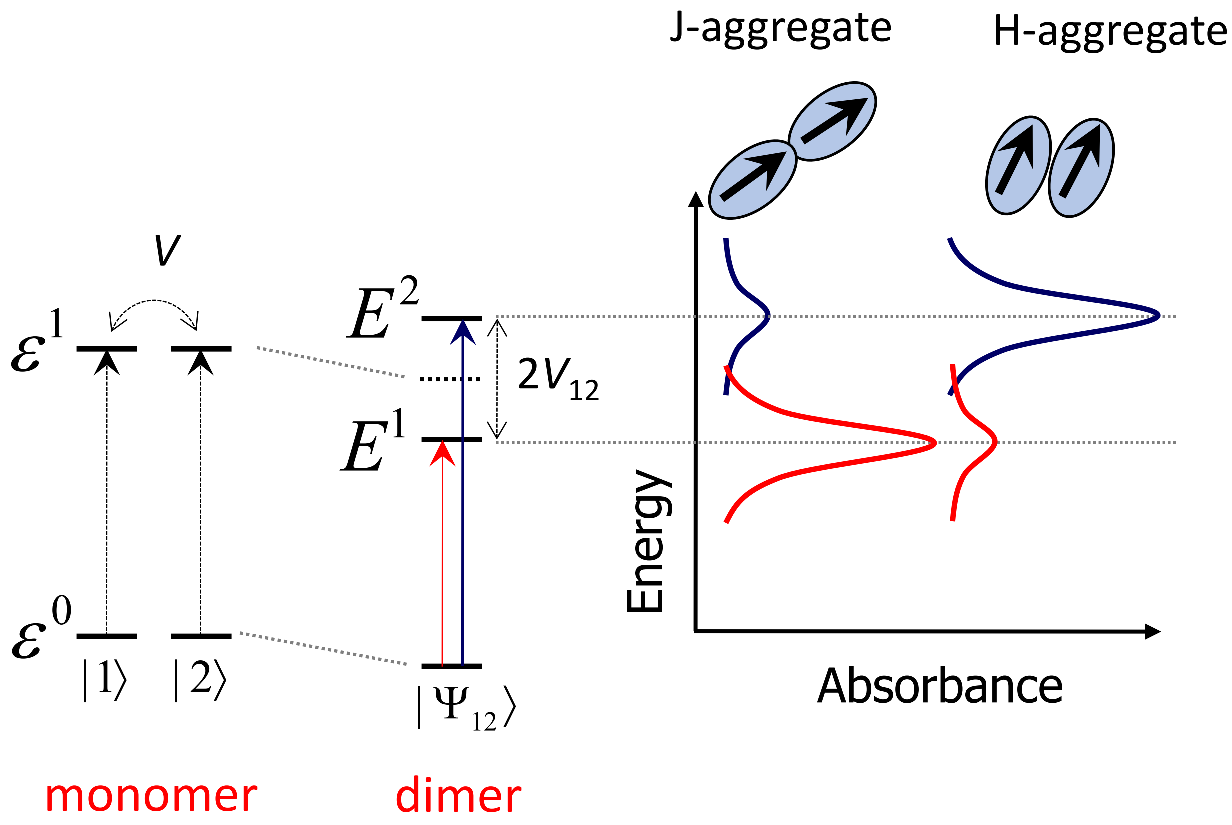
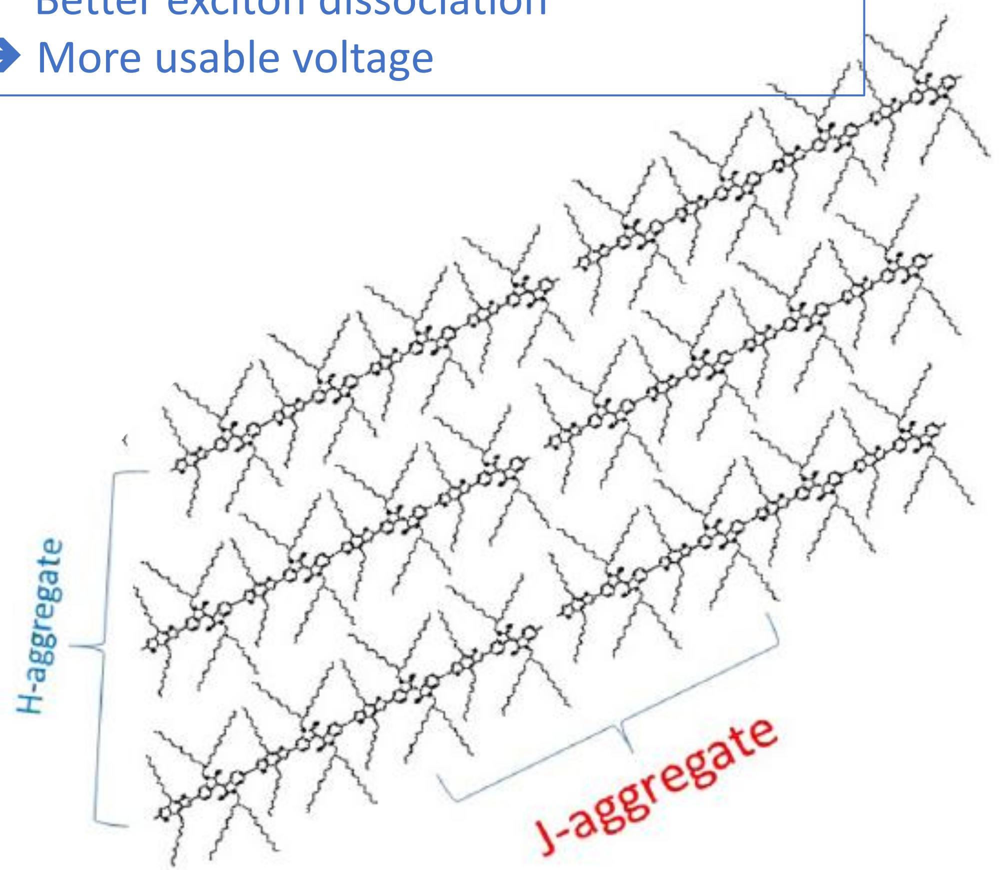


Molecular excitons: quantum coherence

- ✓ Better exciton generation
- ➔ Higher current

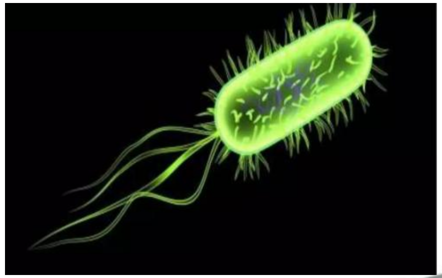
- ✓ Better exciton dissociation
- ➔ More usable voltage



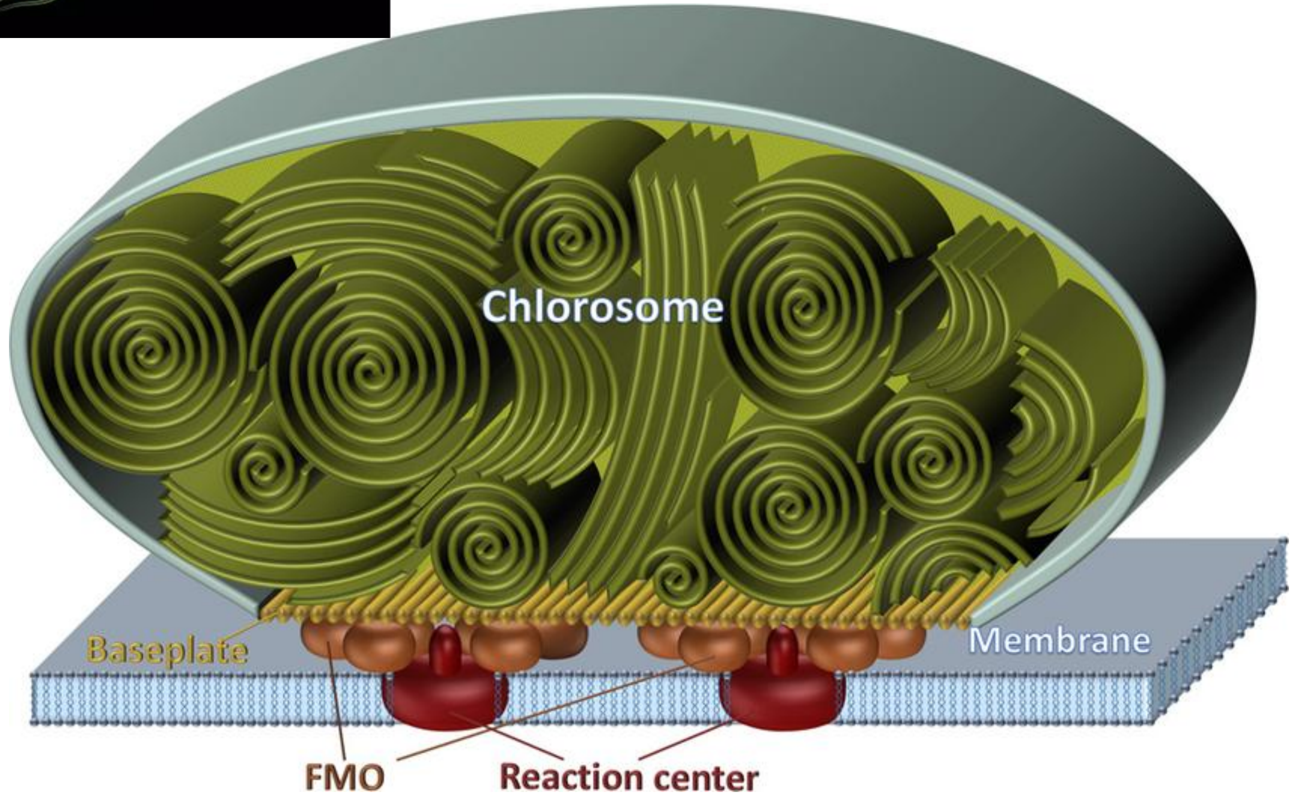


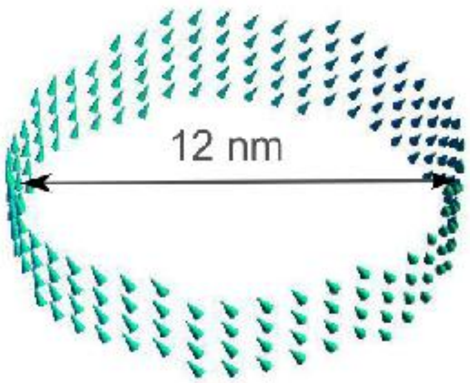
It's incredibly difficult to predict the exact arrangement of self-assembled organic aggregates

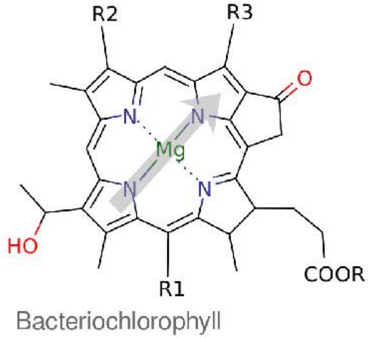
Self-assembled pigment aggregates



High quantum efficiency means robustness to static disorder







perfect molecular crystals!

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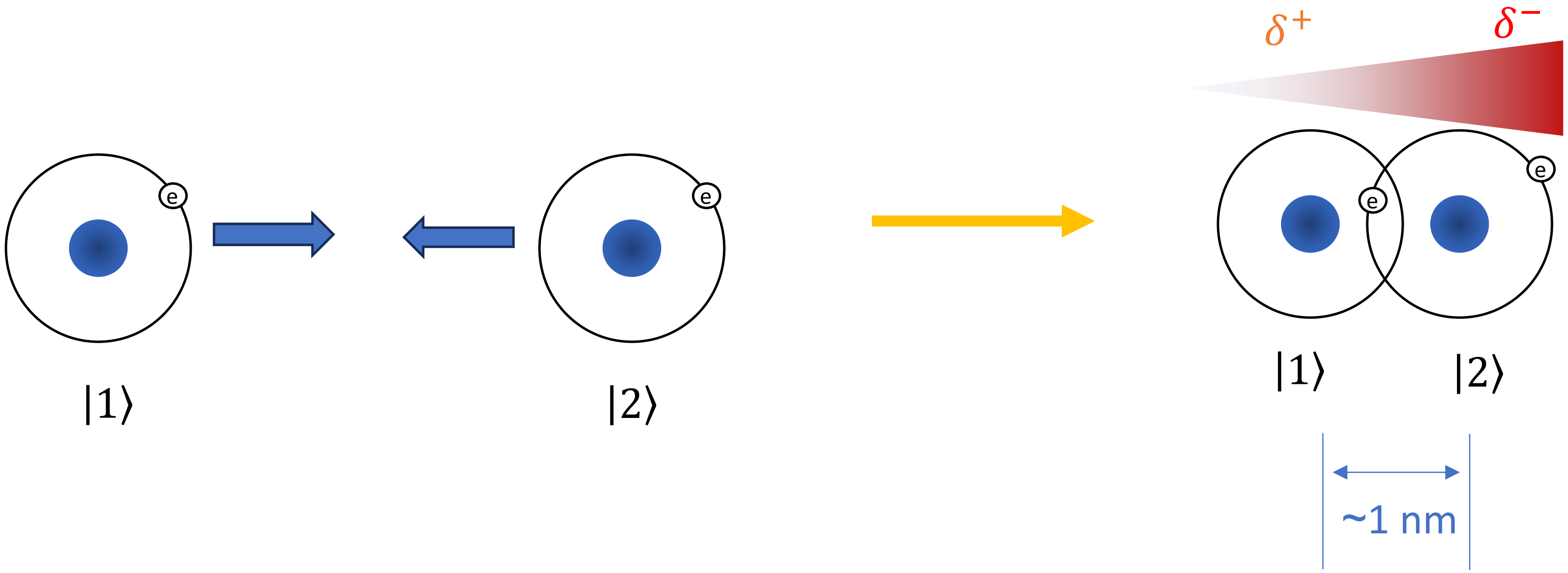
Quantum biology: inspiration from nature

Various EU Key Enabling Technologies are based on quantum-mechanical phenomena and find examples in nature.

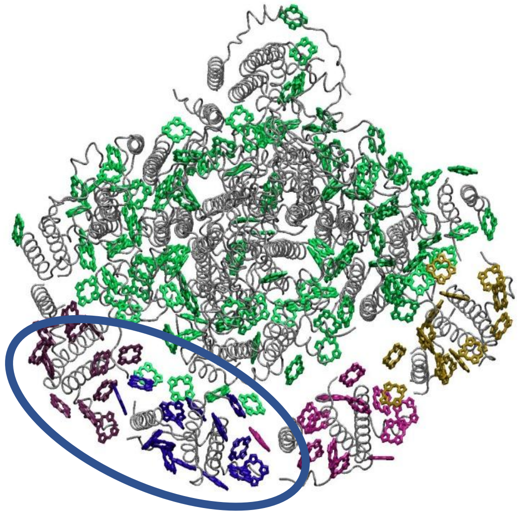
Key Enabling Quantum Technology	Research field	Examples in nature
Single-photon detection in a noisy, low-voltage electrochemical environment at room temperature	Photonics	• Eye • Photoreceptors • Light-harvesting complexes
N_2 fixation at room temperature and pressure	Nanotechnology	Certain bacteria
Chemically powered transport of ions and electrons across nanometres with low dissipation	Nanoelectronics	Transmembrane ion transport across basically every (sub)cellular membrane
H_2 from H^+ without noble metals at 0 V SHE	Advanced Materials	Many organisms, e.g. cyanobacteria
Photo-induced charge separation with near-unity quantum efficiency in a noisy environment at room temperature	Photovoltaics	Photosynthetic photosystems

Charge-transfer states: strong charge gradient

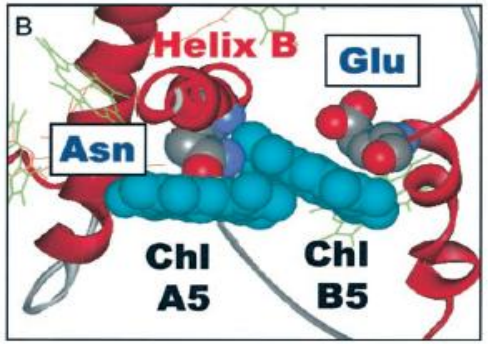


$$|\boldsymbol{CT}\rangle = c_1|1\rangle + c_2|2\rangle$$

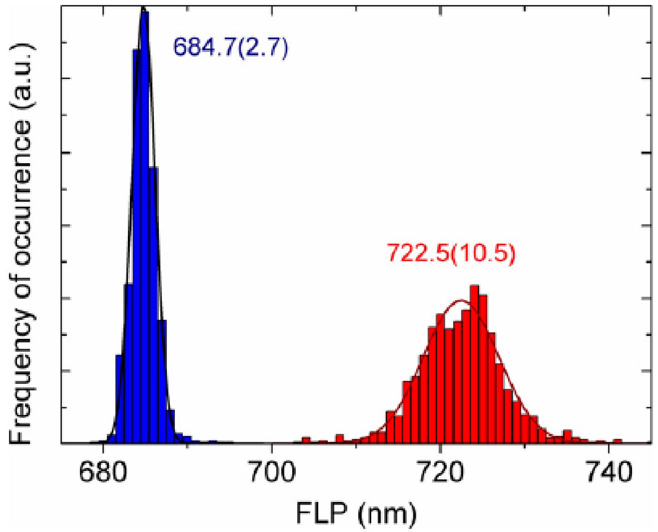
LHCs are strain sensors: sub-Å sensitivity

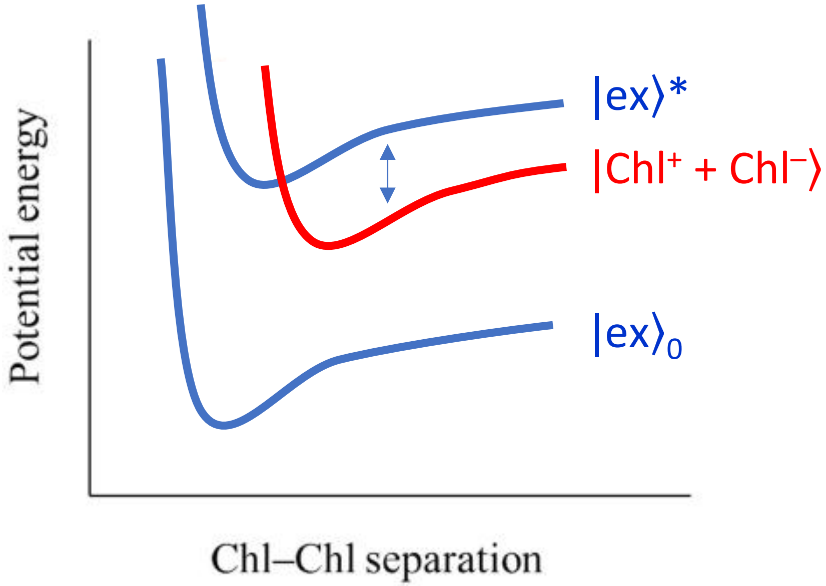


Lhca1/4



$\Delta \sim 0.7 - 0.8$ Å





$$\widehat{H}_{mix} = \epsilon_{ex}|ex\rangle\langle ex| + \epsilon_{CT}|CT\rangle\langle CT| + V(|ex\rangle\langle CT| + |CT\rangle\langle ex|)$$

$$E^{\pm}_{mix} = \frac{\epsilon_{ex} + \epsilon_{CT}}{2} \pm \sqrt{\frac{(\epsilon_{ex} - \epsilon_{CT})^2}{2} + V^2}$$

TPJ Krüger *et al.* *PNAS* 108:13516 (2011)

Take-home messages

- Nature is a rich source of inspiration, even for quantum tech
- Photosynthetic LHCs exploit and finely control quantum phenomena to enhance their biological function in several ways:
  - ✓super-efficient organic solar cells can be created through “programmable” self-assembled molecules
  - ✓ highly sensitive strain sensors
  - ✓ biological single-photon emitters: can they be tuned to deliver on-demand photons for biotech applications?

Steve Jobs

"I think the biggest innovations of the 21st century will be at the intersection of biology and technology. A new era is beginning."

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Funding

UKRI Science and Technology Facilities Council

SA QuTI South African Quantum Technology Initiative

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