Basics of quantum computing and qubit implementation

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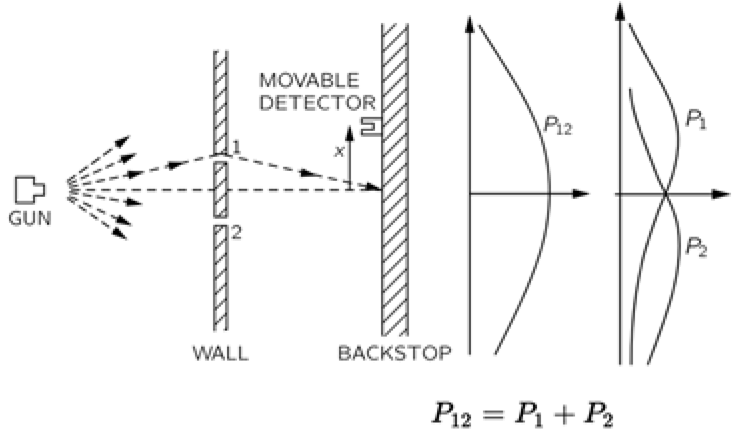
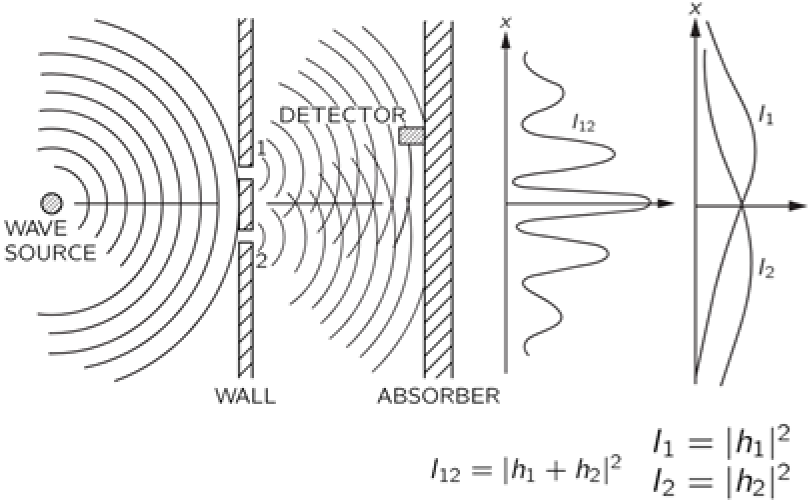
Foundation: classical behavior

Experiment with particles



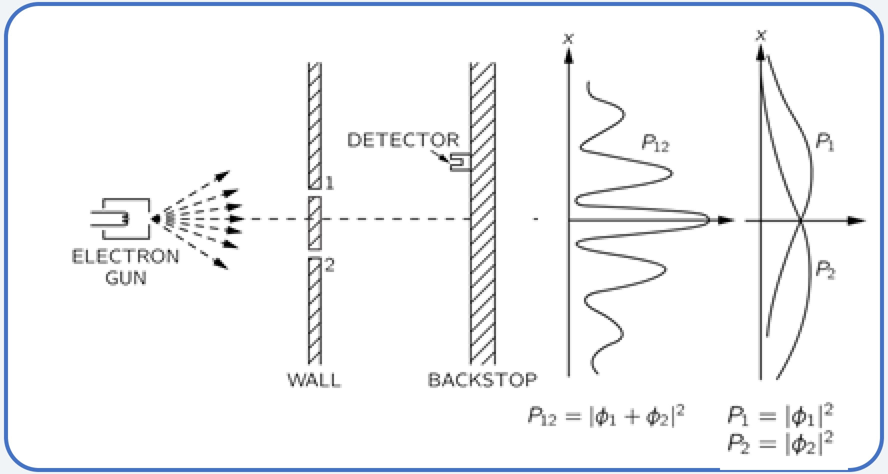
Experiment with waves

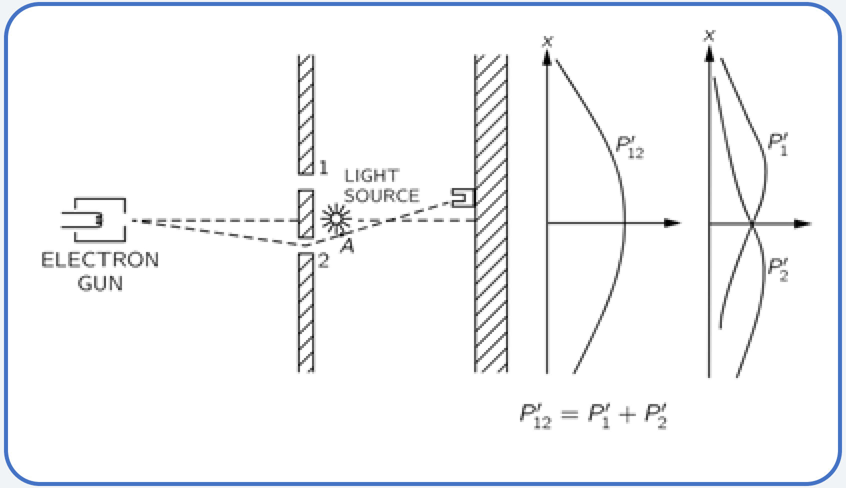


https://www.feynmanlectures.caltech.edu/III_01.html

Foundation: quantum mechanical behavior

Experiment with electrons





https://www.feynmanlectures.caltech.edu/III_01.html

Quantum Mechanics: Basics

- A system is represented by a wavefunction
  - Hilbert space
- Evolution is governed by Schrödinger equation
  - Hamiltonian
- Measurement
  - Hermitian operators
- Superposition
- Entanglement

Quantum Computing: Qubits and Quantum Gates

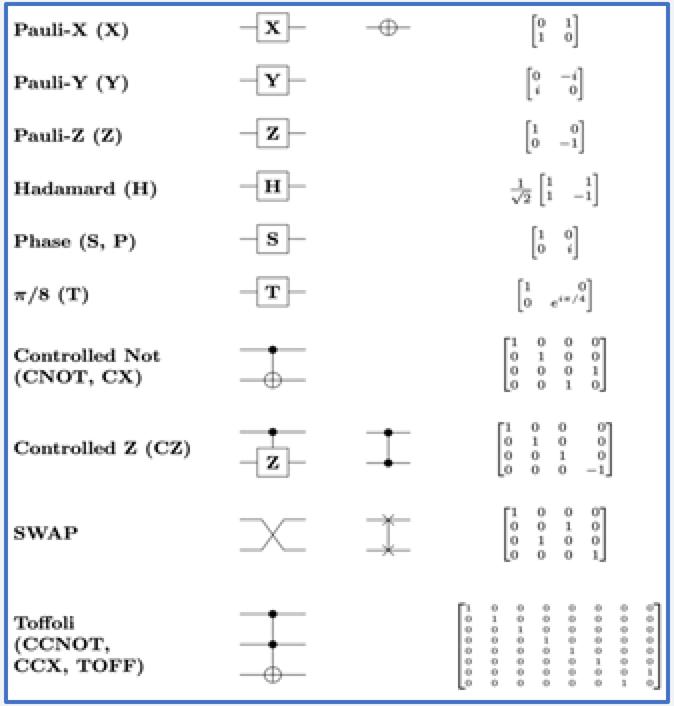
Qubit

A two level quantum system: $|0\rangle$ $|1\rangle$

The qubit state: $\alpha\,|0\rangle + \beta\,|1\rangle$

In real world, we don't want: decoherence.

Quantum Gates



Pauli-X (X)	$\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}$
Pauli-Y (Y)	$\begin{bmatrix}0 & -i\\i & 0\end{bmatrix}$
Pauli-Z (Z)	$\begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}$
Hadamard (H)	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
Phase (S, P)	$\begin{bmatrix}1 & 0\\0 & i\end{bmatrix}$
$\pi/8$ (T)	$\begin{bmatrix}1 & 0\\0 & e^{i\pi/4}\end{bmatrix}$
Controlled Not (CNOT, CX)	$\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{bmatrix}$
Controlled Z (CZ)	$\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&-1\end{bmatrix}$
SWAP	$\begin{bmatrix}1&0&0&0\\0&0&1&0\\0&1&0&0\\0&0&0&1\end{bmatrix}$
Toffoli (CCNOT, CCX, TOFF)	$\begin{bmatrix}1&0&0&0&0&0&0&0\\0&1&0&0&0&0&0&0\\0&0&1&0&0&0&0&0\\0&0&0&1&0&0&0&0\\0&0&0&0&1&0&0&0\\0&0&0&0&0&1&0&0\\0&0&0&0&0&0&0&1\\0&0&0&0&0&0&1&0\end{bmatrix}$

Universal set of gates (CNOT, H, S and T gates)

DiVincenzo's criteria

Quantum Computation

- A scalable physical system with well characterized qubit
- The ability to initialize the state of the qubits to a simple fiducial state
- Long relevant decoherence times
- A “universal” set of quantum gates
- A qubit-specific measurement capability

Quantum Communication/Internet

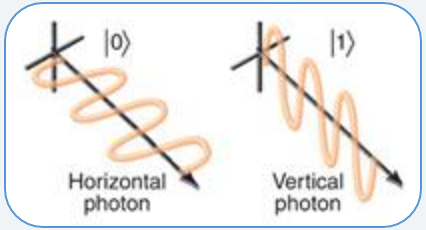
- The ability to interconvert stationary and flying qubits
- The ability to faithfully transmit flying qubits between specified locations

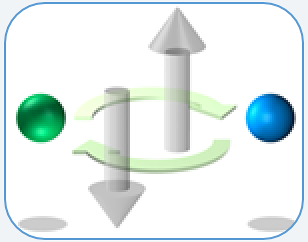
arXiv:quant-ph/0002077

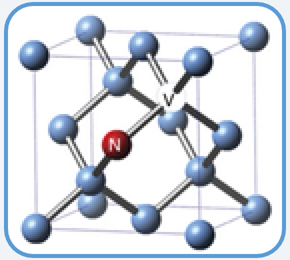
Ways of realizing a qubit

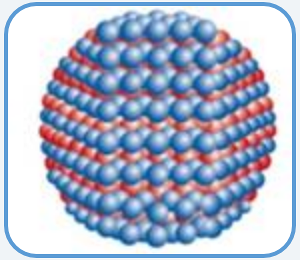
A two level quantum system $|0\rangle$ $|1\rangle$

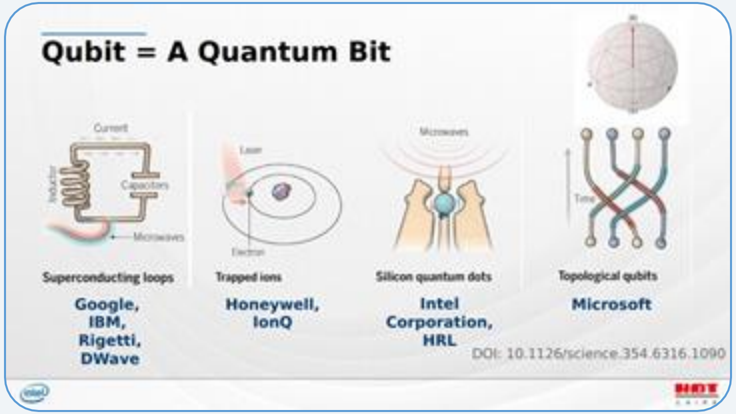
The qubit state: $\alpha\,|0\rangle + \beta\,|1\rangle$







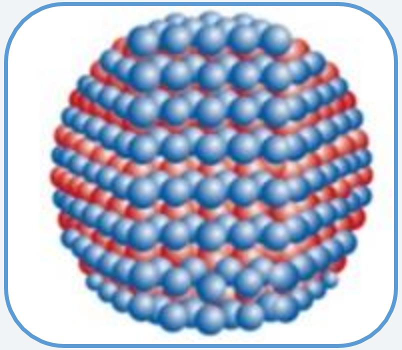


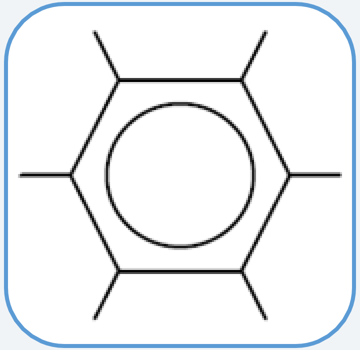


Courtesy: Brian King, MacMaster University
https://medium.com/quantumcomputingindia/qubits-implementation-quantum-hardware-102-ec55e645f9eb
https://physicsworld.com/a/physicists-break-distance-record-for-electron-spin-state-transmission-in-spin-qubits/

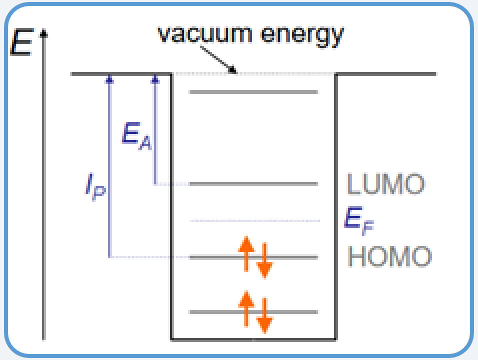
Quantum dots – 0 D conductor

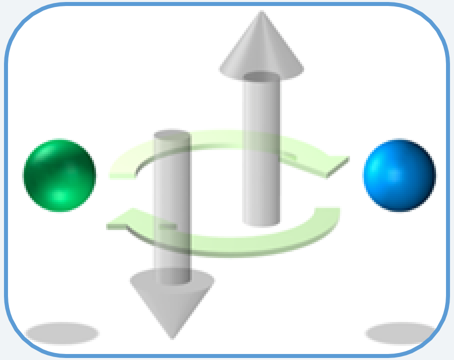
- Electrons confined in all directions.
- Discrete energy levels
- Like big molecule



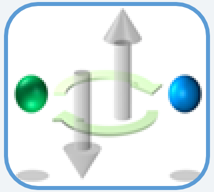


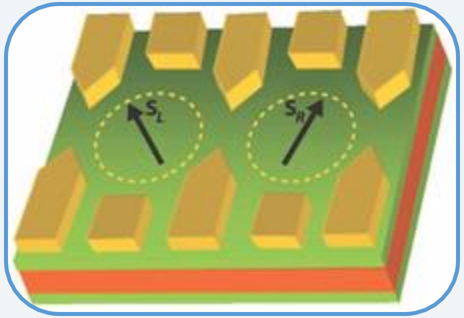
Growth (an example): when InGaAs is grown on GaAs islands form spontaneously, due to the mismatch in the lattice constants.

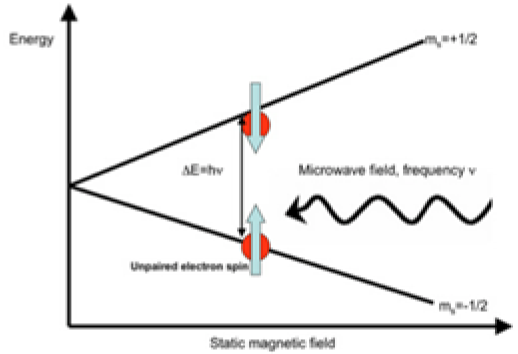




Quantum Dot Qubits

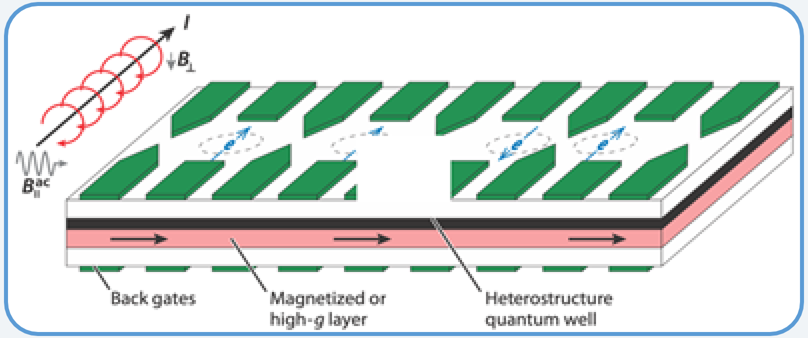






$$\Delta E = \mu_B B m_\ell$$

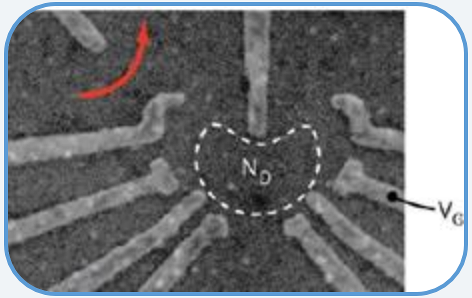
With electric and magnetic fields – both charge and spin degrees of freedom are controlled.



Kloeffel, Christoph, and Daniel Loss. "Prospects for spin-based quantum computing in quantum dots." Annu. Rev. Condens. Matter Phys 4, no. 1 (2013): 51-81.

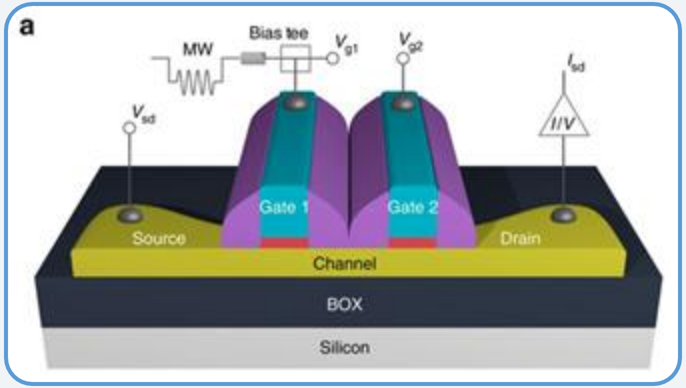
A quantum dot qubit system

Heterostructure Formation → Metal electrical contacts formation → Biasing and measurement

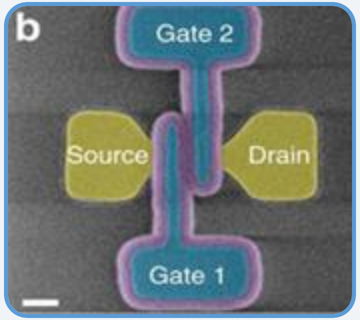


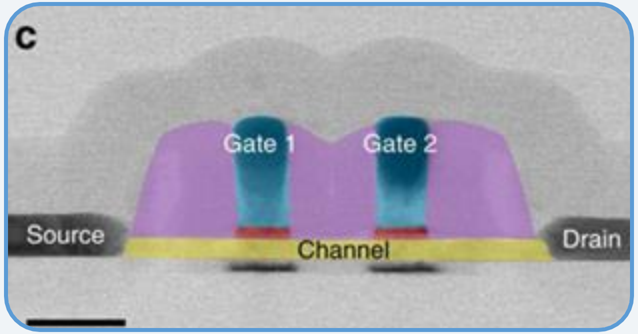
E. A. Laird, “Electrical Control of Quantum Dot Spin Qubit”, Ph.D. Thesis, Harvard University (2009).

Quantum Dot Qubits: CMOS Platform



Qubit on the standard CMOS platform

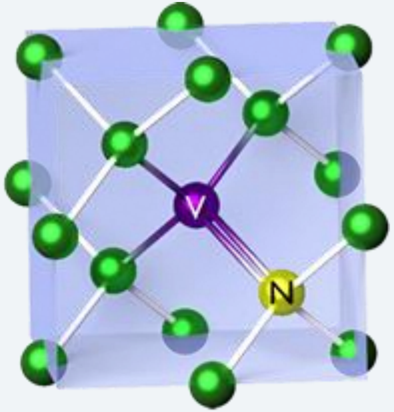


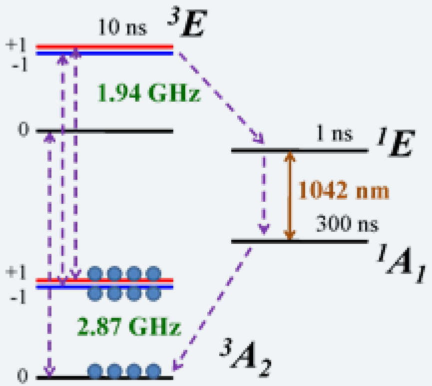


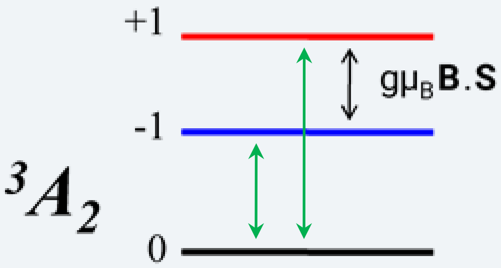
R. Maurand, X. Jehl, D. Kotekar-Patil, A. Corna,H. Bohuslavskyi, R. Laviéville, L. Hutin, S. Barraud, M. Vinet, M. Sanquer, et al. A CMOS silicon spin qubit. Nature Communications, 7:13575, 2016. arXiv: 1605.07599.

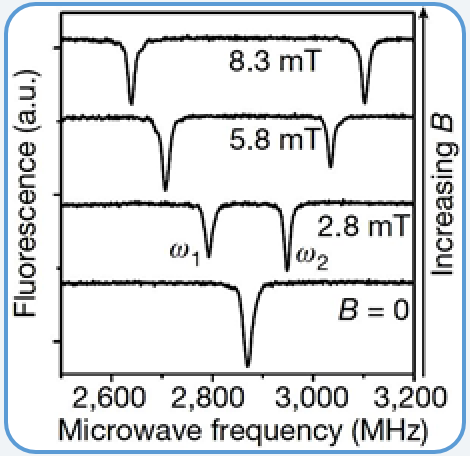
NV Center qubits

- Ground and excited triplet states
- Intermediate singlet states
- Long coherence time (upto ms) at 300K







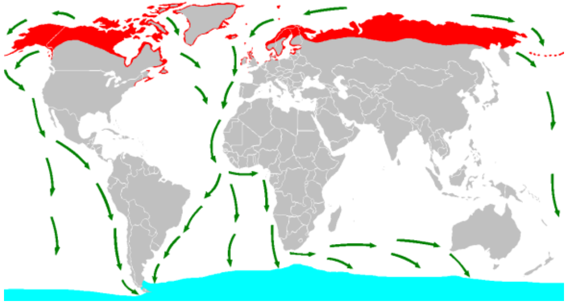


Quantum Effects in Biological Systems and Biomimetic Devices

Bar-tailed Godwit

- **Alaska to New Zealand/Australia**
  - ~ 11,000 km
  - ~ 60 km hr-1
  - ~ 8 days

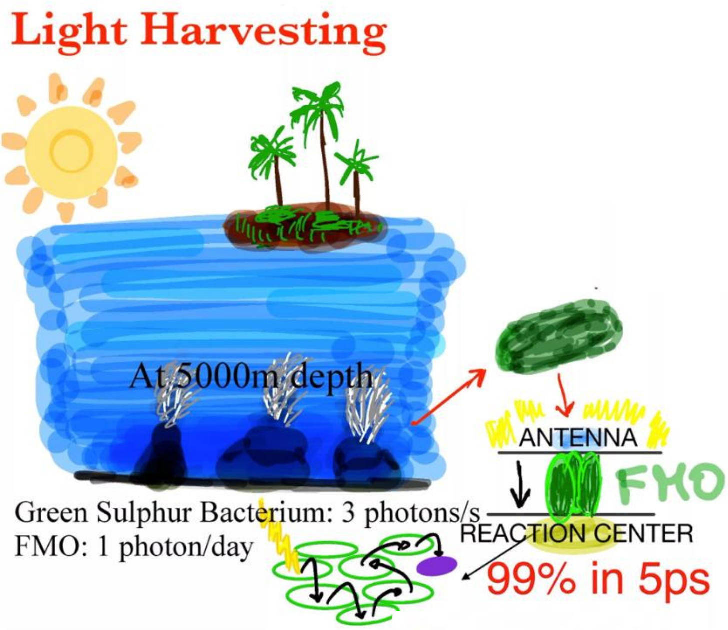
Arctic Tern

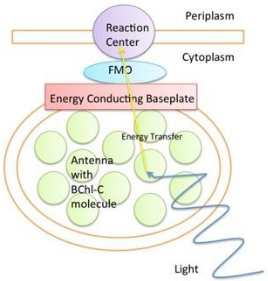


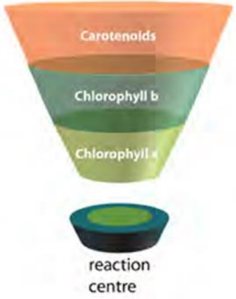
Pole to Pole (50k – 70k km Roundtrip)

Bar-tailed godwit

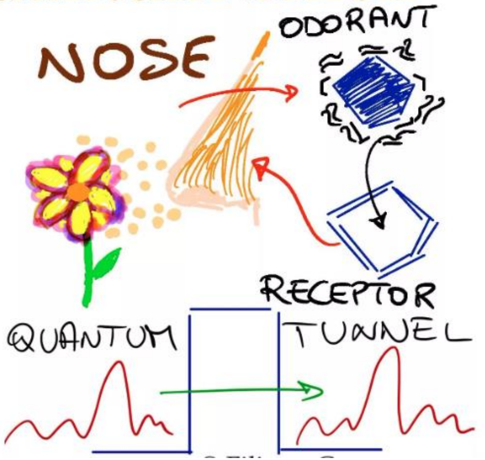
- **Alaska to New Zealand**
  - ~11,000 km
  - ~60 km hr-1
  - ~8 days



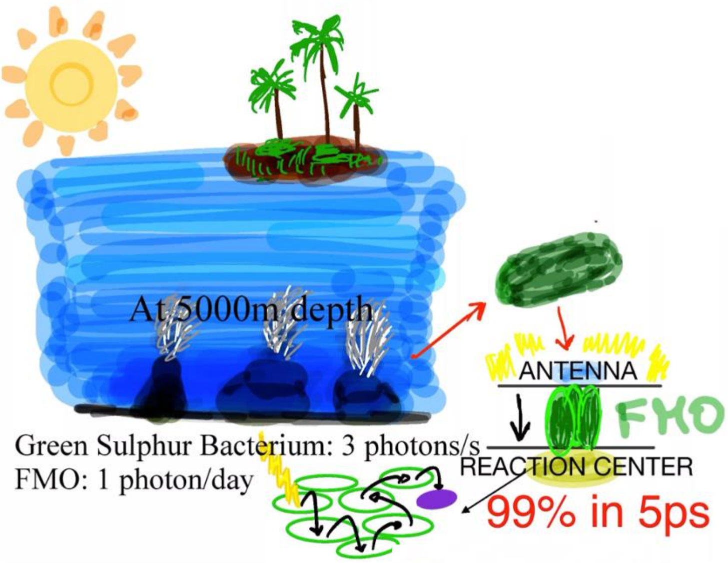


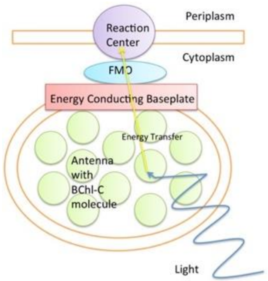


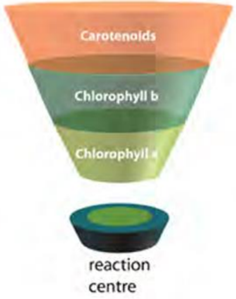
Quantum Smell



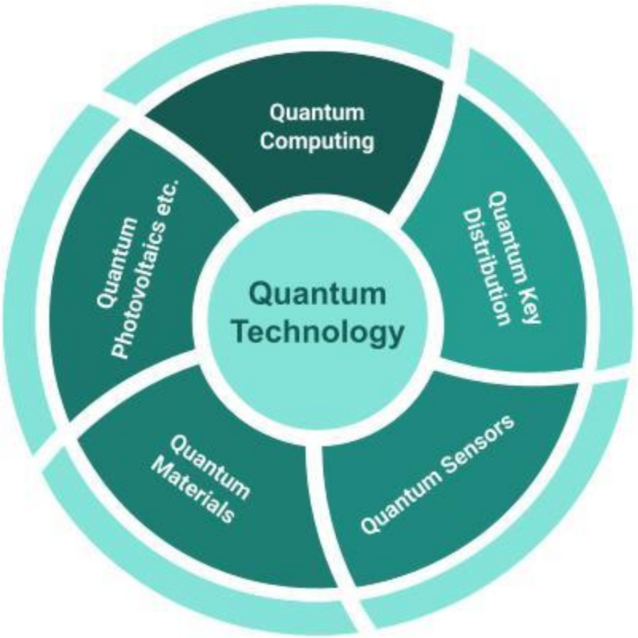
Light Harvesting







Quantum Technology



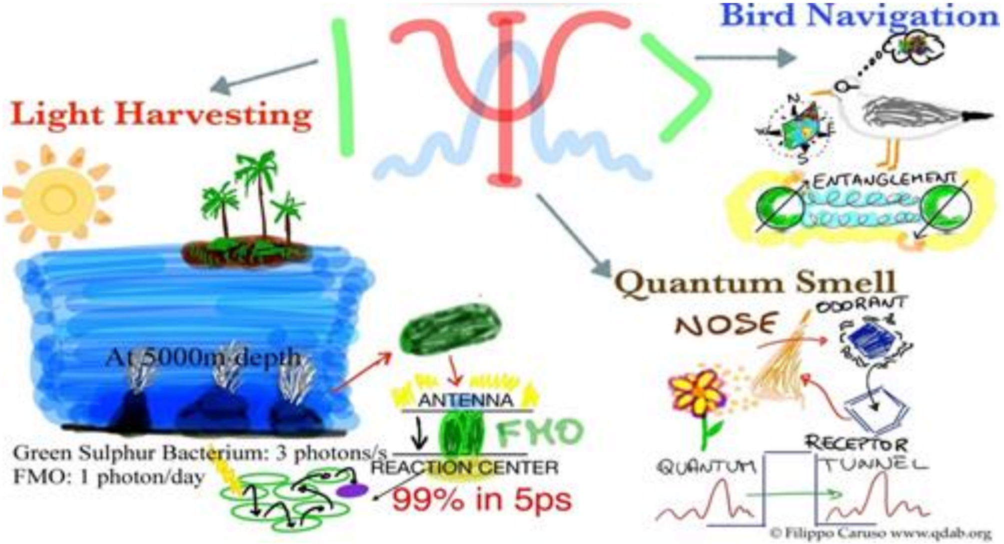
Quantum Coherence

- 'Quantum' superposition
- Responsible for interference effect

Quantum Entanglement

- 'Spooky' action at a distance
- A valuable 'quantum' resource

“Quantum” Biology



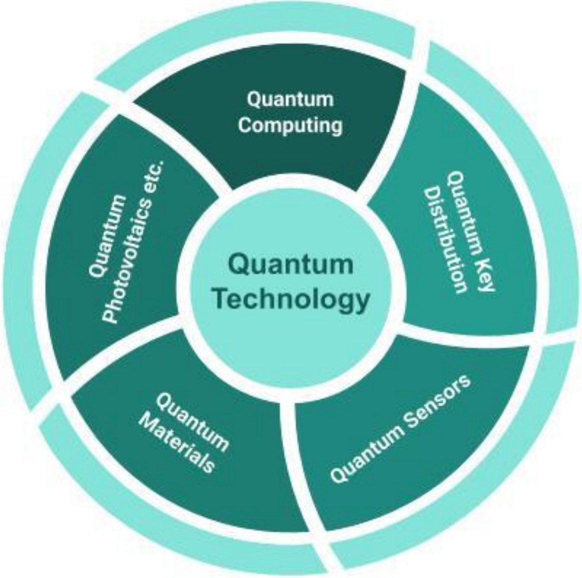
Quantum Coherence

Quantum Entanglement

Quantum Tunneling

Biological systems seem to have figured out a way to sustain and utilize 'quantum’ effects

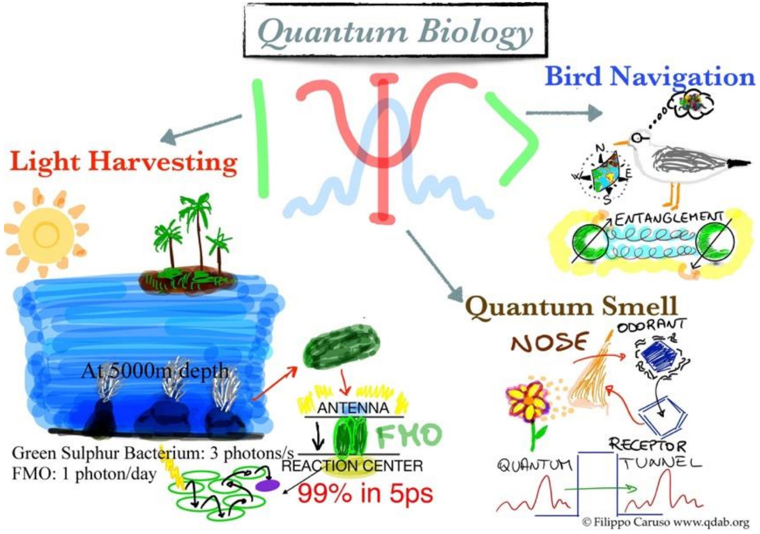
Quantum Technology and Quantum Biology



Quantum Coherence

Quantum Entanglement

Quantum Tunneling



Quantum Biology: History

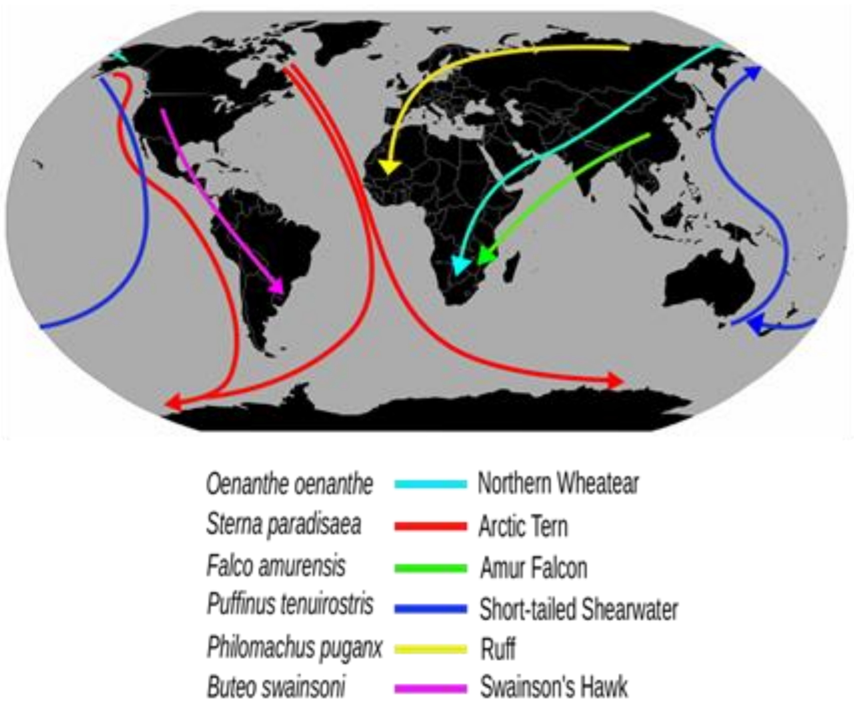
- 1943: Erwin Schrödinger – *"What is Life"*
  - Genetic structure and stability is determined by quantum nature of molecular energy levels
  - "… quantum indeterminacy plays no biologically relevant role…"
  - No consideration of
    - Coherence
    - Entanglement

Non-trivial quantum effects

- **Experiments:**
  - 2007: Fleming et al.: excitonic coherence in EET during light harvesting
  - 2010: Engel et al., Scholes et al.: quantum coherence of EET in LHCs at ambient temperatures

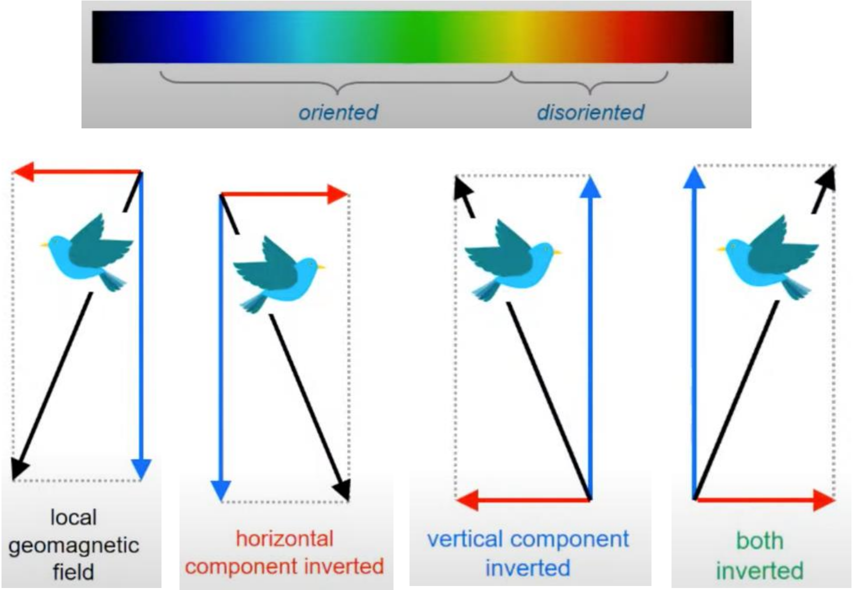
- **Other 'quantum' biology proposals**
  - 1996 Turin: inelastic electron tunneling in olfaction
  - 1998: Schulten et al.: radical pair mechanism of bird navigation
  - 1995: Hameroff, Penrose: quantum coherence in brain microtubules – consciousness?

Avian Magnetoreception



The avian compass: behavioral characteristics

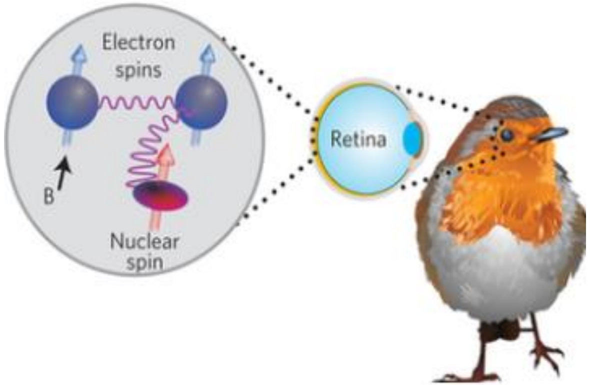
Experiments @ Frankfurt on European Robin: local geomagnetic field = 46 μT



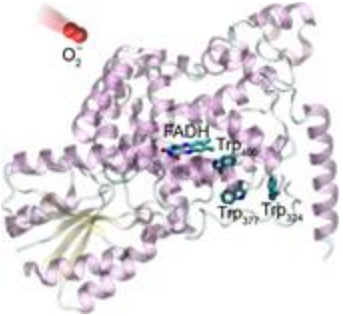
Behavioral characteristics

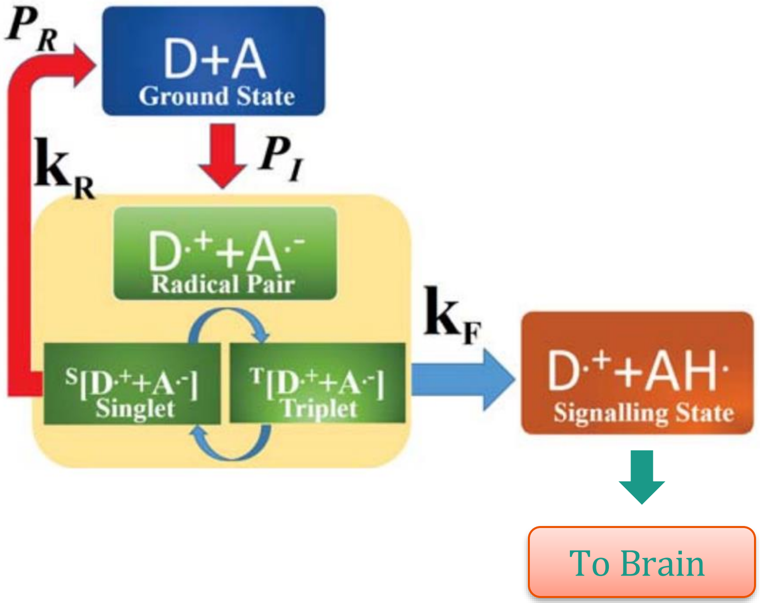
- **Inclination compass only**
  - No North-South distinction
- **Operational in some optical frequency range**
- **RF disruption**
  - Small (50nT) field transverse RF field (specific frequency 1.315 MHz) destroys compass action
- **Adaptive functional window**
  - Dynamic range: ± 30% of local geomagnetic field

The radical pair mechanism



Cryptochrome

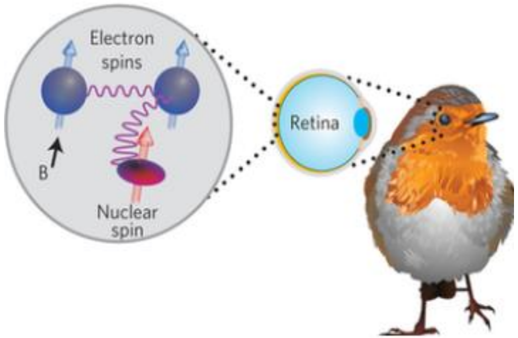


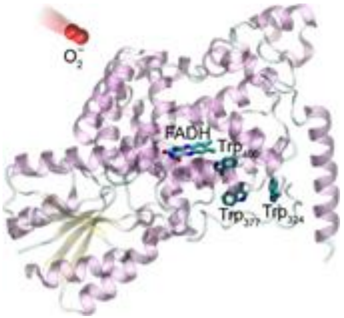


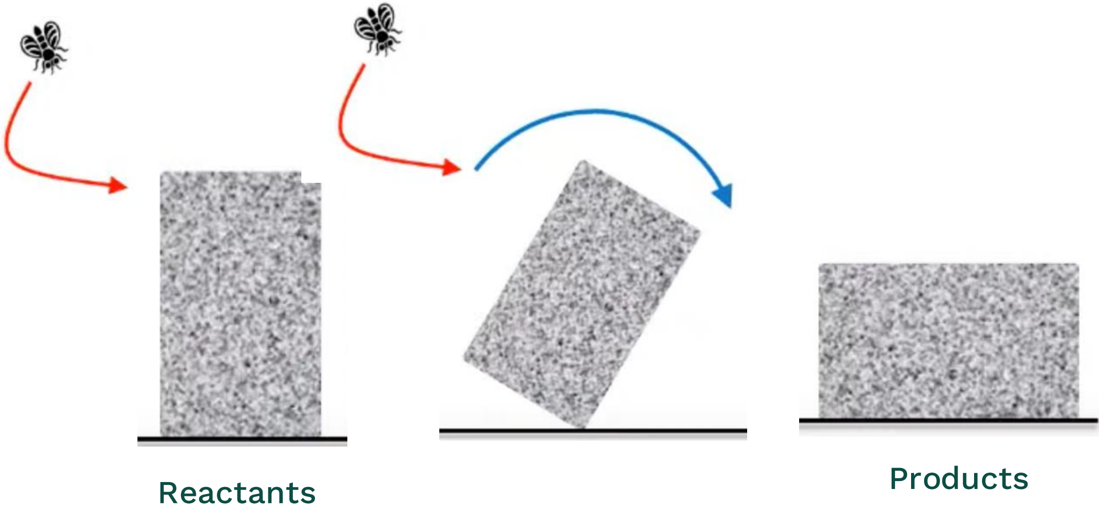
Compass action can be quantified by:

- **Singlet yield:** fraction of the singlet products
- **Triplet yield**
- **Protonated Signaling state**

The radical pair mechanism: energetics

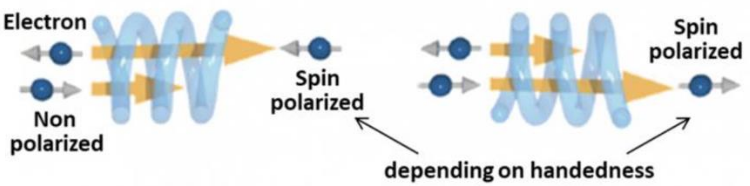




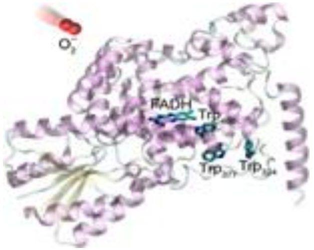


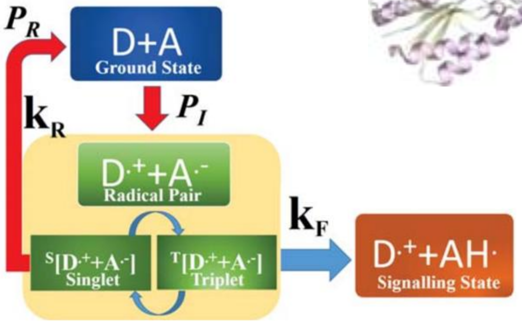
Chirality-induced spin selectivity (CISS) and the RP model

- **Preferential transmission of electrons parallel or anti-parallel to the direction of motion** – based on chirality of the molecule



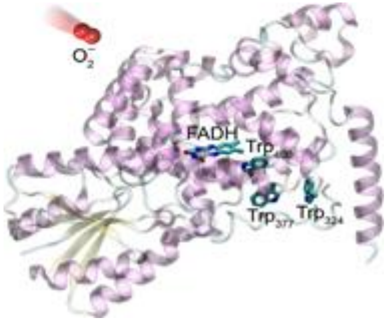
- CISS has been experimentally observed in different contexts:
  - **Electron Transmission**
  - **Electron Transport**
  - **Electron transfer/rearrangement in chemical reactions**





Inclusion of CISS in the RP model

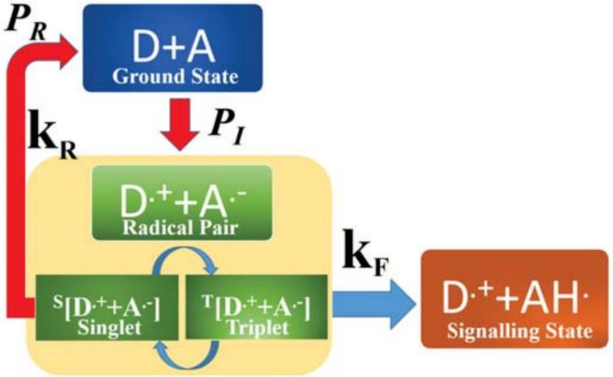
$$\frac{\mathrm{d}\hat{\rho}(t)}{\mathrm{d}t} = -i\left[\hat{H},\hat{\rho}(t)\right]_{-} - \frac{1}{2}k_{\mathrm{R}}\left[\hat{P}^{\mathrm{R}},\hat{\rho}(t)\right]_{+} - k_{\mathrm{F}}\hat{\rho}(t)$$



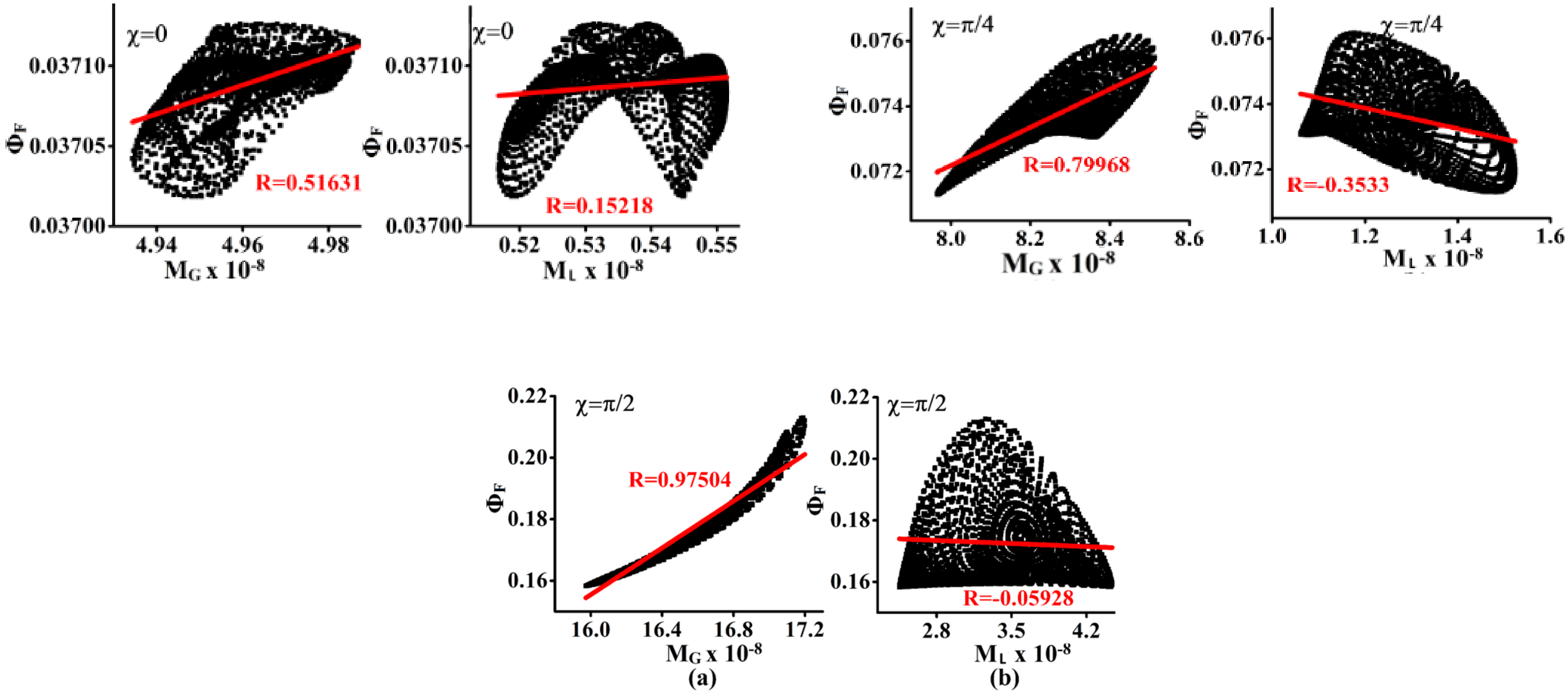
In full CISS case

Only one spin polarity electrons can travel in one direction

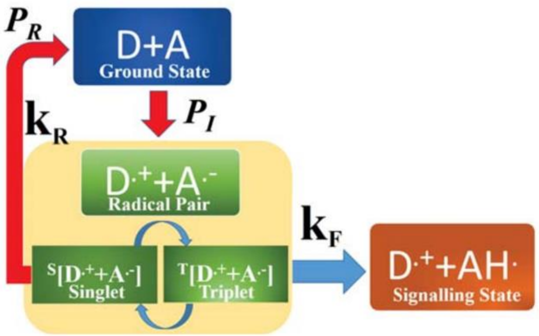
Opposite polarity electrons would travel in the opposite direction

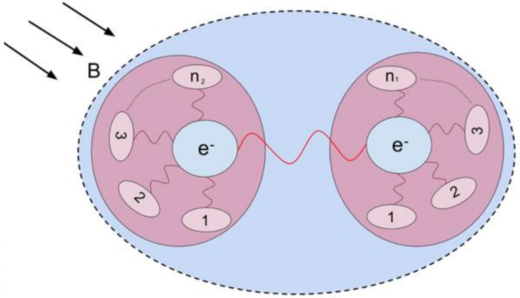


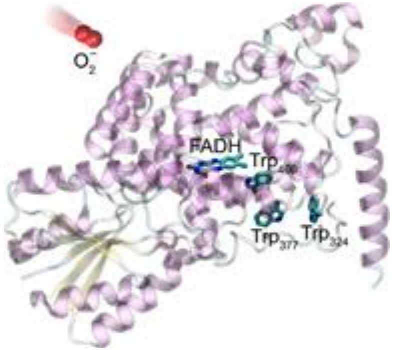
The radical pair model with CISS: Coherence and Signaling State Yield



Radical Pair Mechanism: In conclusion







CISS enhances compass sensitivity and coherence (both local and global)

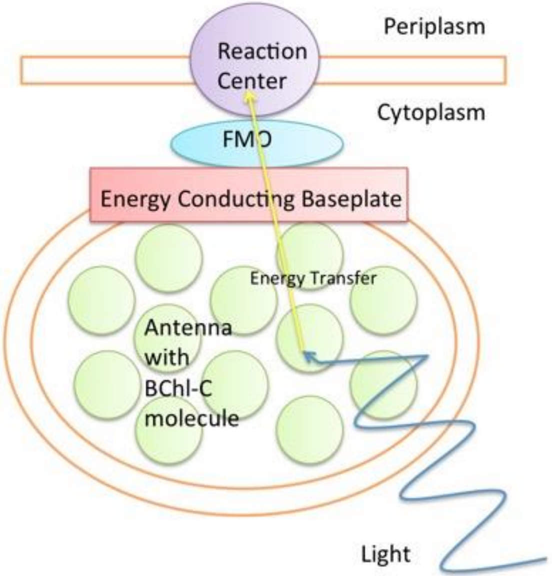
Global coherence shows strong correlation with signaling state yield

Functional Window?	**RF Disruption?**

Emulation of RP Mechanism – Quantum Sensor for navigation

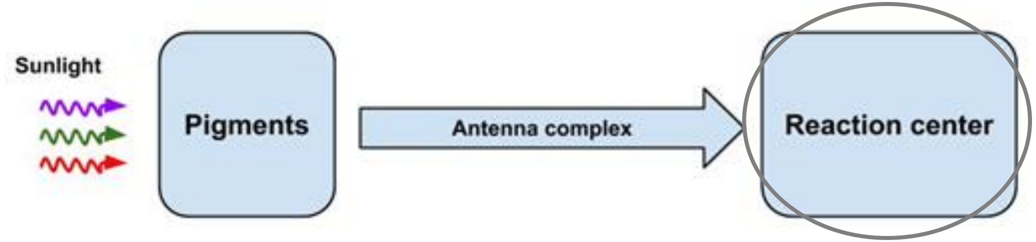
CISS for Quantum Technologies

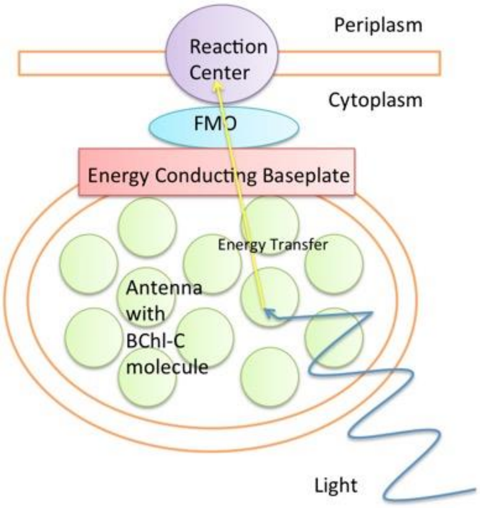
Photosynthetic Apparatus



The Photosynthetic Apparatus: Excitonic Transport and Charge Separation

- **Photosynthesis:** Synthesis of carbohydrates from CO_2 and water in presence of sunlight
- **Steps:**
  - Pigments: Captured photons create excitons
  - Antenna: Excitonic transport from pigments to the reaction center
  - Reaction center: Charge separation





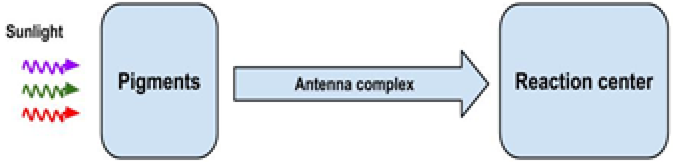
Two crucial steps in photosynthesis

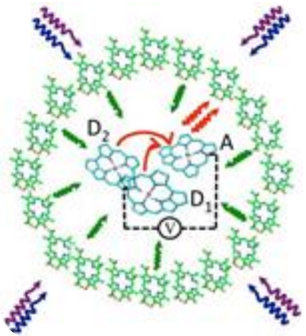
- Excitonic transport through molecular complex
- Charge separation at the reaction center

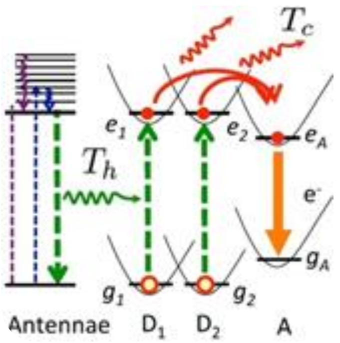
The Reaction Center

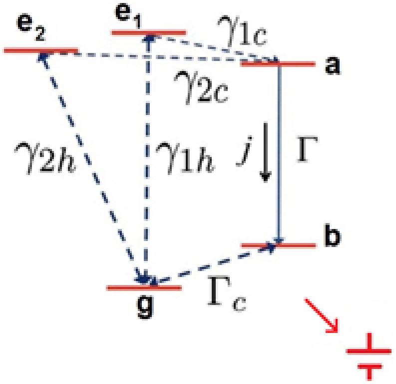
Structure

- Two donors, one acceptor

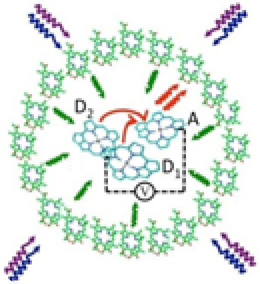


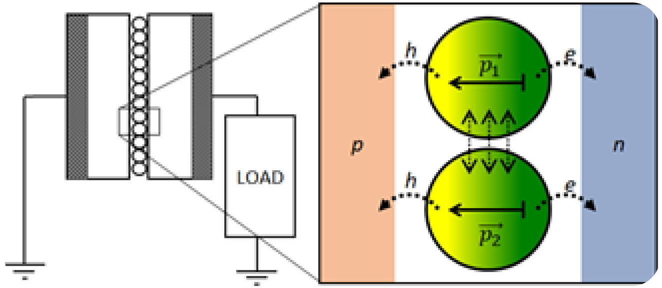




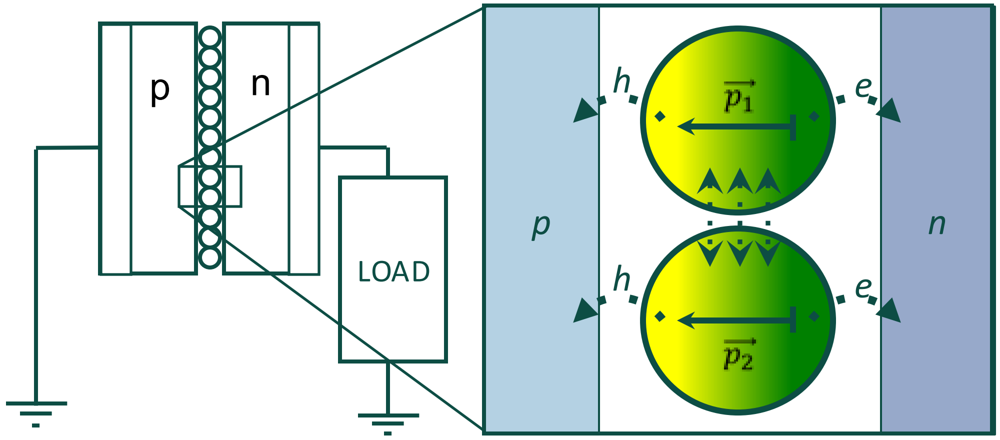


Reaction center emulation



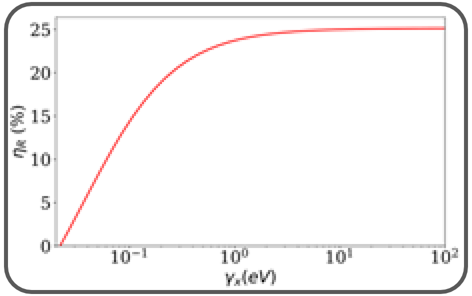


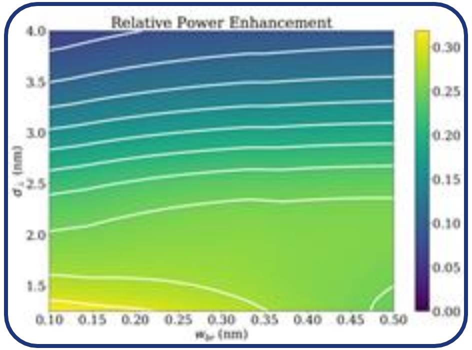
RC Emulation: A Quantum Photocell



- Inspired from photosynthetic reaction center
  And builds on Marlan O. Scully's idea of a quantum photocell.
- Strong built-in electric fields – excitonic dipole-dipole coupling between adjacent dots
- Helps in breaking the detailed balance.
- The photovoltaic cell exhibits enhanced photo-voltage and photocurrent (~25%).

Results (contd…)



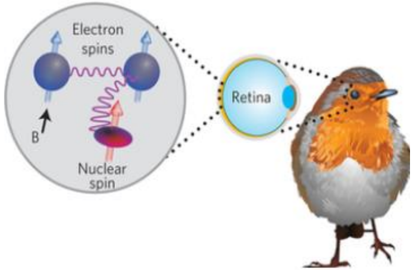


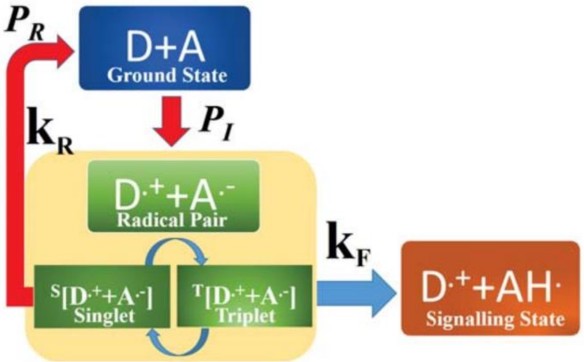
- Relative power enhancement $$\eta_R = \frac{\tilde{P}_{out}^{max} - P_{out}^{max}}{P_{out}^{max}}$$
- Power enhancement upto 25% is observed due to excitonic delocalization.

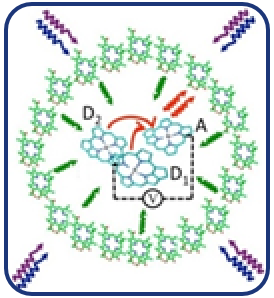
Some observations:

- Greater spacing between dots leads to poorer coupling and reduces efficiency.
- Another mechanism of charge carrier extraction must be found to augment the low tunnelling rates.
  - Phonon mediated transfers could be the key to this.
- The phonon spectrum of GaN quantum dots needs to be studied in detail
  - This and variation of the geometry of the photocell may be done through DFT/tight-binding methods.

In summary


Electron spins
B
Nuclear spin
Retina


P_R
D+A
Ground State
P_I
k_R
$D^{\cdot+}+A^{\cdot-}$
Radical Pair
k_F
$^S[D^{\cdot+}+A^{\cdot-}]$
Singlet
$^T[D^{\cdot+}+A^{\cdot-}]$
Triplet
$D^{\cdot+}+AH^{\cdot}$
Signalling State


D_2
A
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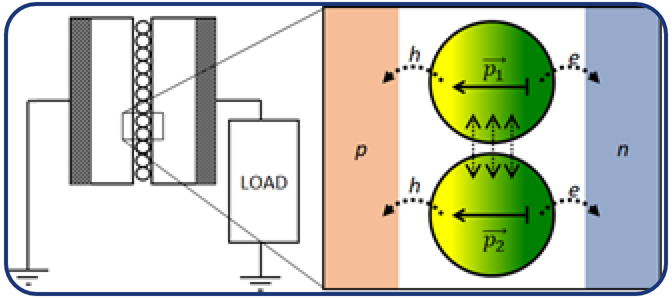
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THANK YOU