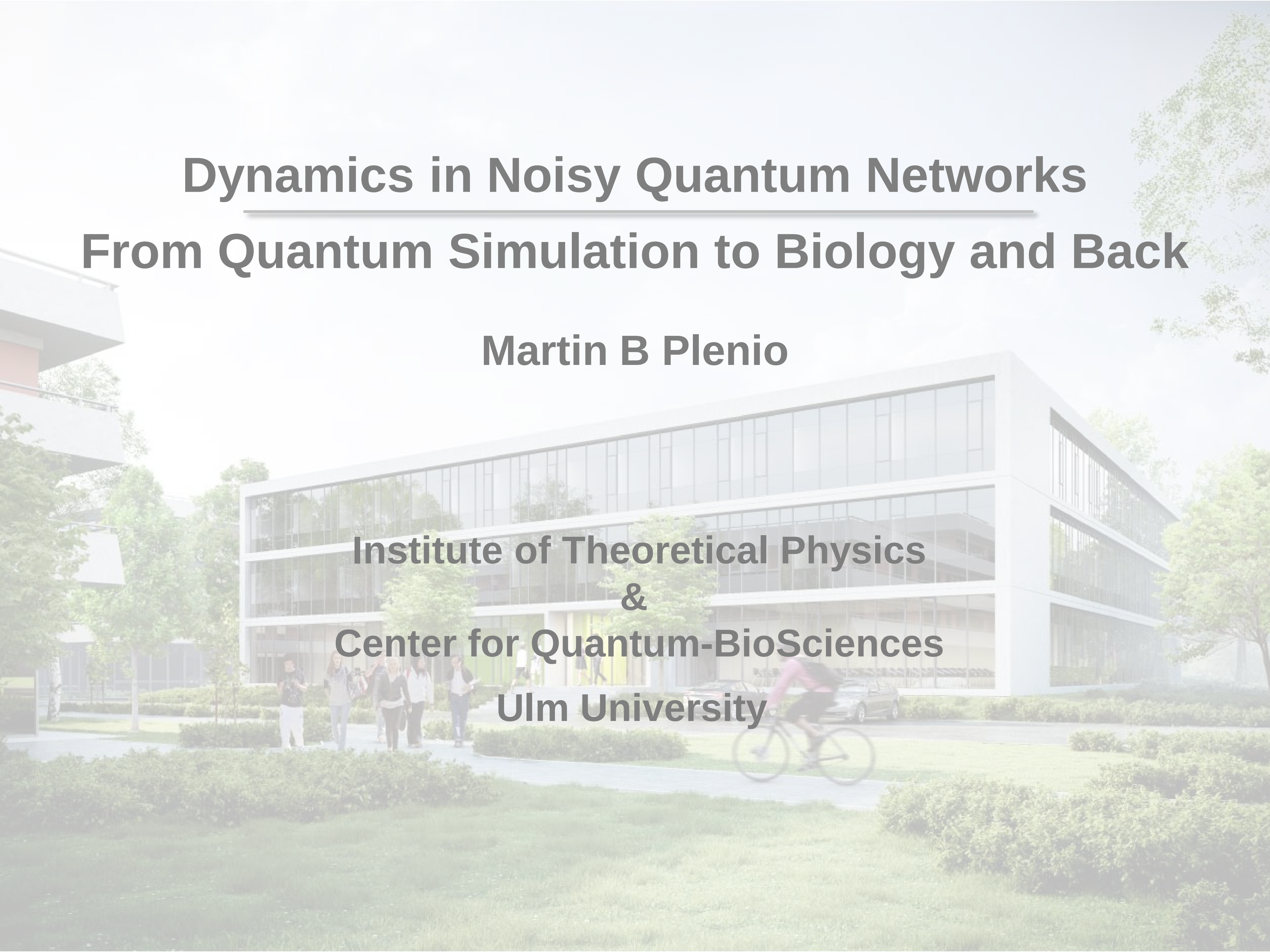


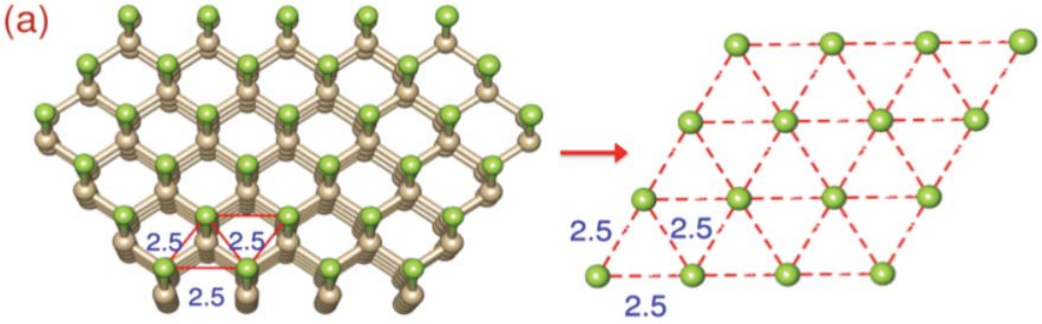
Dynamics in Noisy Quantum Networks

From Quantum Simulation to Biology and Back

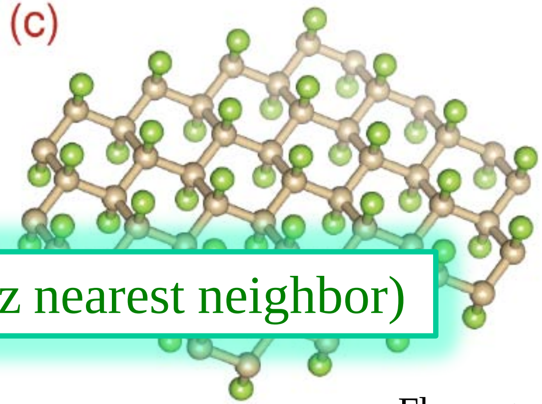
Martin B Plenio

Institute of Theoretical Physics
&
Center for Quantum-BioSciences
Ulm University

A Diamond Surface Simulator

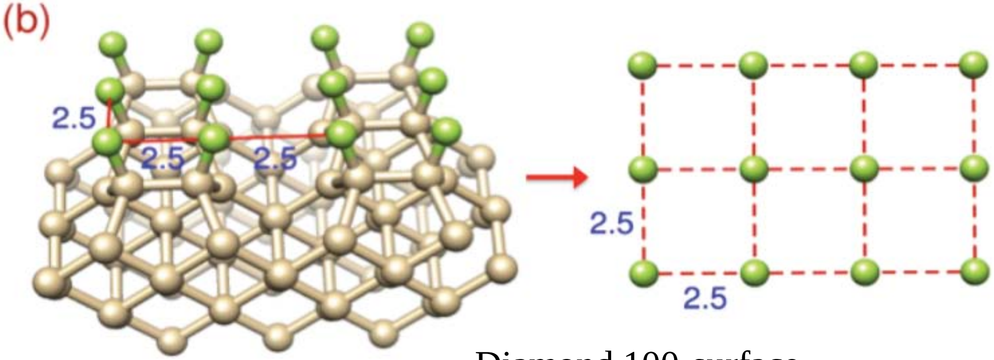


Diamond 111-surface



Fluorographene

F-F (long range dipole) interaction (6.8kHz nearest neighbor)



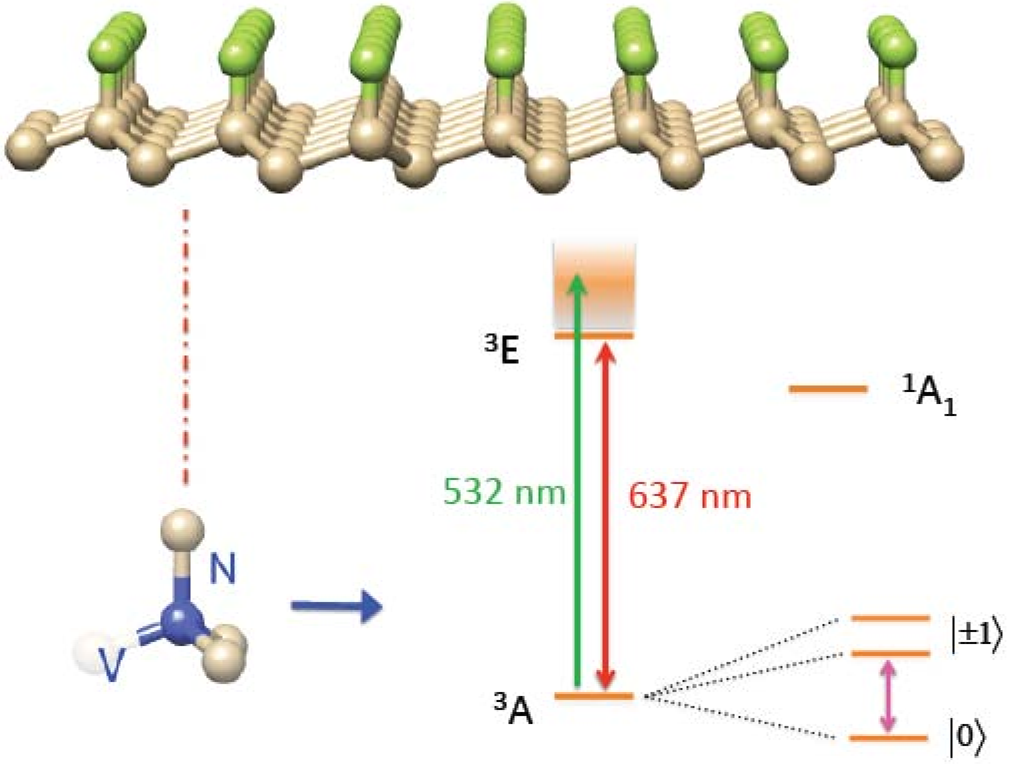
Diamond 100-surface

Cai, Retzker, Jelezko, Plenio, Nature Phys. 2013

A Diamond Surface Simulator

Address three main challenges

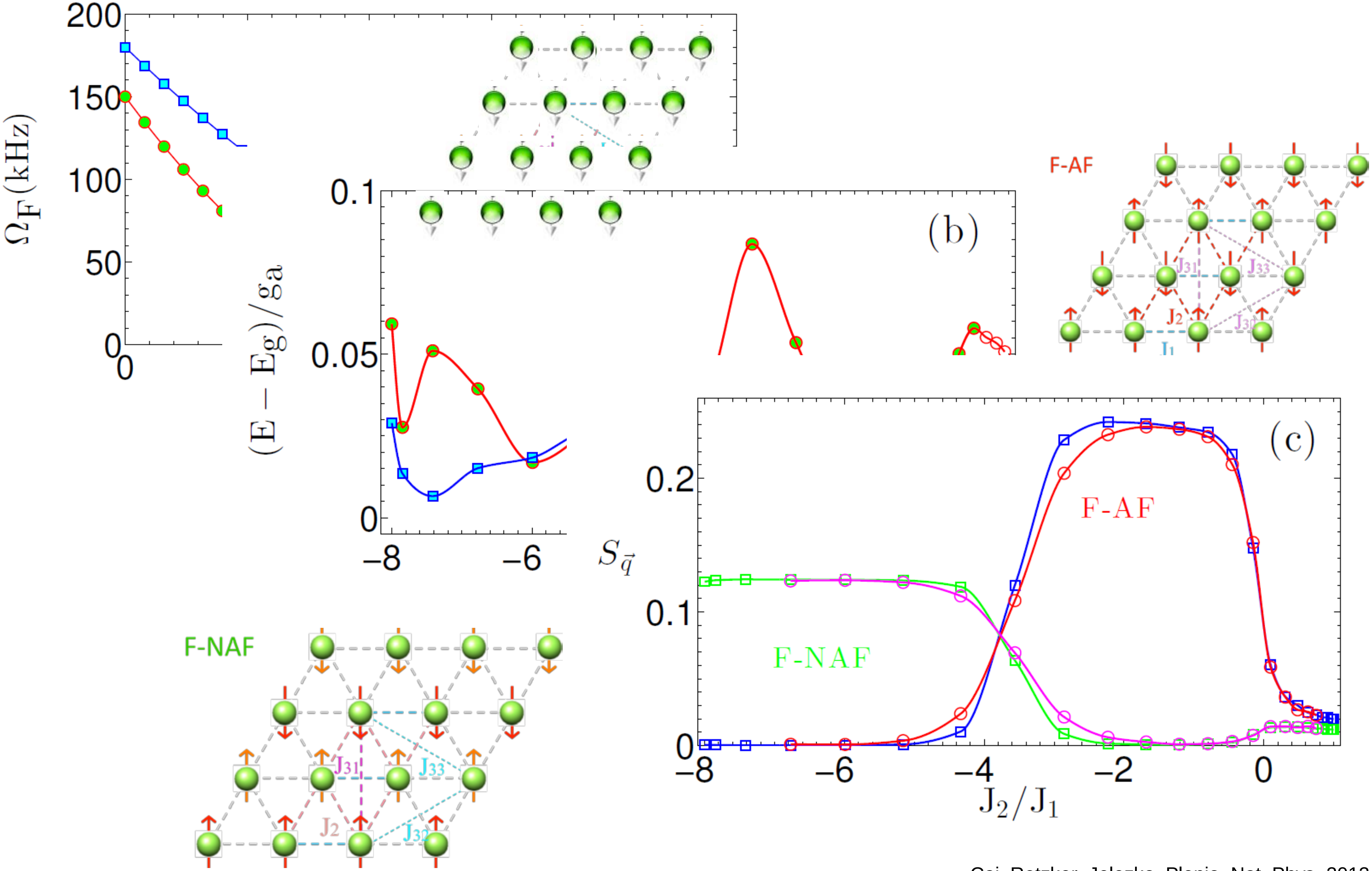
- Initialization of the nuclear spin lattice
- Control of the Hamiltonian of the nuclear spin lattice
- Readout from the nuclear spin lattice



Cai, Retzker, Jelezko, Plenio, Nature Phys. 2013

A Diamond Surface Simulator

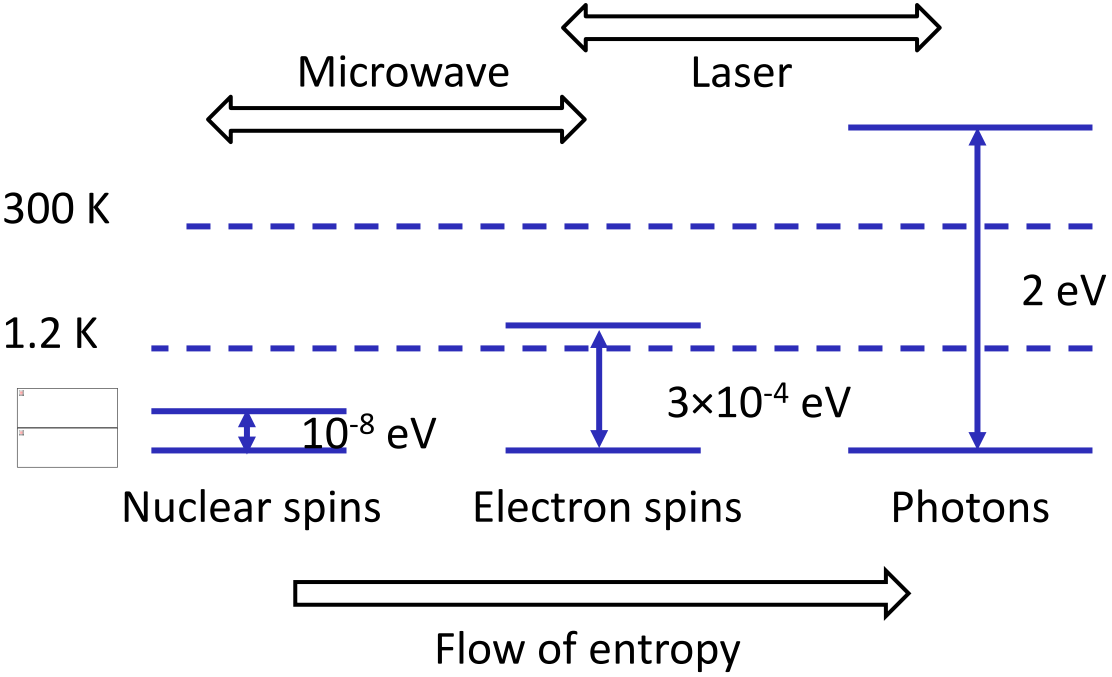
Ground State Preparation & Detecting Quantum Phases



Cai, Retzker, Jelezko, Plenio, Nat. Phys. 2013

An Atomic Scale Fridge

Converting Light to Nuclear Spin Polarisation



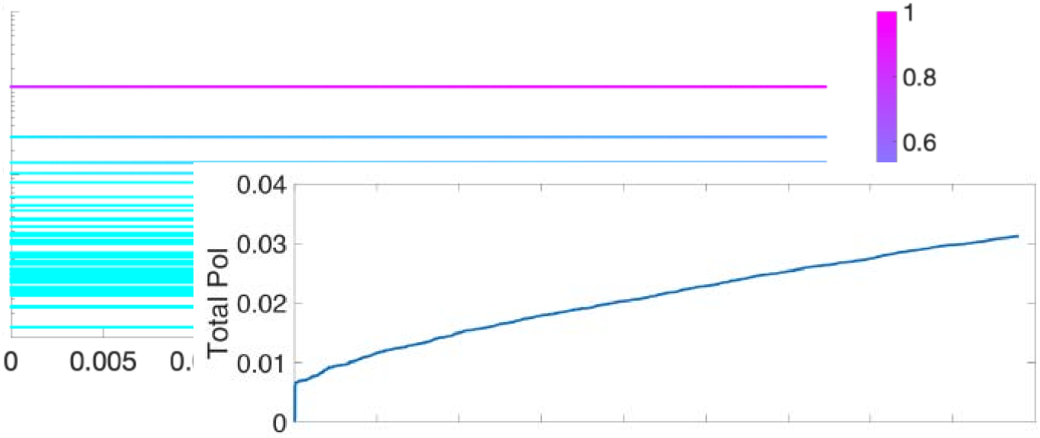
Polarisation Dynamics of Ensembles

Dark States and the Benefits of Noise

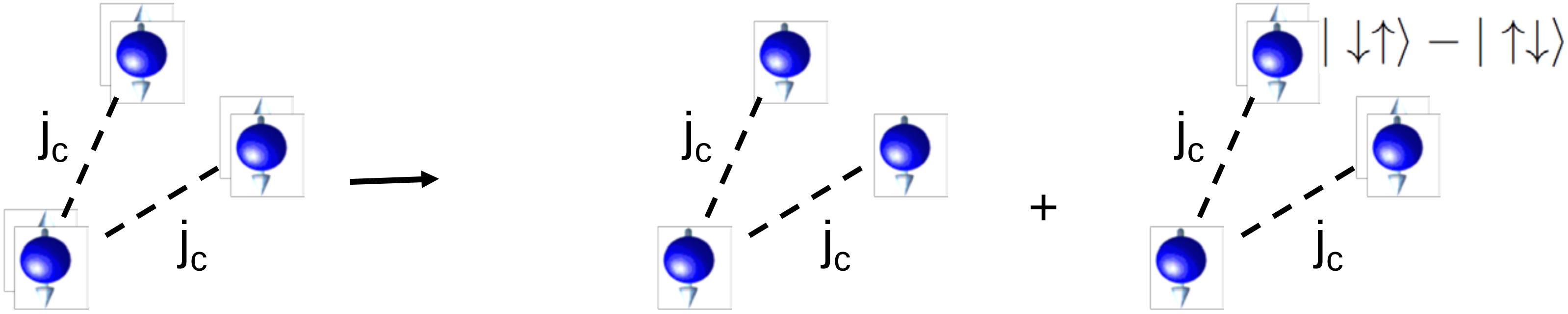
The polarisation protocol reaches a stationary state well before perfect polarisation is reached

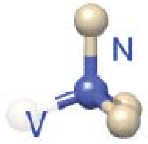
Cai, Retzker, Jelezko, Plenio, Nature Phys. 2013
H-Y Yu, Y. Luo, W. Yao, Chin. Phys. Lett. 2013

No dephasing



Origin: A significant part of the Hilbert space is decoupled due to destructive interference





Plenio, Huelga, Beige, Knight. *Cavity Loss Induced Generation of Entangled Atoms.* Phys. Rev. A 1999

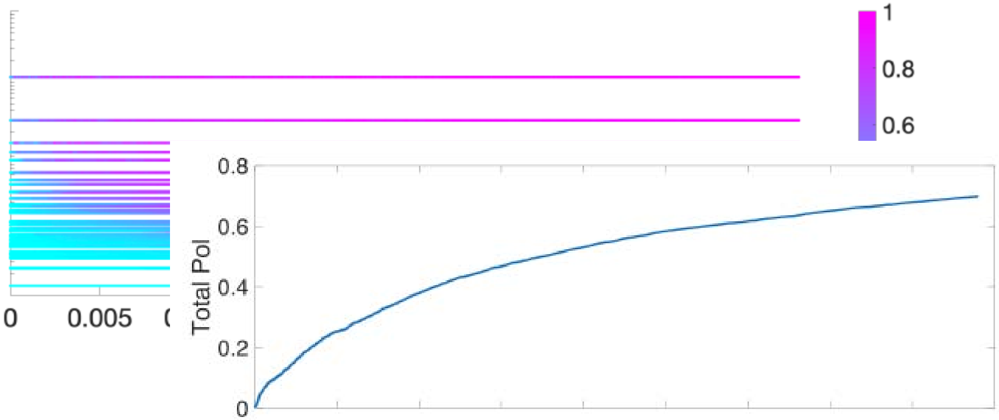
Polarisation Dynamics of Ensembles

Dark States and the Benefits of Noise

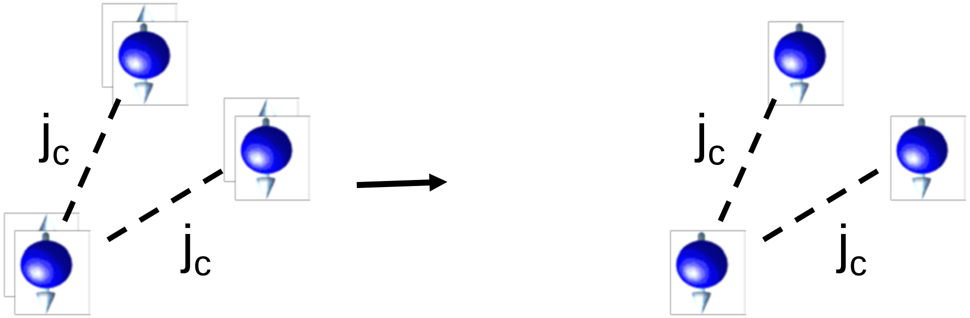
Moderate dephasing

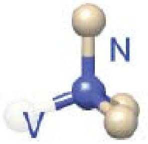
Now polarisation protocol reaches a stationary state that is perfectly polarised

Cai, Retzker, Jelezko, Plenio, Nature Phys. 2013



Origin: Dephasing noise disrupts destructive interference





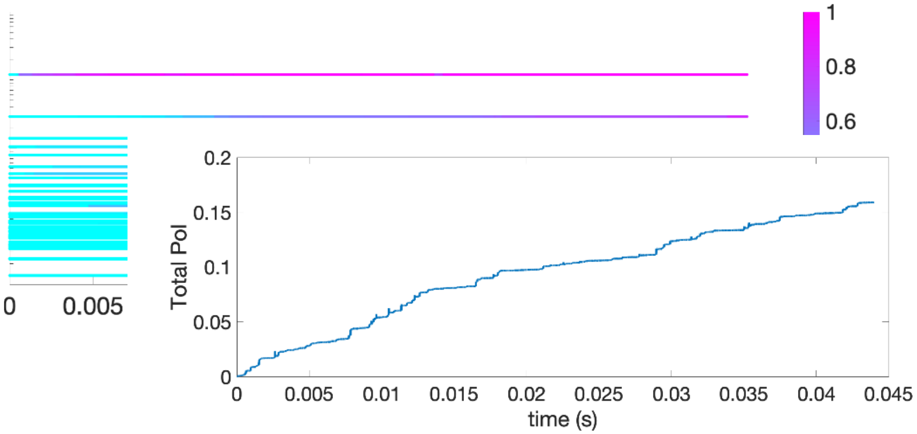
Polarisation Dynamics of Ensembles

Dark States and the Benefits of Noise

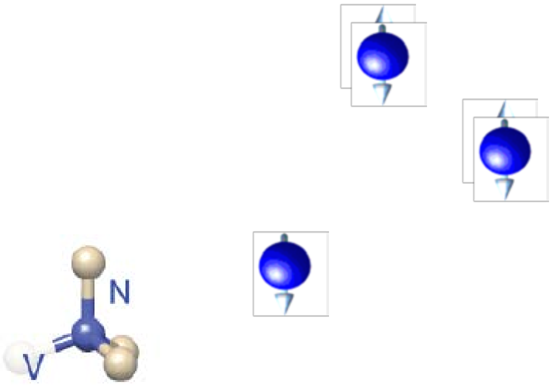
Stong dephasing

Now polarisation protocol fails as diffusion and coupling is suppressed

Cai, Retzker, Jelezko, Plenio, Nature Phys. 2013

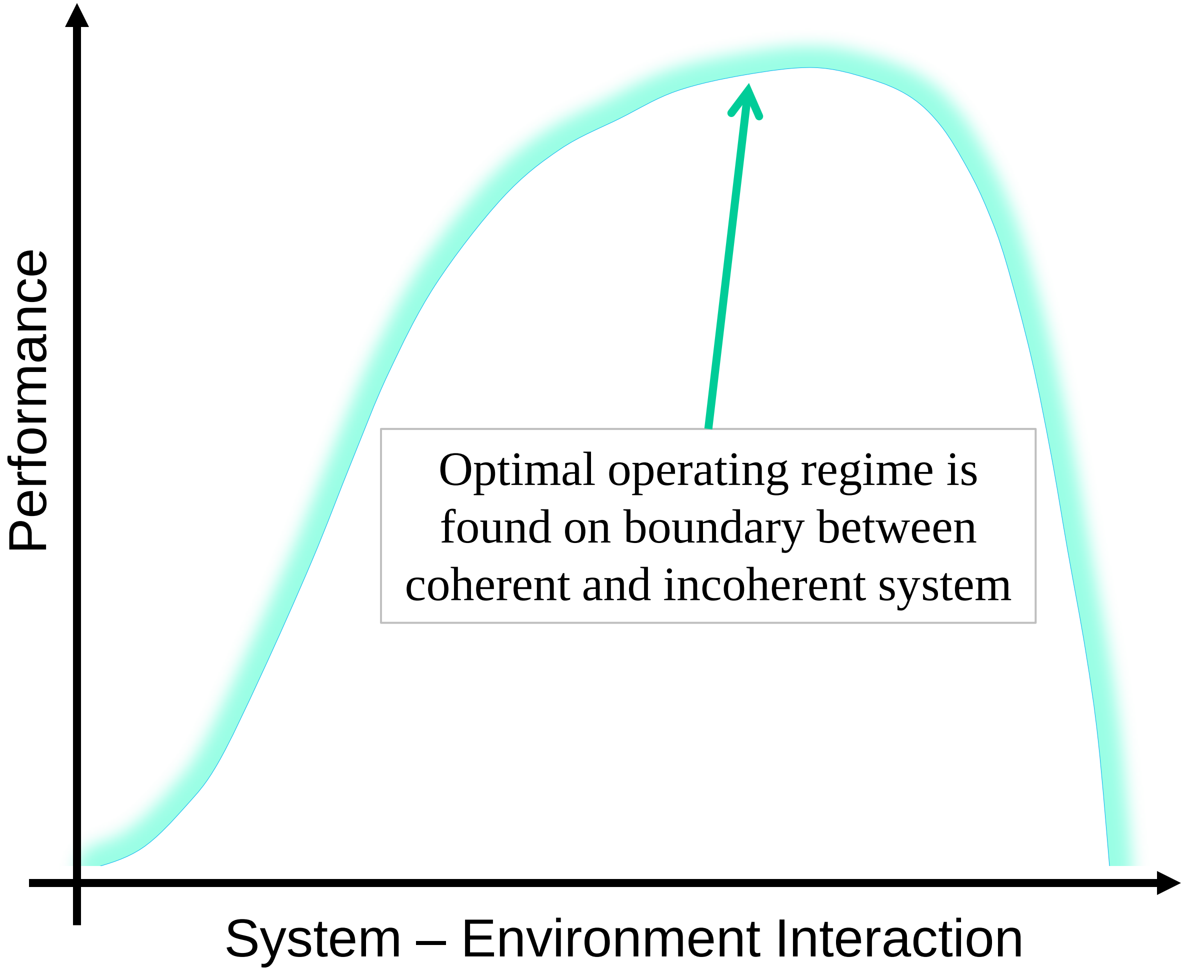


Origin: Dephasing noise disrupts constructive coherence, here the coherent spin diffusion



Environment Assisted Quantum Dynamics

A Moderate Level of Noise is Good



Optimal operating regime is found on boundary between coherent and incoherent system

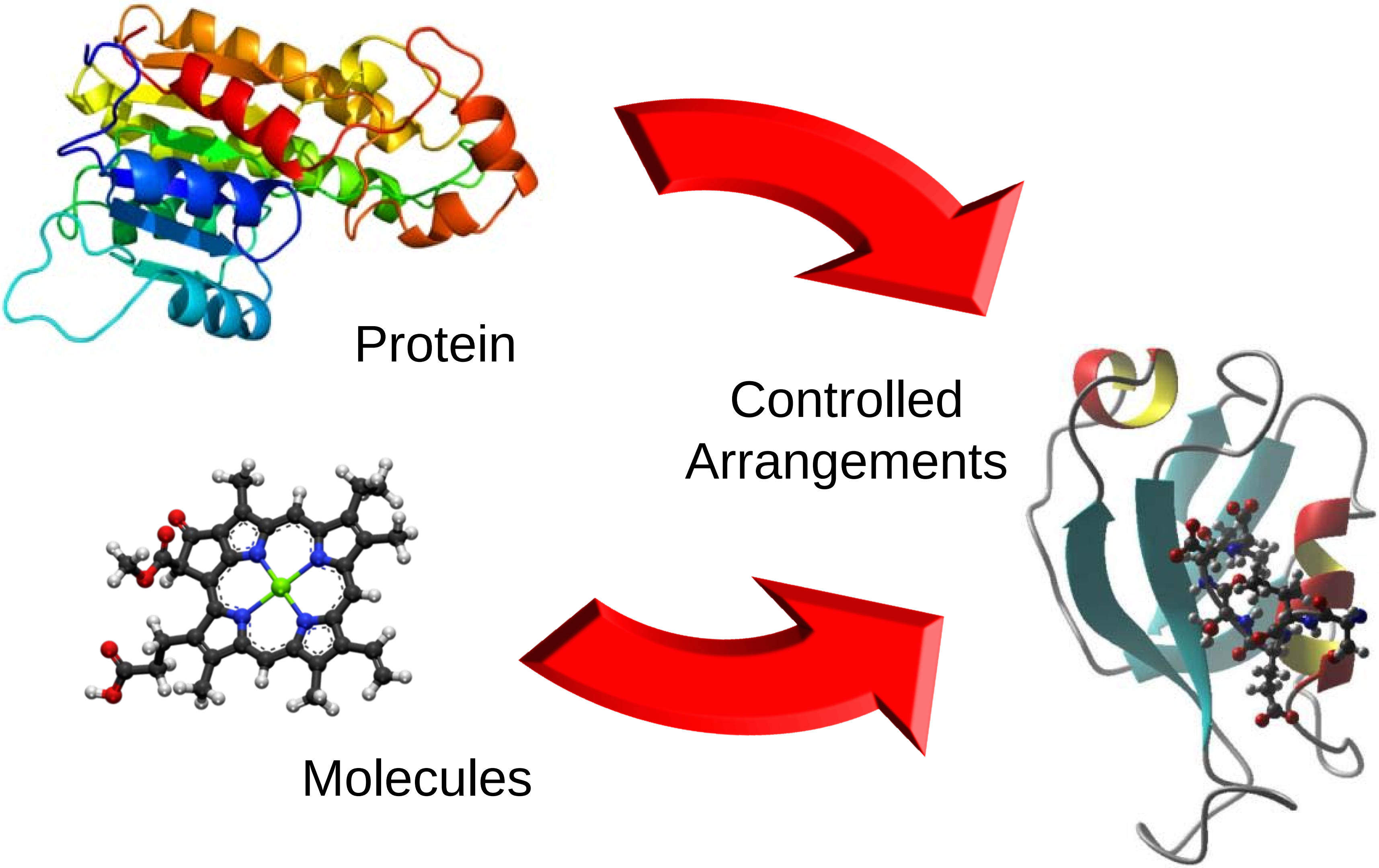
Plenio & Huelga, NJP 2008

Caruso, Chin, Datta, Huelga, Plenio, JCP 2009

Chin, Datta, Caruso, Huelga & Plenio, NJP 2010

Quantum Dynamics in Biology

Controlling Structure of System and Environment



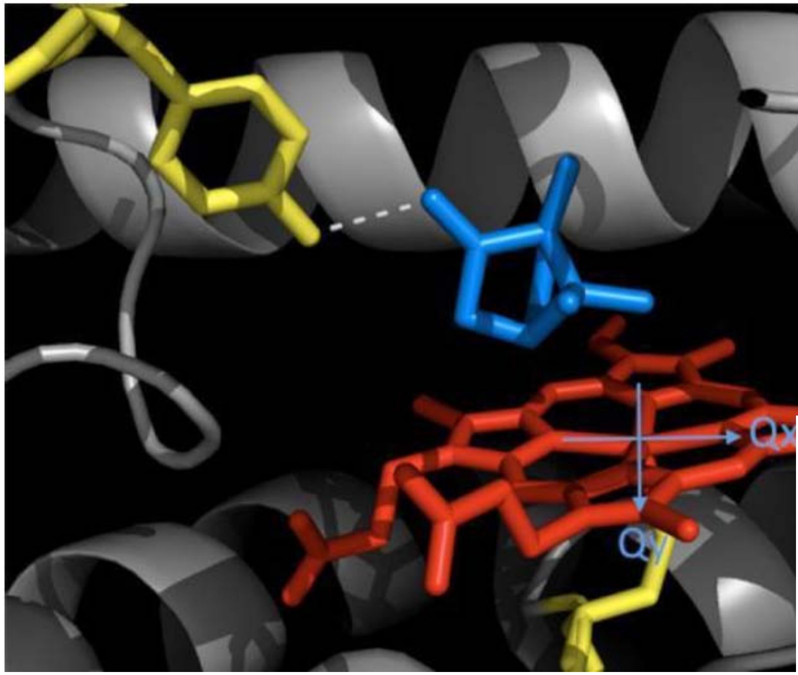
Protein

Controlled Arrangements

Molecules

Quantum Dynamics in Biology

Control Implies Noise

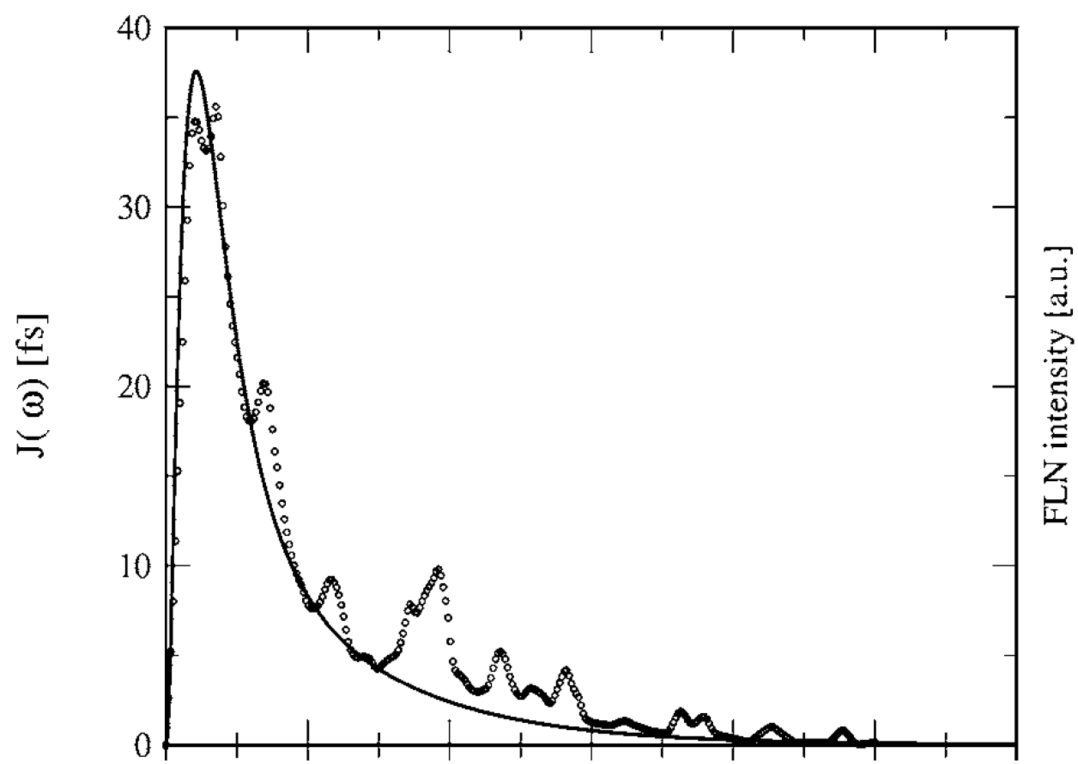


- Coupling is neither weak nor strong
- Spectral density is highly structured
- Difficult to simulate numerically

Vibrations affects
local environment

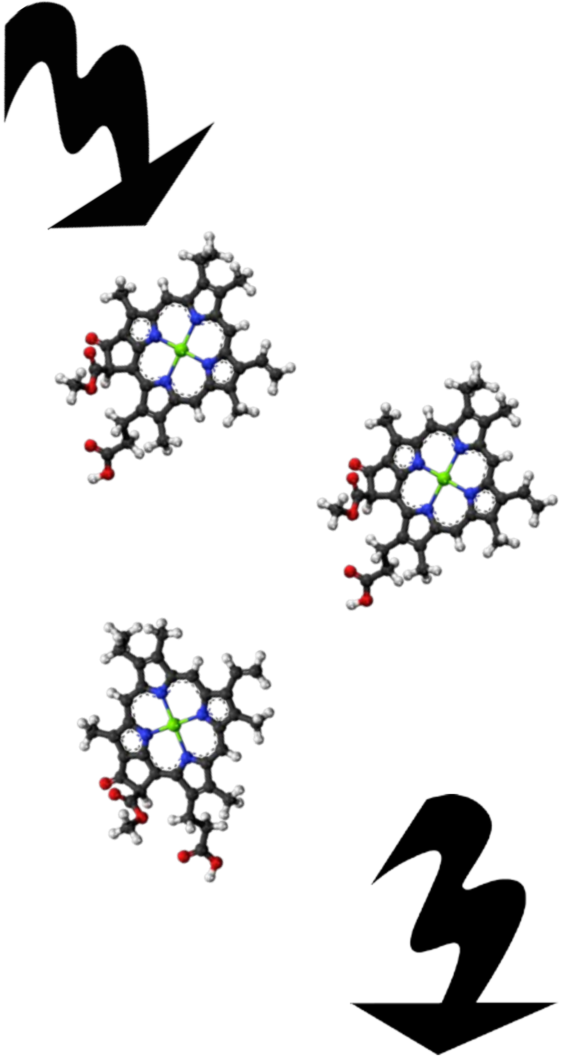
⇨ excitation energy fluctuates

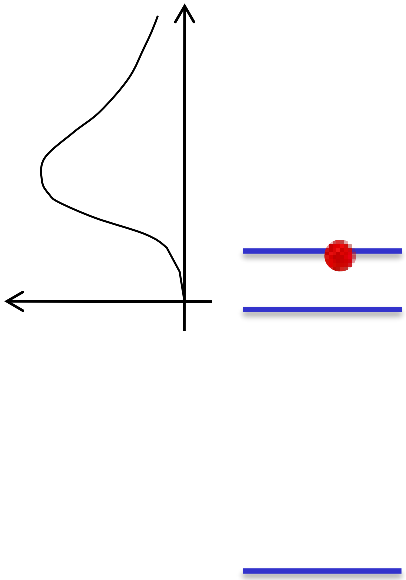
⇨ dephasing



Environment Assisted Quantum Dynamics

Tuning Electronic and Vibrational Structures

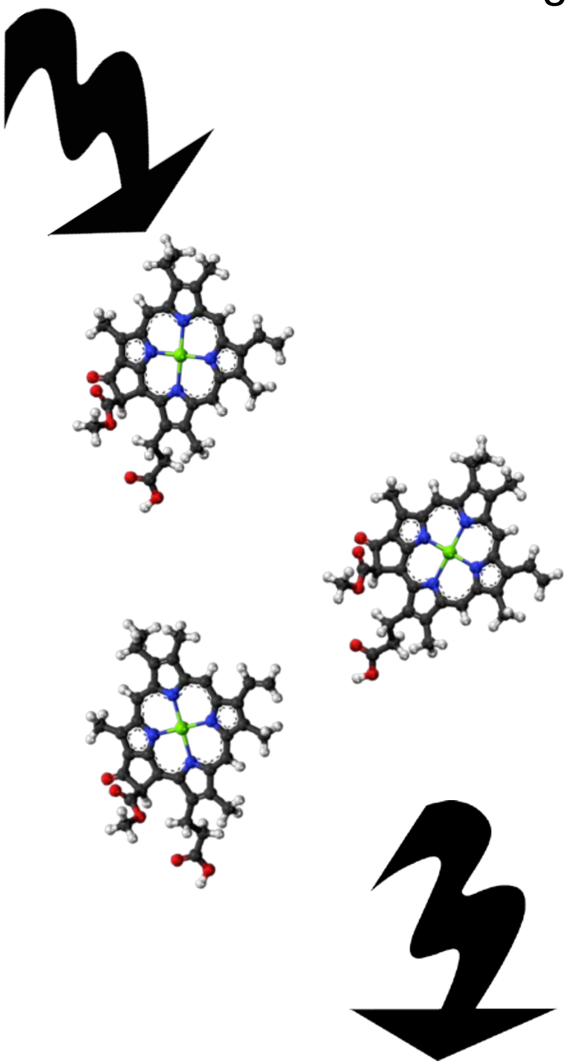


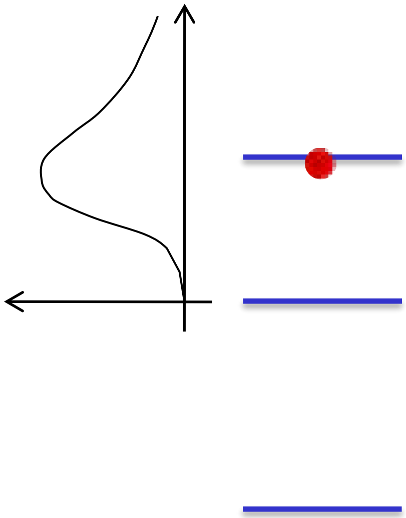


Chin, Datta, Caruso, Huelga & Plenio, NJP 2010
Chin, Huelga, Plenio, Phil. Trans. Roy. Soc. 2012
del Rey, Chin, Huelga, Plenio, J. Phys. Chem. Lett. 2013

Environment Assisted Quantum Dynamics

Tuning Electronic and Vibrational Structures





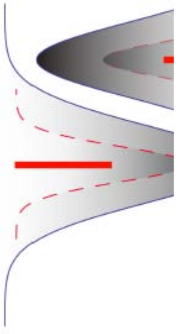
System-Environment interaction not too strong to suppress formation of dressed states

System-Environment interaction strong enough to drive transitions between dressed states

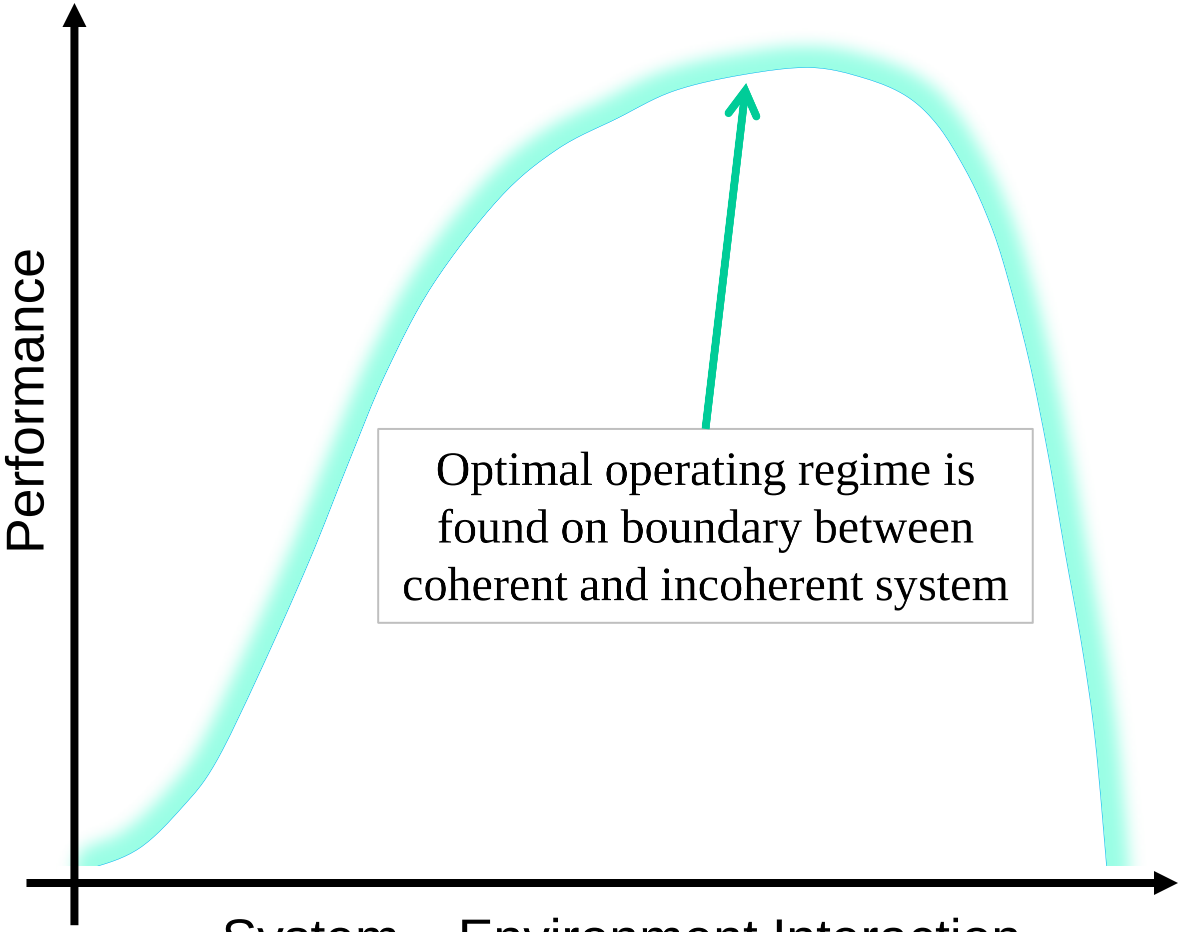
Chin, Datta, Caruso, Huelga & Plenio, NJP 2010
Chin, Huelga, Plenio, Phil. Trans. Roy. Soc. 2012
del Rey, Chin, Huelga, Plenio, J. Phys. Chem. Lett. 2013

Environment Assisted Quantum Dynamics

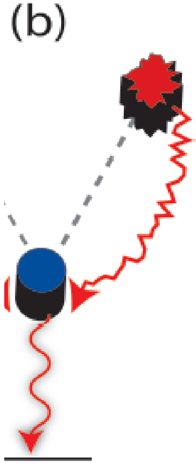
A Moderate Level of Noise is Good



Effectiv
Rate ≅



Optimal operating regime is found on boundary between coherent and incoherent system



$$\frac{1}{+ c_0 + c_{-1}\gamma^{-1}}$$

$\downarrow /$

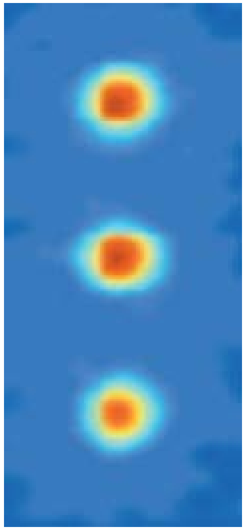
Plenio & Huelga, NJP 2008

Caruso, Chin, Datta, Huelga, Plenio, JCP 2009

Chin, Datta, Caruso, Huelga & Plenio, NJP 2010

Coherence and Environments

Quantum Dynamics in Hot and Noisy Environments



Quantum technologies

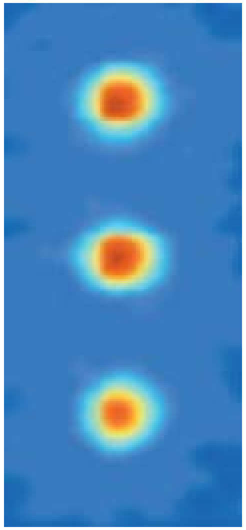
Isolate system to observe & exploit quantum behaviour

Seconds

Timescales

Coherence and Environments

Quantum Dynamics in Hot and Noisy Environments

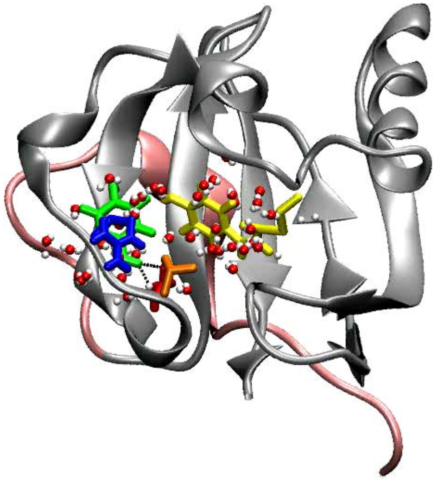


Quantum technologies

Isolate system to observe &
exploit quantum behaviour

Biology

Systems in strong contact
with environment



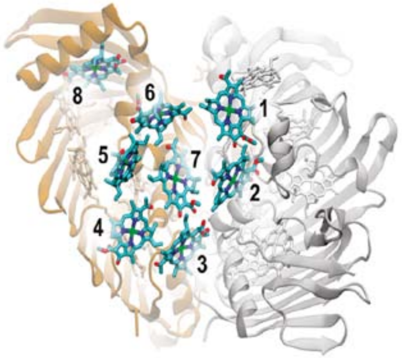
Nuclear spins electron spins excitons & charges

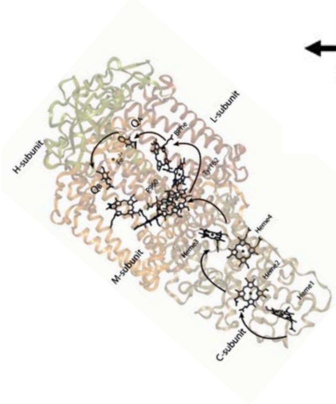
Seconds μs - ns - ps - fs

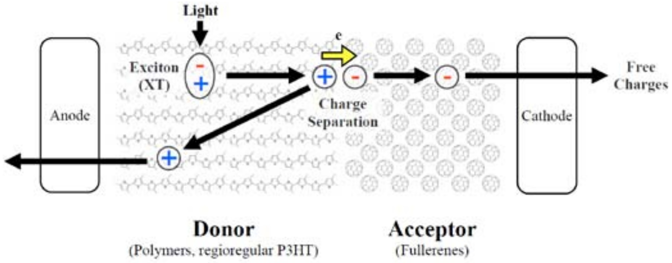
Timescales

Biological Processes: Vibrations, Dynamics & Quanta

Observe Biological (Quantum) Dynamics





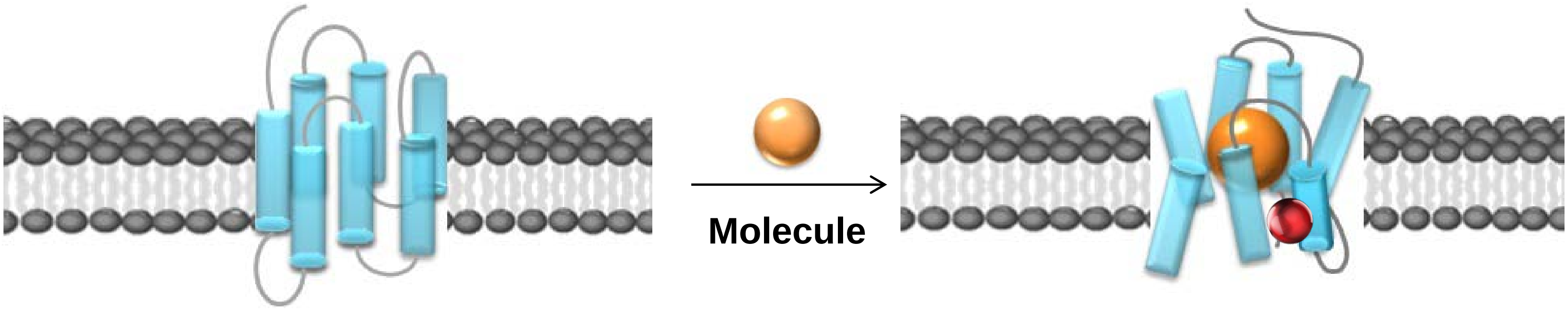


Photosynthesis, Olfaction, Magnetoreception

Huelga & Plenio, Contemporary Physics 54, 181 (2013)

Biological Processes: Vibrations, Dynamics & Quanta

Observe Biological (Quantum) Dynamics



G-protein coupled receptor (GPCR)

Receptor activation

Photosynthesis,

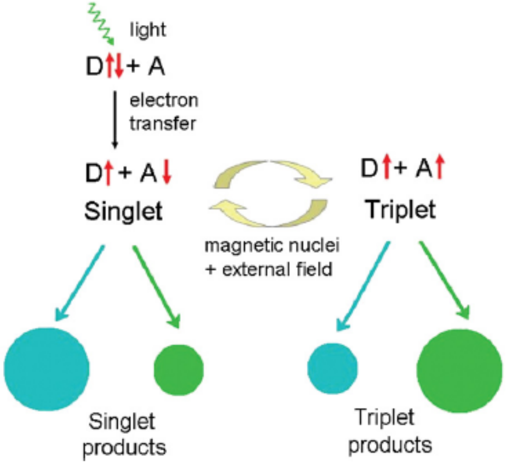
Olfaction,

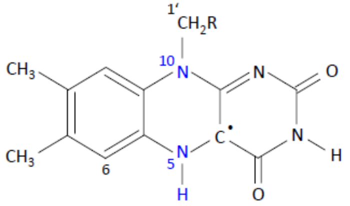
Magnetoreception

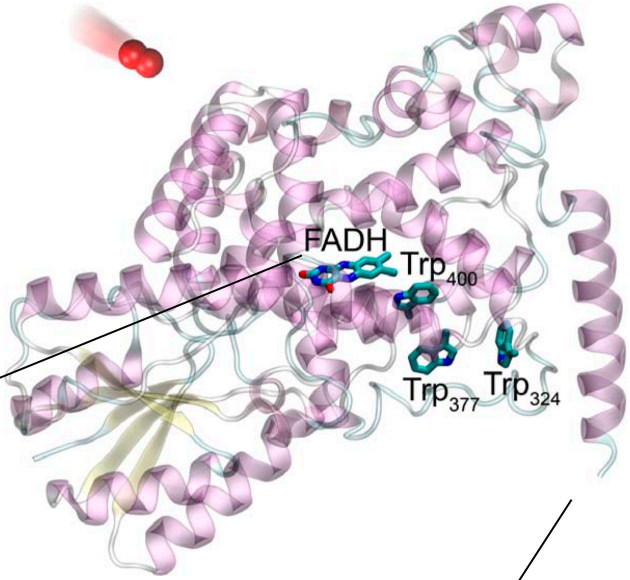
Huelga & Plenio, Contemporary Physics 54, 181 (2013)

Biological Processes: Vibrations, Dynamics & Quanta

Observe Biological (Quantum) Dynamics







Photosynthesis,

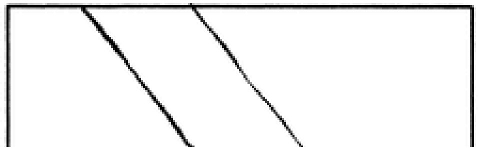
Olfaction,

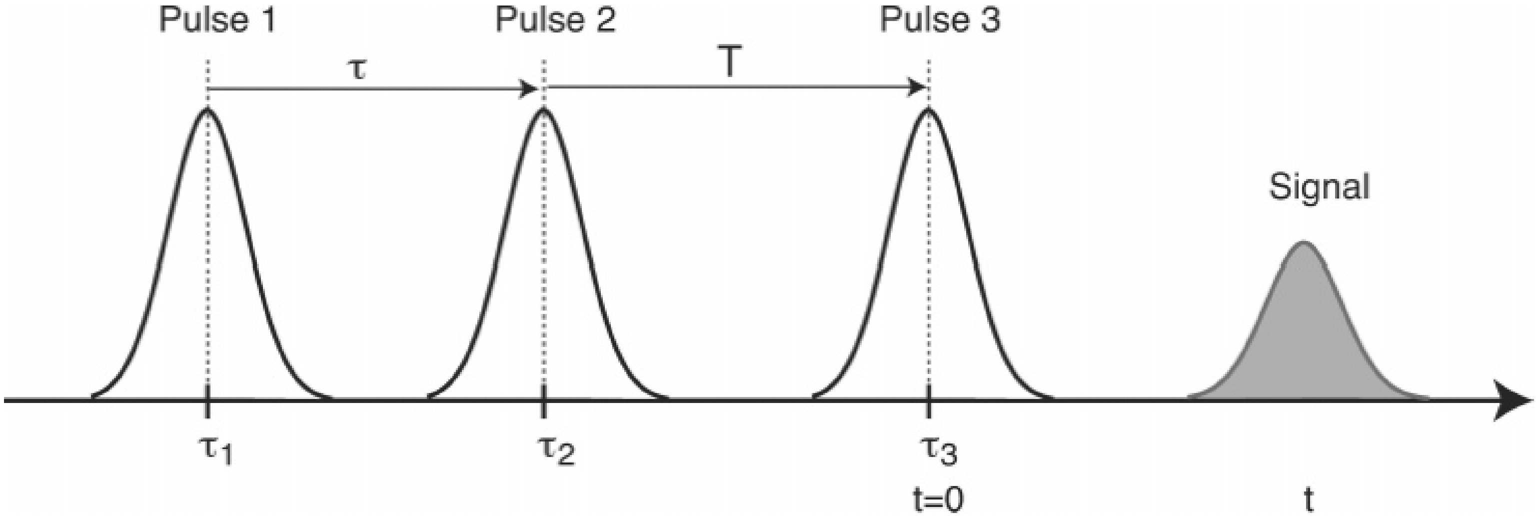
Magnetoreception

Huelga & Plenio, Contemporary Physics 54, 181 (2013)

Measuring Electronic Dynamics

Ultrafast 2D-spectroscopy

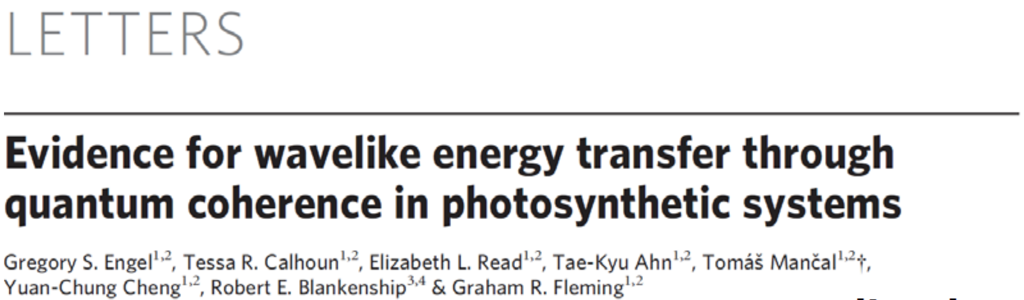




Push with period of the swing gives increases amplitude

Push with half the period of the swing gives small amplitude

Experimental Evidence



LETTERS

Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems

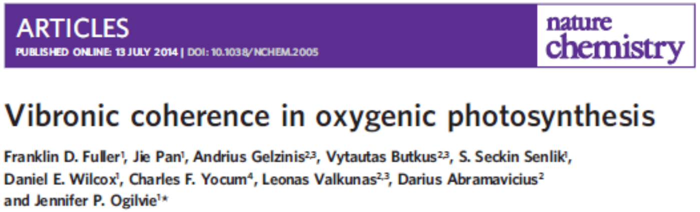
Gregory S. Engel[1,2], Tessa R. Calhoun[1,2], Elizabeth L. Read[1,2], Tae-Kyu Ahn[1,2], Tomáš Mančal[1,2]†,
Yuan-Chung Cheng[1,2], Robert E. Blankenship[3,4] & Graham R. Fleming[1,2]

Engel et al, Nature 446, 782 (2007)

Long-lived quantum coherence in photosynthetic complexes at physiological temperature

Gitt Panitchayangkoon[a], Dugan Hayes[a], Kelly A. Fransted[a], Justin R. Caram[a], Elad Harel[a], Jianzhong Wen[b],
Robert E. Blankenship[b], and Gregory S. Engel[a,1]

Panitchayangkoon et al, PNAS 107, 12766 (2010)



ARTICLES

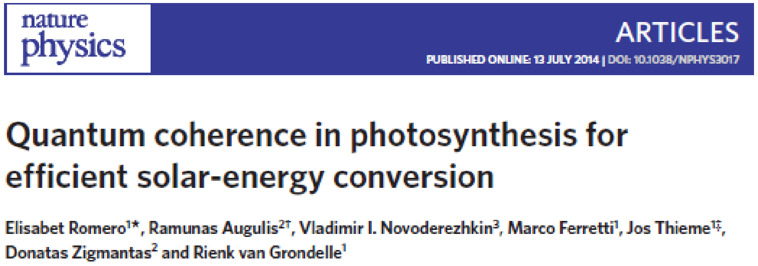
PUBLISHED ONLINE: 13 JULY 2014 | DOI: 10.1038/NCHEM.2005

nature chemistry

Vibronic coherence in oxygenic photosynthesis

Franklin D. Fuller[1], Jie Pan[1], Andrius Gelzinis[2,3], Vytautas Butkus[2,3], S. Seckin Senlik[1],
Daniel E. Wilcox[1], Charles F. Yocum[4], Leonas Valkunas[2,3], Darius Abramavicius[2]
and Jennifer P. Ogilvie[1]*

F. D. Fuller et al, Nature Chem. 6, 706 (2014)



nature physics

ARTICLES

PUBLISHED ONLINE: 13 JULY 2014 | DOI: 10.1038/NPHYS3017

Quantum coherence in photosynthesis for efficient solar-energy conversion

Elisabet Romero[1]*, Ramunas Augulis[2]†, Vladimir I. Novoderezhkin[3], Marco Ferretti[1], Jos Thieme[1]‡,
Donatas Zigmantas[2] and Rienk van Grondelle[1]

E. Romero et al, Nature Phys. 10, 676 (2014)

nature COMMUNICATIONS

ARTICLE

Received 21 Jan 2015 | Accepted 4 Jun 2015 | Published 9 Jul 2015

DOI: 10.1038/ncomms8755

OPEN

Vibronic origin of long-lived coherence in an artificial molecular light harvester

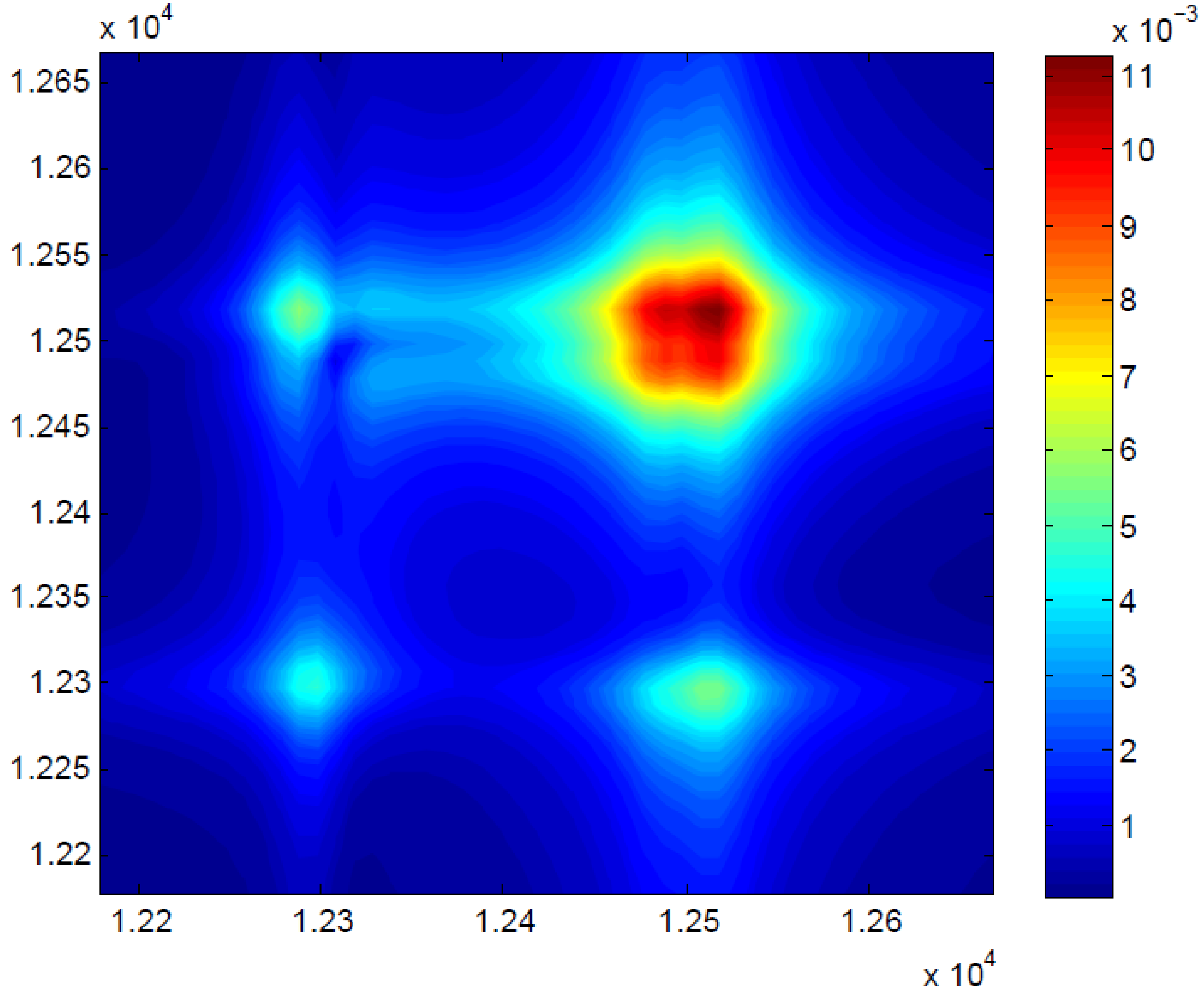
James Lim[1,*], David Paleček[2,3,*], Felipe Caycedo-Soler[1], Craig N. Lincoln[4], Javier Prior[5], Hans von Berlepsch[6],
Susana F. Huelga[1], Martin B. Plenio[1], Donatas Zigmantas[2] & Jürgen Hauer[4]

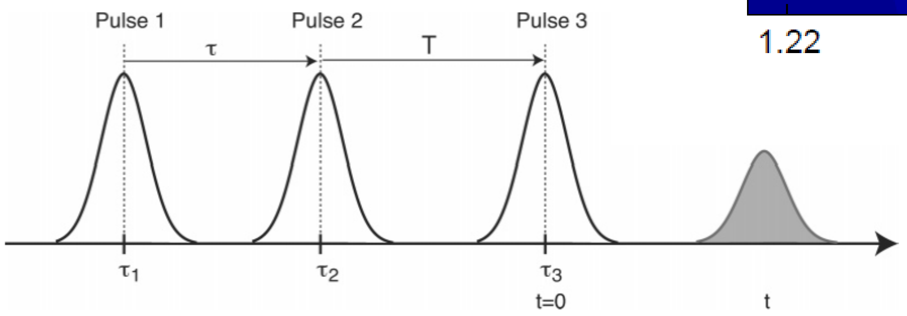
J. Lim et al, Nature Comm. 6, 7755 (2015)

■ ■ ■

Non-equilibrium System-Environment Dynamics

Long-lived Coherence at 277K

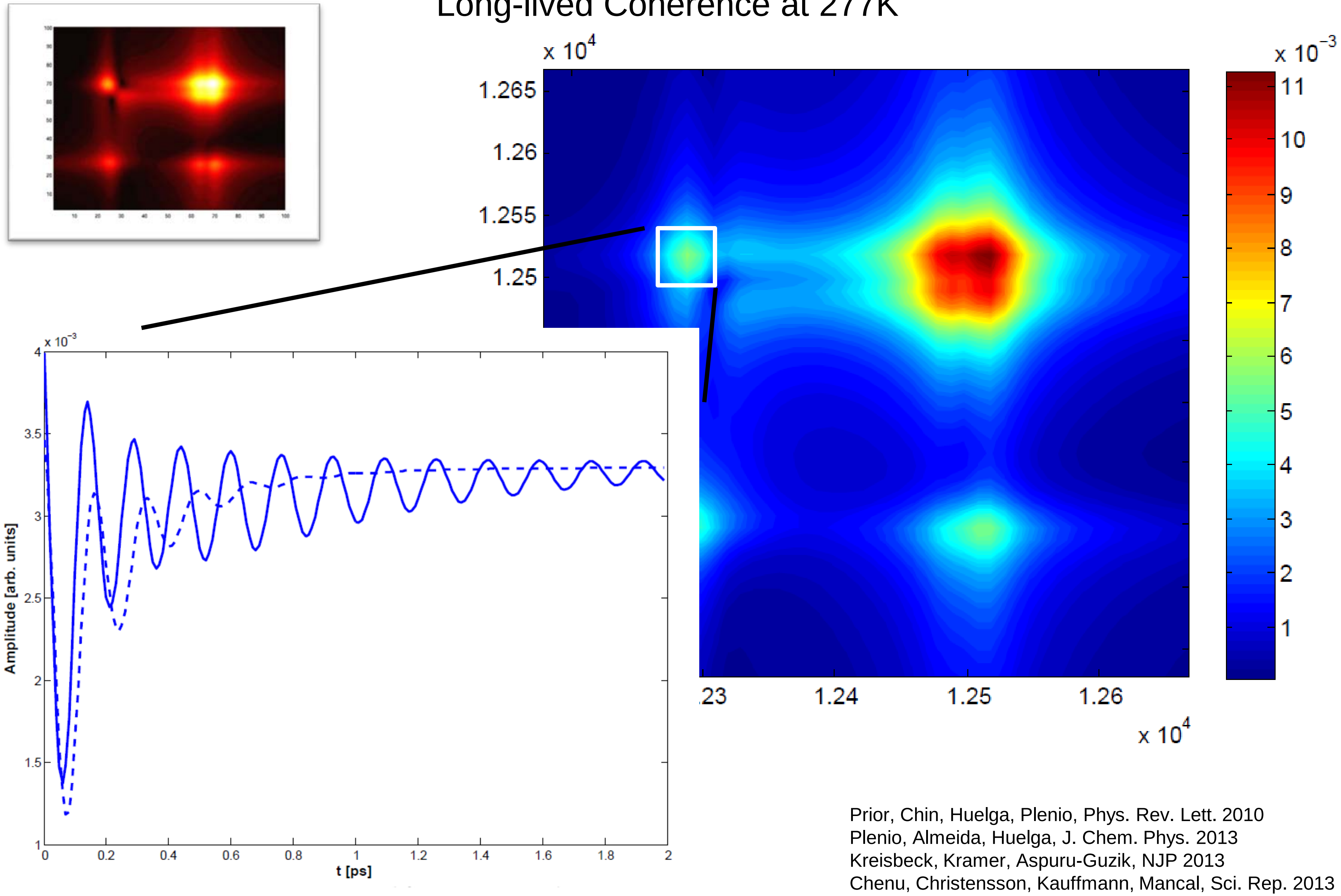




Prior, Chin, Huelga, Plenio, Phys. Rev. Lett. 2010
Plenio, Almeida, Huelga, J. Chem. Phys. 2013
Kreisbeck, Kramer, Aspuru-Guzik, NJP 2013
Chenu, Christensson, Kauffmann, Mancal, Sci. Rep. 2013
Tiwari, Peters, Jonas, PNAS 2013

Non-equilibrium System-Environment Dynamics

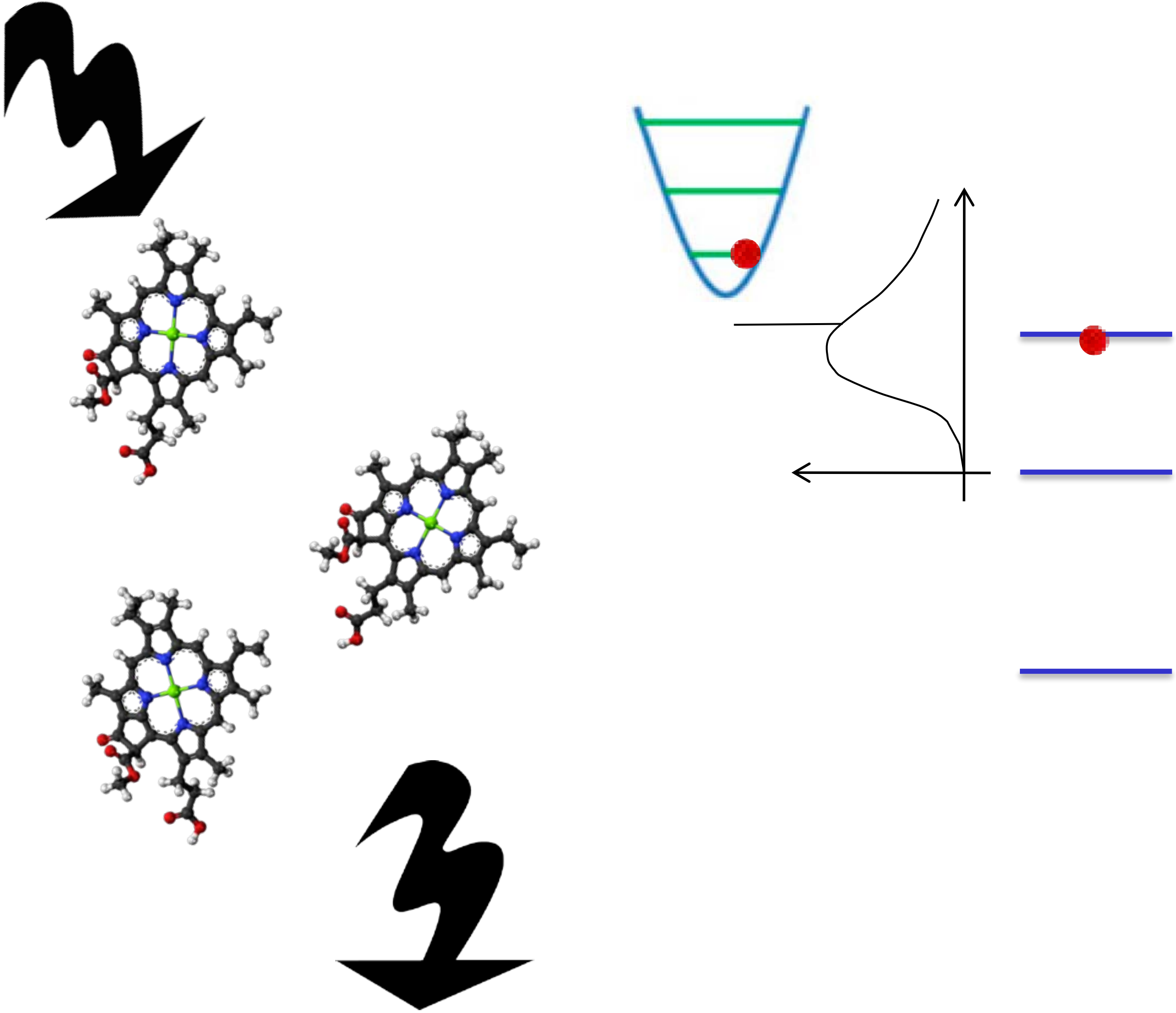
Long-lived Coherence at 277K



Prior, Chin, Huelga, Plenio, Phys. Rev. Lett. 2010
Plenio, Almeida, Huelga, J. Chem. Phys. 2013
Kreisbeck, Kramer, Aspuru-Guzik, NJP 2013
Chenu, Christensson, Kauffmann, Mancal, Sci. Rep. 2013
Tiwari, Peters, Jonas, PNAS 2013

Environment Assisted Quantum Dynamics

Tuning Electronic and Vibrational Structures



Excitonic and vibrational resonance allows for periodic exchange of excitation and maintains electronic oscillatory dynamics

Transport Dynamics for Sensing

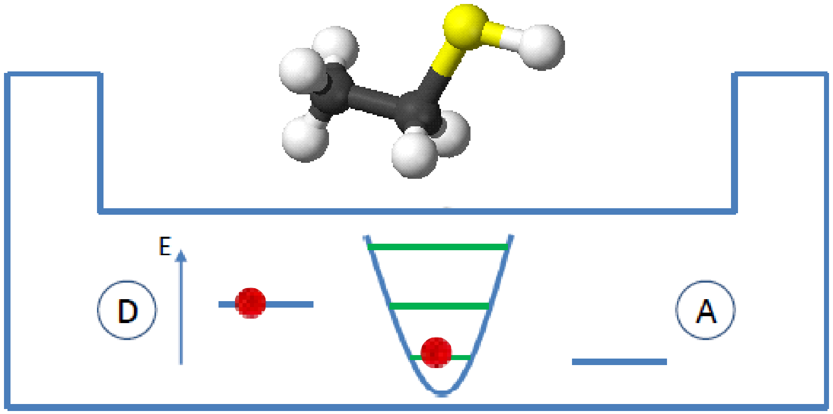
Sensing a ~~Vibration~~ Molecule

Turin, Chem. Sens. 1996
Brookes, Hartoutsiou, Horsfield & Stoneham, PRL 2007
Solov‘yov, Chang, Schulten, PCCP 2012

Differentiation of isotopic odorants:
Franco, Turin, Mershn, Skoulakis, PNAS 2011
Gane, Georganakis, Maniati, Vamvakias, Ragoussis, Skoulakis, Turin, PLOS 2012

Transport Dynamics for Sensing

Sensing a ~~Vibration~~ Molecule



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Differentiation of isotopic odorants:
Franco, Turin, Mershn, Skoulakis, PNAS 2011
Gane, Georganakis, Maniati, Vamvakias, Ragoussis, Skoulakis, Turin, PLOS 2012

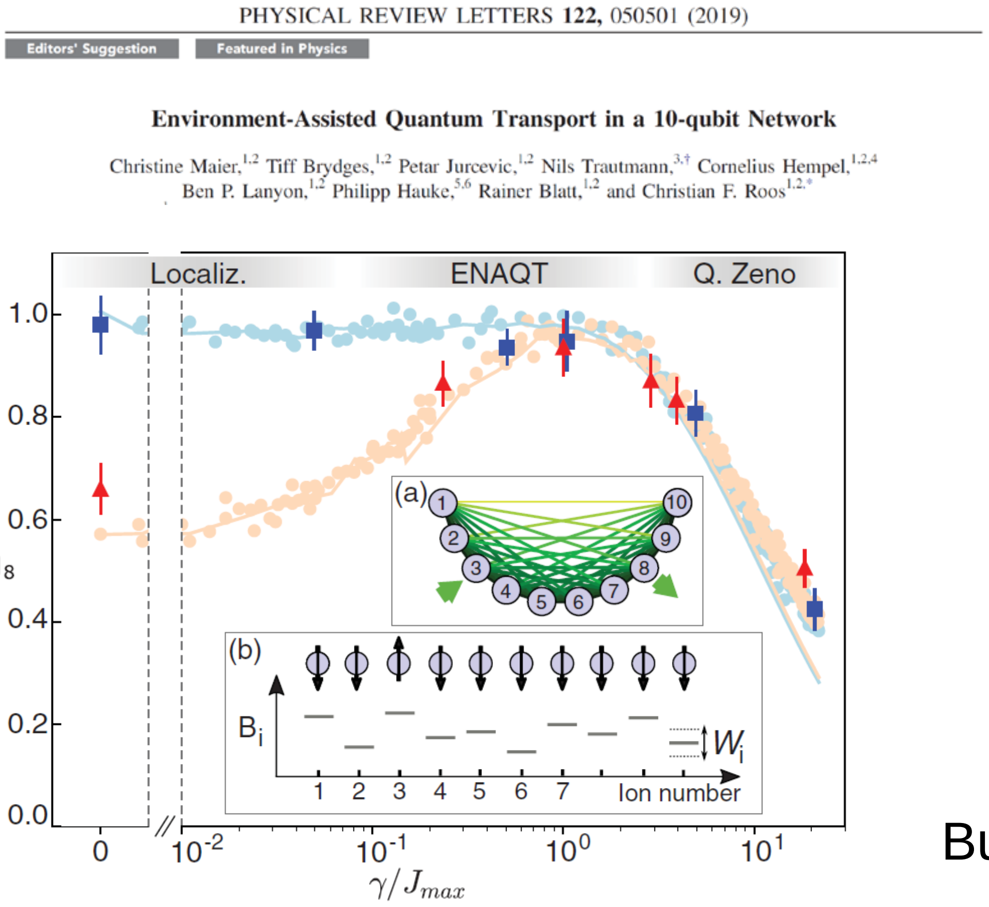
Quantum Simulation Challenge

System-Environment interaction is in a non-Markovian regime in which standard Master equation deliver qualitatively and quantitatively wrong answers.

Requires costly computational methods for accurate modeling

Already 5-10 sites with approximated spectral density is at the limit of current classical computer technology.

Quantum Simulation Challenge

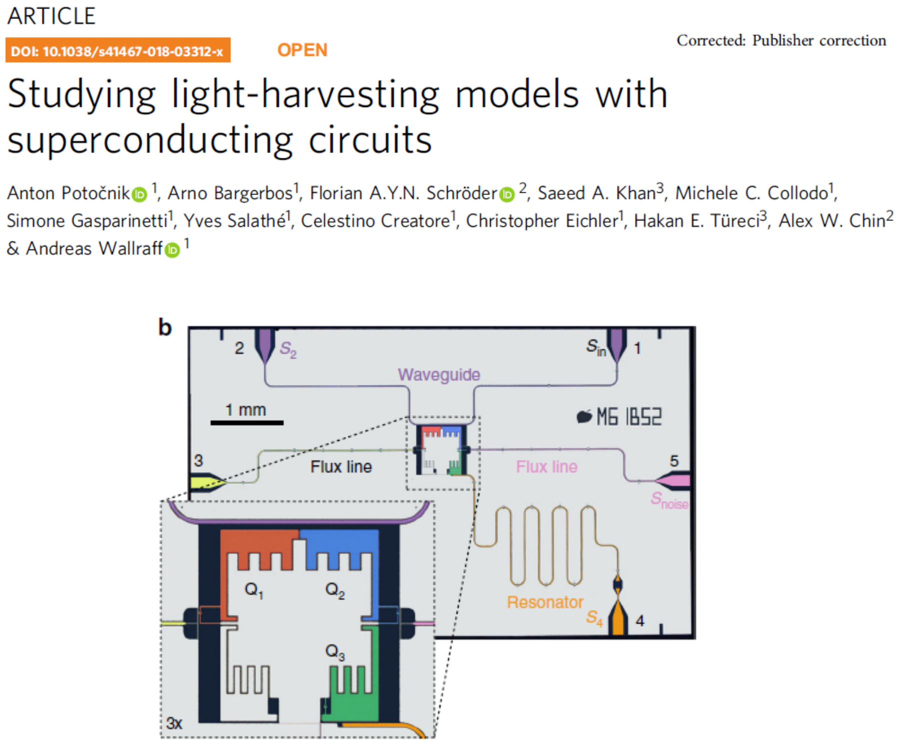


PHYSICAL REVIEW LETTERS **122,** 050501 (2019)

Editors' Suggestion **Featured in Physics**

Environment-Assisted Quantum Transport in a 10-qubit Network

Christine Maier,[1,2] Tiff Brydges,[1,2] Petar Jurcevic,[1,2] Nils Trautmann,[3,†] Cornelius Hempel,[1,2,4]
Ben P. Lanyon,[1,2] Philipp Hauke,[5,6] Rainer Blatt,[1,2] and Christian F. Roos[1,2,*]



ARTICLE

DOI: 10.1038/s41467-018-03312-x OPEN

Corrected: Publisher correction

Studying light-harvesting models with superconducting circuits

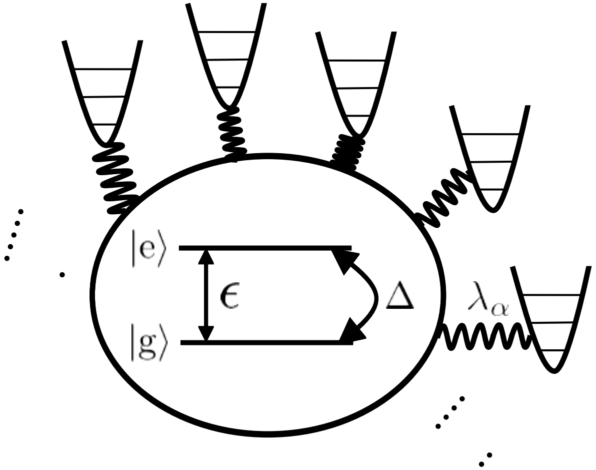
Anton Potočnik[1], Arno Bargerbos[1], Florian A.Y.N. Schröder[2], Saeed A. Khan[3], Michele C. Collodo[1], Simone Gasparinetti[1], Yves Salathé[1], Celestino Creatore[1], Christopher Eichler[1], Hakan E. Türeci[3], Alex W. Chin[2] & Andreas Wallraff[1]

But: Environmental noise are classical fluctuating fields

No backaction of system on environment

The (Multi)Spin-Boson Model

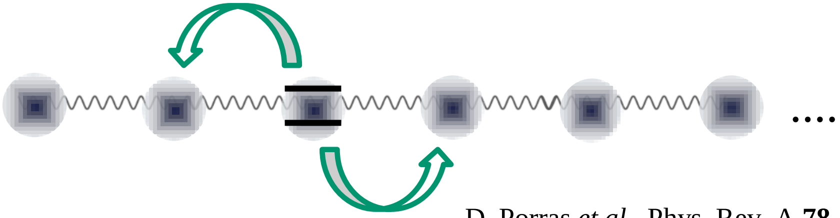
…



$$H = \frac{\epsilon}{2}\sigma^z - \frac{\hbar\Delta}{2}\sigma^x - \sigma^z \sum_\alpha \frac{\hbar\lambda_\alpha}{2}(a_\alpha + a_\alpha^\dagger) + \sum_\alpha \hbar\omega_\alpha a_\alpha^\dagger a_\alpha$$

U. Weiss *Quantum Dissipative systems* (World Scientific, Singapore, 2007)

Possible Trapped Ion Realisation



D. Porras *et al.*, Phys. Rev. A **78**, 010101(R) (2008)

Nice but experimentally very demanding

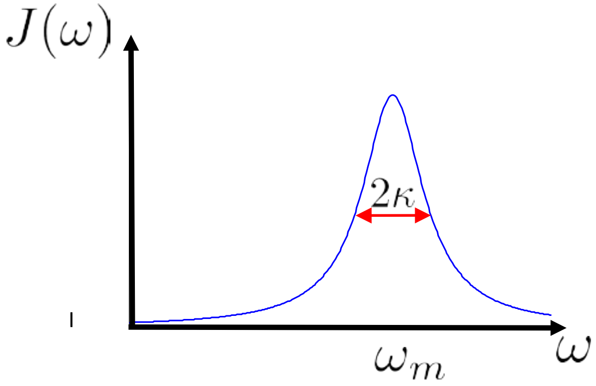
- needs many ions ($N \geq 50$ mesoscopic environment)
- control of a long chain is hard

The (Multi)Spin-Boson Model

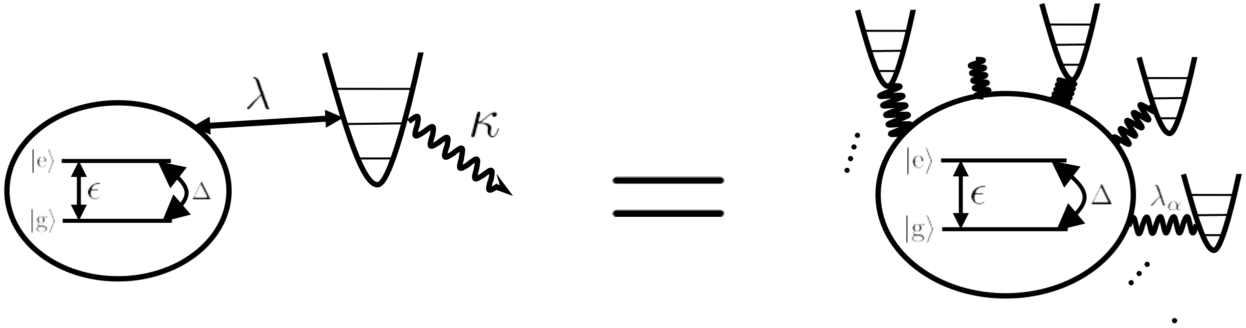
An Efficient Trapped Ion Realisation

- Spin-boson model with Lorentzian spectral density

$$J_{\mathrm{eff}}(\omega) = \lambda^2 \left[\frac{\kappa}{\kappa^2 + (\omega - \omega_m)^2} - \frac{\kappa}{\kappa^2 + (\omega + \omega_m)^2} \right]$$



- Spin coupled to small number of damped oscillators



Lemmer, Cormick, Tamascelli, Schaetz, Huelga, Plenio, NJP 20, 073002 (2018)

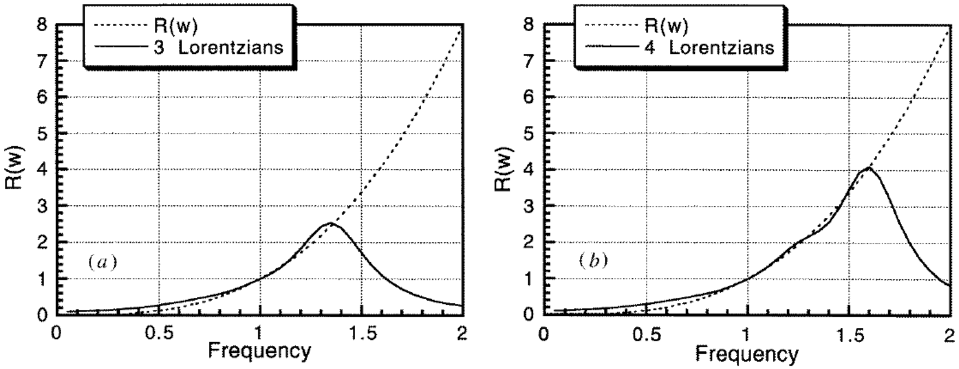
The (Multi)Spin-Boson Model

An Efficient Trapped Ion Realisation

- Every spectral density can be decomposed as a superposition of Lorentzians

- Exact decomposition for $\kappa_n \to 0$
  Good approximation for $\kappa_n \ll \omega_n$

- Non-Markovian spectral densities can be approximated in this way



Heuristic approach:
P. Stenius and A. Imamoglu,
Quantum Semiclass. Opt. **8**, 283 (1996)

Mathematical Proof of Equivalence:
D. Tamascelli, A. Smirne, S.F. Huelga, M.B. Plenio
Phys. Rev. Lett. 120, 030402 (2018)

Further developments to interacting damped HO
F. Mascherpa, A. Smirne, D. Tamascelli, P. Fernandez-Acebal, S. Donadi, S.F. Huelga, M.B. Plenio, e-Print arXiv:1904.04822

Quantum Dynamics in Biology

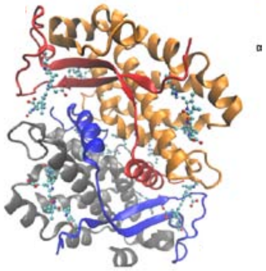
Engines at the Nanoscale

Faster, smaller, more quantum

Fluctuations grow, more noise

Interplay of Coherent
Dynamics and Environment

Experimental
Tools



Numerical
Modelling

Design Principles

Nuclear spins electron spins excitons & charges

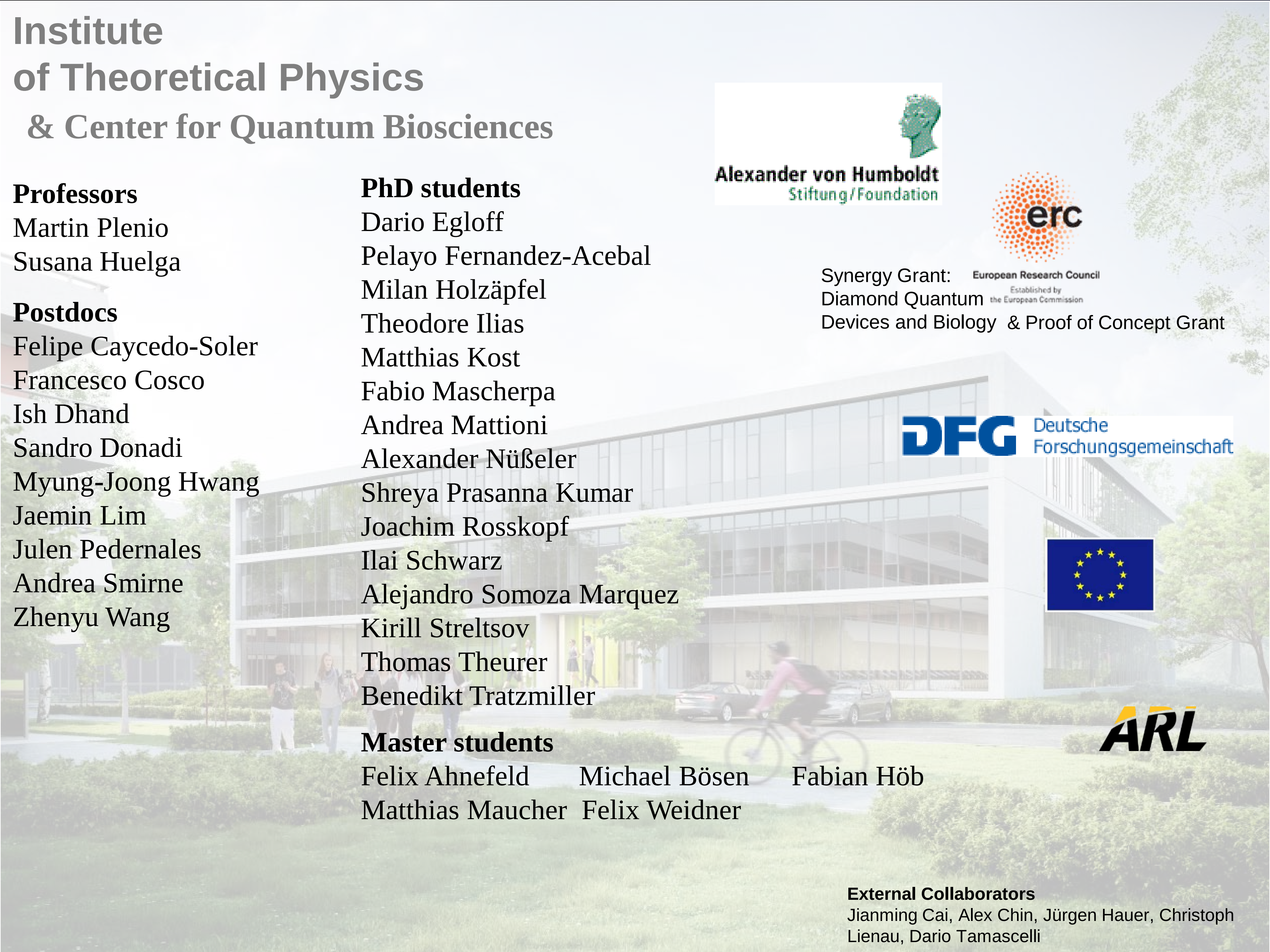
μs - ns - ps - fs

The Theory Team @ Ulm

Quantum Information, Quantum Technologies, Quantum Sensing & Quantum Biology

Center for QuantumBioSciences with dedicated Research Building starting operation end of May 2019

Institute
of Theoretical Physics
& Center for Quantum Biosciences



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ARL

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