Photosynthetic light harvesting – control through disorder

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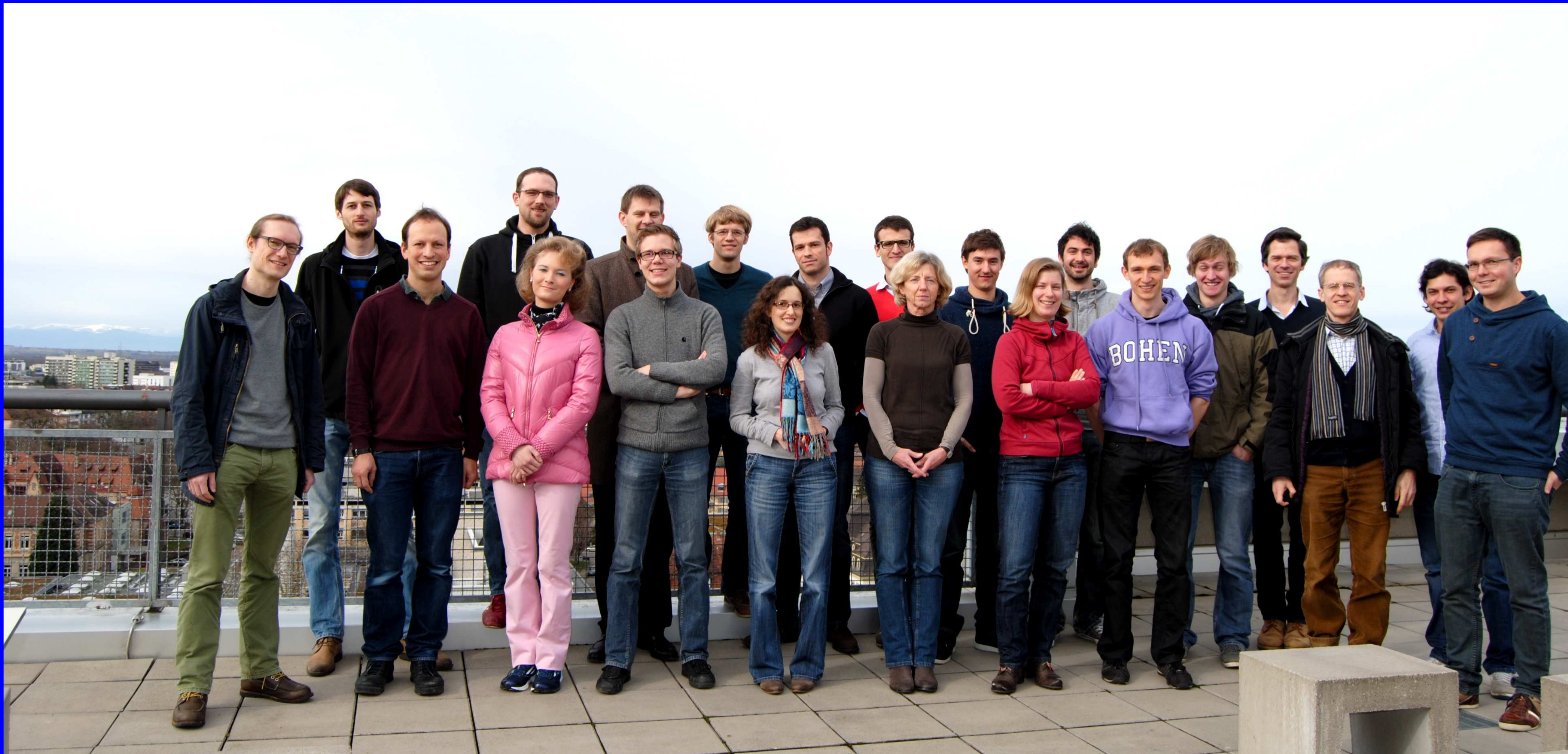
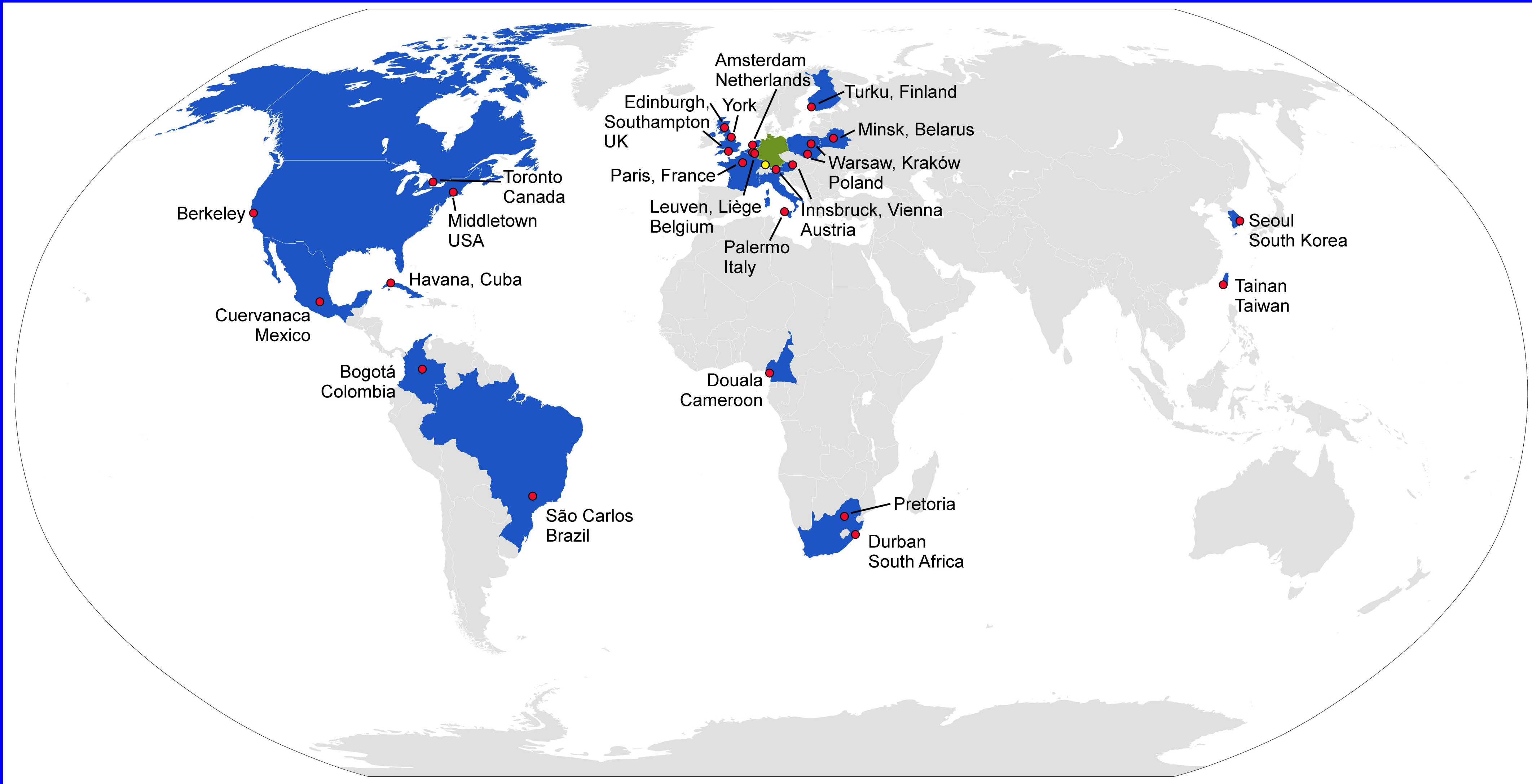
Nonlinear Dynamics in Quantum Systems

École des sciences avancées de Luchon, 15 March 2015

Nonlinear Dynamics in Quantum Systems



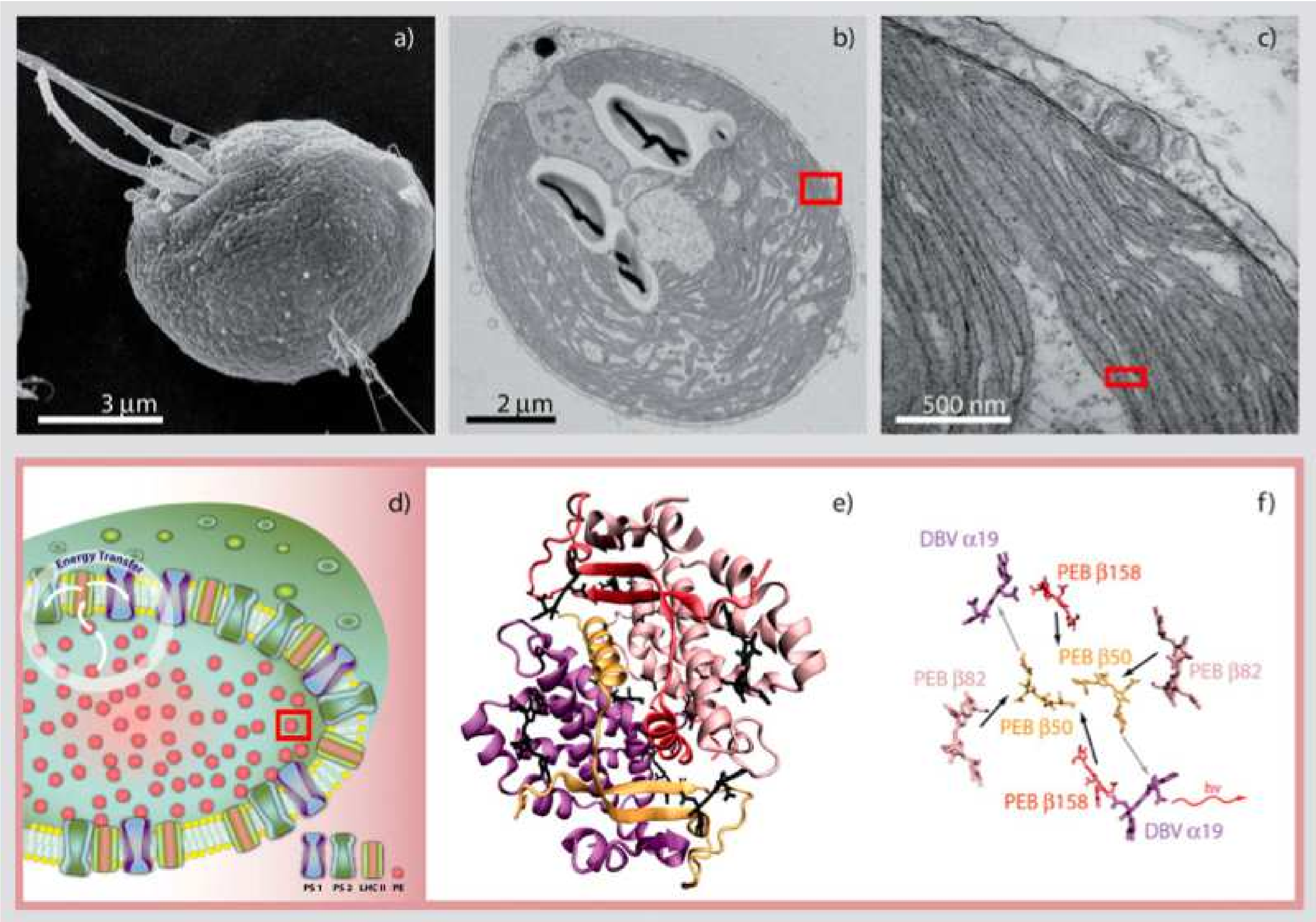
In Collaboration with . . .



funded by DFG, DAAD, AvH and VolkswagenStiftung

Experimental evidence of coherence in photosynthesis

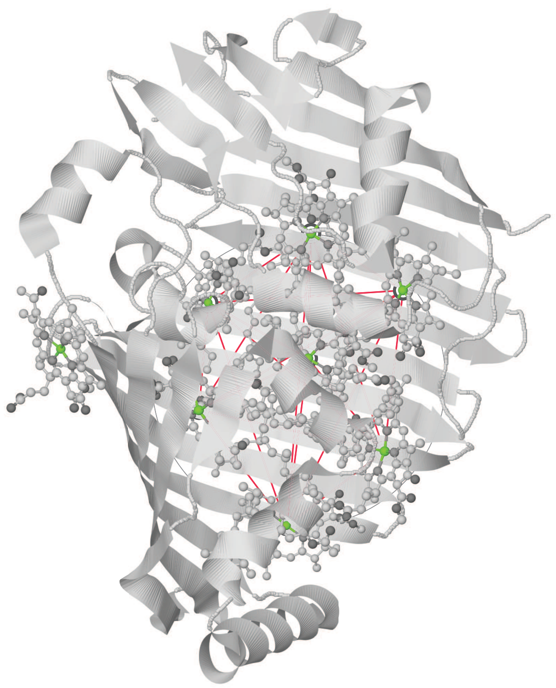
Zoom into a cryptophyte alga – *Proteomonas sulcata*

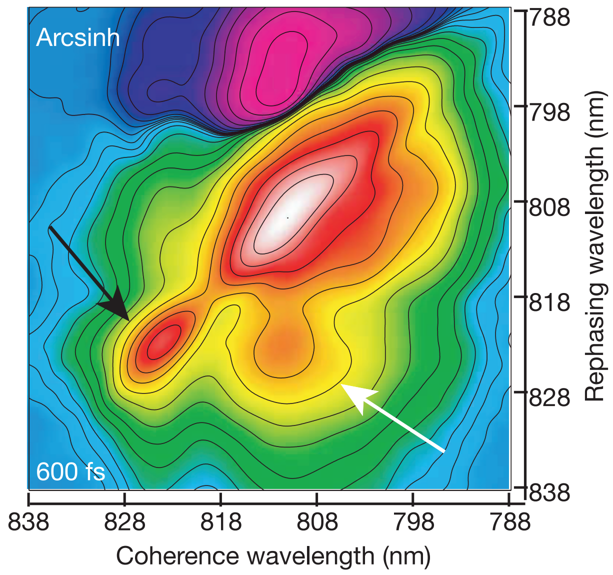


[Scholes et al., 2012]

Quantum coherence in “plants” – a provocation!

FMO photosynthetic complex (green sulfur bacteria) 2D spectroscopy





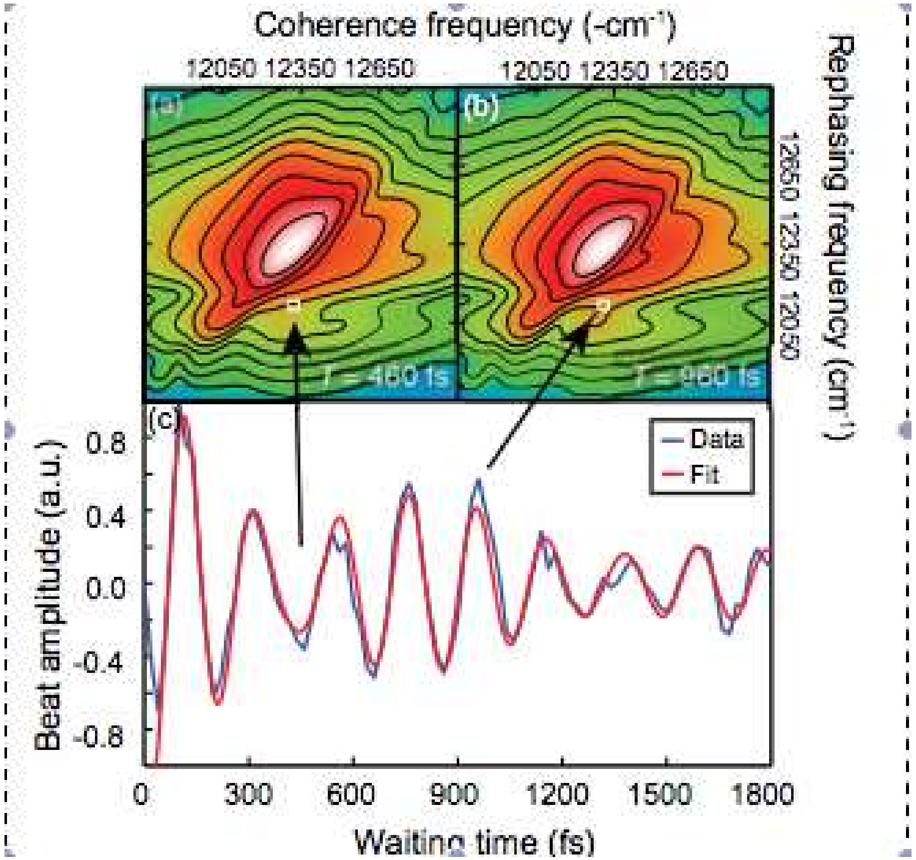
light harvesting antenna complexes (e.g., “FMO”) funnel excitations from receptor to reaction center with $\geq 95\ \%$ **quantum efficiency**

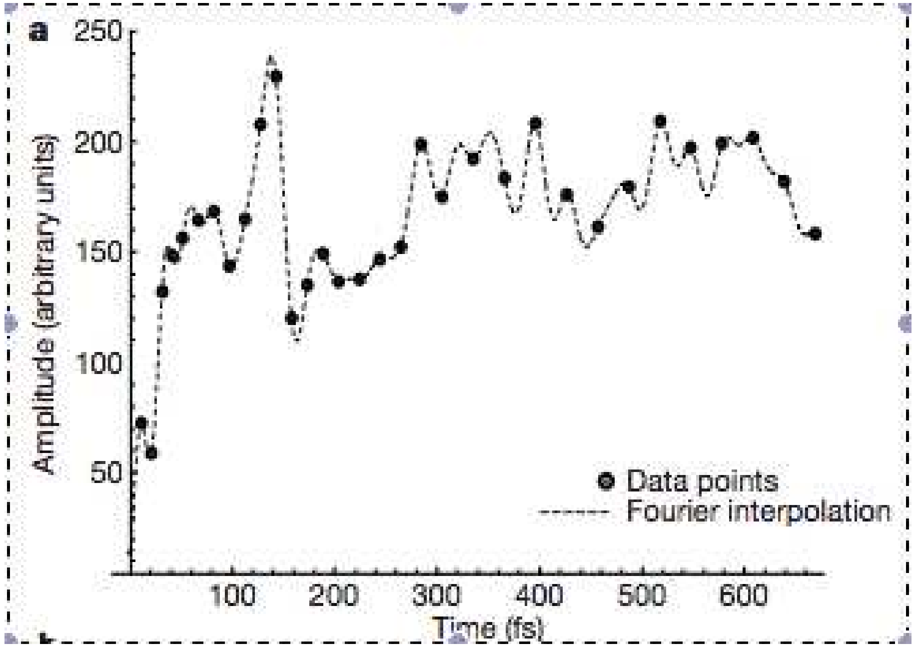
at ambient temperature [Engel et al., 2007; Collini et al., 2009; D.B. Turner et al., 2011]

in noisy, multi-hierarchical environment

??? ORIGIN OF THIS EFFICIENCY ???

Difficult experiments on dirty systems!



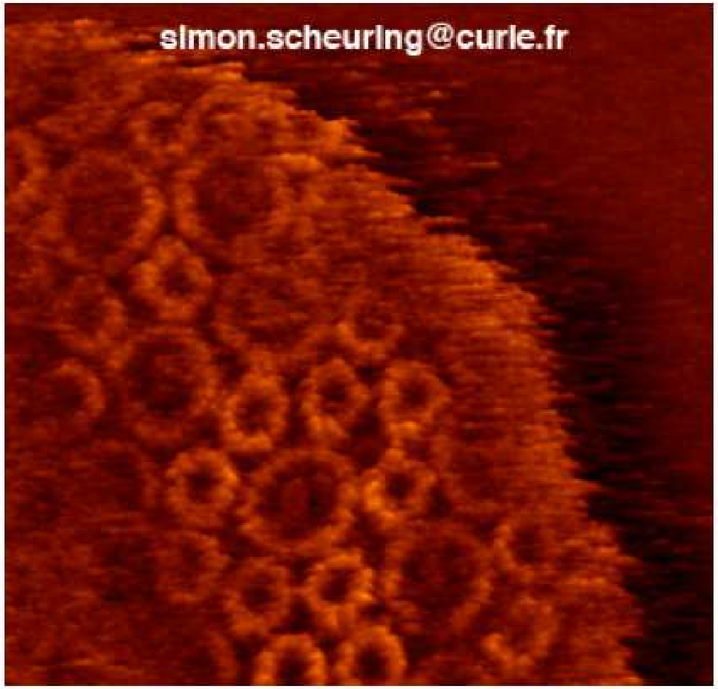


[Engel et al, 2010 (left), vs. Fleming et al., 2007 (right);

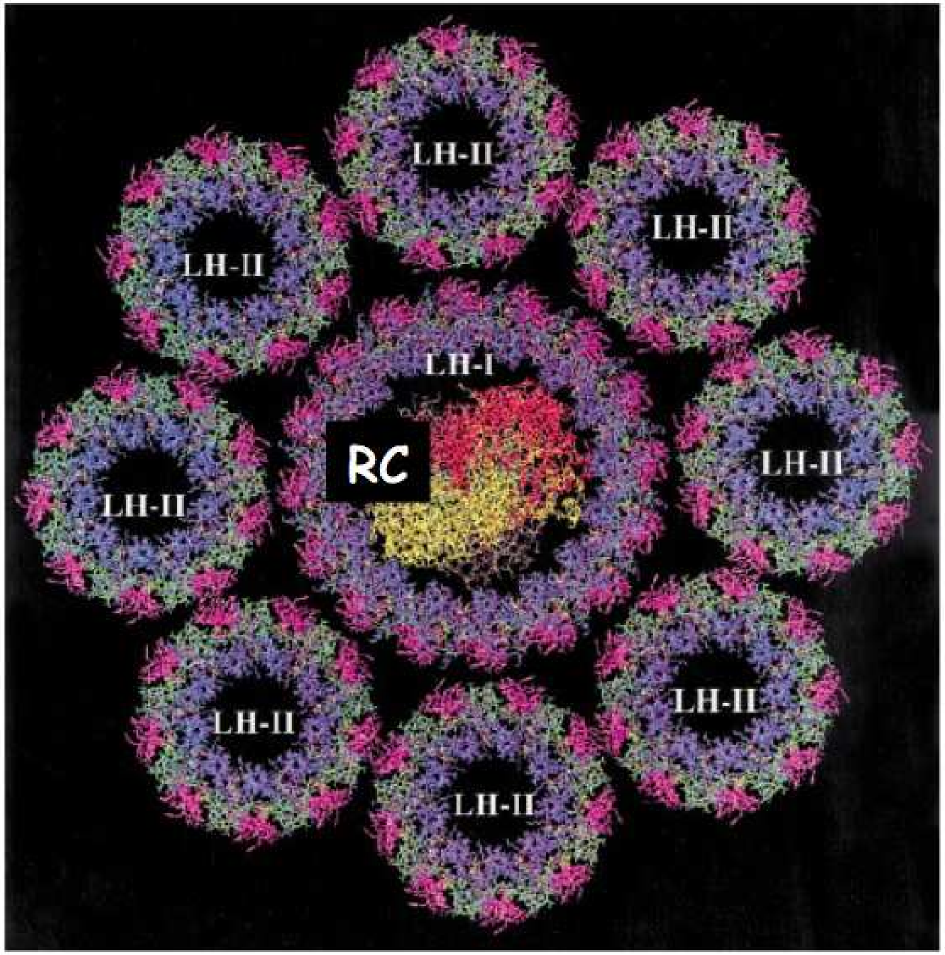
NOW WITH ERROR BARS: Turner et al., 2011;

SINGLE MOLECULE experiments: Krüger et al., 2011; Hildner et al., 2012]

Photosynthetic complex of purple bacteria



Scheuring *et al.*, EMBO J. **23** (2004) 4127



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

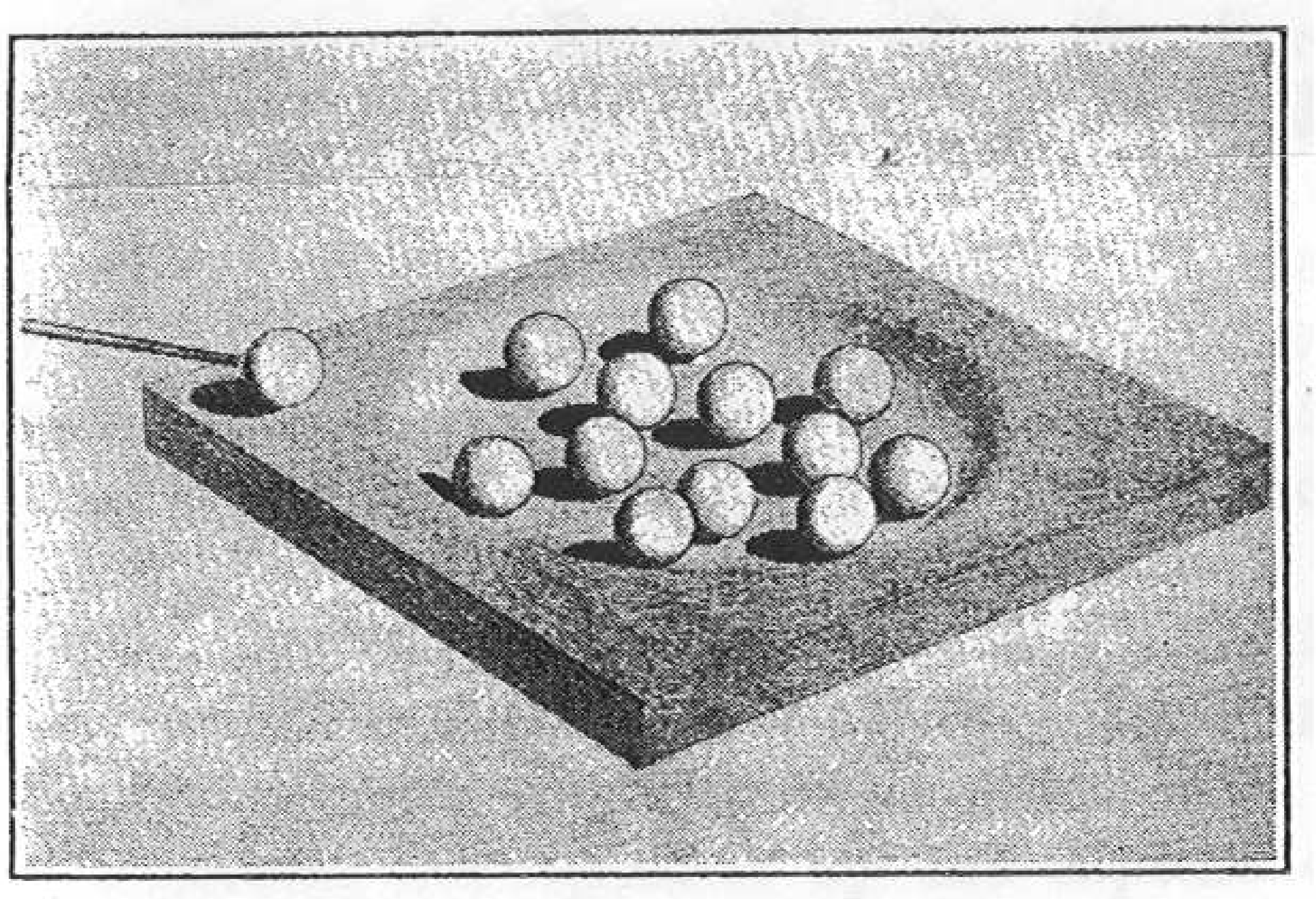
[talk by Richard Hildner, Freiburg, 2012]

Observations/issues

- extended states; coherence over large distances; ~ 10 Å $\ldots 100$ nm $\ldots$
- long-lived coherences, in some cases even at ambient temperatures
- . . . longer than typical population transfer times $\sim 200 \ldots 300$ fs
- widely variable architectures; often disordered systems
- inhomogeneous broadening/dephasing vs. decoherence
- the matrix matters
- need both, effective theoretical descriptions to fit experimental results
- and models with the perspective for conceptual understanding

Complex/“disordered” quantum transport

Exemplary transport problems – nuclear matter

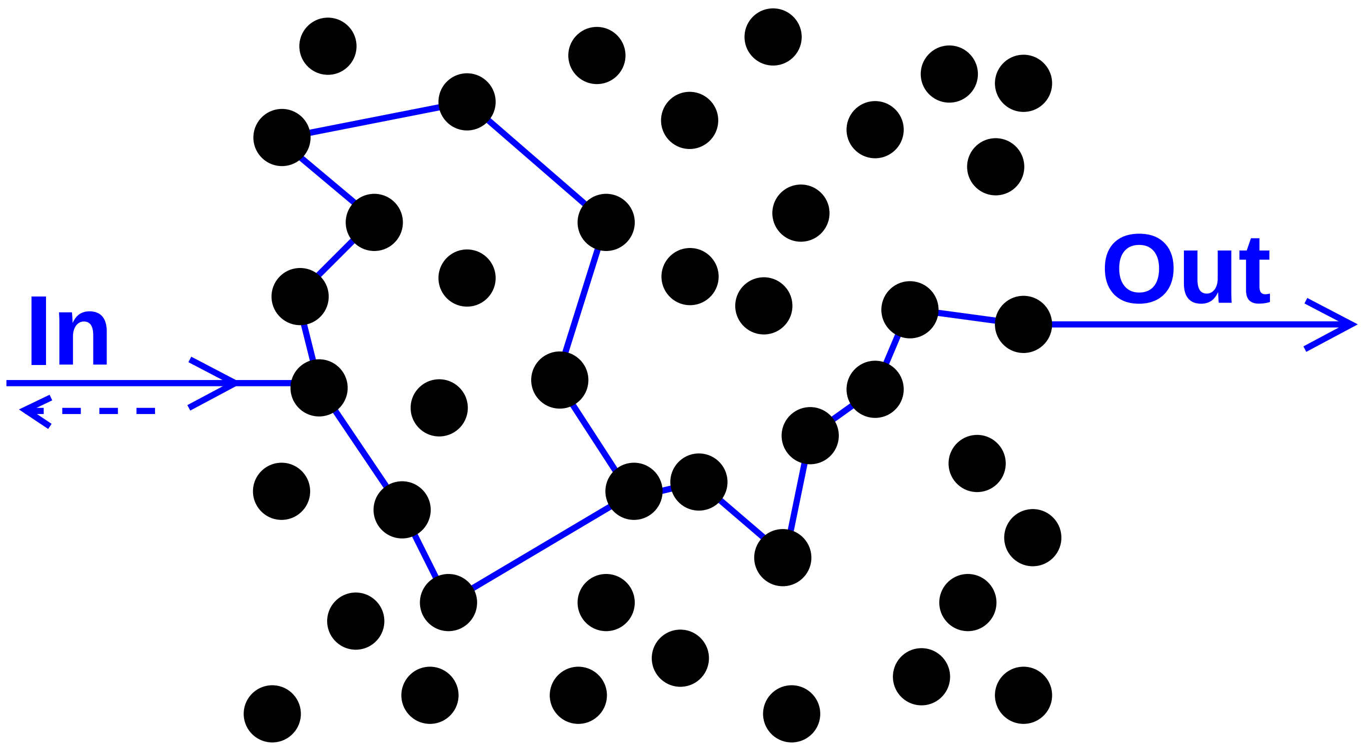


[N. Bohr, 1936]

compound nuclear reactions

complex, microscopically uncontrolled dynamics of interacting particles

Exemplary transport problems – condensed matter

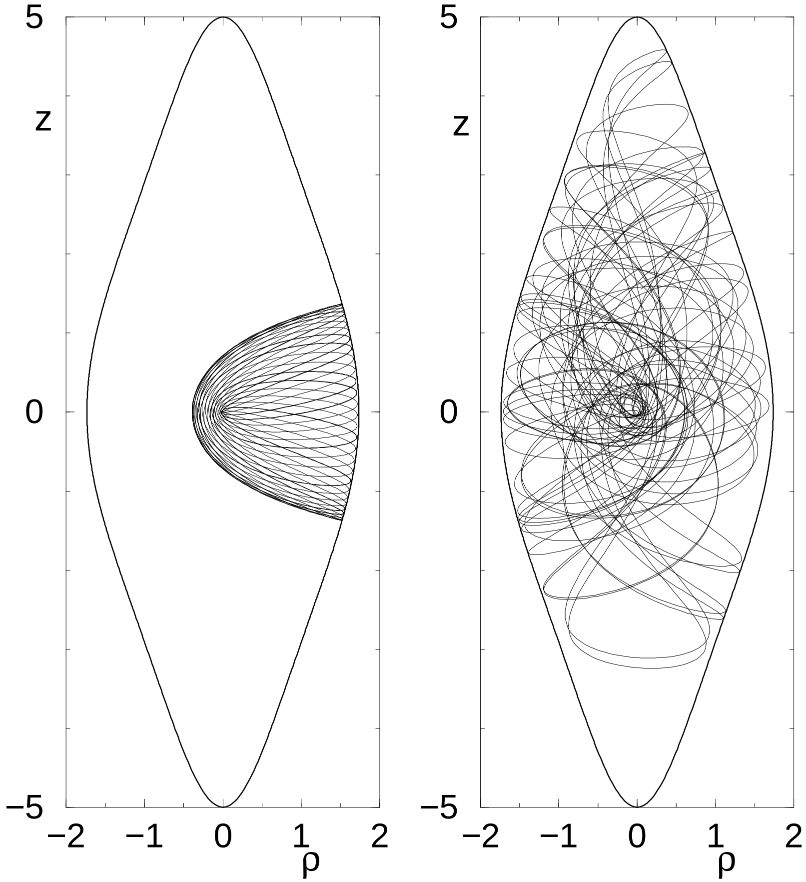


[Anderson 1958; Labeyrie et al., 1999]

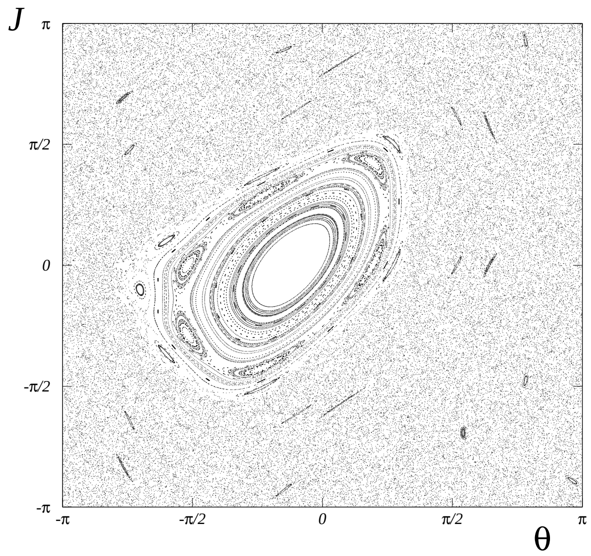
multiple scattering in a disordered medium
coherent superposition of many transmission amplitudes

Exemplary transport problems – atomic matter

near integrable **chaotic**



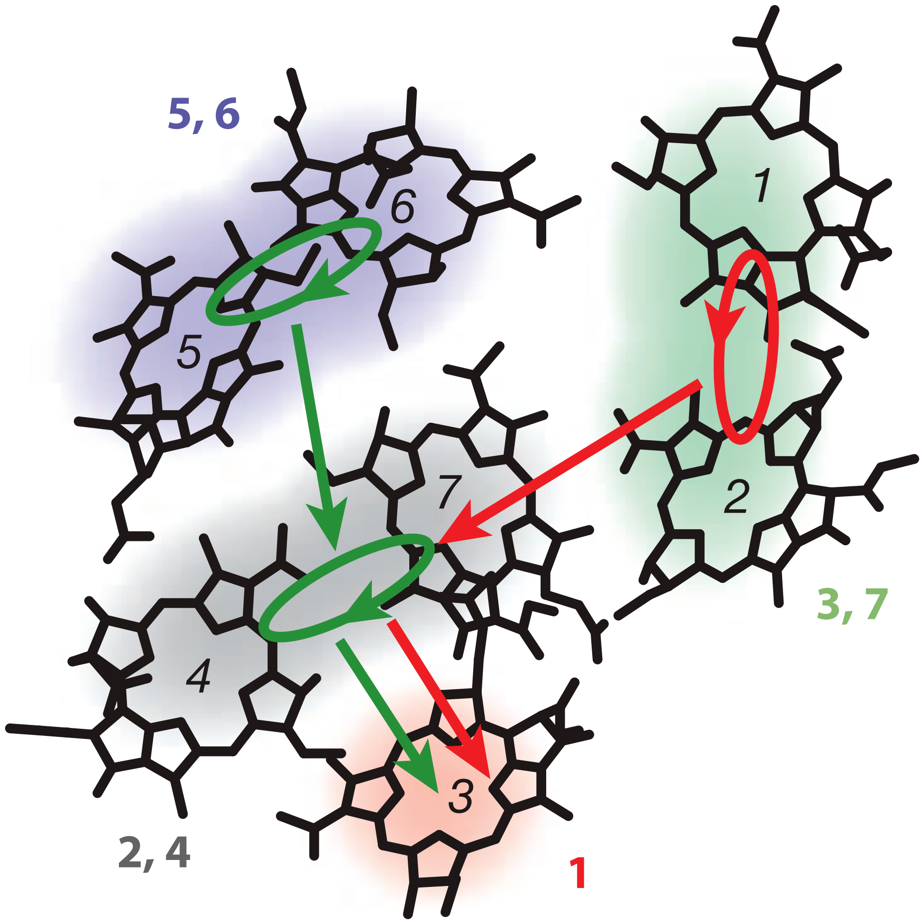
[Delande & Gay, 1986]



atomic hydrogen in a static magnetic field

strong, nonlinear coupling of few degrees of freedom

Exemplary transport problems – soft matter

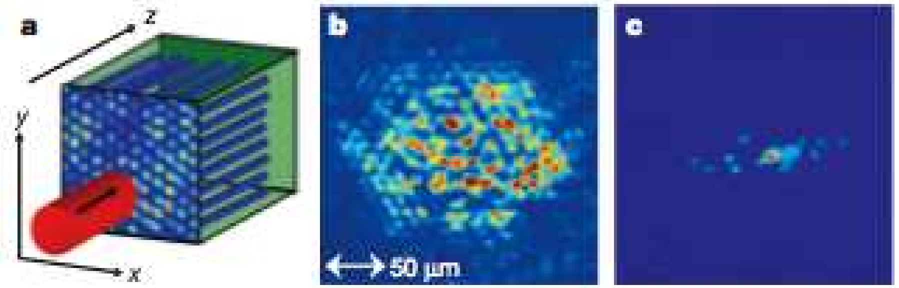


[T Brixner et al, 2006]

excitation transport in FMO

has disorder and strongly coupled (background) degrees of freedom

Disorder/chaos as a handle for coherent control



Transport and Anderson localization in disordered two-dimensional photonic lattices

Tal Schwartz[1], Guy Bartal[1], Shmuel Fishman[1] & Mordechai Segev[1]

PRL 96, 063904 (2006) PHYSICAL REVIEW LETTERS week ending 17 FEBRUARY 2006

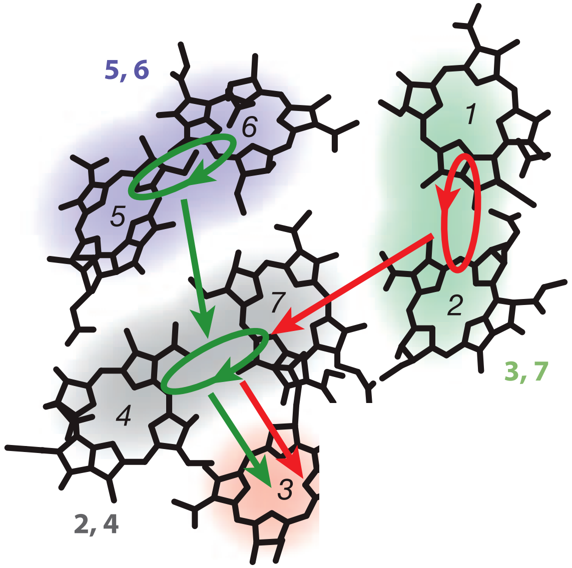
Observation of the Critical Regime Near Anderson Localization of Light

Martin Störzer, Peter Gross, Christof M. Aegerter, and Georg Maret

PRL 102, 183001 (2009) PHYSICAL REVIEW LETTERS week ending 8 MAY 2009

Microwave-Driven Atoms: From Anderson Localization to Einstein's Photoeffect

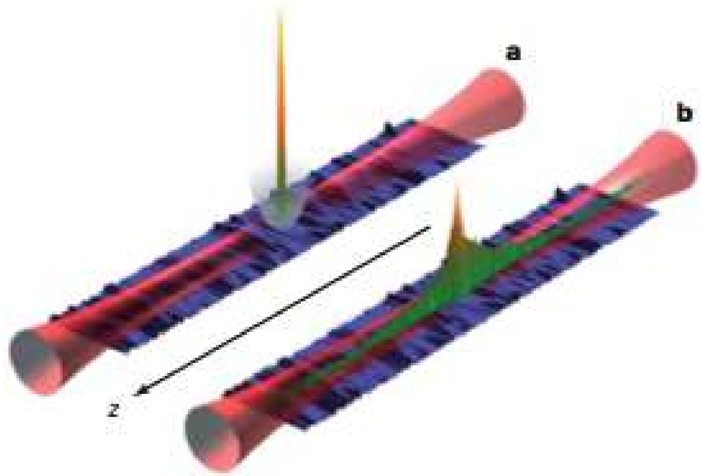
Alexej Schelle,[1,2] Dominique Delande,[2] and Andreas Buchleitner[1]



Quantum-Coherent Electronic Energy Transfer: Did Nature Think of It First?

Gregory D. Scholes*

Department of Chemistry, Institute for Optical Sciences and Centre for Quantum Information and Quantum Control, University of Toronto, 80 St. George Street, Toronto, Ontario, M5S 3H6 Canada



Direct observation of Anderson localization of matter waves in a controlled disorder

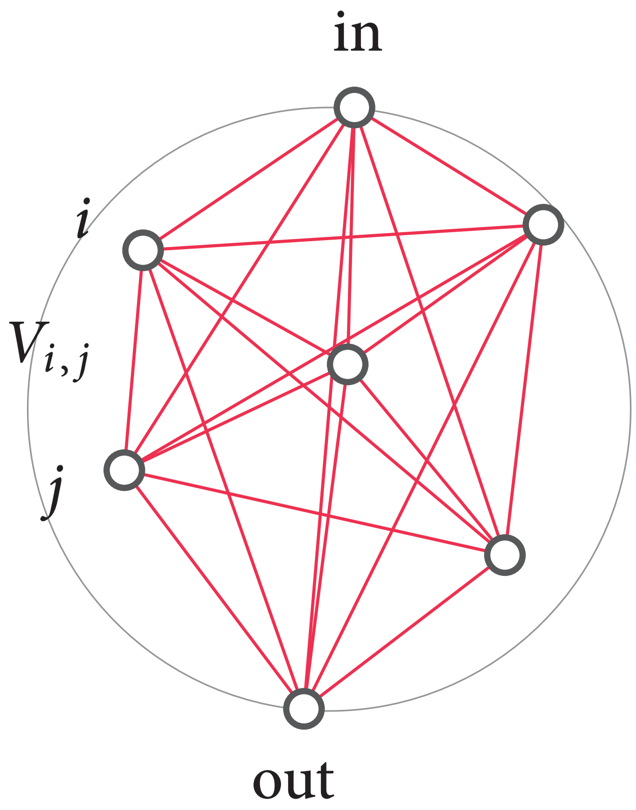
Juliette Billy[1], Vincent Josse[1], Zhanchun Zuo[1], Alain Bernard[1], Ben Hambrecht[1], Pierre Lugan[1], David Clément[1], Laurent Sanchez-Palencia[1], Philippe Bouyer[1] & Alain Aspect[1]

Hence, a statistical, coherent transport model rather than an effective, open system dynamical description!

Stark physical abstraction

– FMO as a 3D random network of sites –

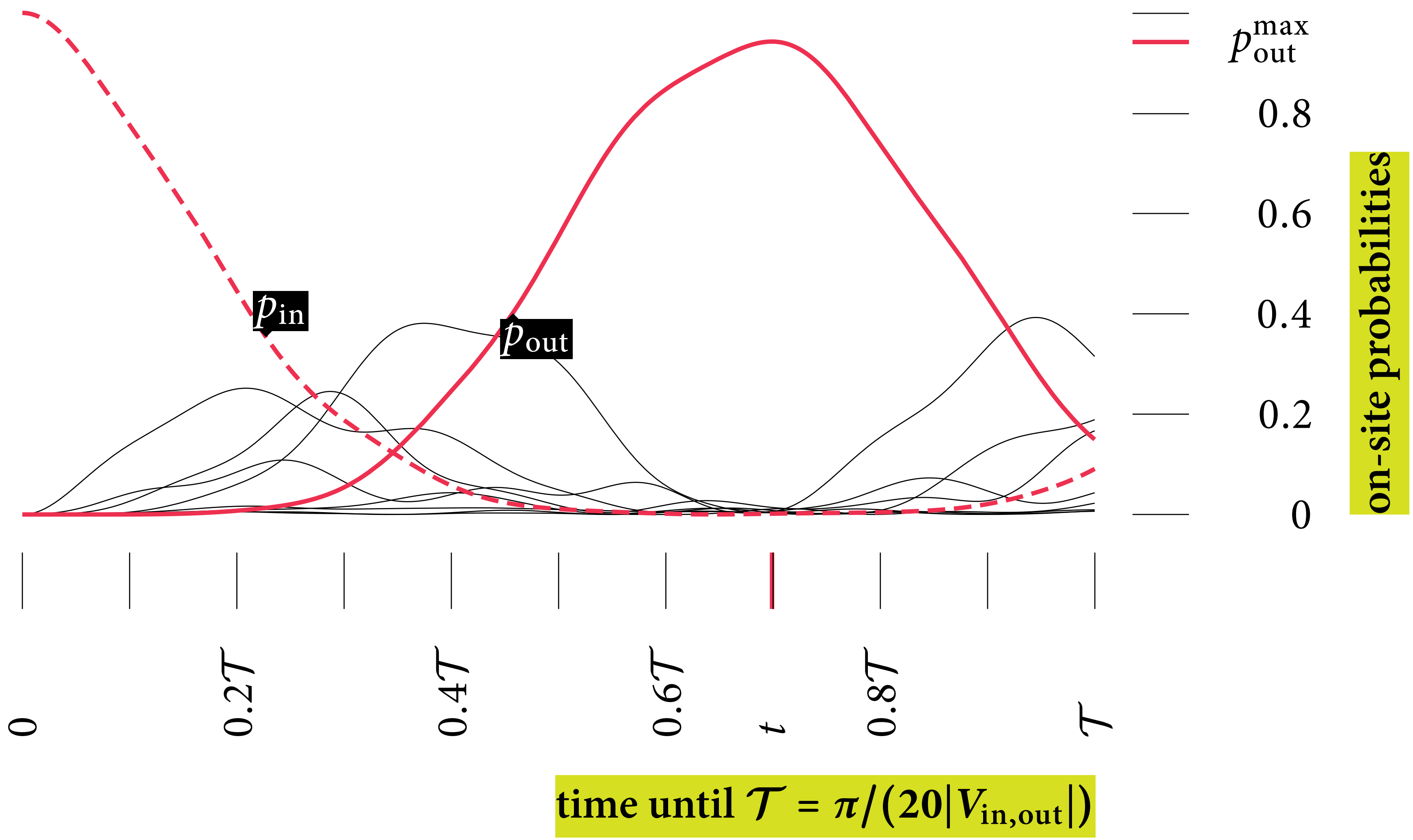
– coherent dynamics on finite, fully connected, random graph –



- $H = \sum_{i \neq j=1}^{N} v_{i,j} \sigma_{+}^{(j)} \sigma_{-}^{(i)}$
- **intersite coupling** $v_{i,j} \sim r_{i,j}^{-3}$
- **excitation injected at "in"**
- **excitation delivered at "out"**
- **remaining sites randomly placed within sphere**
- **efficient** $\equiv$ **large** p_{out}**, after short times**

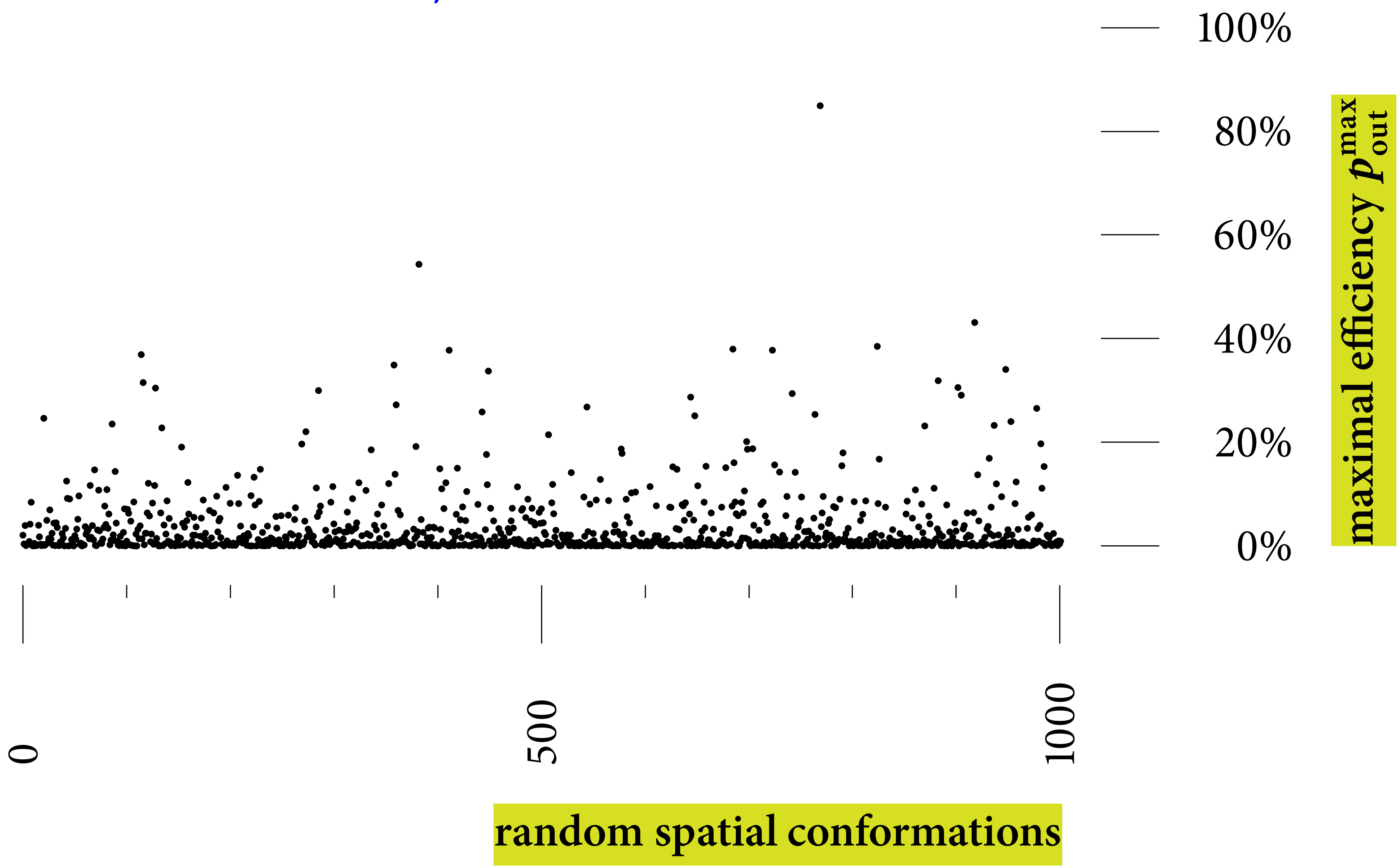
Transport efficiency

time evolution of on-site probabilities $p_i = |\langle i|U(t)|\text{in}\rangle|^2$



Transport efficiency vs. configuration

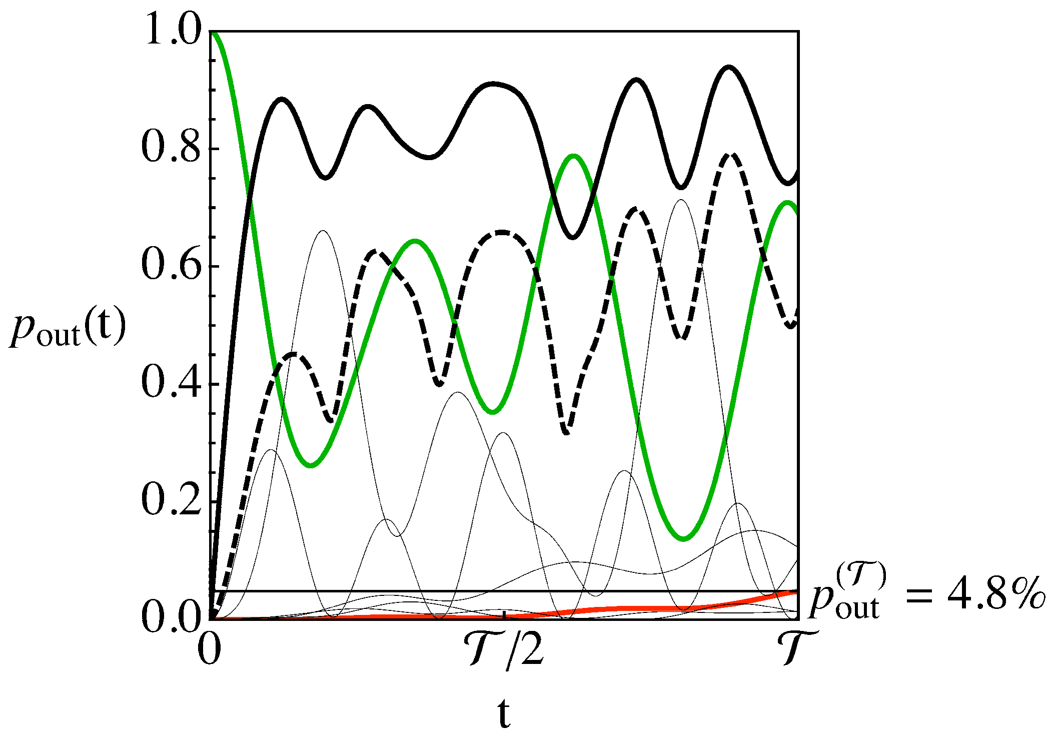
characteristic, deterministic and LARGE fluctuations!



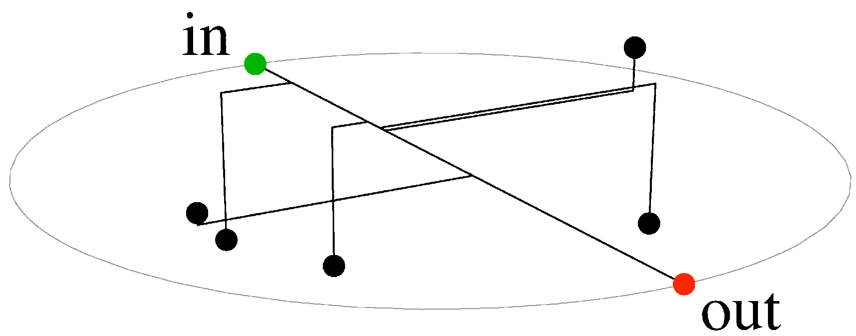
→ rare, optimal configurations – mostly "localized" transport ←

Typical evolution and configuration

typical population dynamics



typical configuration



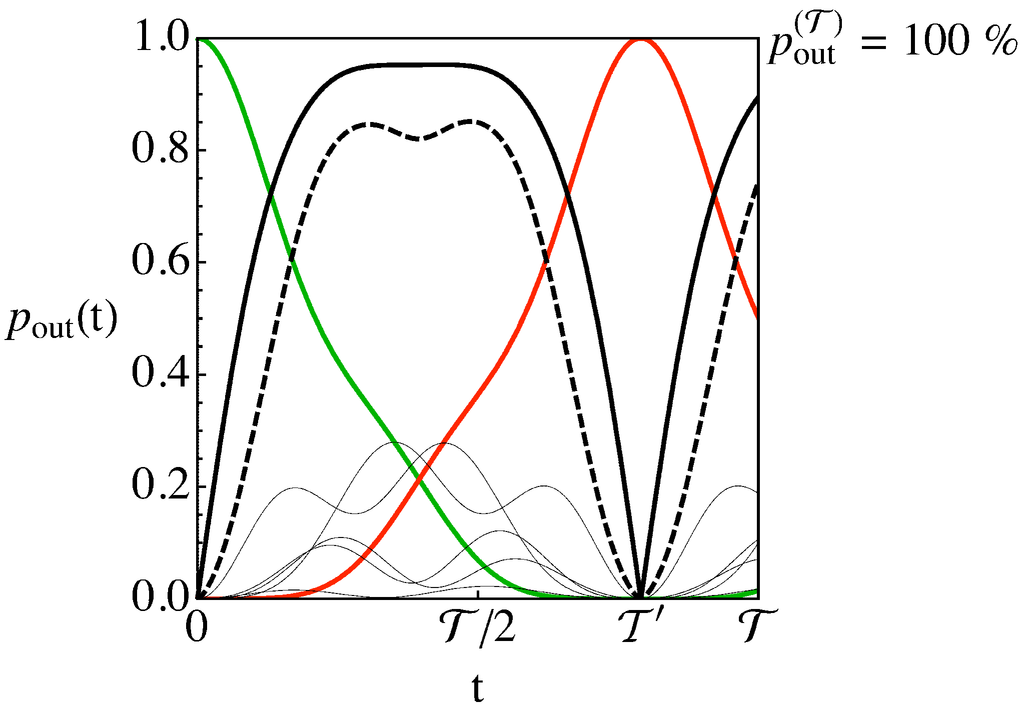
excitation refocusses (partially) at wrong site

output site population low

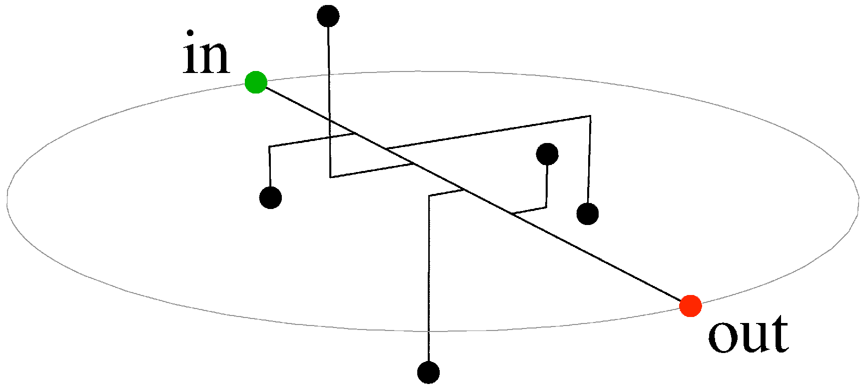
OPTIMIZE!

Optimal evolution and configuration

optimized population dynamics



optimized configuration



excitation perfectly refocusses on output!

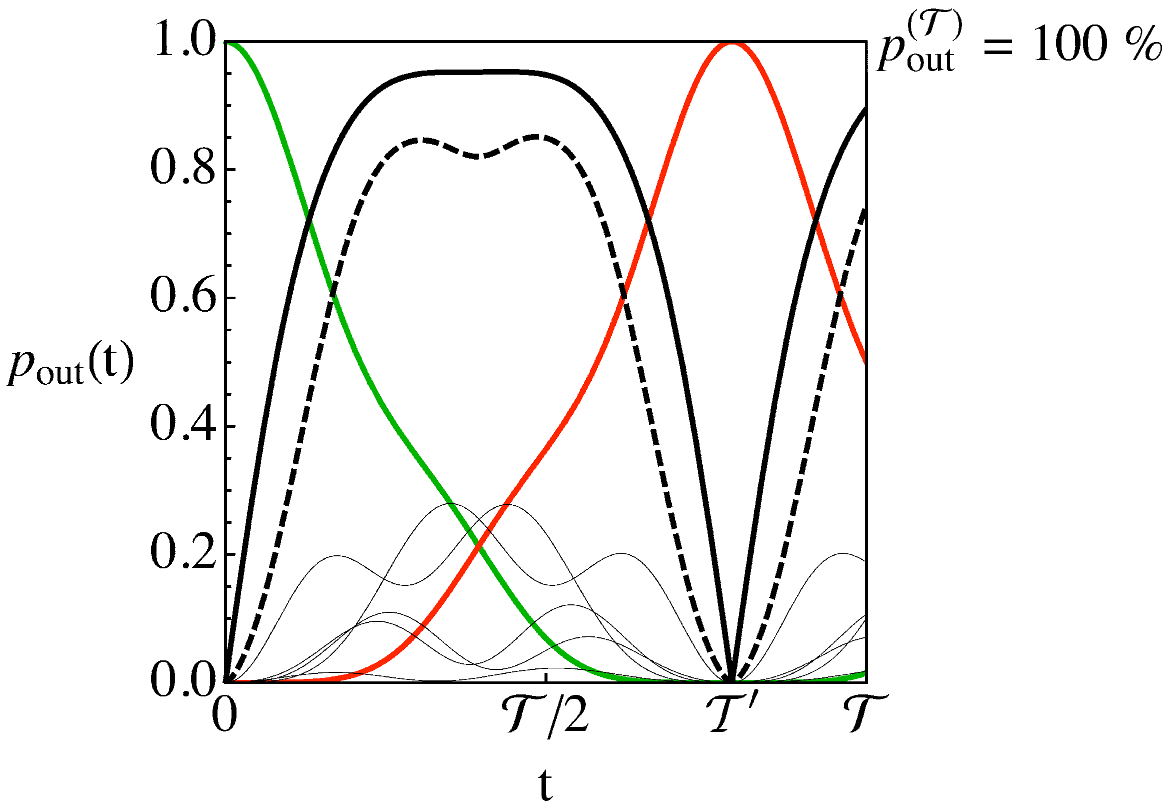
optimization by genetic algorithm from typical configuration

evolution might have done the same!?!

Design principles

Model ingredients

an incident of optimal dynamics



- **centro-symmetric Hamiltonian**
  H, $HJ = HJ$, $J_{i,j} = \delta_{i,N-j+1}$

- H has **"dominant doublet"**, i.e. eigenvectors $|\tilde{\pm}\rangle$ with

$$|\langle\tilde{\pm}, \pm\rangle|^2 > \alpha \approx 1\,,$$

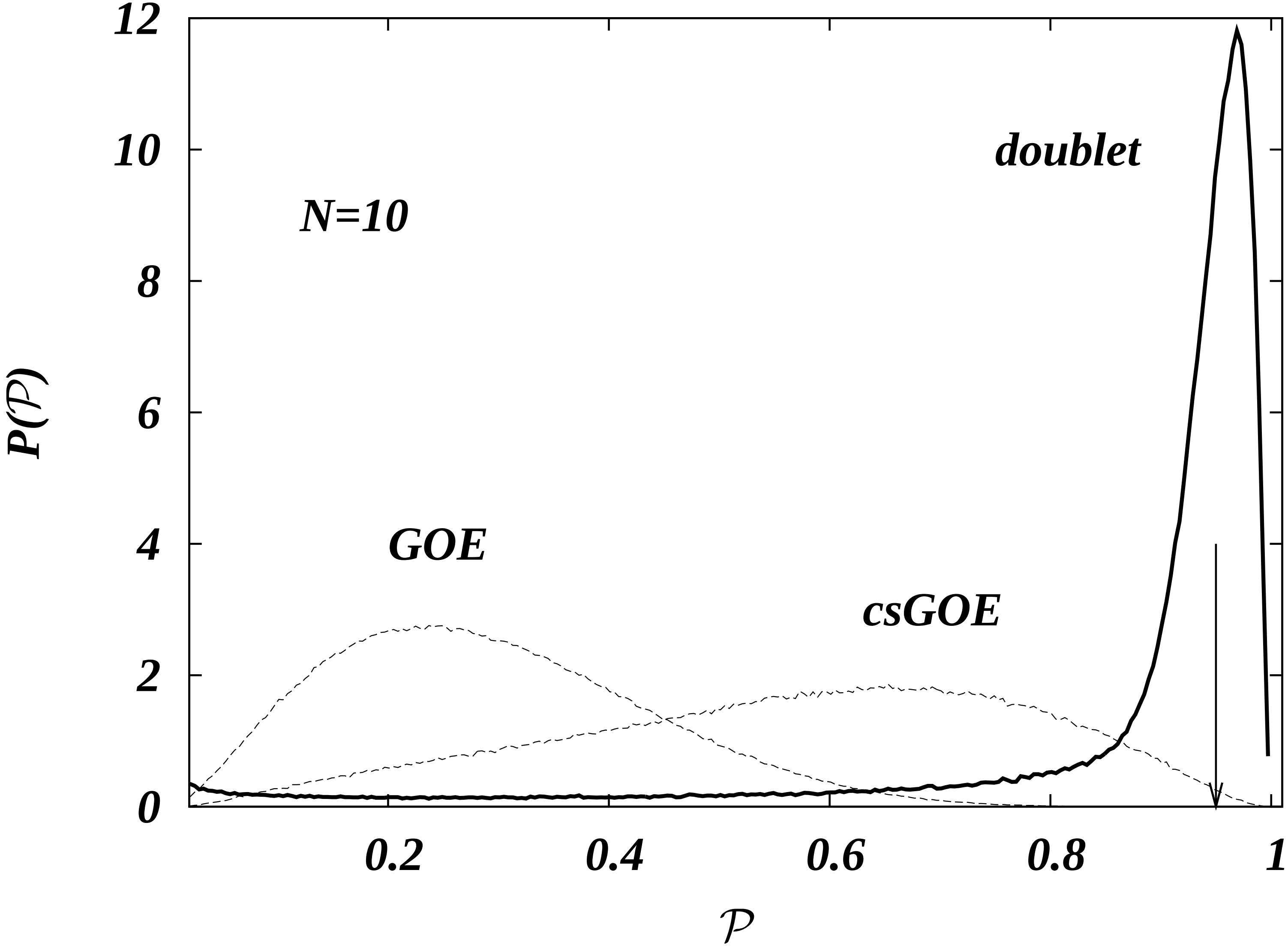
  where

$$|\pm\rangle = (|\text{in}\rangle \pm |\text{out}\rangle)/\sqrt{2}$$

- H **randomly sampled from Gaussian Orthogonal Ensemble (GOE)**

Distribution of efficiencies for distinct design principles

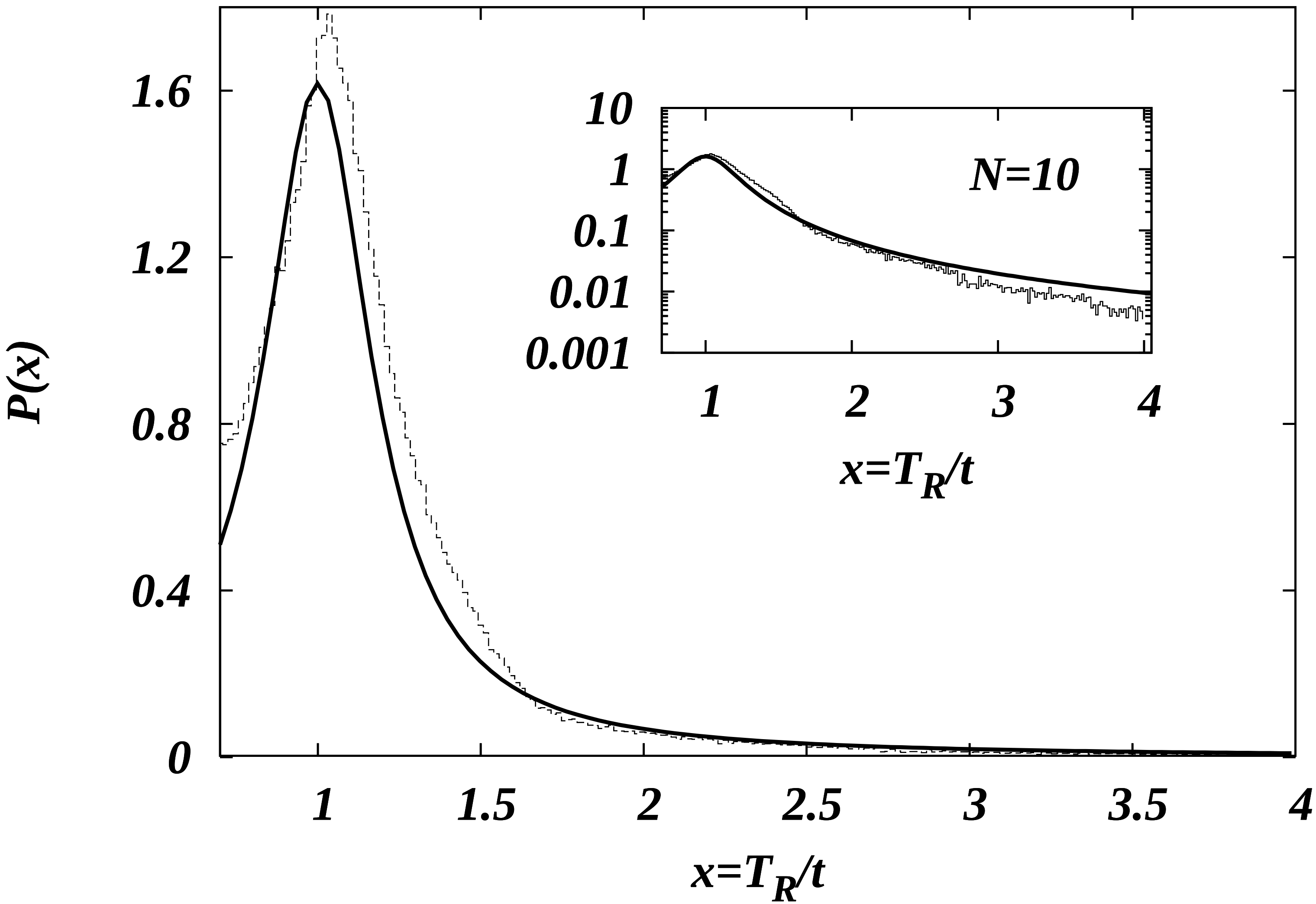
dramatic efficiency enhancement . . .



. . . if centrosymmetric with dominant doublet!! [Walschaers et al., 2013]

Statistically robust distribution of inverse transfer times

Size, density of states, average coupling strength doorway sites-bulk **ALONE** matter!



optimal configurations in *algebraic* tail!

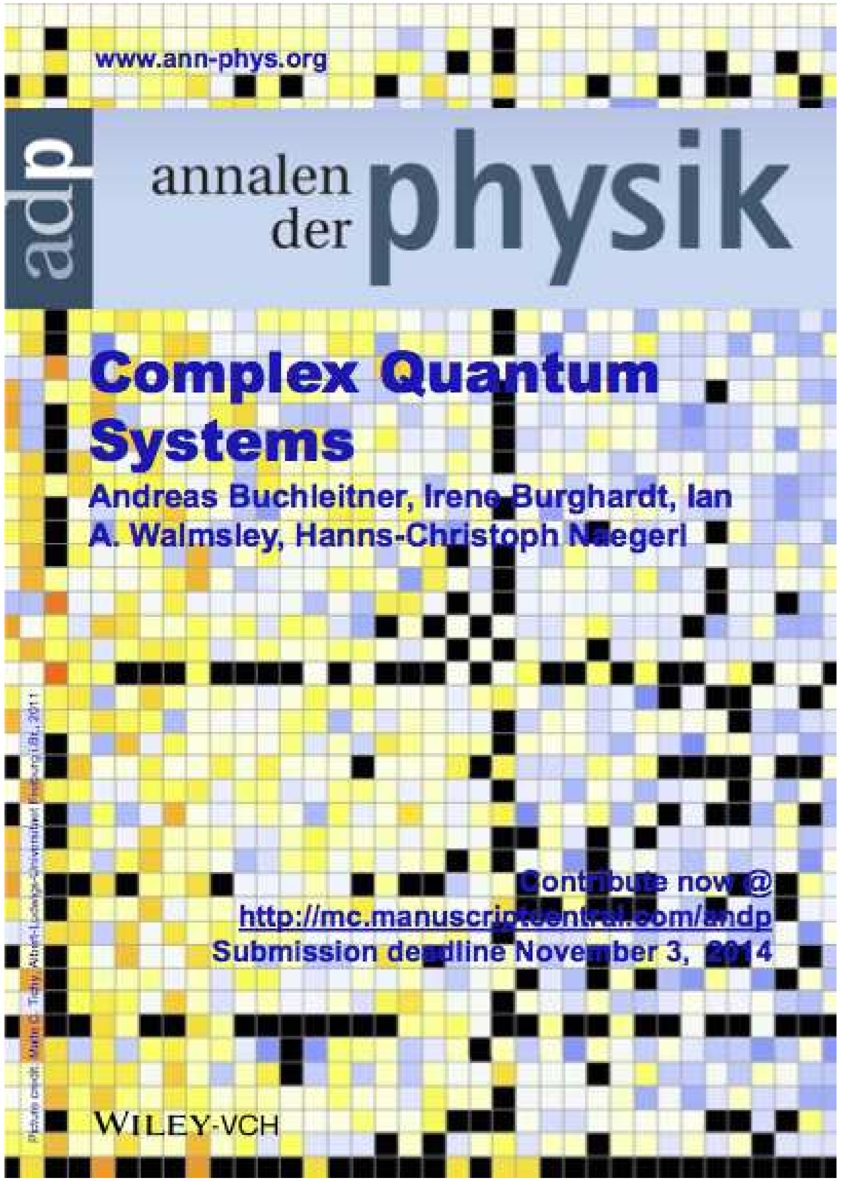
In biological functionality coherence *could* matter, since . . .

- . . . constructive multipath interference enhances efficiency
- . . . optimal conformations are not too rare
- . . . conformational details don't matter for statistics
- statistical control of function by disorder and redundancy!?!
- generic picture of quantum system with not too many, strongly coupled (here: *vibr*ational and electr*onic*) degrees of freedom (CAT)
  [Tomsovic & Ullmo, 1994; Zakrzewski et al., 1998]

What's missing for a deeper understanding

- **predictive/falsifiable theory on experimentally accessible observables**
- **experimental means for targeted intervention**
- **role of superstructure(s) – in space and time**
- **scenarios for functional relevance of microscopic coherence**

Literature/Propaganda



– Semiconductors and Semimetals 83, 1 (2010); PRE 83, 021912 (2011); EPL 96, 10001 (2011); JPB 44, 184012 (2011); Energy Environ. Sci. 5, 9374 (2012); PRL 111, 180601 (2013); NJP 16, 055002 (2014)

– PhD Torsten Scholak, Freiburg 2011; diploma Tobias Zech, 2012; PhD Simeon Sauer, 2013; PhD Frank Schlawin, 2015; PhD Manuel Gessner, 2015; PhD Mattia Walschaers, 2015

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