Transport on network-like structures
– from light harvesting to boson sampling

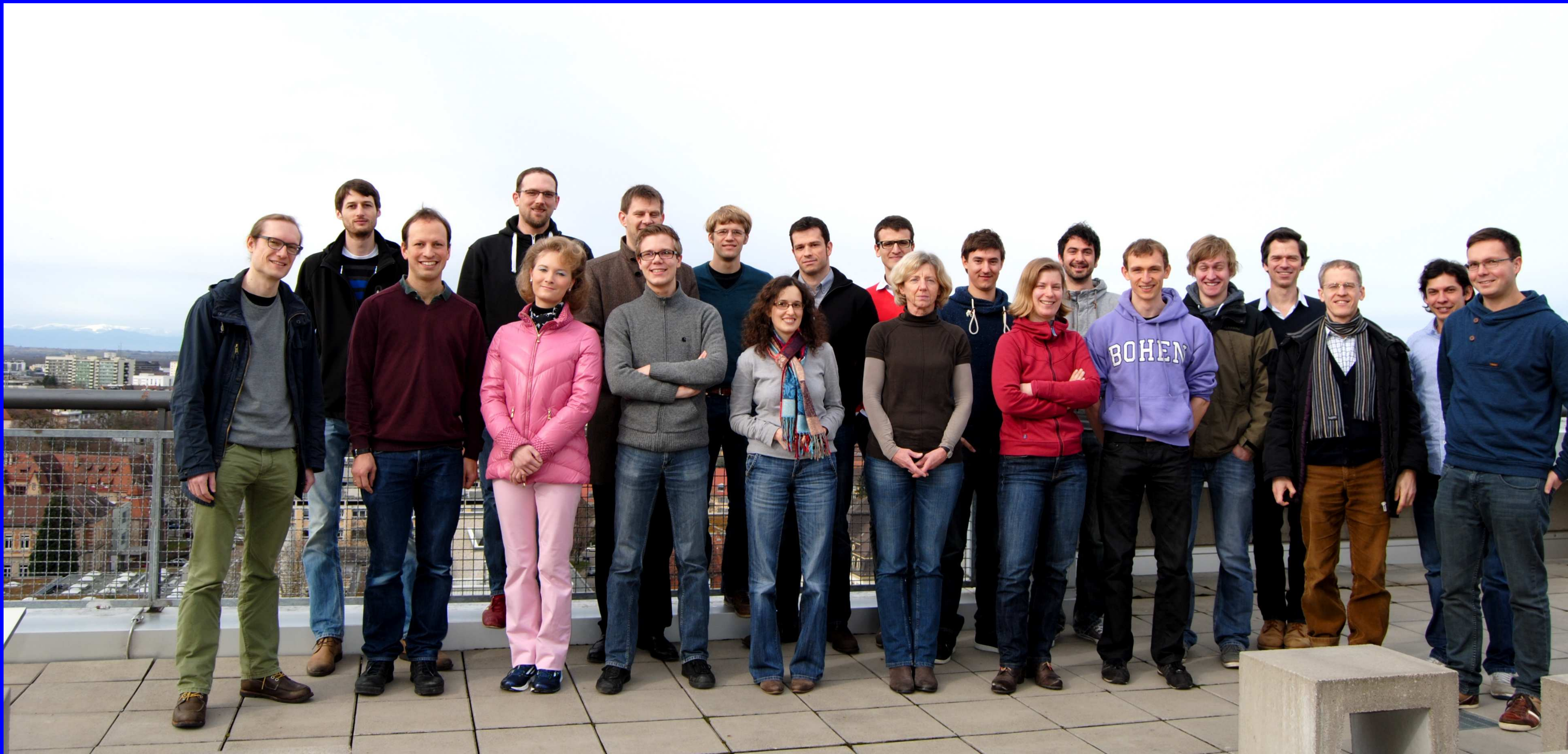
Andreas Buchleitner

Quantum optics and statistics
Institute of Physics, Albert Ludwigs University of Freiburg
www.quantum.uni-freiburg.de

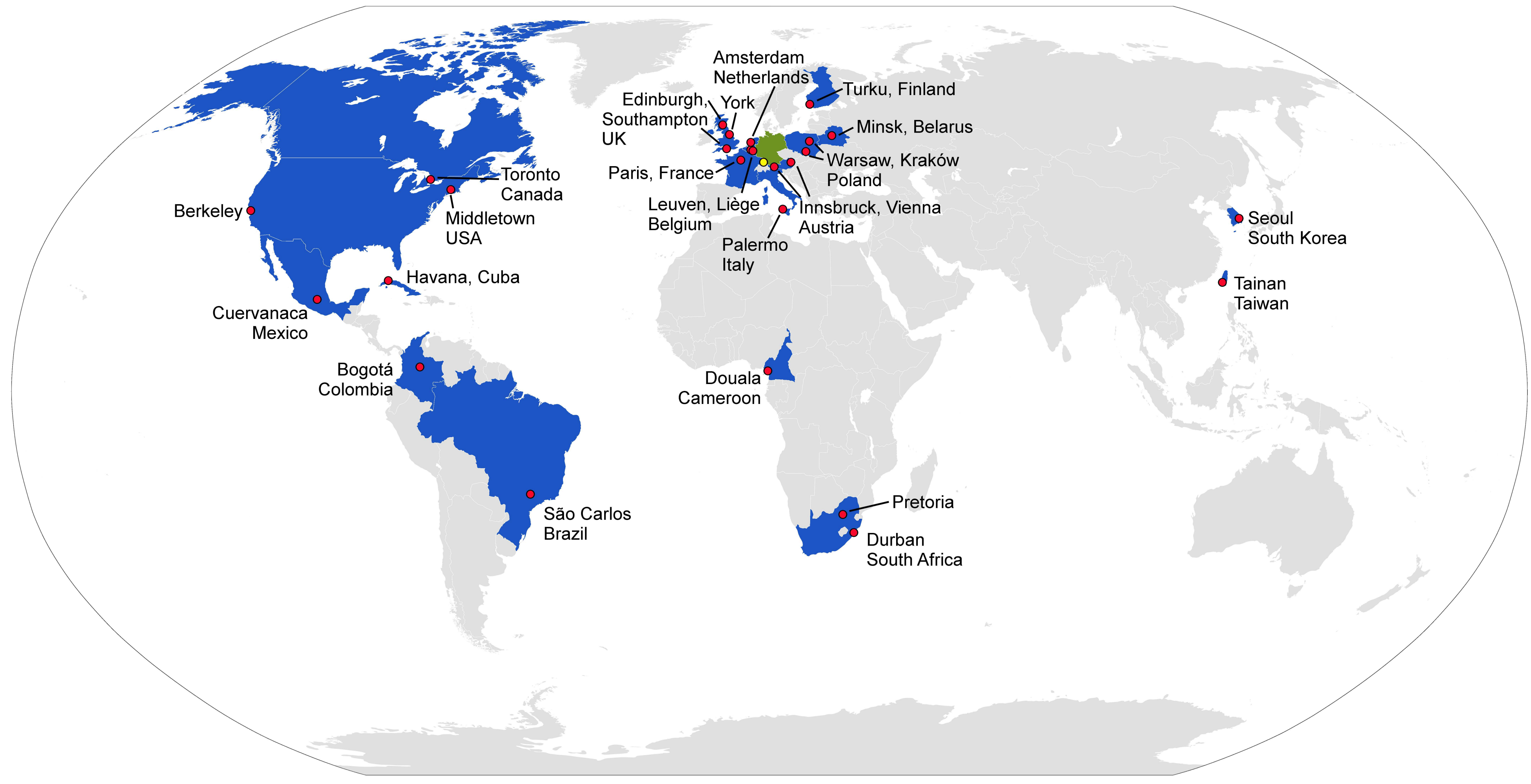
Nonlinear Dynamics in Quantum Systems

Large Scale Quantum Phenomena in Biological Systems, Galiano Island, 7 June 2014

Nonlinear Dynamics in Quantum Systems



In Collaboration with . . .



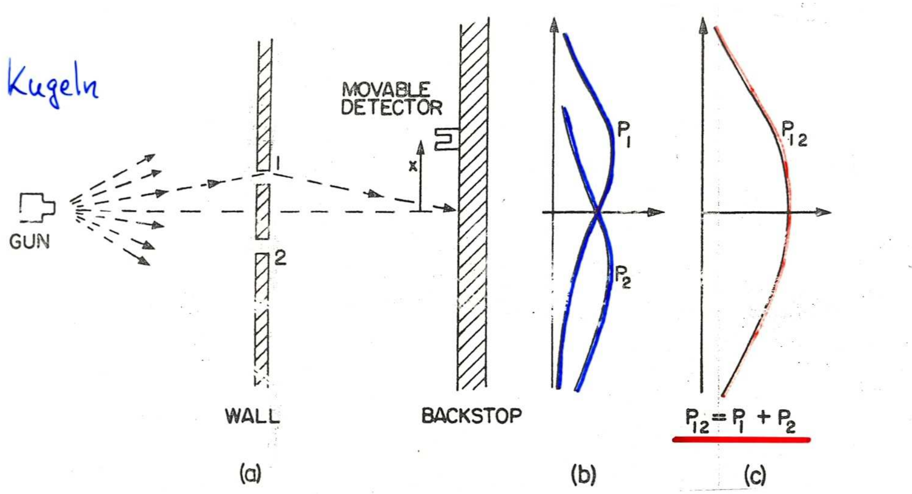
funded by DFG, DAAD, AvH and VolkswagenStiftung

Facts

Waves and Particles

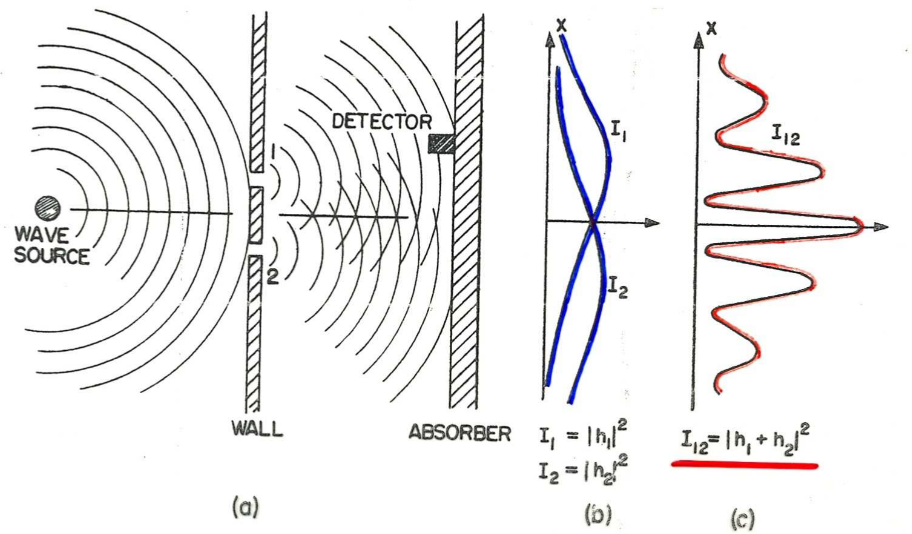
Interferenz am Doppelspalt (?)

Kugeln



1. **no Interference** with balls
   - balls are **granular**
   - summing up **probabilities**

Wellen

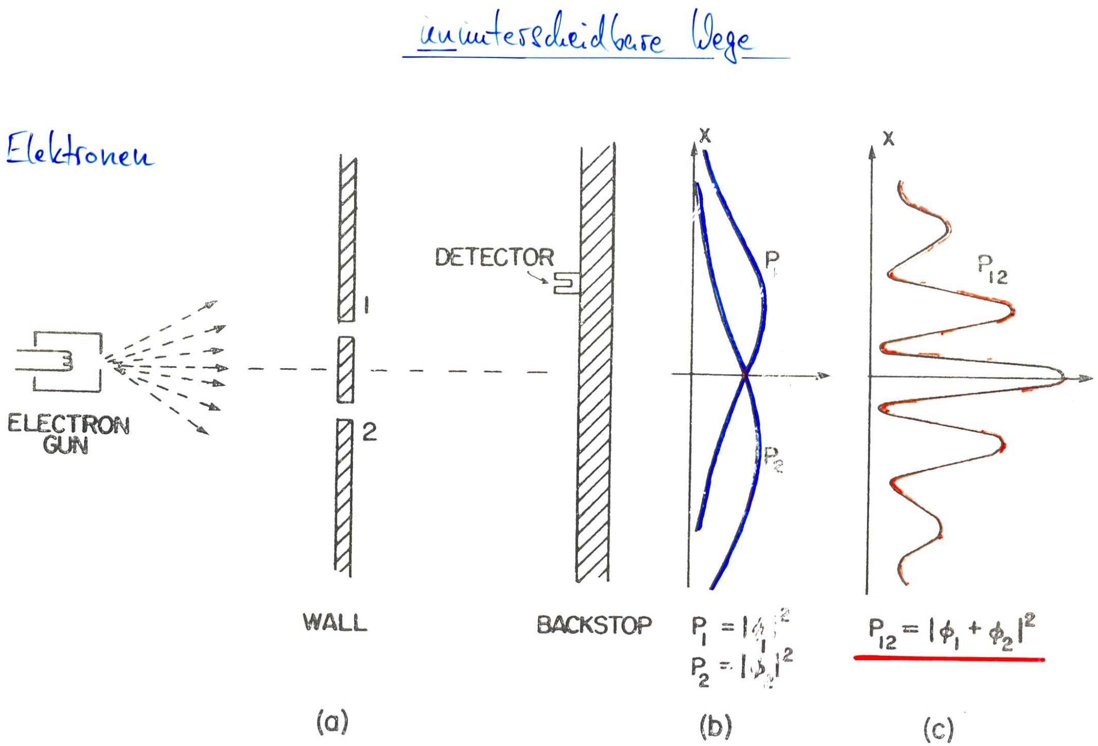


2. **Interference** with water waves
   - **continuous** intensity distribution
   - Summing up **amplitudes** (has phase = mountains and valleys)

[Feynman, Lecture Notes of Physics]

Wave-Particle-Dualism

- **Particle does *not* have position *and* velocity!**

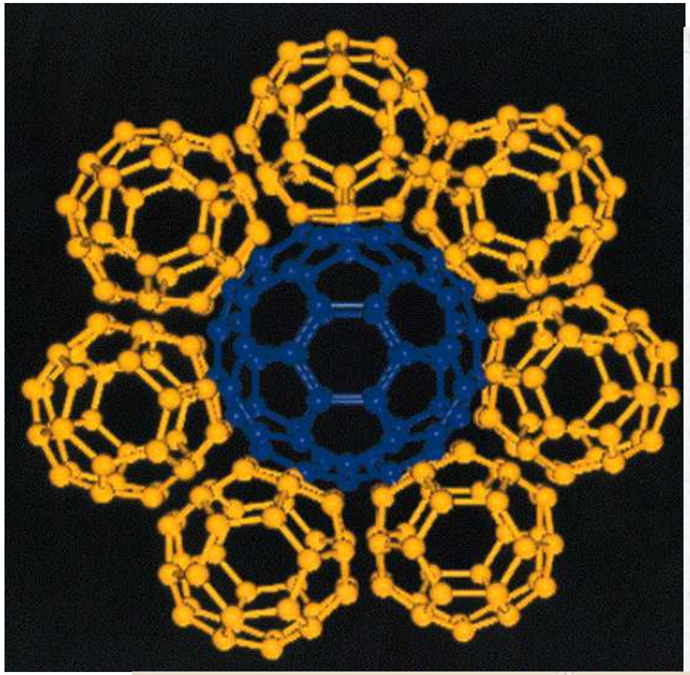


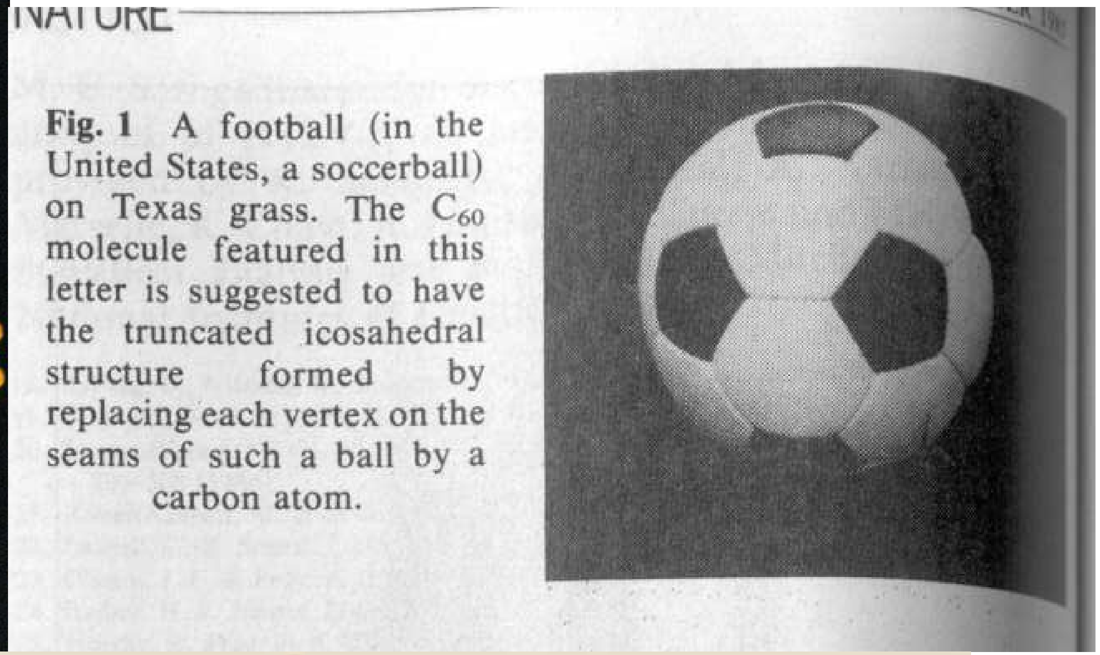
[Feynman, Lecture Notes of Physics]

- **Eins und Eins gibt Keins! – "The Moon isn't there if we don't watch (provided it's only us to watch)!"**

  [B. d'Espagnat, 2002, see also FASZ 2nd March 2008]

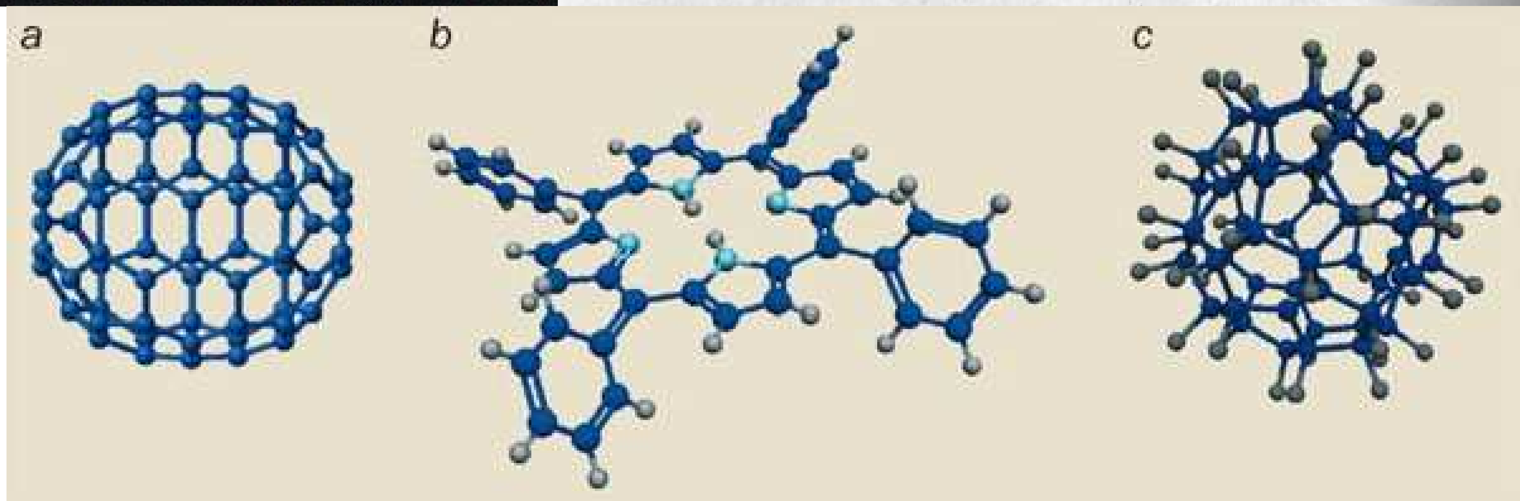
Interference with ever larger objects





NATURE

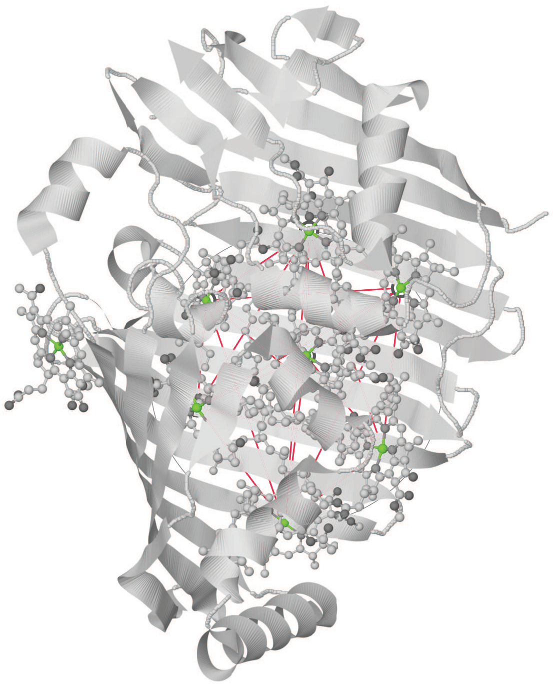
Fig. 1 A football (in the United States, a soccerball) on Texas grass. The C_{60} molecule featured in this letter is suggested to have the truncated icosahedral structure formed by replacing each vertex on the seams of such a ball by a carbon atom.



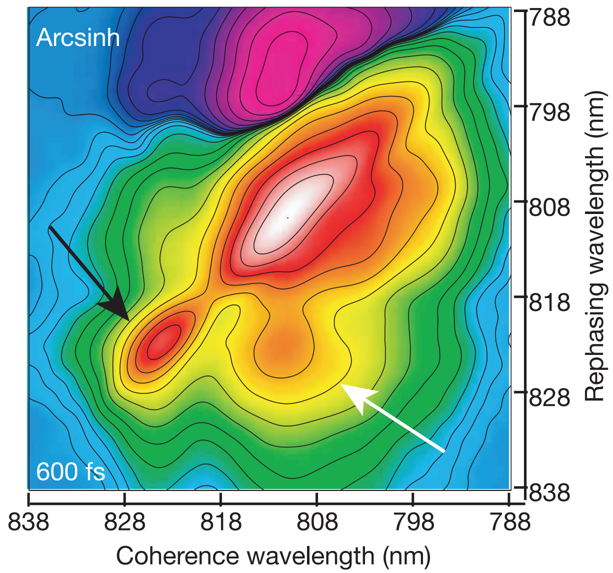
[Hornberger et al., Physics World 2005]

Quantum coherence in "vegetables" – a provocation!

FMO photosynthetic complex (green sulfur bacteria)



2D spectroscopy

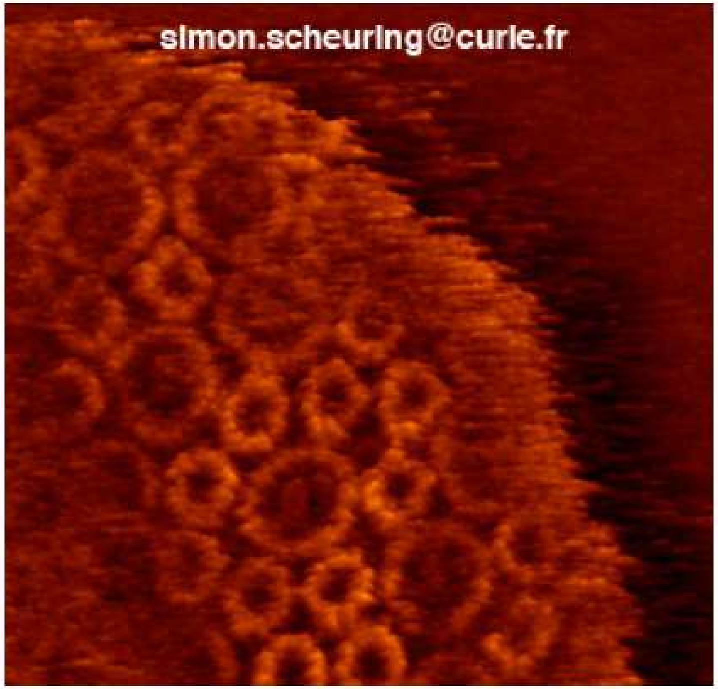


light harvesting antenna complexes (e.g., "FMO") funnel excitations from receptor to reaction center with $\geq 95\ \%$ **quantum efficiency**

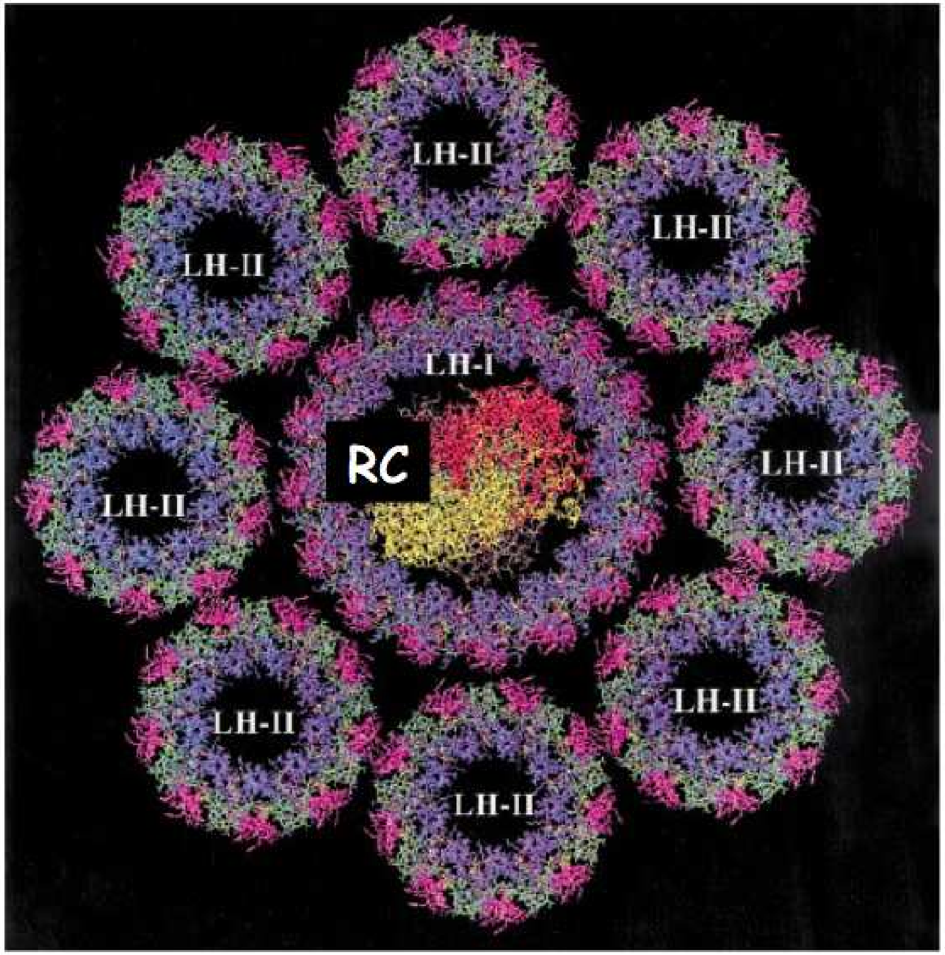
at ambient temperature [Engel et al. (2007); Collini et al. (2009), D.B. Turner et al (2011)]

in noisy, multi-hierarchical environment

There are many ways to Rome - e.g., purple bacteria



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



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

Observations/issues

- observe interference when efficiently decouple/screen the "interfering" degree of freedom (bucky balls)

- coherences possibly "long-lived", though certainly *transient* (e.g., at ambient temperatures)

- biology offers rather variable architectures; essentially always garnished with "disorder", along with some robust/coarse grained structural features and redundancy

- disorder is *distinct* from noise!

Menu

Statistically optimised transport in FMO

[some perspectives]

a different variant of "large" scale quantum effects

Philosophy for “FMO”

here: *“constrained” disorder = many copies, common structural features on some scales, accidental variations on other scales*

well known: disorder induces dramatic changes of quantum transport properties

control transport statistics by coarse grained constraints

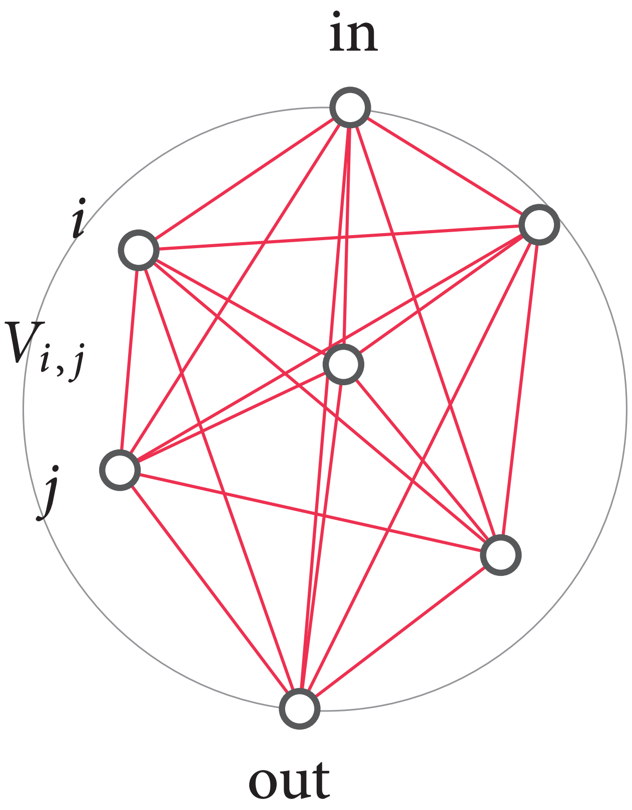
statistics robust – by construction

Minimal model

Abstract network model of FMO

– FMO as a 3D random network of sites –

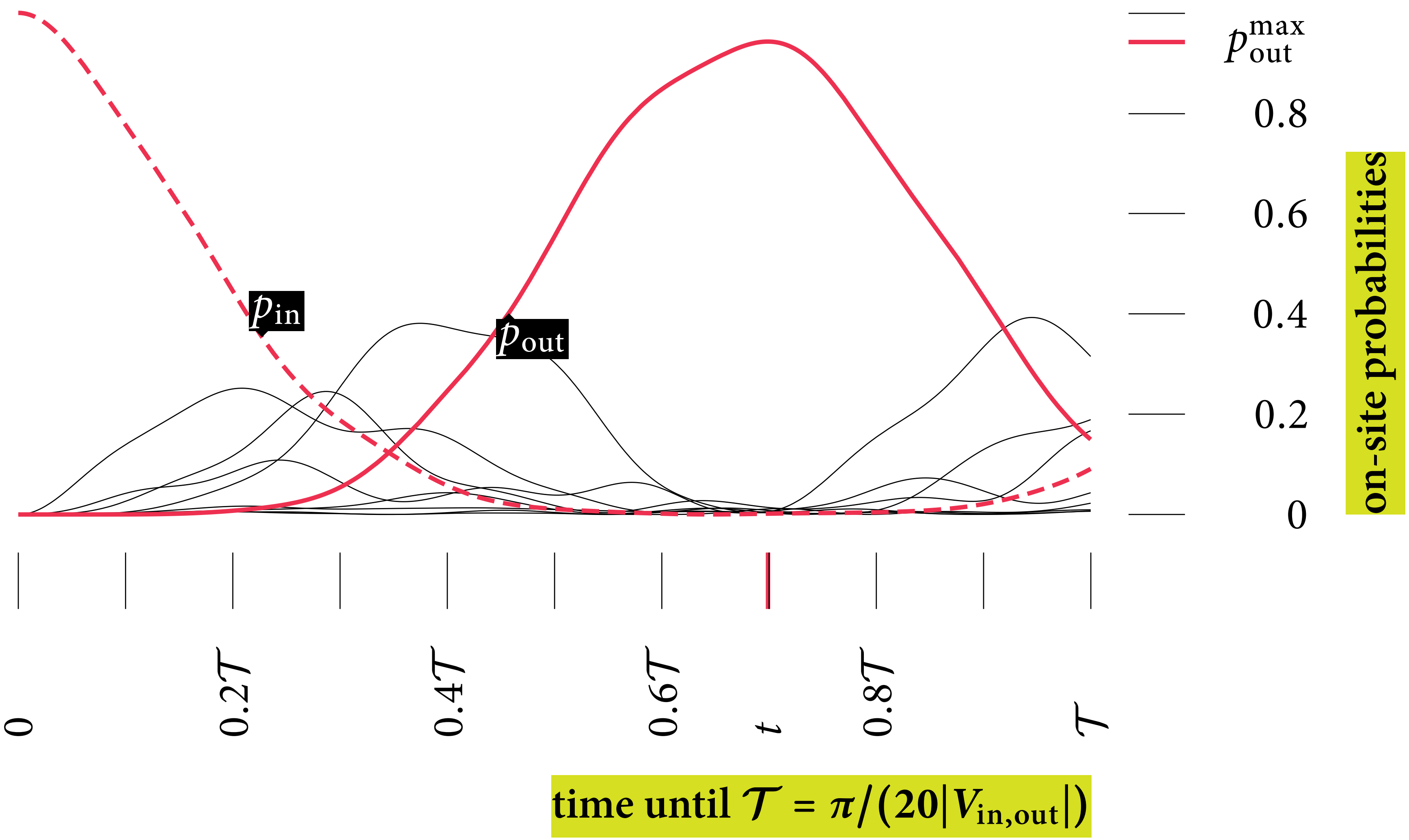
– coherent dynamics on finite, fully connected, random graph –



- $H = \sum_{i \neq j=1}^{N} v_{i,j} \sigma_{+}^{(j)} \sigma_{-}^{(i)}$
- **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**

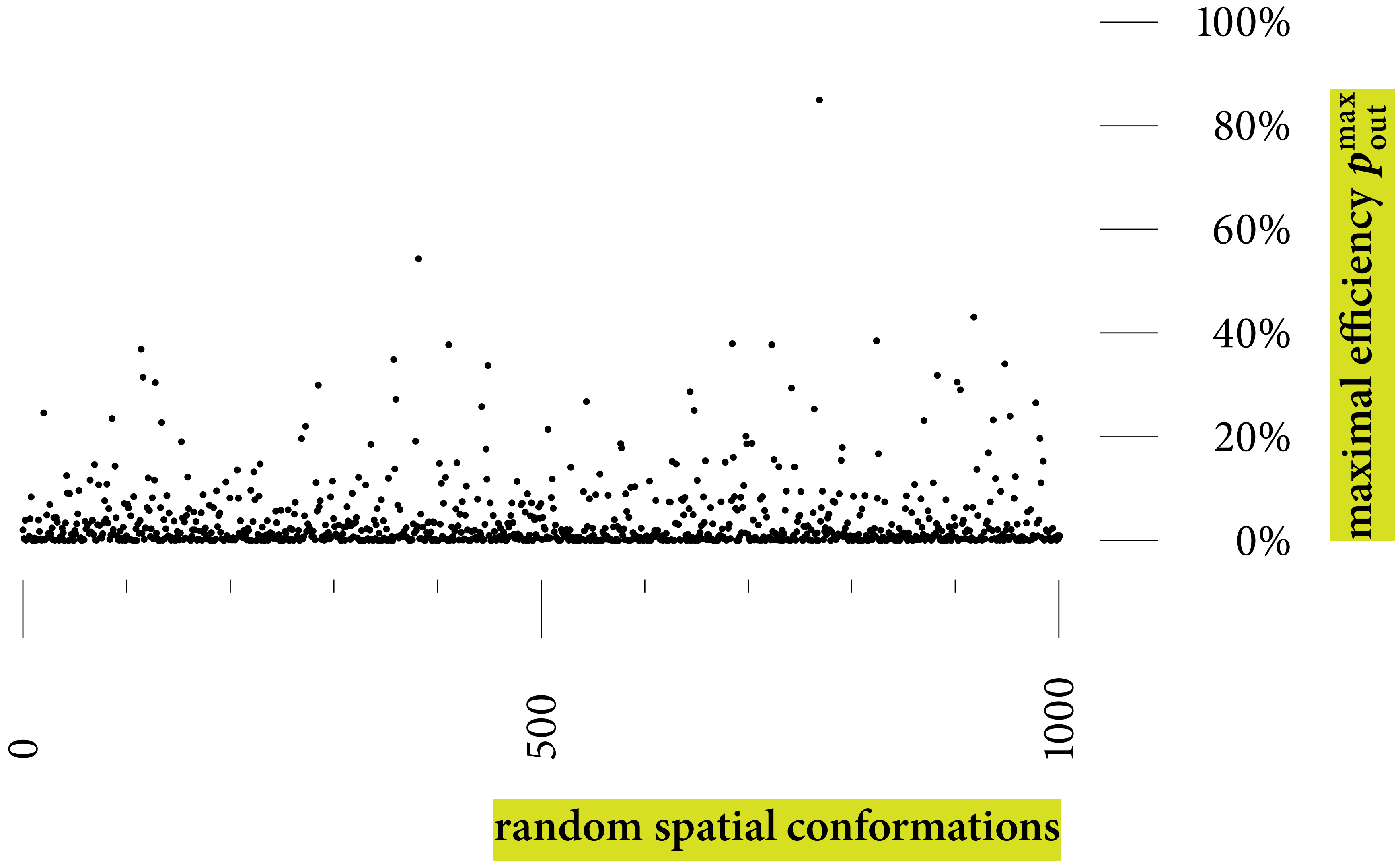
Transport efficiency

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



Transport efficiency vs. configuration

characteristic, LARGE QUANTUM fluctuations!



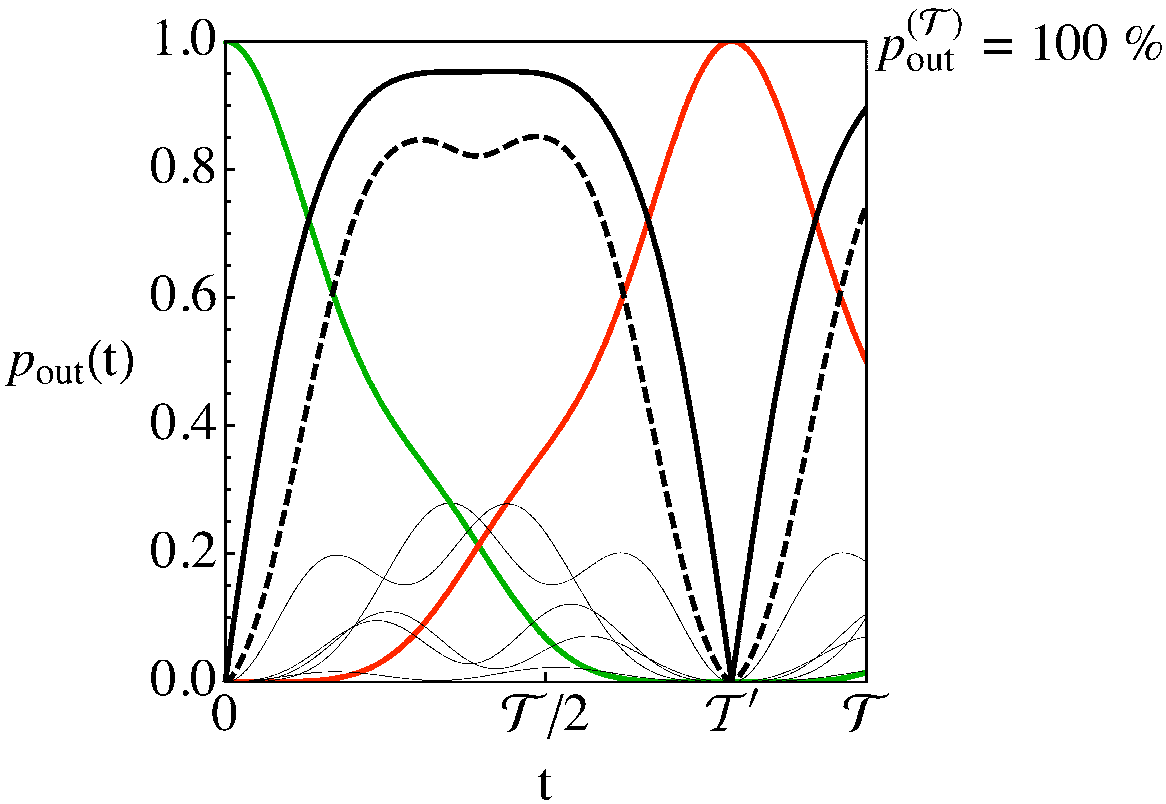
→ rare, optimal configurations – mostly localized transport ←

→ ??conceivable that evolution optimises coherent quantum transport?? ←

Optimal design – constraints and statistics

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

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

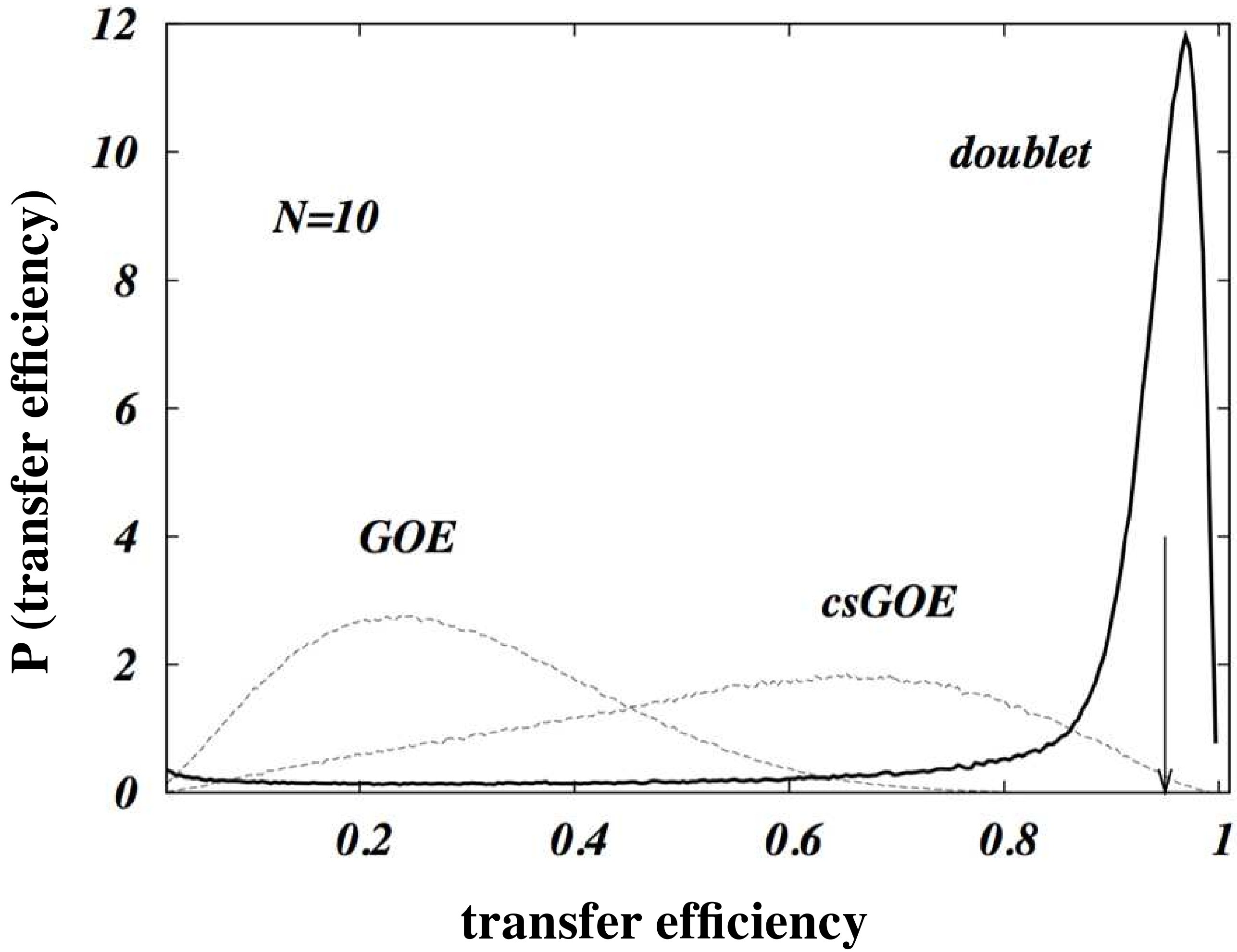
where

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

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

Design principles control distribution of transfer efficiencies

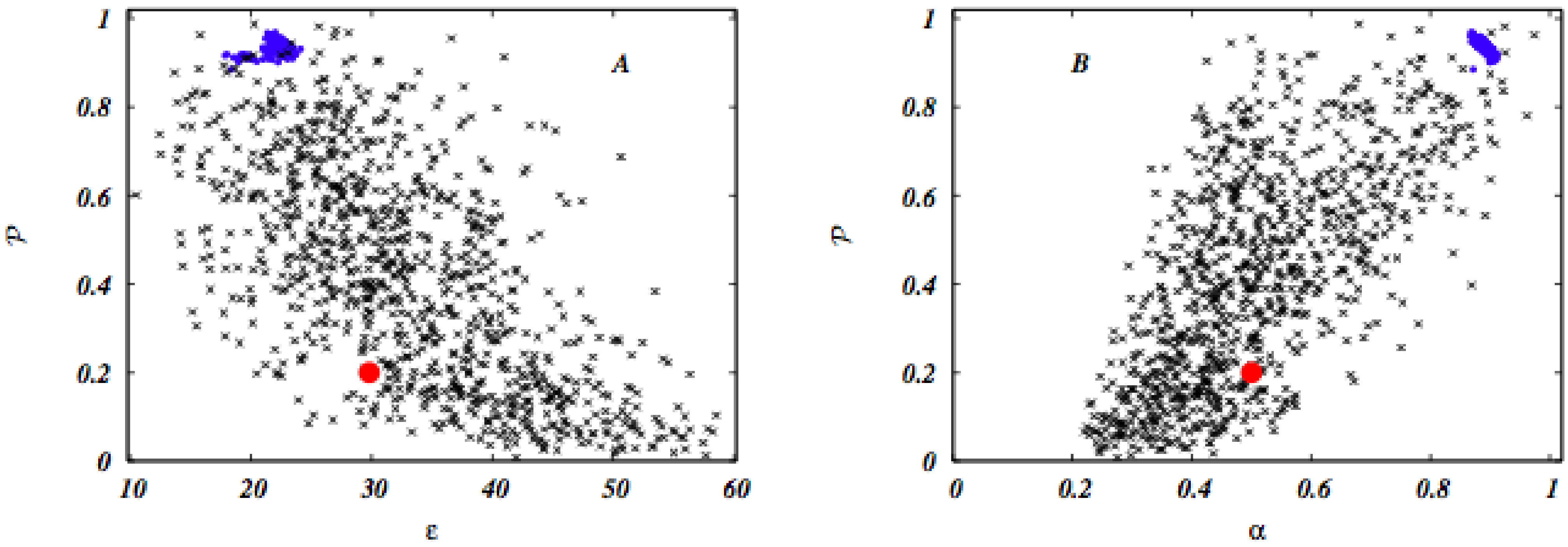
dramatic efficiency enhancement . . .



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

Does this model fit available experimental data?

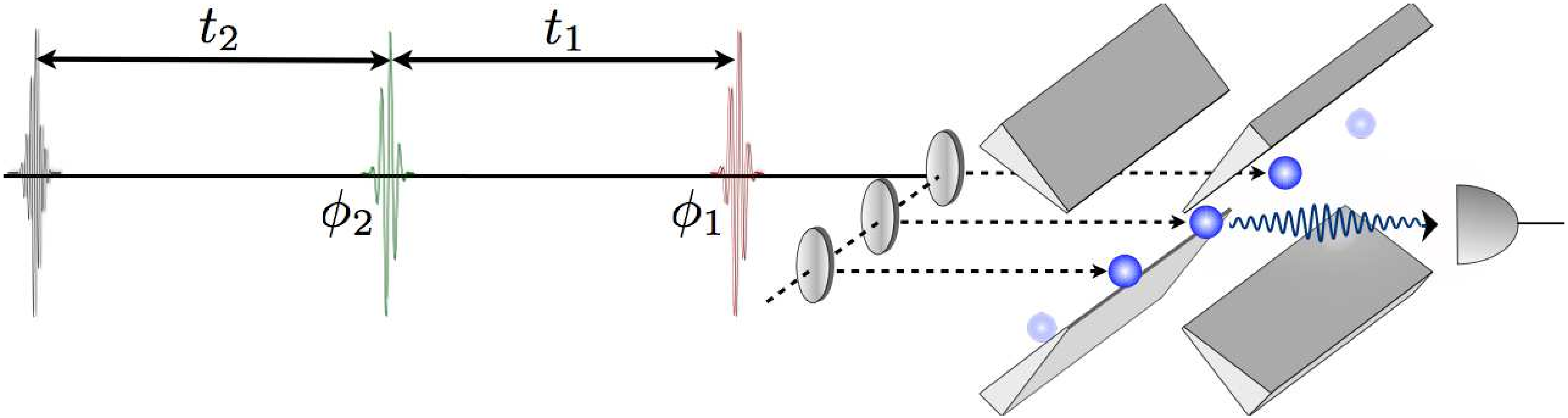
genetic optimisation (blue) of dipole orientations
starting from published structure data (red) [Tronrud et al., 2009; Schmidt am Busch et al., 2011] **. . .**



. . . to be compared to benchmark ensemble (crosses)
seeded with random dipole orientations [Walschaers et al., 2013]
[ϵ – deviation from centro-symmetry; α – dominant doublet strength]

What's missing for a better understanding

Even cleaner experiments

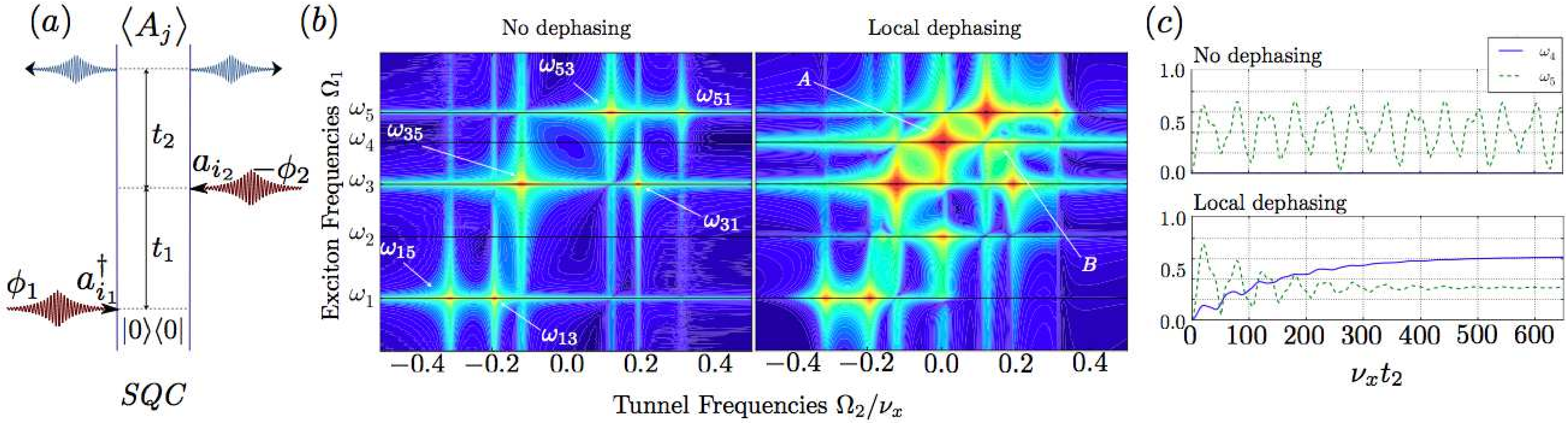


[Gessner et al, 2014]

2D spectroscopy with single-site addressability – as in ion traps

well-defined initial conditions, read-out, coupling-in/-out, statistics

E.g., coherent vs. incoherent transport



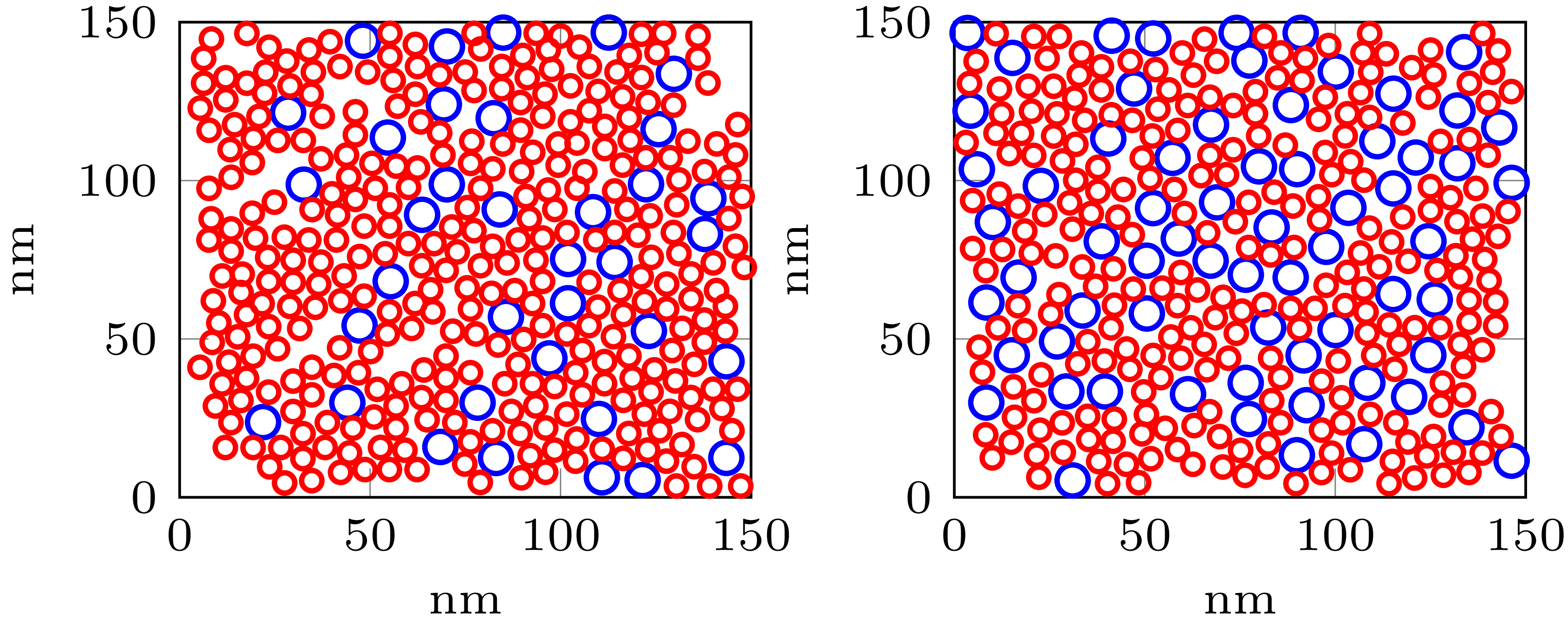
[Gessner et al, 2014]

dephasing-induced population of otherwise "dark" ω_4-state

unambiguous signature in zero-frequency 2D signal

Clarify hierarchy of superstructures

LHI (blue)-LHII (red) distribution in photosynthetic membrane of Rhodospirillum photometricum



[Scheuring & Sturgis, 2005]

Membrane structure under low- (left) and high-light (right) conditions

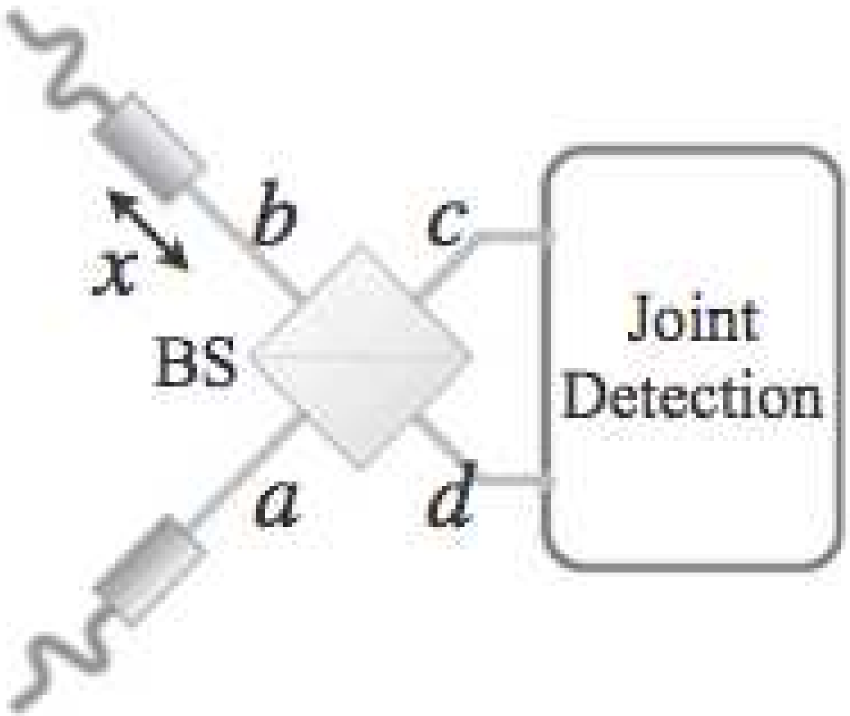
How (if at all) are quantum and classical processes matched for functionality?

Another way of making things “large”

More than one excitation – complexity from many-particle interferences rather than from “network” structure

Two photons, one (balanced) beam splitter

one photon in each mode a and b – distinguishability controlled by path delay x



coincident detection in output modes c and d

- coincidence probability if **distinguishable:** $P(2;1,1) = 1/2$
- coincidence probability if **indistinguishable:** $P(2;1,1) = 0$

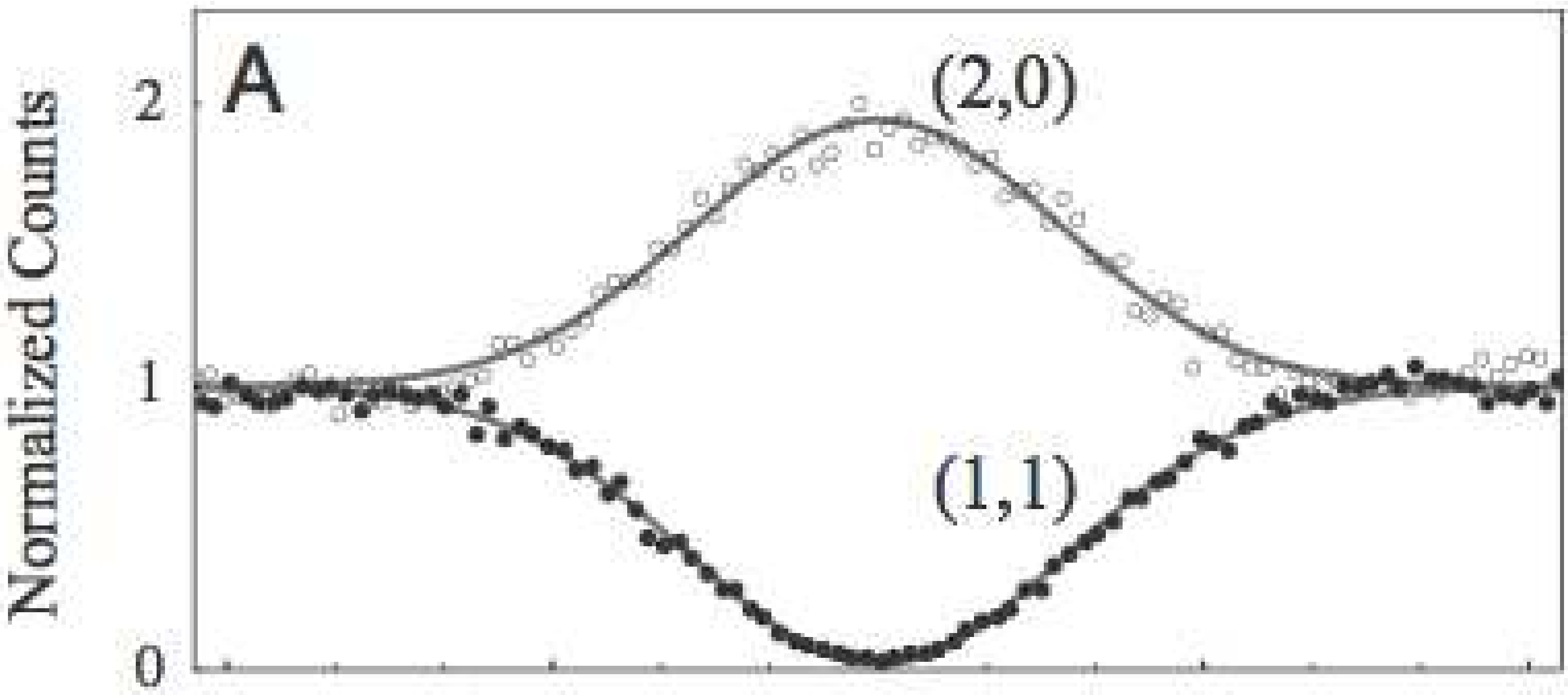
if indistinguishable: destructive interference of two two-particle trajectories

[Shi & Alley (1986, 1988); Hong, Ou & Mandel (1987)]

What happens "in between"?

Experimental test

middle of plot: fully indistinguishable – edges: fully distinguishable

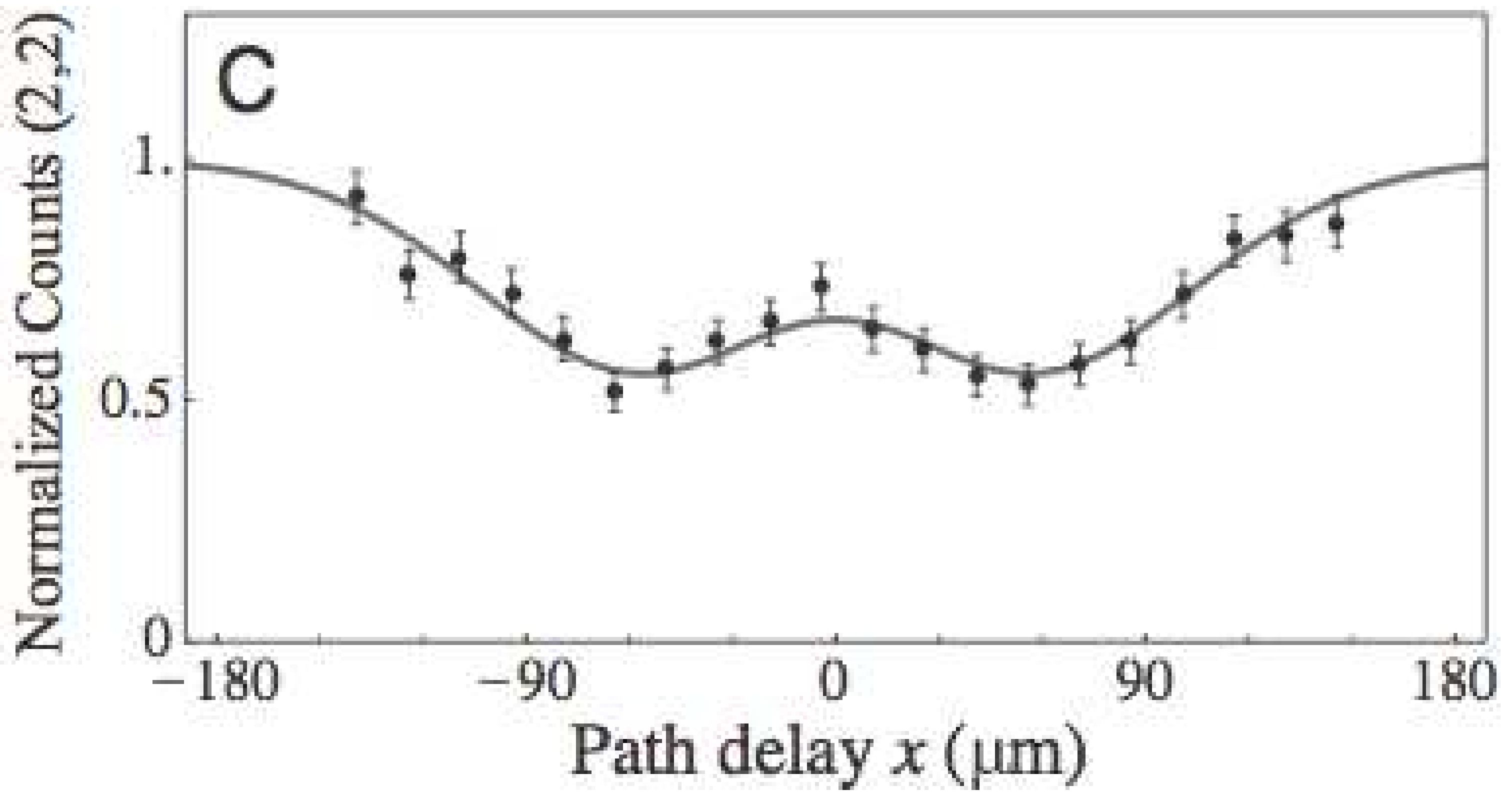


The more two-particle which-way information, the less interference – as for single-particle scenario! [Ra et al., 2013]

More than two *is* different!

two photons per input mode (four-photon interference)

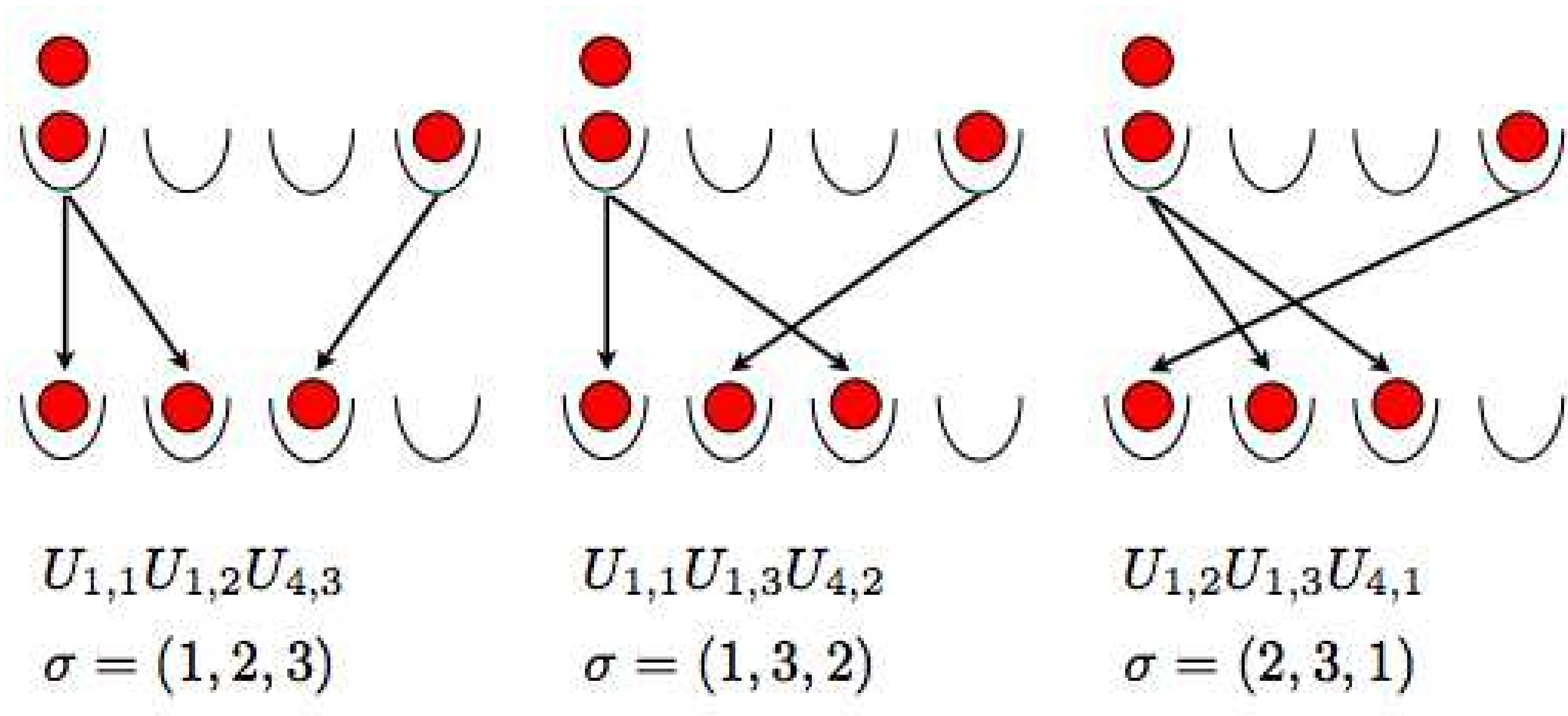
Non-monotonic quantum-to-classical transition of $P(4;2,2)$



Gaining which-path information (increasing x)
generically **leads to a** *non-monotonic* **quantum-to-classical transition!**
consequence for many-particle decoherence theory?

[Tichy et al., 2011; Ra et al., 2013]

Generalized problem:
mapping n-boson input state on n-boson output state

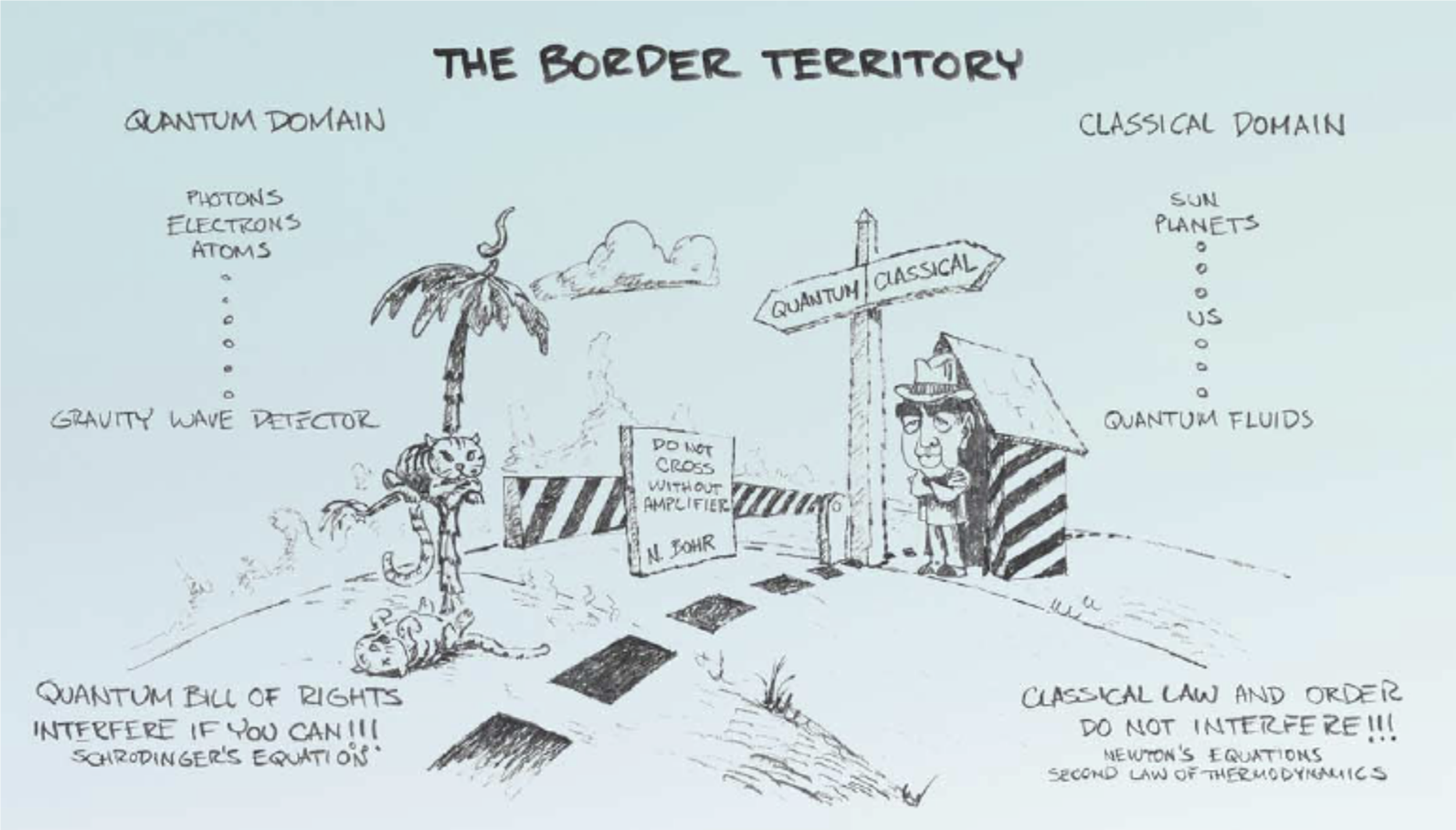


coherent sum of up to $n!$ amplitudes – computationally "hard" – "boson sampling"

[Tichy et al, 2010 ff., Aaronson & Arkhipov, 2011]

Hence, remains an open question. . .

?which size? **?which temperature?**



[Zurek]

$\hbar \to 0$, $t \to \infty$, $T \to \infty$, $N \to \infty$

Open issues & requirements

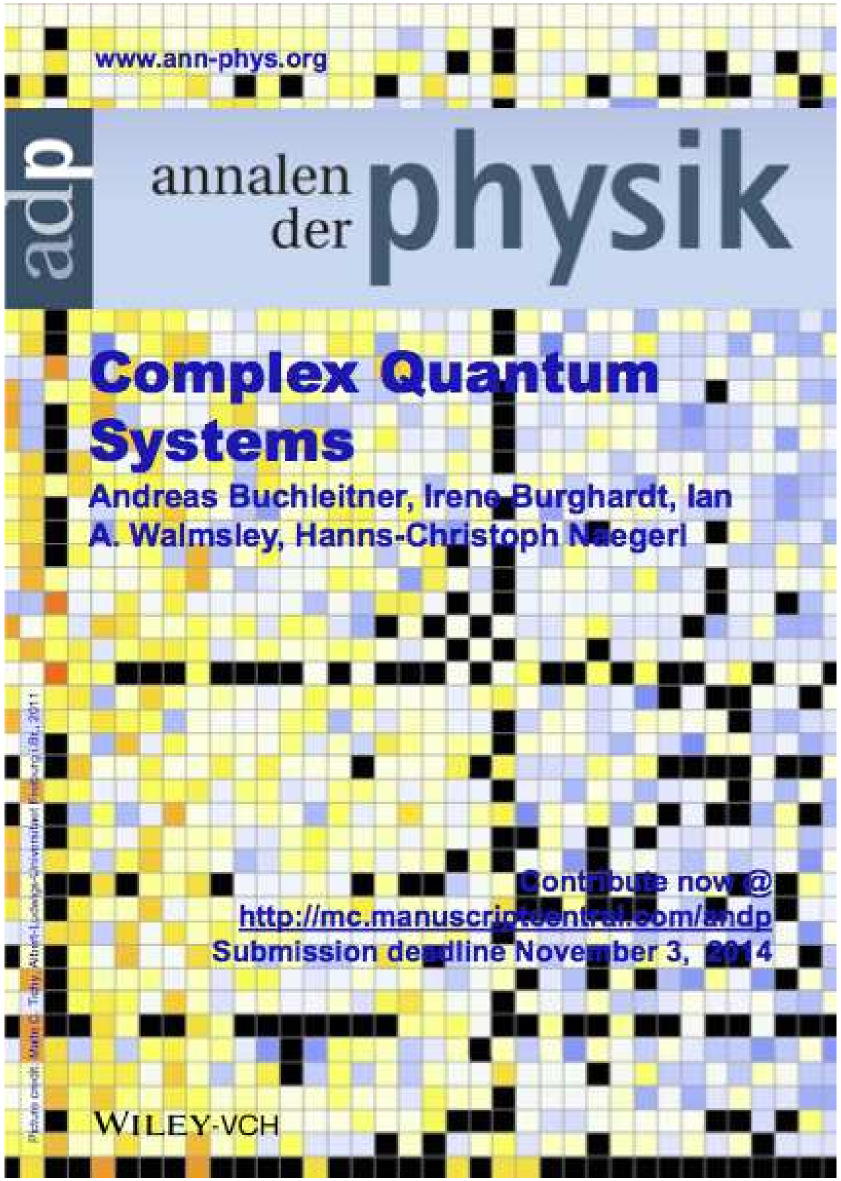
- **Make sure we employ the same terms for the same concepts, in substance – e.g. what do we mean by *coherence* or *large scales/macroscopic*? Use Ockham's razor!**

- **Are large scale quantum effects those in the semiclassical domain (e.g., Gutzwiller)?**

- **The specificity of a complex quantum system is inscribed in characteristic fluctuations, rather than in mean values – hence, need experimental record of statistics.**

- **Does it pass the ping-pong test?**

Literature/Propaganda



PhD Malte Tichy, 2011;
diploma Klaus Mayer, 2011;
PhD Torsten Scholak, 2011;
diploma Tobias Zech, 2012;
PhD Frank Schlawin, 2014;
PhD Manuel Gessner, 2015;
PhD Mattia Walschaers, 2015;
PhD Chahan Kropf, 2016
@ www.quantum.uni-freiburg.de
@ http://www.frias.uni-freiburg.de/en/routes-to-frias/foci/quantum