Is information really physical?

Andrew Briggs – Oxford University

FQXi

Physics of Information Conference

Vieques, Puerto Rico, January 5-10, 2014

JOHN TEMPLETON FOUNDATION

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TWCF theme: *The Power of Information*

Does information have causal power, or is its role merely explanatory?

i. What is the ontological status of information?
ii. What is the relation of information to its embodiment?
iii. How does information's causative role relate to physical causation, and how is over-determination avoided?
iv. How does information relate to its context?
v. How is information accessed and recognised, and how is what is meaningful selected from incoming data?
vi. What is the relation between the various definitions of information, especially Shannon information and contextual information?
vii. How is information hierarchically ordered?

TWCF theme: *The Power of Information*

1 The emergence of life as a transition in causal and informational architecture – Paul Davies

2 Information at the quantum physics/statistical mechanics nexus – Christopher Timpson

3 Causal foundations of biological information – Paul Griffiths

4 The causal power of information in a quantum world – Gerard Milburn

5 Does information have causal power? – Giulio Tononi

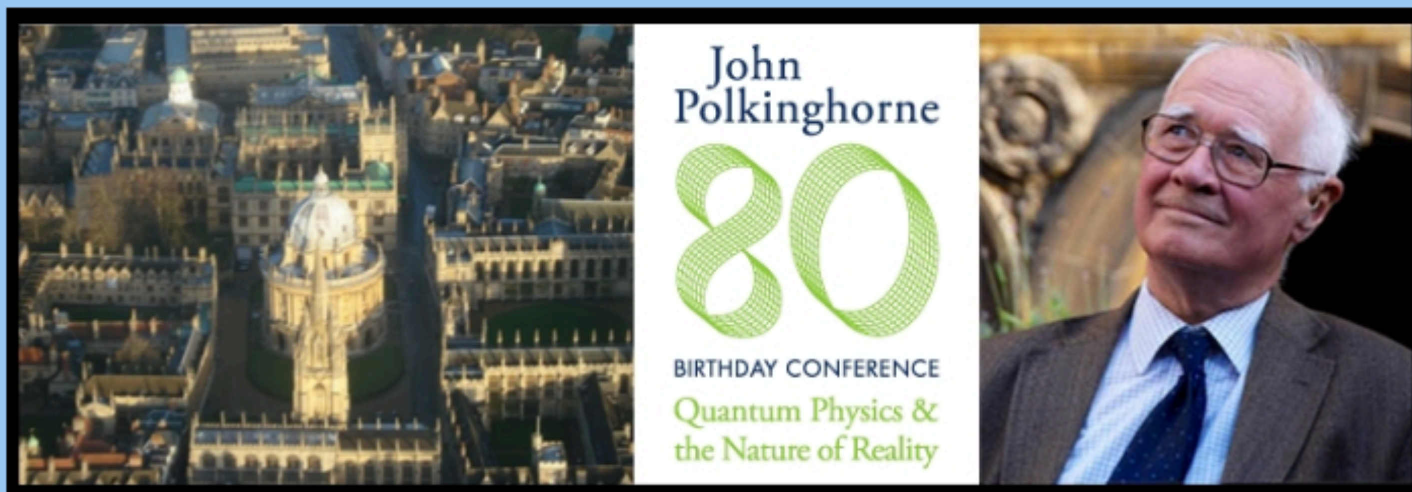
6 Constructor Information Theory – Simon Benjamin and David Deutsch

7 Agency and (quantum) physics – Hans Briegel

8 Information theory, ecosystems, and Schrödinger's paradox – David Wolpert

The Oxford Questions

26th-29th September 2010
St Anne's College Oxford



Co-Chairs: Andrew Briggs, Jeremy Butterfield and Anton Zeilinger

The Oxford Questions on the foundations of quantum physics.
G.A.D. Briggs, J.N. Butterfield, A. Zeilinger. *Proc. R. Soc. A* **469**, 20130299 (2013)

Experiments to probe the foundations of quantum physics

a. What experiments can probe macroscopic superpositions, including tests of Leggett-Garg inequalities?

b. What experiments are useful for large complex systems, including technological and biological?

c. How can the progressive collapse of the wave function be experimentally monitored?

The Oxford Questions on the foundations of quantum physics.
G.A.D. Briggs, J.N. Butterfield, A. Zeilinger. *Proc. R. Soc. A* **469**, 20130299 (2013)

The Quantum Measurement Problem

It is convenient to classify reactions to this problem into three broad classes, defined by the following three different views on the status of QM:

(a) QM is the complete truth about the physical world, at all levels, and describes an external reality.

(b) QM is the complete truth (in the sense that it will always give reliable predictions concerning the nature of experiments) but describes no external reality.

(c) QM is not the complete truth about the world; at some level between that of the atom and that of human consciousness, other non–quantum mechanical principles intervene.

Personally, if I could be sure that we will forever regard QM as the whole truth about the physical world, I think I should grit my teeth and plump for option (b).

A.J. Leggett, *Science* **307**, 871-2 (2005)

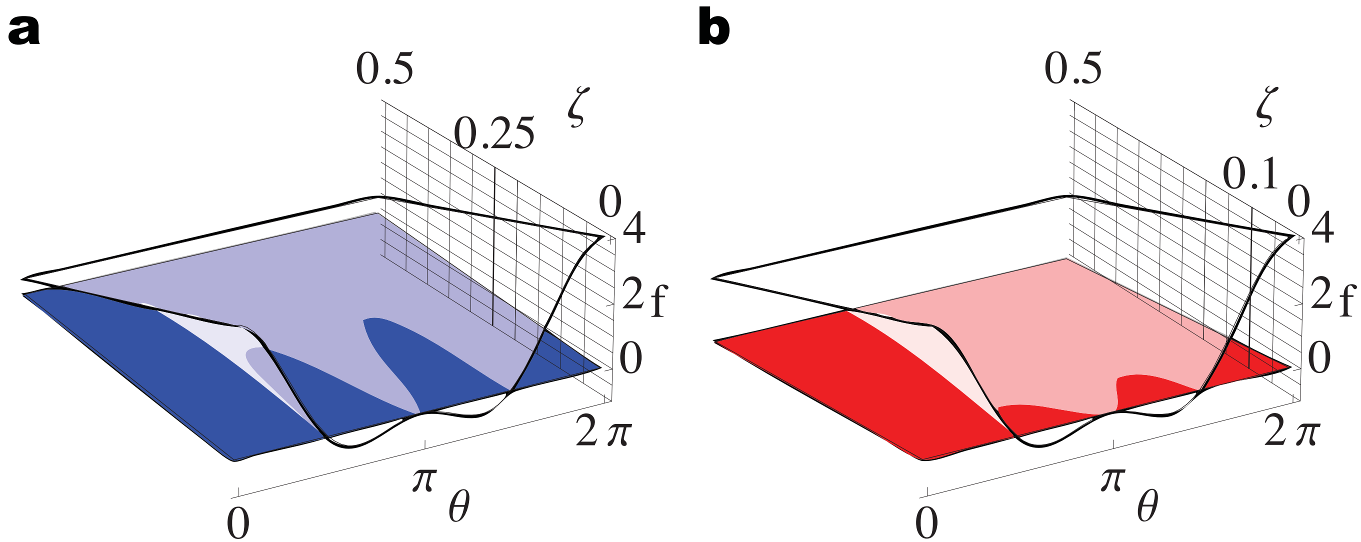
Leggett-Garg inequality – P in Si

For ... ns to

inva

1.

2.



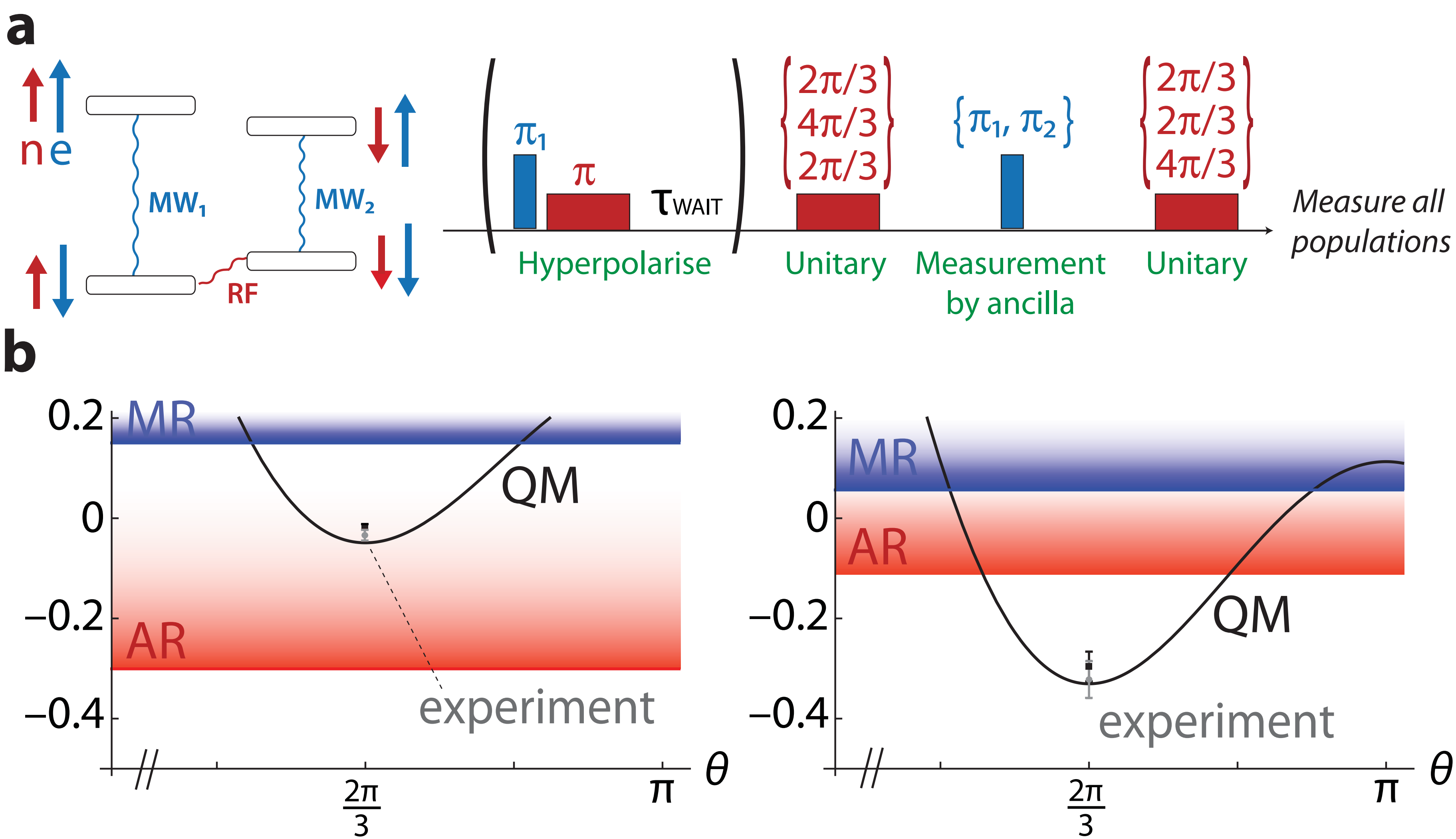
$$K_{ij} = \langle Q(t_i) Q(t_j) \rangle .$$

$$f = K_{12} + K_{23} + K_{13} + 1 .$$

$$realist : f \geq 0 .$$

G.C. Knee *et al.*, *Nat. Commun.* **3**, 606 (2012)

Leggett-Garg inequality – P in Si



G.C. Knee *et al.*, *Nat. Commun.* **3**, 606 (2012)

Quantum three box paradox

- Rules: Alice may open only box 3, Bob has boxes 1 and 2.
- Alice tells Bob: "I'll place the ball in the box in position 3 and then shuffle the boxes randomly. You can open box in position 1 *or* 2 (but not both) – I promise not to look. Then I'll shuffle the boxes again and open box 3."
- Alice wagers Bob: "I bet that I can use box 3 to predict when you *saw* the ball in boxes 1 or 2. I can do this with > 50% odds."

R.E. George *et al.*, *Proc. Natl. Acad. Sci.* **110**, 3777-3781 (2013)

Experimental procedure

$$|I\rangle = \frac{|1\rangle + |2\rangle + |3\rangle}{\sqrt{3}}$$

M_1

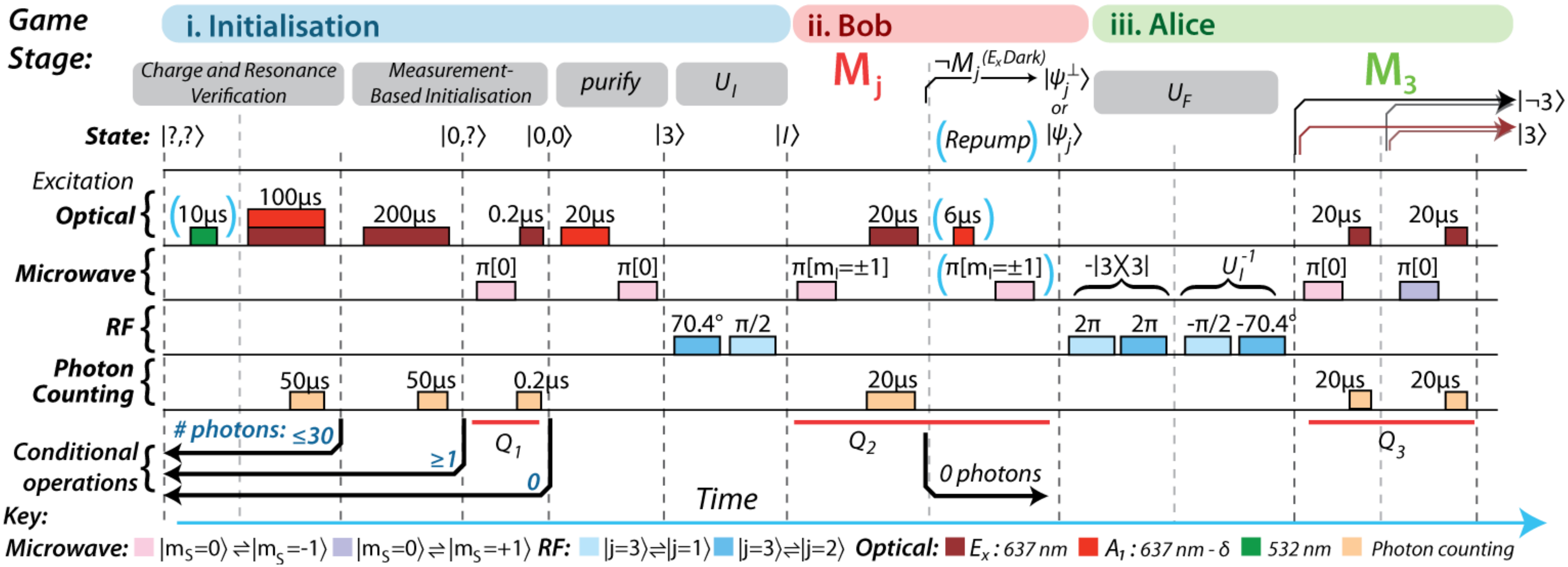
$$|\Psi'\rangle = |1\rangle$$

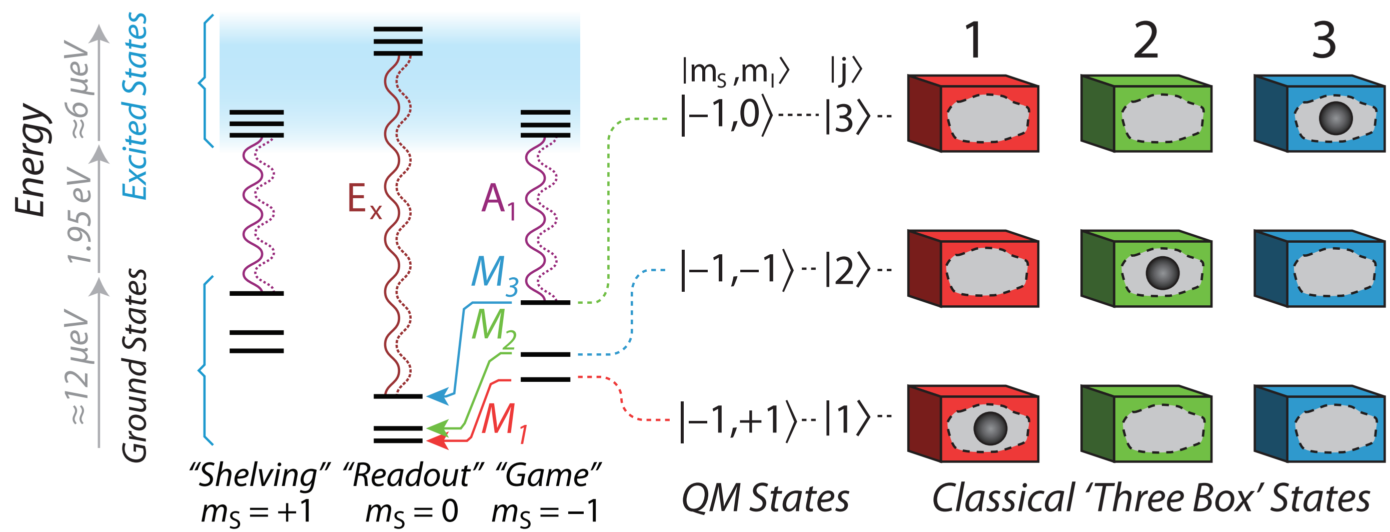
$$|\Psi'\rangle = \frac{|2\rangle + |3\rangle}{\sqrt{2}}$$

$$|F\rangle = \frac{|1\rangle + |2\rangle - |3\rangle}{\sqrt{3}}$$

R.E. George *et al.*, *Proc. Natl. Acad. Sci.* **110**, 3777-3781 (2013)

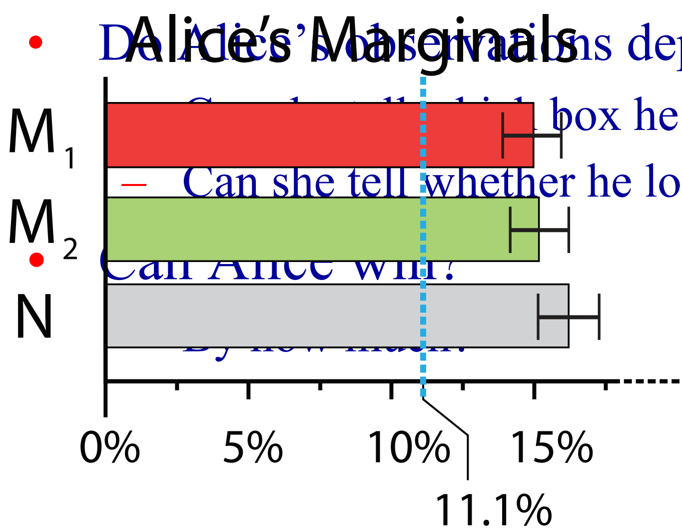
Experimental procedure

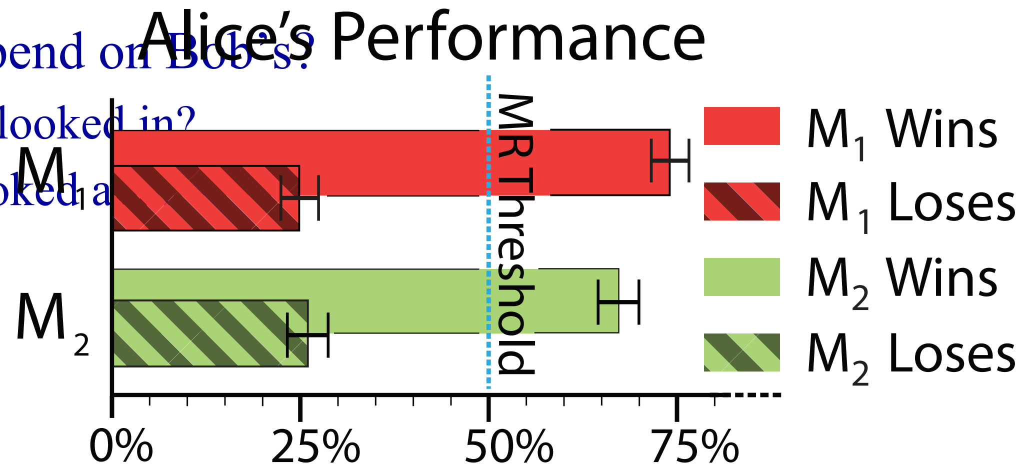




Alice's measurements

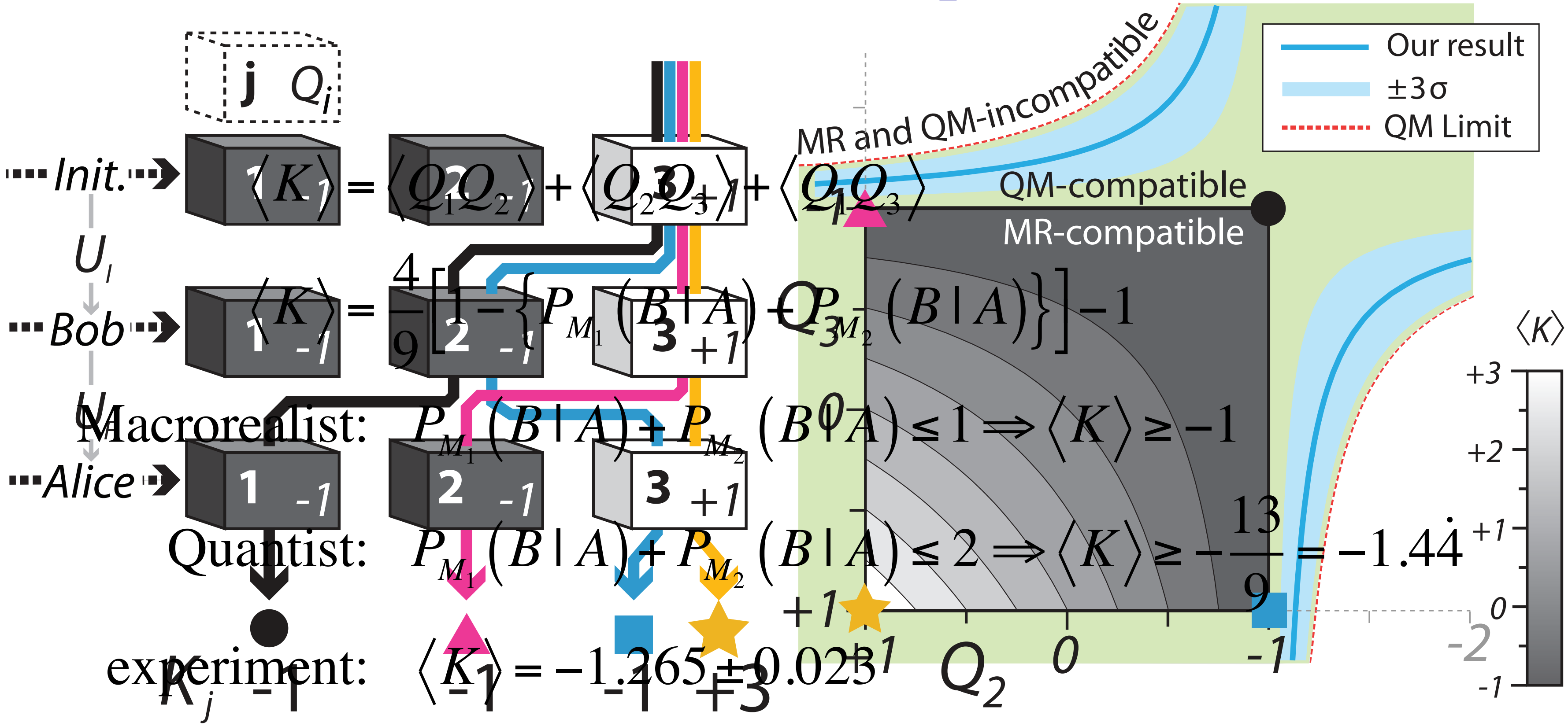
- Do Alice's observations depend on Bob's?
  - Can she tell which box he looked in?
  - Can she tell whether he looked a
- Can Alice win?
  - By how much?





R.E. George *et al.*, *Proc. Natl. Acad. Sci.* **110**, 3777-3781 (2013)

Quantum three box paradox



$$\langle K \rangle = \langle Q_1 Q_2 \rangle + \langle Q_2 Q_3 \rangle + \langle Q_1 Q_3 \rangle$$

$$\langle K \rangle = \frac{4}{9}\left[1 - \left\{P_{M_1}(B|A) + P_{M_2}(B|A)\right\}\right] - 1$$

Macrorealist: $P_{M_1}(B|A) + P_{M_2}(B|A) \le 1 \Rightarrow \langle K \rangle \ge -1$

Quantist: $P_{M_1}(B|A) + P_{M_2}(B|A) \le 2 \Rightarrow \langle K \rangle \ge -\frac{13}{9} = -1.4\dot{4}$

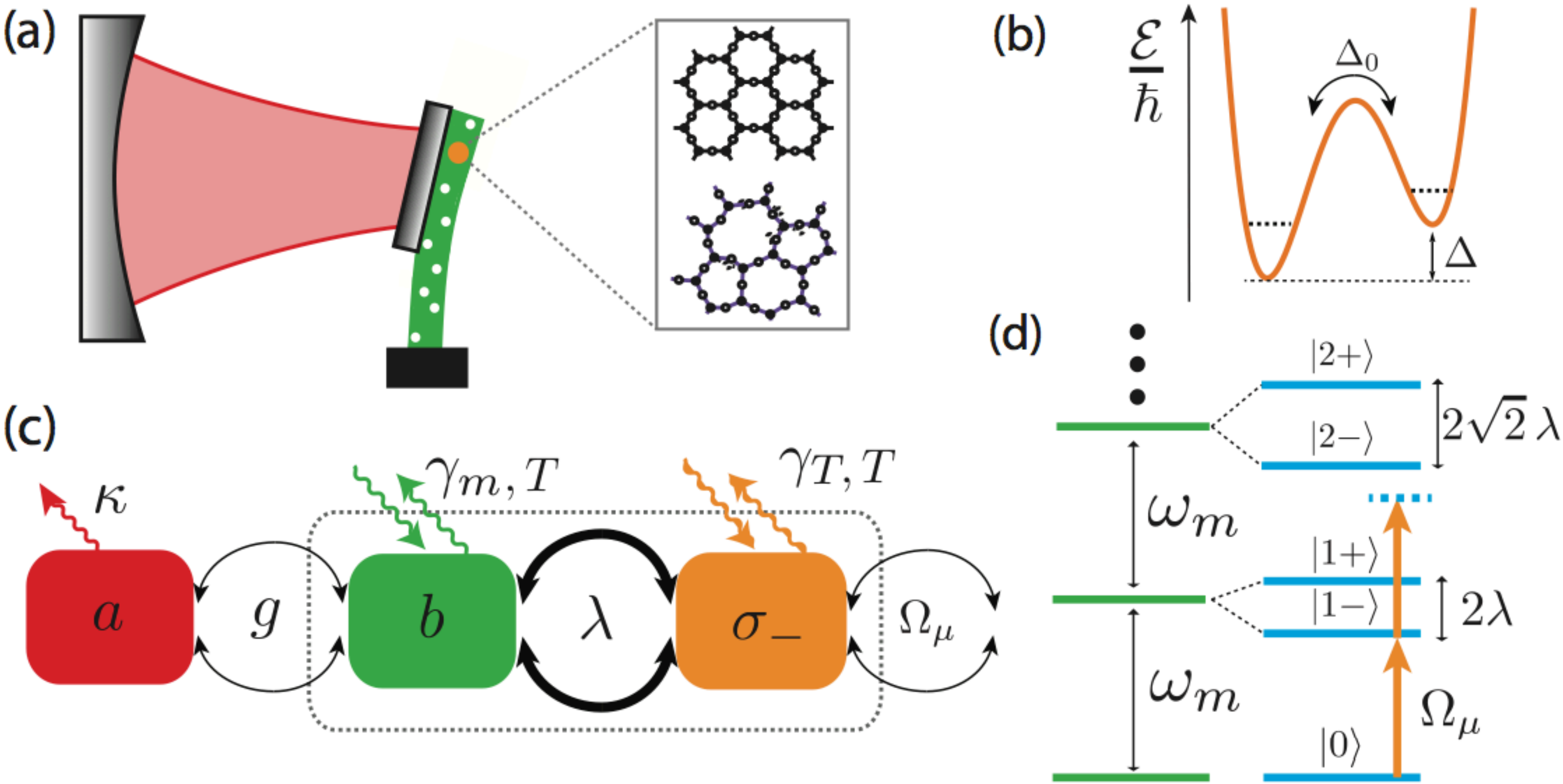
experiment: $\langle K \rangle = -1.265 \pm 0.023$

11.3 σ under fair sampling assumptions

7.8 σ if attributed to Alice cheating

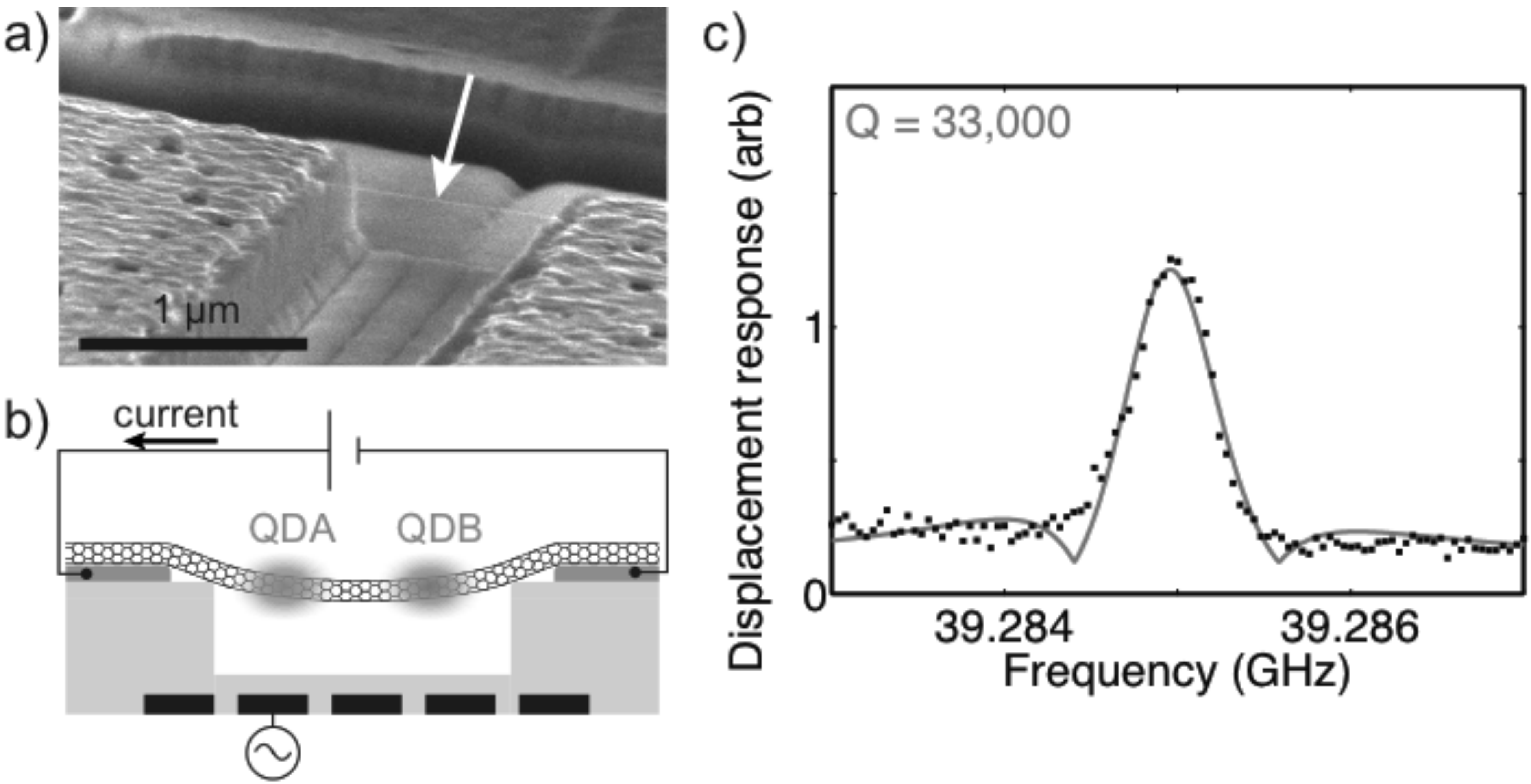
R.E. George *et al.*, *Proc. Natl. Acad. Sci.* **110**, 3777-3781 (2013)

What experiments can probe macroscopic superpositions?



T. Ramos *et al.*, arXiv:1302.1855

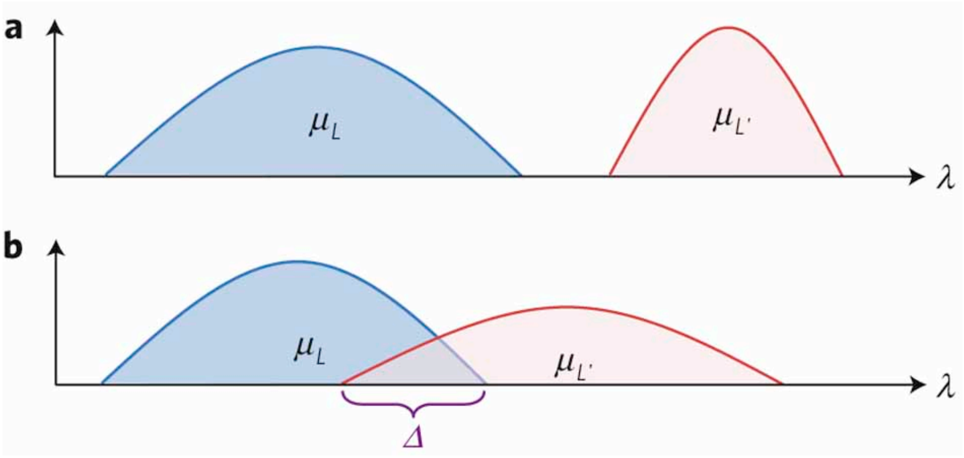
What experiments can probe macroscopic superpositions?

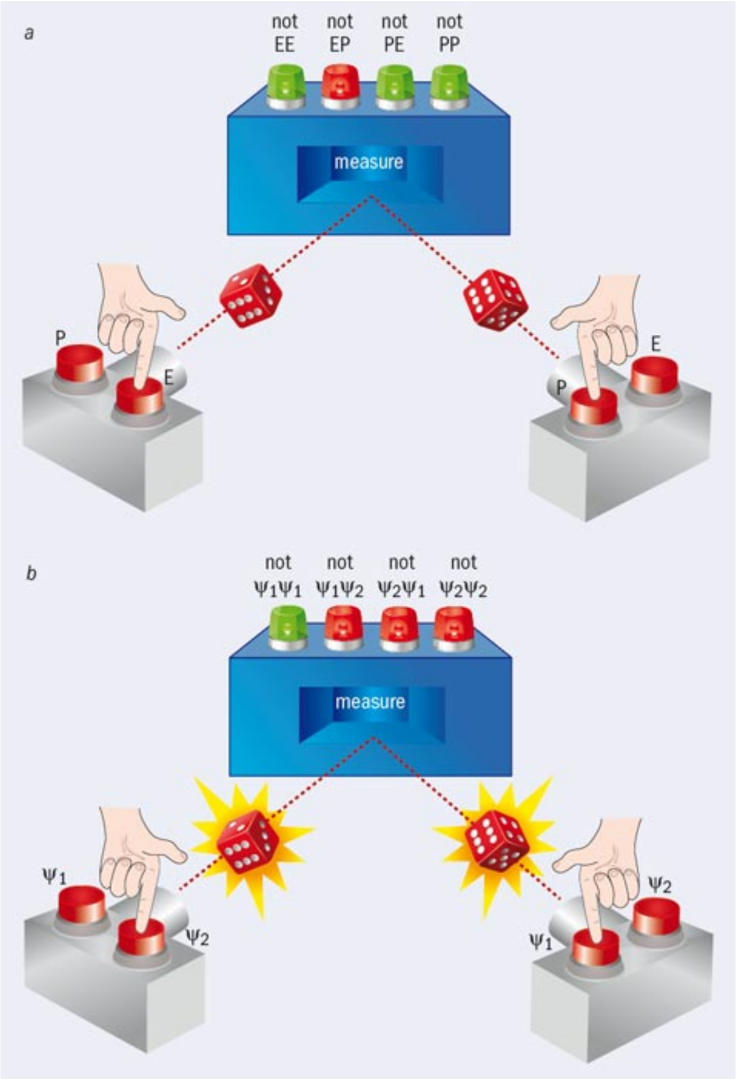


E.A. Laird *et al.*, *Nano. Lett.* **12**, 193-197 (2012)

How statistical are quantum states?

- Non-orthogonality: you can prepare different quantum states for which no single measurement will unfailingly distinguish them.
- Can this be interpreted statistically, with overlap of the probability distributions of some underlying states?
- The Pusey-Barrett-Rudolph theorem rules out statistical interpretations on the basis of certain assumptions.





M.F. Pusey *et al.*, *Nature Physics* **8**, 475-478 (2012)

How statistical are quantum states?

- Are quantum states real? Lucian Hardy, arXiv:1205.1439
  - *Realism*. Each time a system is prepared there exists an underlying state of reality, λ, which we will call the ontic state.
  - *Possibilistic completeness*. The ontic state, λ, is sufficient to determine whether any outcome of any measurement has probability equal to zero of occurring or not.
  - *Restricted ontic indifference*. Any quantum transformation on a system which leaves a particular given pure quantum state, $|0\rangle$, unchanged can be implemented in such a way that it does not affect the underlying ontic states, $\lambda \in \Lambda_{|0\rangle}$, in the ontic support of $|0\rangle$.
  - The real result of this paper is that any ψ-epistemic model must violate restricted ontic indifference (and therefore also violate ontic indifference).
- No ψ-epistemic model can fully explain the indistinguishability of quantum states. Barrett, Cavalcanti, Lal, Maroney, arXiv:1310.8302
  - From an analysis of preparations and measurements on a single system, we have derived an upper bound on the extent to which probability distributions corresponding to distinct quantum states can overlap.
  - An experimental challenge is to perform an experiment with sufficient precision that maximally ψ-epistemic models are ruled out.

Quantum Theory, the Church-Turing Principle and the Universal Quantum Computer

David Deutsch

This is called the 'Church-Turing hypothesis'; according to Turing,

Every 'function which would naturally be regarded as computable' can be computed by the universal Turing machine. (1.1)

The conventional, non-physical view of (1.1) interprets it as the quasi-mathematical conjecture that all possible formalizations of the intuitive mathematical notion of 'algorithm' or 'computation' are equivalent to each other.

I can now state the physical version of the Church-Turing principle :

'Every finitely realizible physical system can be perfectly simulated by a universal model computing machine operating by finite means'. (1.2)

This formulation is both better defined and more physical than Turing's own way of expressing it (1.1), because it refers exclusively to objective concepts such as 'measurement', 'preparation' and 'physical system', which are already present in measurement theory.

Proc. R. Soc. Lond. A **400**, 97-117 (1985)

The physical nature of information

Rolf Landauer

Information is not a disembodied abstract entity; it is always tied to a physical representation. It is represented by engraving on a stone tablet, a spin, a charge, a hole in a punched card, a mark on paper, or some other equivalent.

Our scientific culture normally views the laws of physics as predating the actual physical universe. The laws are considered to be like a control program in a modern chemical plant; the plant is turned on after the program is installed. *In the beginning was the Word and the Word was with God, and the Word was God* (John 1:1) attests to this belief. *Word* is a translation from the Greek *Logos* "thought of as constituting the controlling principle of the universe".

Physics Letters A **217**, 188-193 (1996)

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