Entanglement between masses as a probe of the quantumness of gravity

Mauro Paternostro

Queen's University Belfast

Workshop Quantum Foundations.

The physics of "what happens" and the measurement problem

Frascati, 25 May 2017

The resolution of frustration (and the fun that comes from it)

Mauro Paternostro

Queen's University Belfast

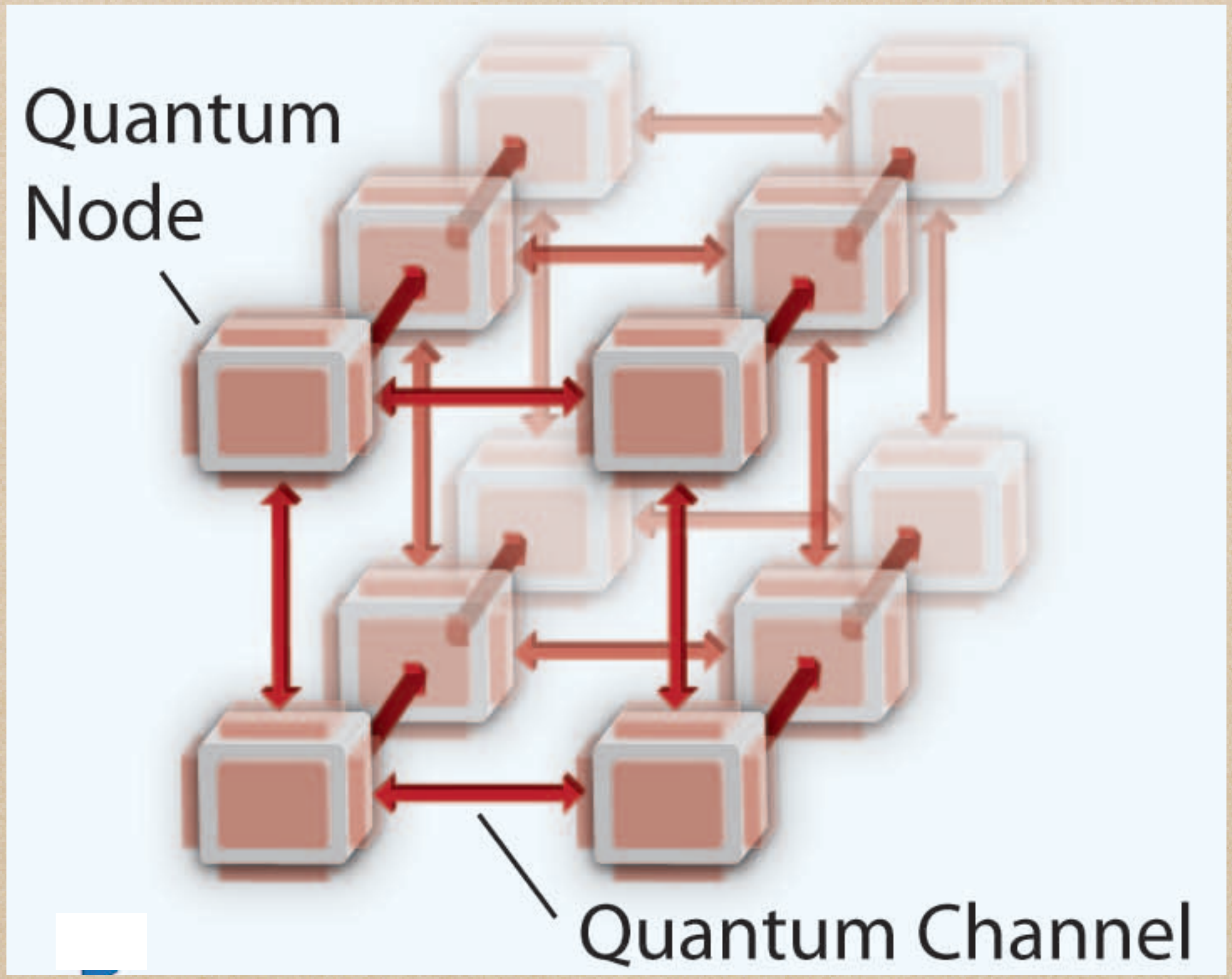
Workshop Quantum Foundations.

The physics of "what happens" and the measurement problem

Frascati, 25 May 2017

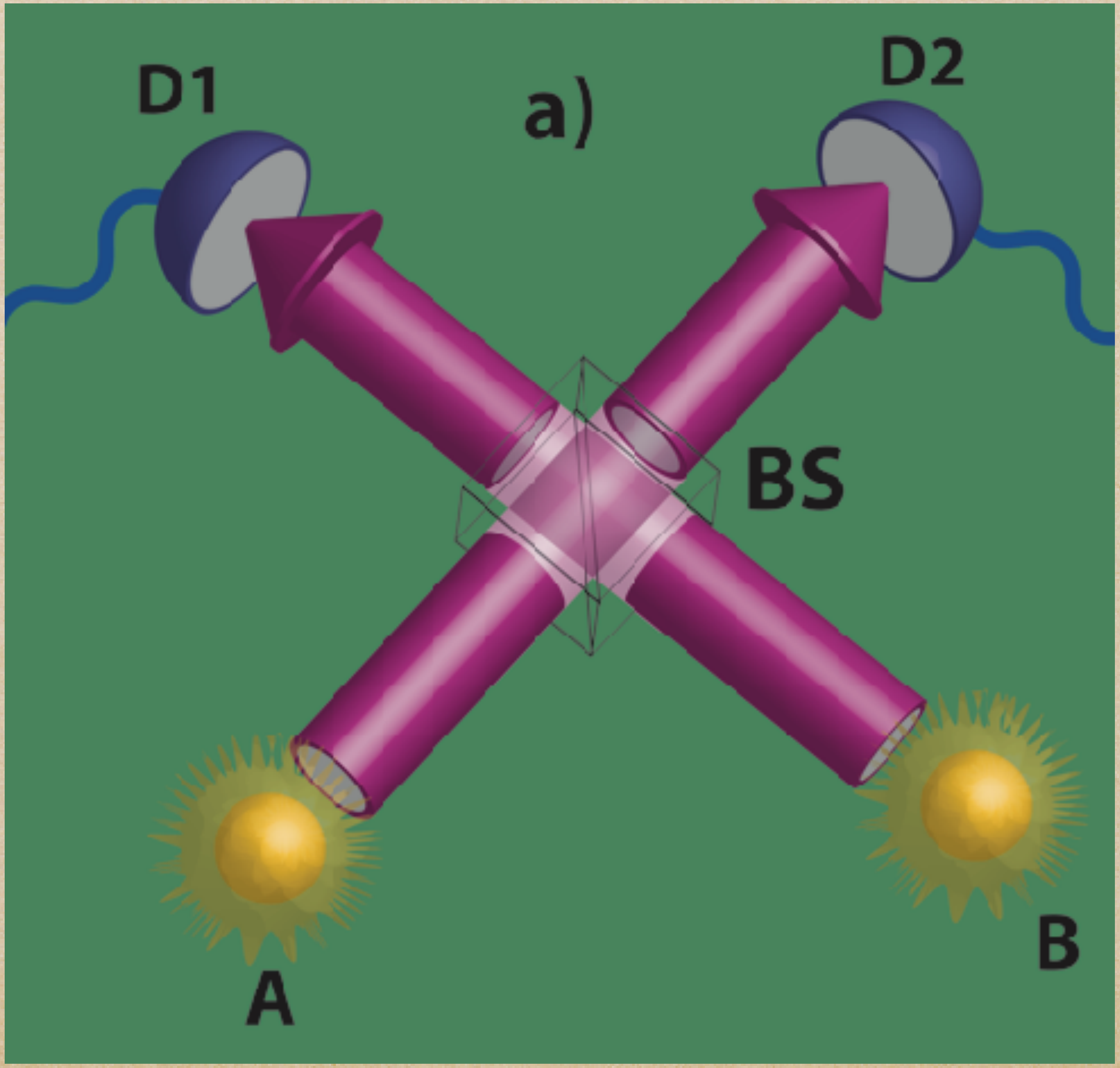
QTEQ QUANTUM TECHNOLOGY at QUEEN'S

Quantum internet?

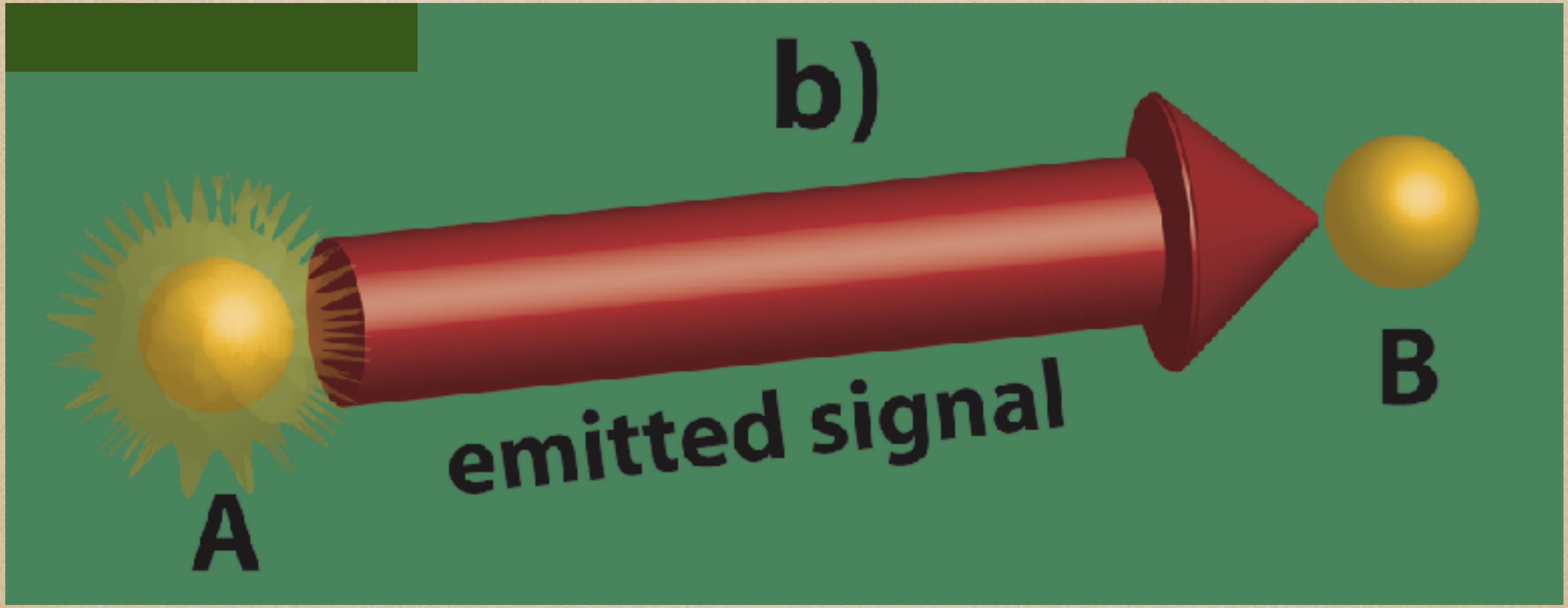


H. J. Kimble, Nature ***453****, 1023 (2008)*

Choose what you like!

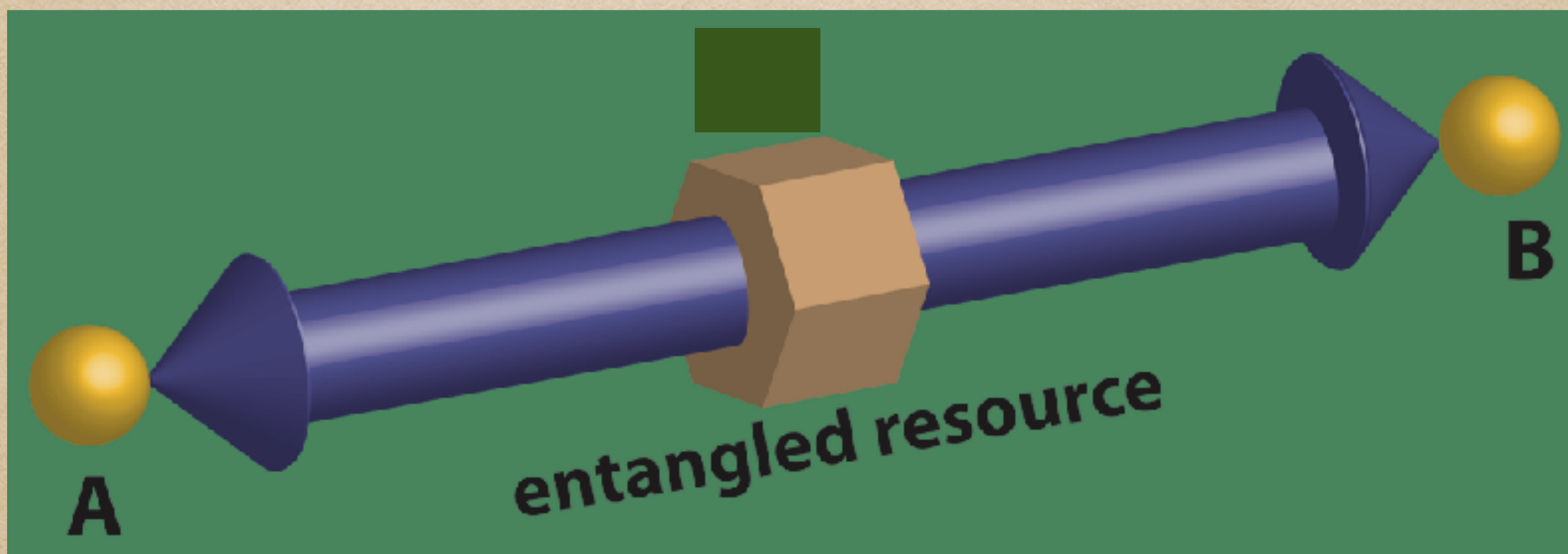


Choose what you like!



QTEQ
QUANTUM TECHNOLOGY at QUEEN'S

Choose what you like!



Long-term frustration

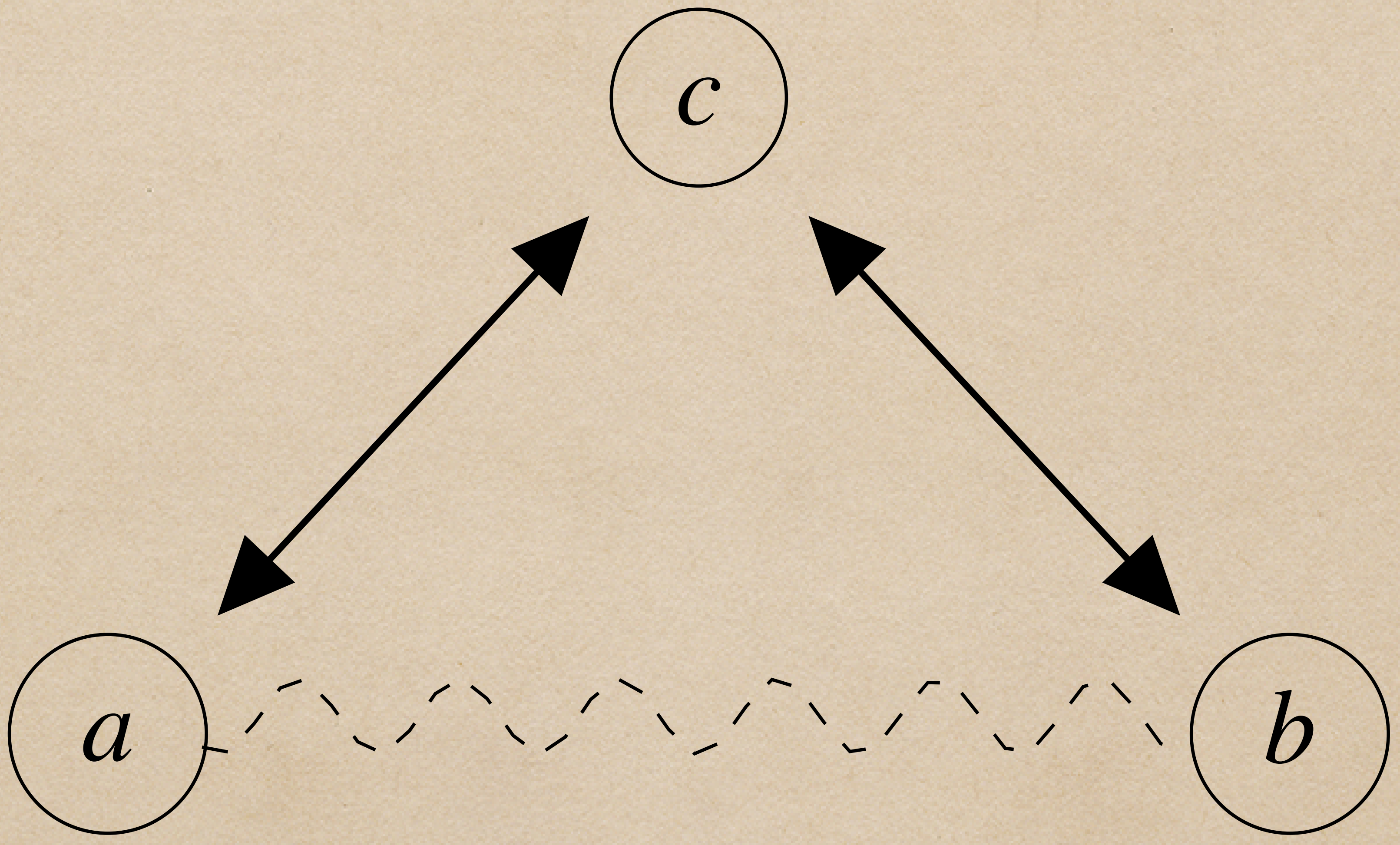
Separable states can be used to distribute entanglement

T. S. Cubitt,[1] F. Verstraete,[1] W. Dür,[2] and J.I. Cirac[1]

[1]*Max Plank Institut für Quantenoptik, Hans–Kopfermann Str. 1, D-85748 Garching, Germany*
[2]*Sektion Physik, Ludwig-Maximilians-Universität München, Theresienstr. 37, D-80333 München, Germany*
(Dated: February 21, 2003)

We show that no entanglement is necessary to distribute entanglement; that is, two distant particles can be entangled by sending a third particle that is never entangled with the other two. Similarly, two particles can become entangled by continuous interaction with a highly mixed mediating particle that never itself becomes entangled. We also consider analogous properties of completely positive maps, in which the composition of two separable maps can create entanglement.

The Cubitt et al. protocol

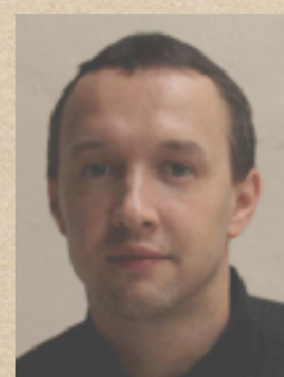


T. S. Cubitt, F. Verstraete, W. Duer, and J. I. Cirac, Phys. Rev. Lett. 91, 037902 (2003)

QUB-NUS-IQC collaboration

Kavan Modi (Oxford&NUS)

April 2011



Tomasz Paterek (NTU)

Mauro Paternostro (QUB)

May 2011

Feb. 2011

Marco Piani (IQC)

Separable states can be used to distribute entanglement

T. S. Cubitt,[1] F. Verstraete,[1] W. Dür,[2] and J.I. Cirac[1]

[1]*Max Plank Institut für Quantenoptik, Hans–Kopfermann Str. 1, D-85748 Garching, Germany*
[2]*Sektion Physik, Ludwig-Maximilians-Universität München, Theresienstr. 37, D-80333 München, Germany*
(Dated: February 21, 2003)

We show that no entanglement is necessary to distribute entanglement; that is, two distant particles can be entangled by sending a third particle that is never entangled with the other two. Similarly, two particles can become entangled by continuous interaction with a highly mixed mediating particle that never itself becomes entangled. We also consider analogous properties of completely positive maps, in which the composition of two separable maps can create entanglement.

Separable states can be used to distribute entanglement

T. S. Cubitt,[1] F. Verstraete,[1] W. Dür,[2] and J.I. Cirac[1]

[1]*Max Plank Institut für Quantenoptik, Hans–Kopfermann Str. 1, D-85748 Garching, Germany*
[2]*Sektion Physik, Ludwig-Maximilians-Universität München, Theresienstr. 37, D-80333 München, Germany*
(Dated: February 21, 2003)

We show that no entanglement is necessary to distribute entanglement; that is, two distant particles can be entangled by sending a third particle that is never entangled with the other two. Similarly, two particles can become entangled by continuous interaction with a highly mixed mediating particle that never itself becomes entangled. We also consider analogous properties of completely positive maps, in which the composition of two separable maps can create entanglement.

QUB-NUS-IQC collaboration

QTEQ
QUANTUM TECHNOLOGY at QUEEN'S

Centre for Quantum Technologies
NUS National University of Singapore

Quantum Discord Workshop 2012
9 - 13 January 2012 . Singapore

Talk: "distributing entanglement through separable states"

Tomasz Paterek
(NTU)

Alex Streltsov (Dusseldorf) :
"We have the same results.."

The paper(s)

Quantum Cost for Sending Entanglement

Alexander Streltsov,* Hermann Kampermann, and Dagmar Bruß
Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, D-40225 Düsseldorf, Germany
(Received 20 March 2012; published 18 June 2012)

Quantum Discord Bounds the Amount of Distributed Entanglement

T. K. Chuan,[1] J. Maillard,[2] K. Modi,[3,1] T. Paterek,[1,4,*] M. Paternostro,[5] and M. Piani[6,†]
[1]*Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, 117543 Singapore*
[2]*Blackett Laboratory, Imperial College London, Prince Consort Road, London SW7 2BZ, United Kingdom*
[3]*Department of Physics, University of Oxford, Clarendon Laboratory, Oxford, OX1 3PU, United Kingdom*
[4]*Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore*
[5]*Centre for Theoretical Atomic, Molecular, and Optical Physics, School of Mathematics and Physics, Queen's University, Belfast BT7 1NN, United Kingdom*
[6]*Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, 200 University Avenue West, Waterloo, Ontario N2L 3G1, Canada*
(Received 1 April 2012; published 16 August 2012)

Using Separable Bell-Diagonal States to Distribute Entanglement

Alastair Kay
Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543, Singapore and Keble College, Parks Road, Oxford OX1 3PG, United Kingdom
(Received 10 April 2012; published 21 August 2012)

QTEQ QUANTUM TECHNOLOGY at QUEEN'S

Principia discordiae

K. Modi, A. Brodutch, H. Cable, T. Paterek, and V. Vedral, Rev. Mod. Phys. 84, 1655 (2012)

Separable=classical?

$$\varrho = |+\rangle_A\langle+| \otimes |0\rangle_B\langle 0| + |1\rangle_A\langle 1| \otimes |1\rangle_B\langle 1|$$

$$|+\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$$

Two non-orthogonal states are not perfectly distinguishable

A projective measurement still perturbs the state

The eigenstates of the density matrix could well be superpositions (even entangled, although this is not the case here..)

In general, separable states do not have classical nature

QTEQ QUANTUM TECHNOLOGY at QUEEN'S

A new classification

Definition 1. *A bipartite state* ρ *is: (i)* separable [20] *if it can be written as* $\sum_i p_k \sigma_k^A \otimes \sigma_k^B$*, where* p_k *is a probability distribution and each* σ_k^X *is a quantum state, and* entangled *if non-separable; (ii)* classical-quantum *(CQ) if it can be written as* $\sum_i p_i |i\rangle\langle i| \otimes \sigma_i^B$*, where* $\{|i\rangle\}$ *is an orthonormal set,* $\{p_i\}$ *is a probability distribution and* σ_i^B *are quantum states; (iii)* classical-classical *(CC), or* (strictly) classically correlated [3, 5]*, if there are two orthonormal sets* $\{|i\rangle\}$ *and* $\{|j\rangle\}$ *such that* $\rho = \sum_{ij} p_{ij} |i\rangle\langle i| \otimes |j\rangle\langle j|$*, with* p_{ij} *a joint probability distribution for the indexes* (i, j).

M. Piani, P. Horodecki, and R. Horodecki, Phys. Rev. Lett. 100, 090502 (2008)

Classical picture

$$I(A:B) = H(A) + H(B) - H(A,B)$$

$$J(A:B) = H(A) - H(A|B)$$

$$J(B:A) = H(B) - H(B|A)$$

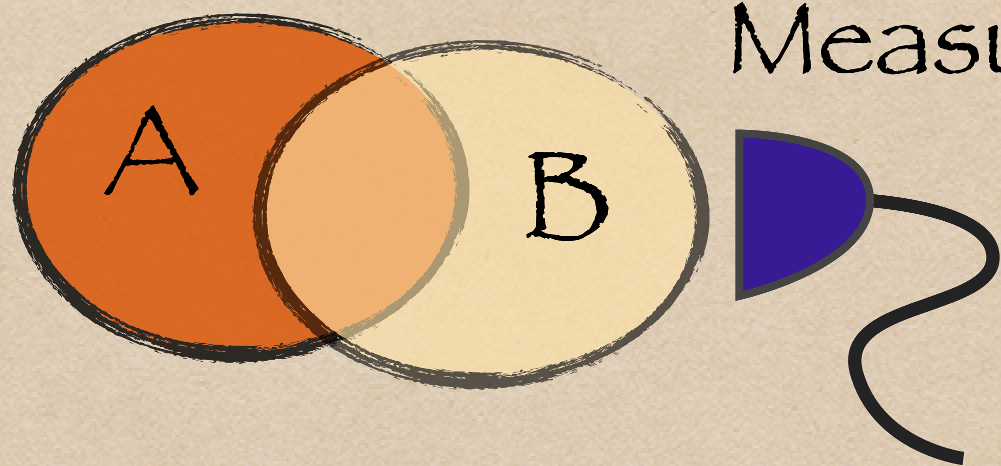
$$I(A:B) = J(A:B) = J(B:A)$$

(Bayes)

QTEQ QUANTUM TECHNOLOGY at QUEEN'S

Quantum picture

Measurement



$\mathcal{D}$ = Total correlations (quantum+classical) - Total amount of classical correlations

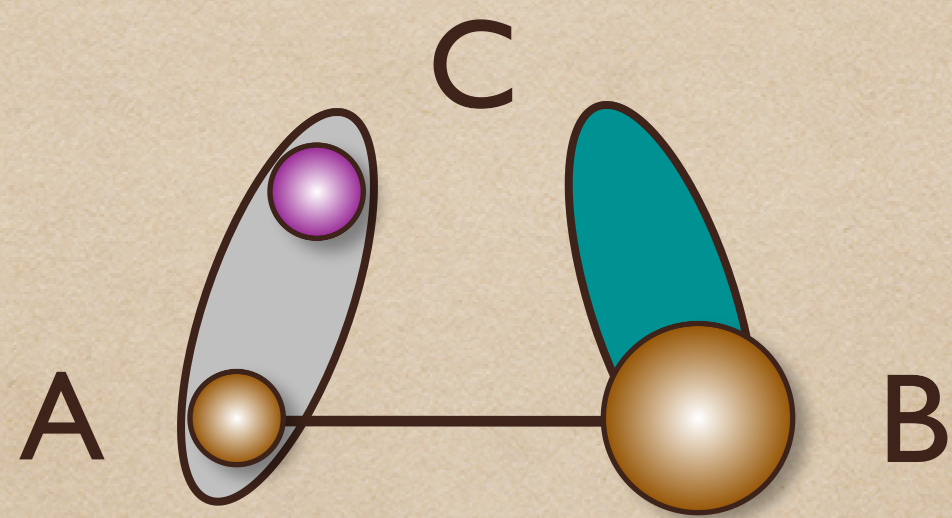
classical $\neq$ separable

The set of zero-discord states is zero-measure

H. Ollivier and W. H. Zurek, Phys. Rev. Lett. 88, 017901 (2001)

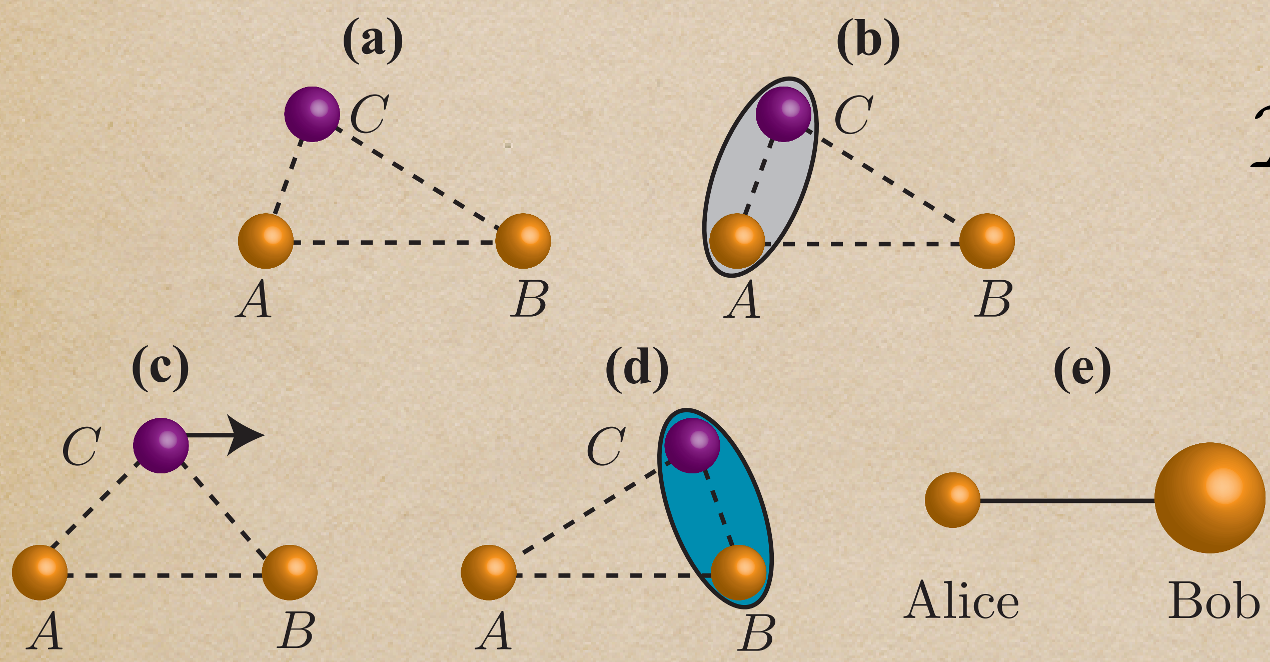
Take-home message

The entanglement-gain in a quantum communication protocol is bound by the degree of pre-available quantum discord



T. K. Chuan, J. Maillard, K. Modi, T. Paterek,
M. Paternostro, and M. Piani, Phys. Rev. Lett. 109, 070501 (2012)

Goal 1: discord is key



Natural..

$$\mathcal{I}_{\text{final}} - \mathcal{I}_{\text{initial}} \leq \mathcal{I}_{\text{comm}}$$

Expected...

$$\mathcal{E}_{\text{final}} - \mathcal{E}_{\text{in}} \leq \mathcal{E}_{\text{comm}}$$

True...

Theorem 1.—For any tripartite state $\rho = \rho_{ABC}$ it holds

$$|\mathcal{E}_{A:CB}(\rho) - \mathcal{E}_{AC:B}(\rho)| \leq \mathcal{D}_{AB|C}(\rho)$$

QTEQ QUANTUM TECHNOLOGY at QUEEN'S

Discord is key

Lemma 1. *Given $\rho = \rho_{ABC}$, consider Π_C^*, the optimal projective measurement on C for the sake of $\mathcal{D}_{AB|C}(\rho)$. Let p_i be the probability of outcome i for such a measurement, and ρ_{AB}^i be the corresponding conditional states of AB; i.e., $\Pi_C^*(\rho_{ABC}) = \sum_i p_i \rho_{AB}^i \otimes |i\rangle\langle i|_C$. Then*

$$\begin{aligned}\mathcal{E}_{A:CB}(\rho) &\leq \mathcal{D}_{AB|C}(\rho) + \sum_i p_i \mathcal{E}_{A:B}(\rho_{AB}^i) \\ &= \mathcal{D}_{AB|C}(\rho) + \mathcal{E}_{A:CB}[\Pi_C^*(\rho)] \\ &= \mathcal{D}_{AB|C}(\rho) + \mathcal{E}_{AC:B}[\Pi_C^*(\rho)].\end{aligned}$$

K., M., & P. Horodecki, and J. Oppenheim, Phys. Rev. Lett. 94, 200501 (2005)

Theorem 1. *For any tripartite state $\rho = \rho_{ABC}$ it holds*

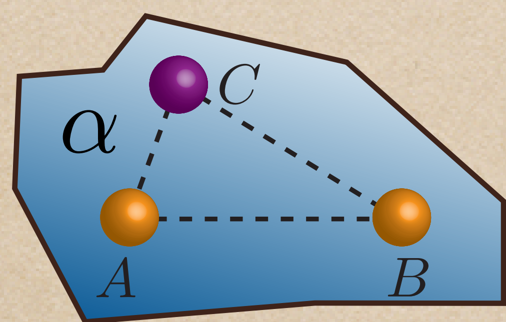
$$|\mathcal{E}_{A:CB}(\rho) - \mathcal{E}_{AC:B}(\rho)| \leq \mathcal{D}_{AB|C}(\rho).$$

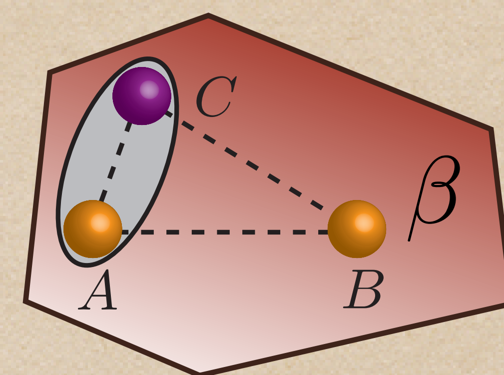
Proof.—
$$\begin{aligned}\mathcal{E}_{A:CB}(\rho) &\leq \mathcal{D}_{AB|C}(\rho) + \mathcal{E}_{AC:B}(\Pi_C^*(\rho)) \\ &\leq \mathcal{D}_{AB|C}(\rho) + \mathcal{E}_{AC:B}(\rho)\end{aligned}$$

finally, invert the role of A and B

T.K. Chuan, J. Maillard, K. Modi, T. Paterek, M. Paternostro, and M. Piani, Phys. Rev. Lett. 109, 070501 (2012)

Entanglement distribution via separable states





$$\beta = \mathcal{M}_{AC}(\alpha)$$

Using Theorem 1: $\mathcal{E}_{A:CB}(\beta) \leq \mathcal{E}_{AC:B}(\alpha) + \mathcal{D}_{AB|C}(\beta)$

Suppose $\mathcal{D}_{AB|C}(\beta)=0 \Rightarrow \beta = \sum_i p_i \rho^i_{AB} \otimes |i\rangle\langle i|_C$

$\mathcal{E}_{A:CB}(\beta) \leq \mathcal{E}_{AC:B}(\alpha)$

impossible to distribute entanglement via LOCC!

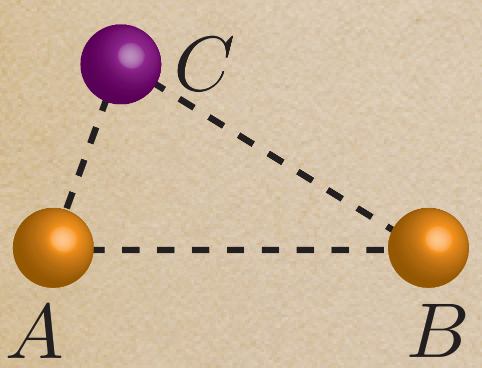
The resolution of frustration

General (Cubitt et al.) framework: what we want

$$\mathcal{E}_{B:AC}(\alpha) = 0$$

$$\mathcal{E}_{C:AB}(\beta) = 0$$

$$\mathcal{E}_{A:BC}(\beta) > 0$$



1) Swap B and C & consider that discord is nonincreasing under operations on the unmeasured party

2) Use Theorem 1

$$\mathcal{E}_{A:CB}(\beta) \leq \mathcal{E}_{AB:C}(\beta) + \mathcal{D}_{AC|B}(\alpha)$$

3) If condition holds, then

$$\mathcal{E}_{A:CB}(\beta) \leq \mathcal{D}_{AC|B}(\alpha)$$

4) For C initially uncorrelated with A&B

$$\mathcal{E}_{A:CB}(\beta) \leq \mathcal{D}_{A'|B}(\alpha)$$

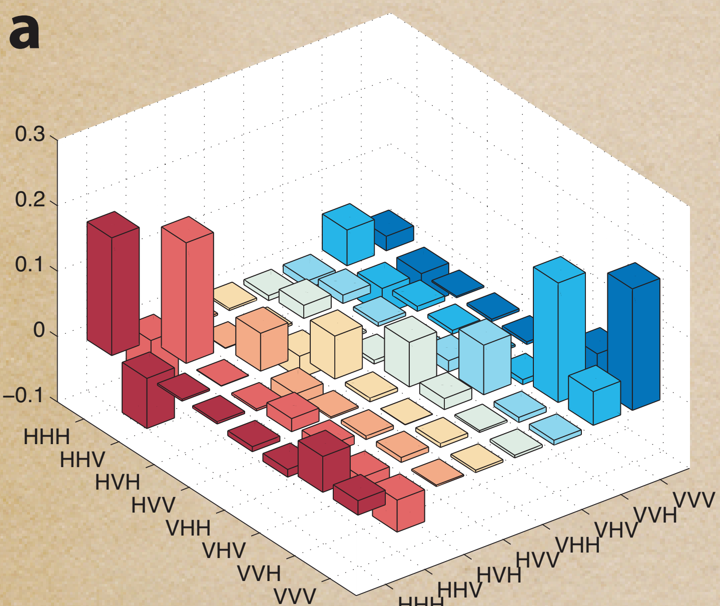
Precisely what Cubitt et al. had.....

QTEQ QUANTUM TECHNOLOGY at QUEEN'S

An experimental test

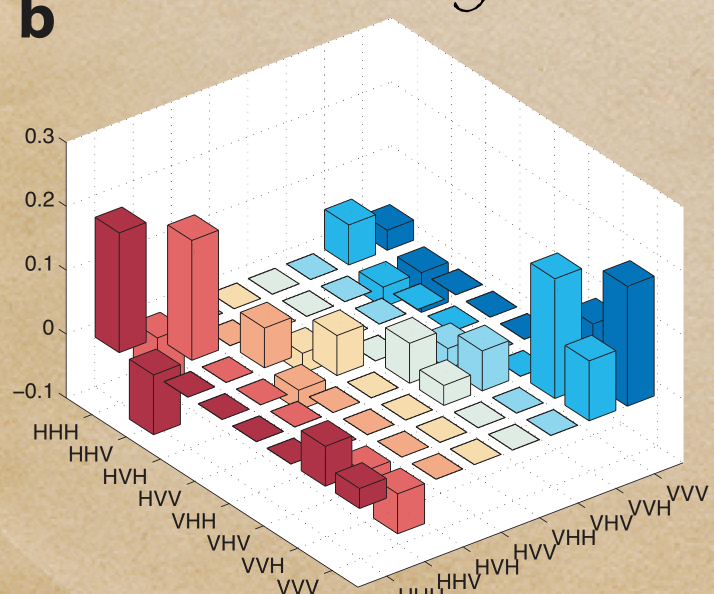
Experiment

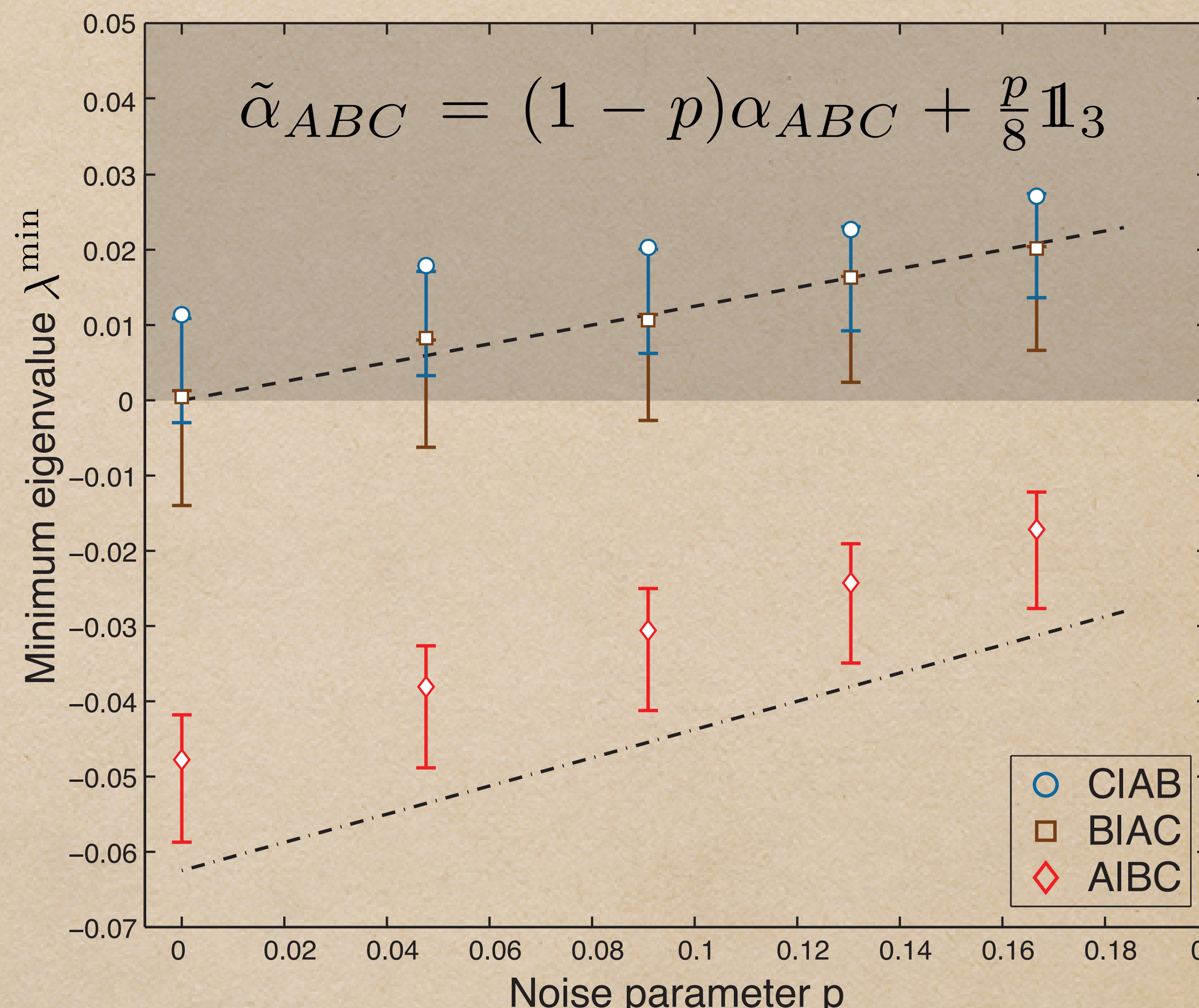
a



Theory

b

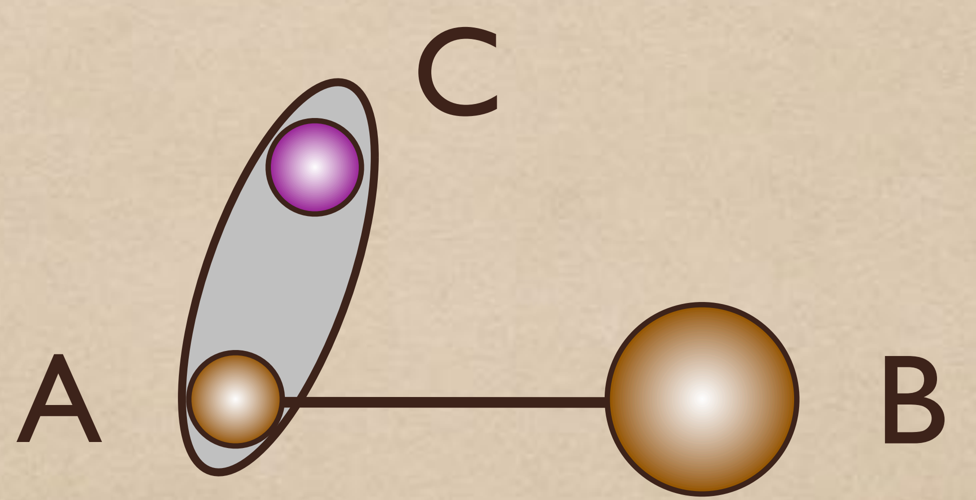




A. Fedrizzi, M. Zuppardo, G. Gillett, M. Broome, M. de Almeida, M. Paternostro, A. White, and T. Paterek, Phys. Rev. Lett. 111, 230504 (2013)

Instrumental result

The entanglement-gain in a quantum communication protocol is bound by the degree of pre-available quantum discord



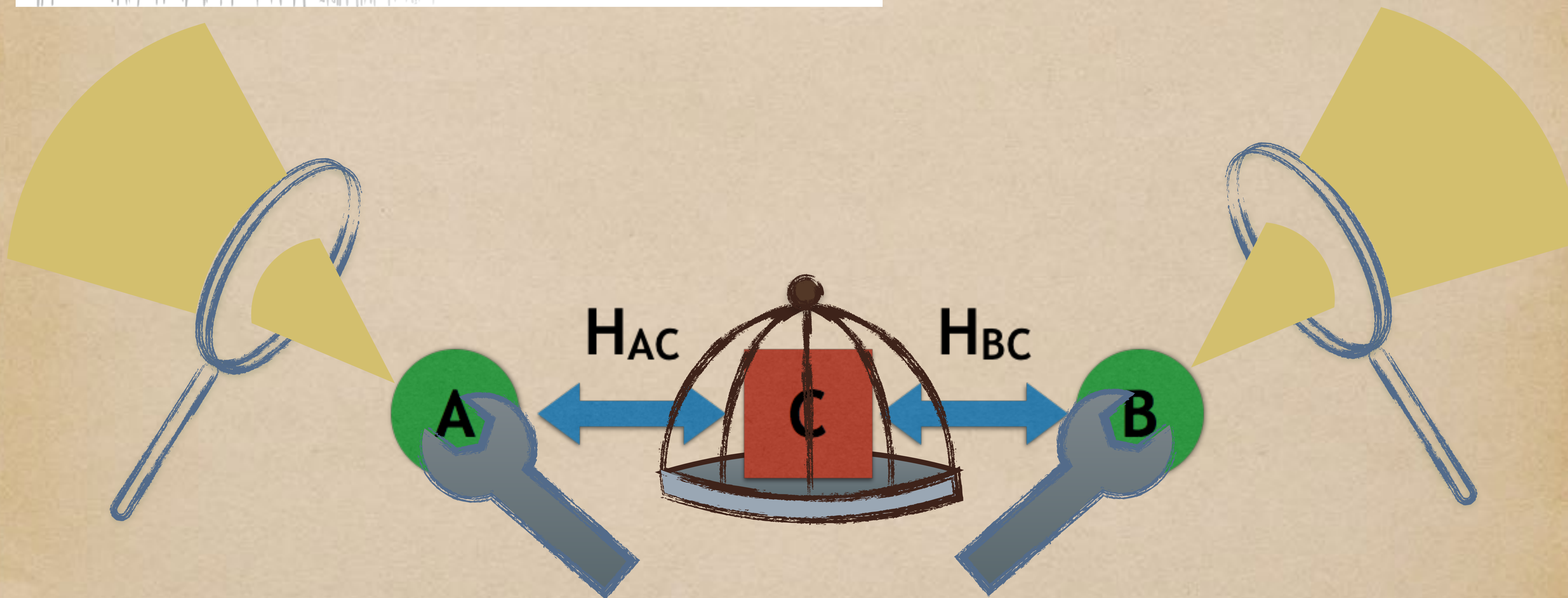
For any tripartite state $\rho = \rho_{ABC}$ it holds

$$|E_{A:BC}(t) - E_{AC:B}(t)| \leq D_{AB|C}(t)$$

T K Chuan, J Maillard, K Modi, T Paterek, MP, and M Piani, Phys Rev Lett 109, 070501 (2012)

QTEQ QUANTUM TECHNOLOGY at QUEEN'S

The dynamical setting



First assume that $[H_{AC}, H_{BC}] = 0$

$$E_{AC:B}(0) - E_{A:BC}(0) \leq D_{AB|C}(0),$$

$$E'_{A:BC} - E'_{AC:B} \leq D'_{AB|C}(\text{after } H_{AC})$$

τ is the final time of the experiment

T. Krisnanda, M. Zuppardo, MP, T. Paterek, arXiv:1607.01140

The general setting

$$E'_{AC:B} = E_{AC:B}(0) - E_{A:BC}(0) \leq D_{AB|C}(0),$$

$$E'_{A:BC} - E'_{AC:B} \leq D'_{AB|C}(\text{after } H_{AC})$$

$$||$$

$$E_{A:BC}(\tau)$$

$$E_{A:BC}(\tau) - E_{A:BC}(0) \leq D_{AB|C}(0) + D'_{AB|C}$$

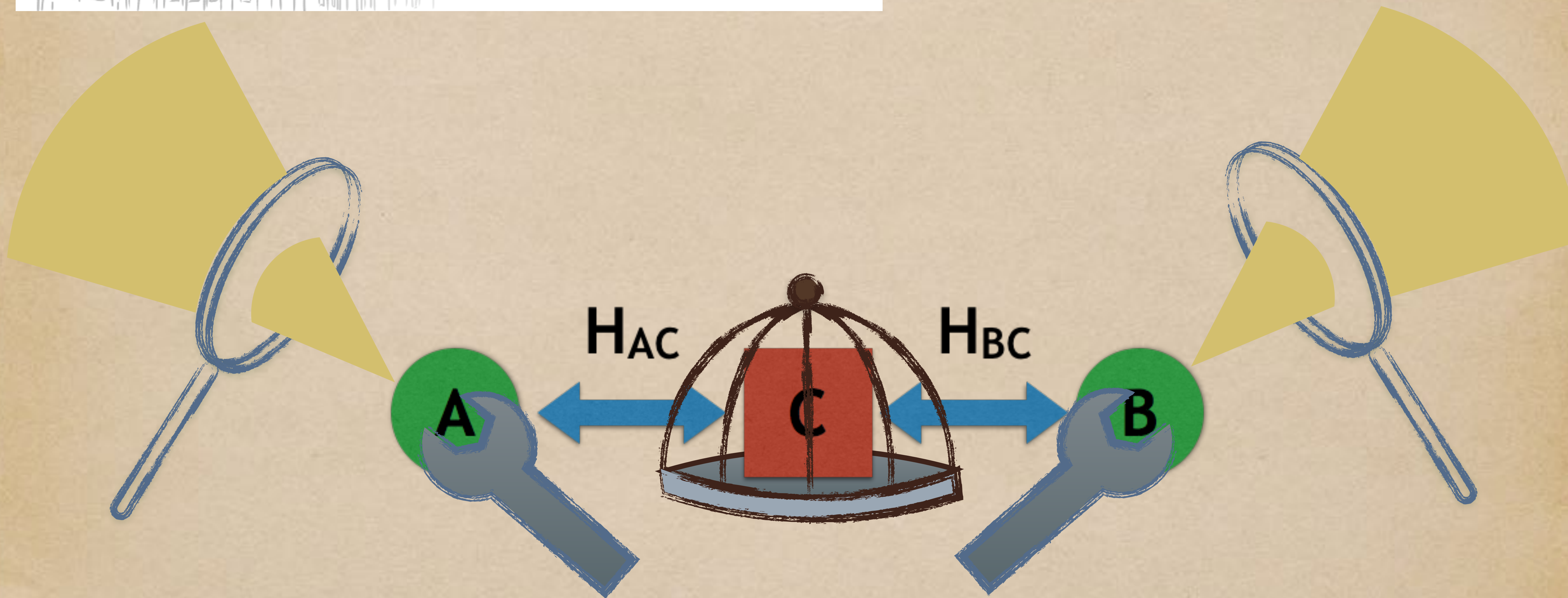
Entanglement gain in partition A : BC mediated by C

Non-classicality of C entails an entanglement gain

T. Krisnanda, M. Zuppardo, MP, T. Paterek, arXiv:1607.01140

QTEQ QUANTUM TECHNOLOGY at QUEEN'S

The general setting



$$[H_{AC}, H_{BC}] \neq 0 \qquad U = \lim_{n\to\infty} \left(e^{-iH_{BC}\Delta t} e^{-iH_{AC}\Delta t}\right)^n$$

$$\Delta t = \tau/n \to 0. \qquad E_{A:BC}(\Delta t) - E_{A:BC}(0) \leq D_{AB|C}(0) + D'_{AB|C}$$

T. Krisnanda, M. Zuppardo, MP, T. Paterek, arXiv:1607.01140

Can "C" be classical and exploitable?

Can entanglement be increased by interacting with an always classical C?

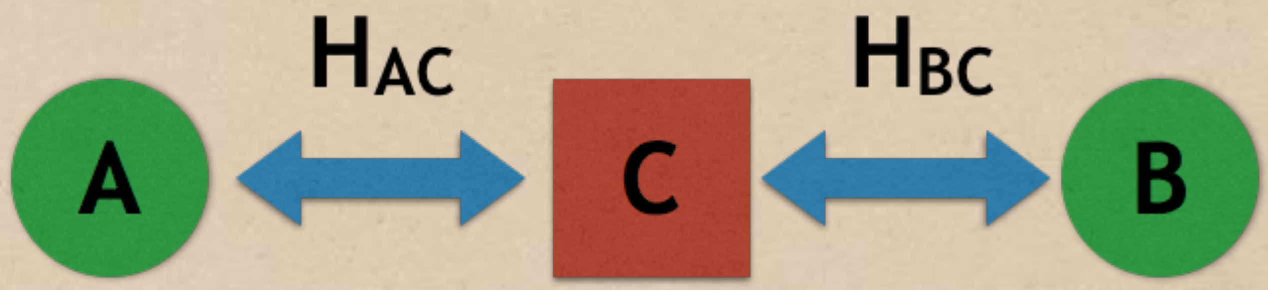
Theorem. *For a three party system with Hamiltonian* $H_{AC} + H_{BC}$*, entanglement* $E_{A:BC}$ *is constant if discord* $D_{AB|C} = 0$ *at all times.*

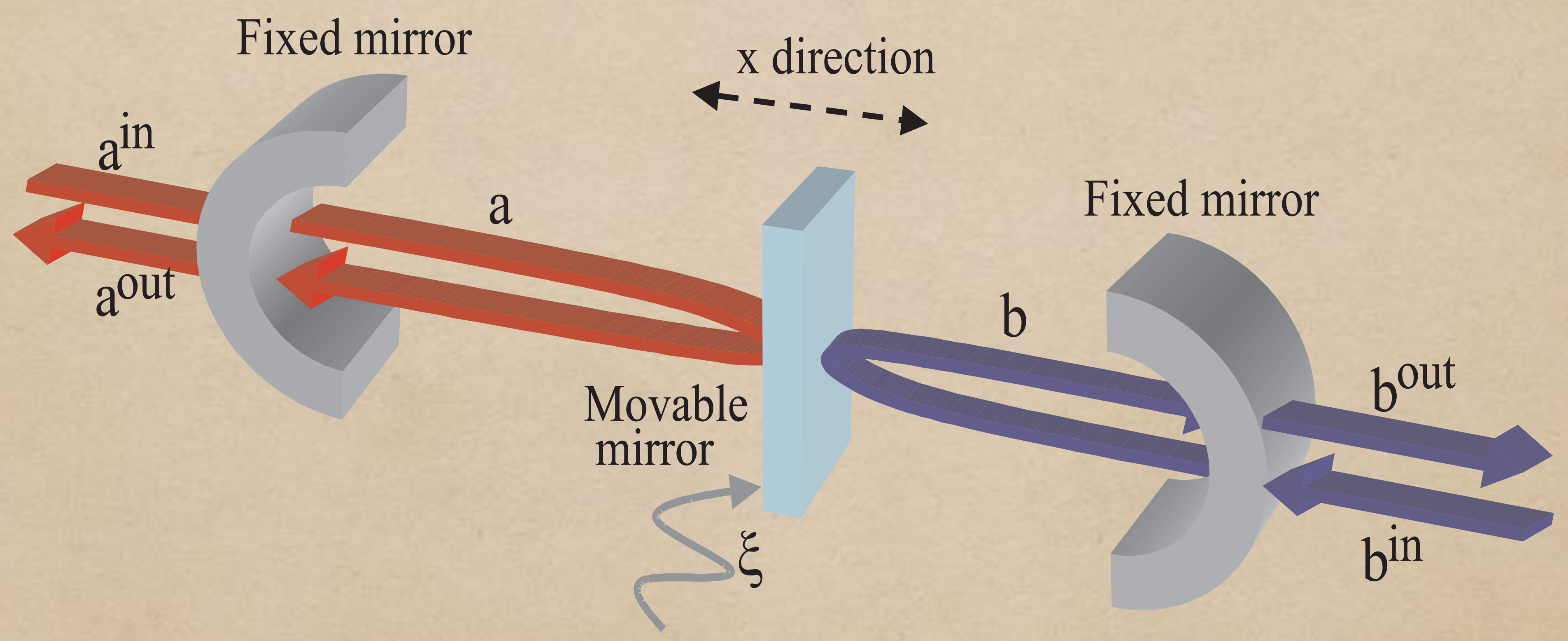
Perfect position to study the non-classical nature of C from the observation of A&B only!

$$\Downarrow$$

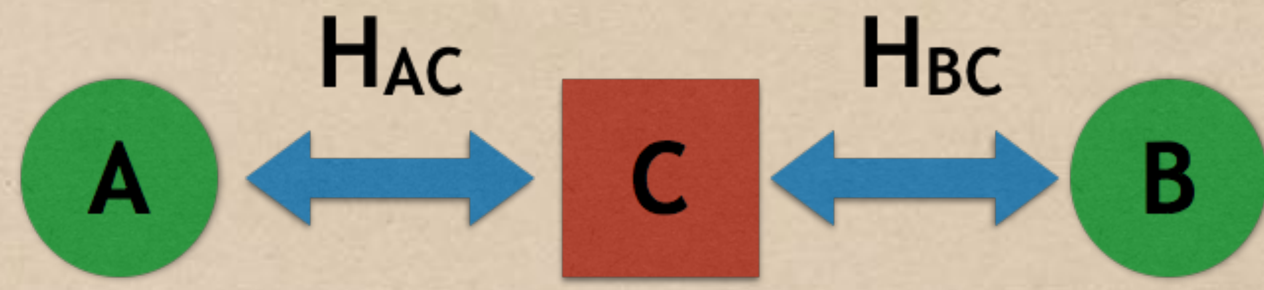
Entanglement gain is a good candidate...

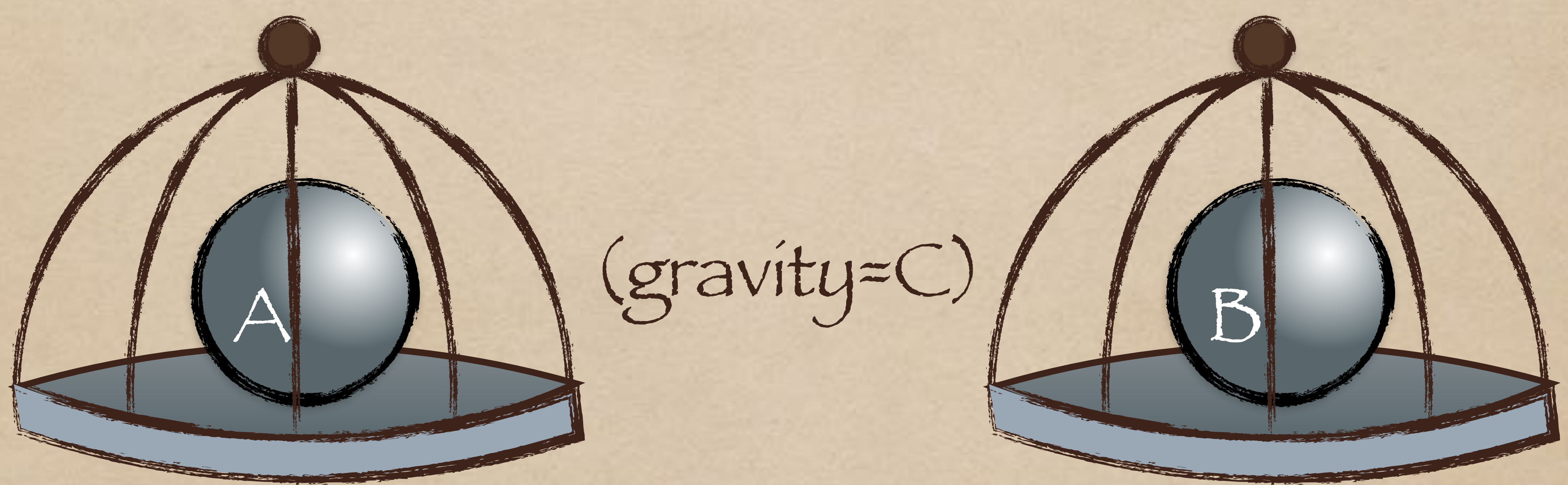
A possible experimental scenario





Can we learn something about gravity?

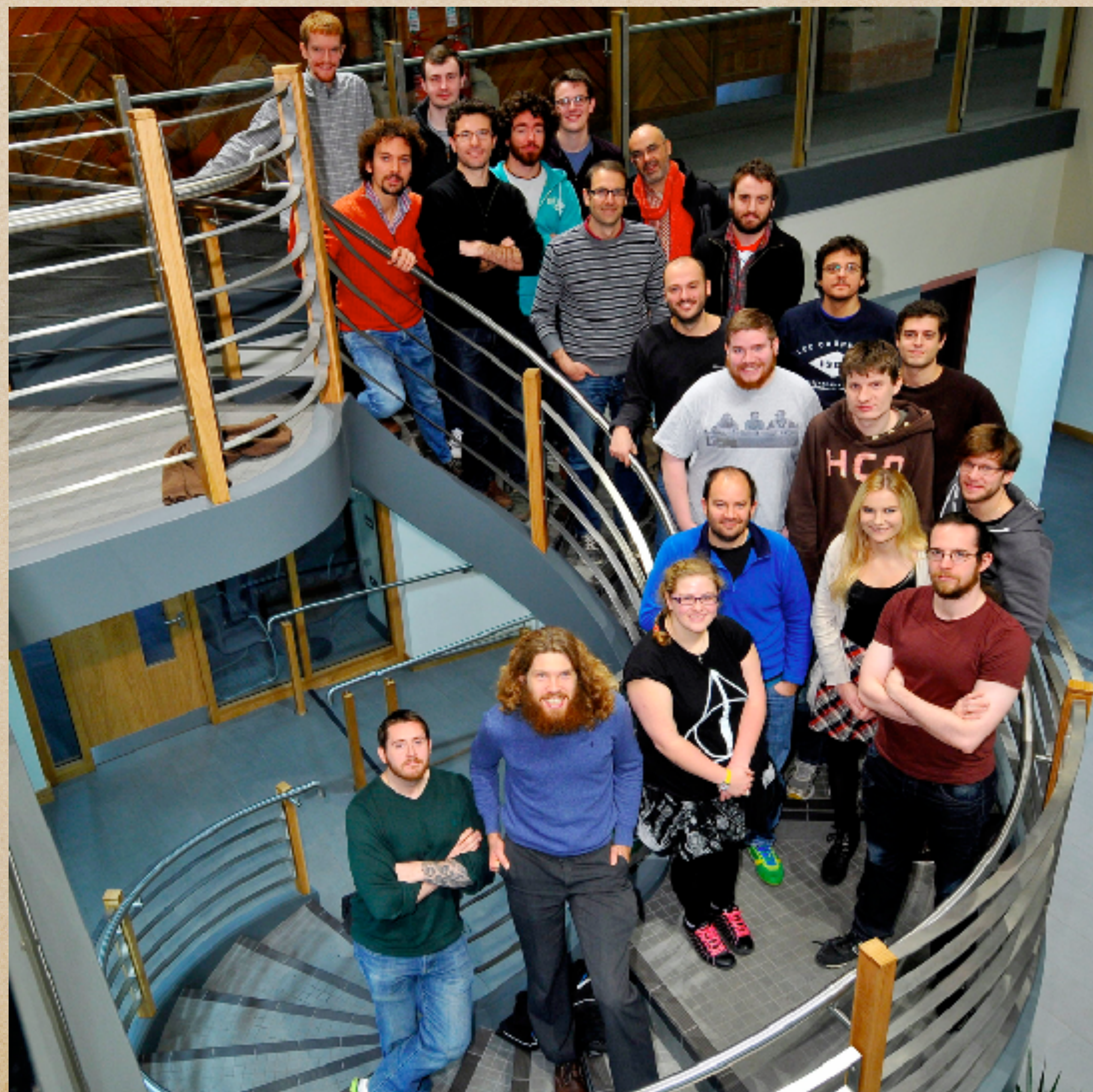




T. Krisnanda, M. Zuppardo, MP, T. Paterek, arXiv:1607.01140

QTEQ
QUANTUM TECHNOLOGY at QUEEN'S

The Belfast crew



Go raibh maith agaibh

QTEQ
QUANTUM TECHNOLOGY at QUEEN'S

Department for Employment and Learning
www.delni.gov.uk

CIÊNCIA SEM FRONTEIRAS

SEVENTH FRAMEWORK PROGRAMME

Alexander von Humboldt Stiftung/Foundation

JSF Julian Schwinger Foundation

Royal Commission Exhibition of 1851

EPSRC
Pioneering research and skills

THE ROYAL SOCIETY

JOHN TEMPLETON FOUNDATION
SUPPORTING SCIENCE~INVESTING IN THE BIG QUESTIONS

newton international fellowships

QTEQ
QUANTUM TECHNOLOGY at QUEEN'S

For Hendrik