Title: Witnesses of non-classicality beyond quantum theory - VIRTUAL

Speakers: Chiara Marletto

Series: Quantum Foundations

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Abstract: The theory of quantum computation has brought us rapid technological developments, together with remarkable improvements in how we understand quantum theory. In this talk, I shall describe the foundations of a theoretical programme to extend the quantum theory of computation beyond quantum theory itself, based on the recently proposed constructor theory. I will then explain a recent application of this new approach to the problem of witnessing quantum effects in gravity.

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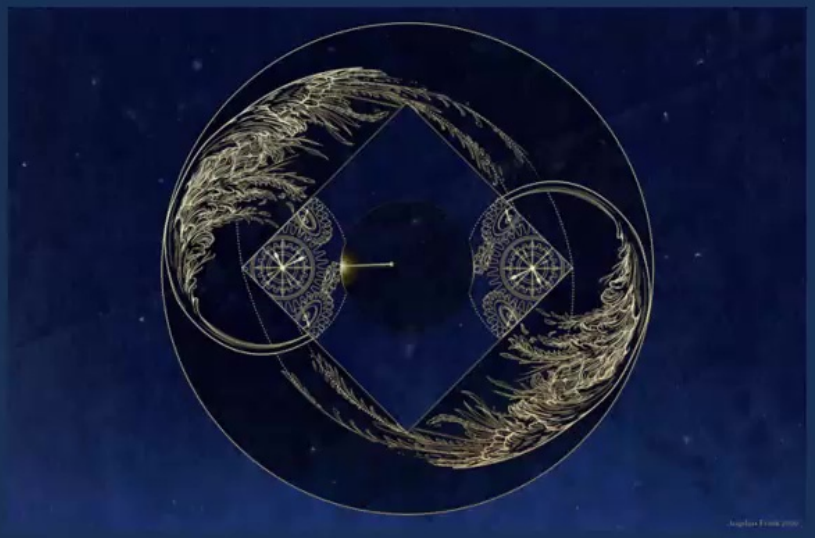
Witnesses of non-classicality beyond quantum theory



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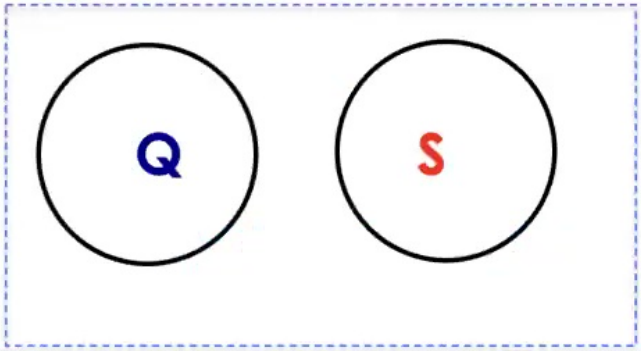
Vision

- Develop a new approach to physics going beyond dynamical laws, capitalizing on the theory of quantum and classical computation.
- The aim is to address unsolved issues in existing dynamical laws (e.g. irreversibility, quantum/classical divide, macroscopic physics being only approximate, etc.)
- New explanations deliver new predictions and provide guidelines to guess future theories of physics.

Method: Constructor Theory

- It is a candidate to expand on the theory of quantum computation, and to deliver the theory of more general programmable machines (constructors).
- It also provides novel physical principles - unifying quantum and classical information, thermodynamics, and the physics of life.

Hybrid systems



A hybrid system is a system composed of a quantum system Q interacting with another system S whose dynamics is partly unknown.

Examples:

- S = gravity and Q = quantum mass;
- S= macroscopic biomolecule whose dynamics is intractable; Q= quantum light field.

Beyond Quantum Computation

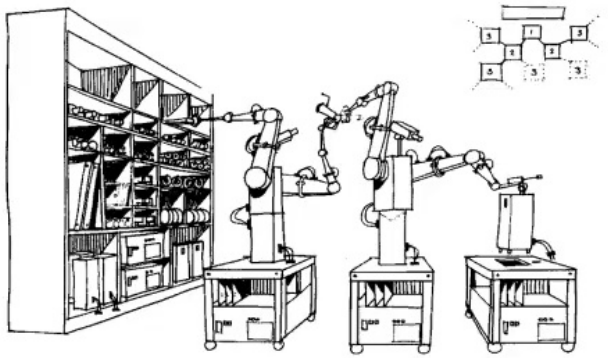
Quantum information theory assumes quantum theory's laws.

We need to make it more general to apply it to hybrid systems.

From computers to constructors

Universal computer: a programmable computer whose repertoire includes all physically possible *computations*.
(A. Turing, D. Deutsch)

But there are tasks that a universal computer cannot perform (e.g. constructing a copy of itself from raw materials)



Universal constructor:
A programmable machine that can perform any task that is physically allowed.
(J. von Neumann)

Constructor Theory's Programme

Laws are expressed as principles about which ***tasks*** *are* ***possible****, which are* ***impossible*** *and why*

Dynamics and 'initial' conditions are emergent consequences of the principles.

Deutsch, D. "Constructor theory". Synthese. **190** (18): 4331–4359. 2012.

A constructor C for a task T is a system that is capable of performing the task T while retaining its ability to do so again

$$C + \textit{Input attributes} \rightarrow C + \textit{Output attributes}$$

C can be reused – it is unchanged in its capacity to perform the task.

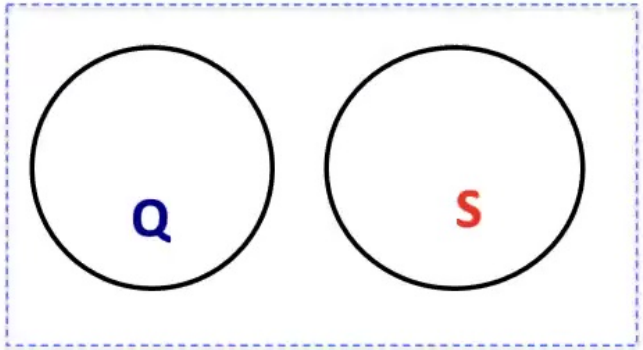
$$\textit{Input attributes} \xrightarrow{C} \textit{Output attributes}$$

A task is impossible if there is a principle forbidding its being performed to arbitrarily high accuracy by a constructor, possible otherwise

Note the fundamental difference between dynamically allowed transformations and possible tasks!

Application of constructor theory:
witnessing non-classicality in hybrid systems

Hybrid Systems: beyond quantum computation



Questioning the universality of unitary quantum theory:

Is it possible to have a hybrid system composed of a quantum system interacting with one that is fully classical?

'Totalitarian' property of quantum theory

"...the quantization of a given system implies also the quantization of any other system to which it can be coupled [...] Quantum theory must immediately be extended to all physical systems, including the gravitational field."

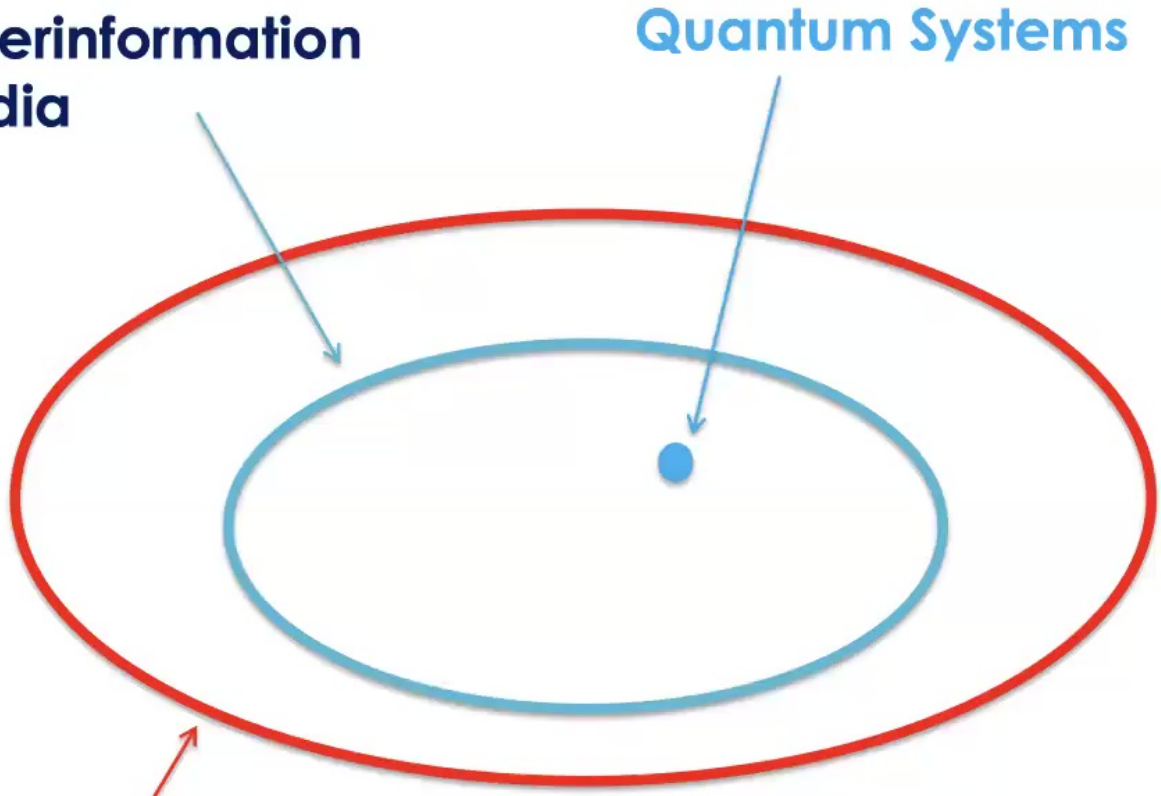
B. S. DeWitt, in: Gravitation: an introduction to current research, edited by L. Witten (Wiley, New York, 1962).

Can DeWitt's argument be improved?

- It assumes many dynamics-specific features
- It's desirable to extend it to a more general set of assumptions, holding for quantum theory, but also for other classical theories, and possibly quantum theory's successor.

One can use the Constructor Theory of Information to tackle this problem.

D. Deutsch, C. Marletto, Proceedings of RoyalSociety A, 471:20140540, 2014.



D. Deutsch, C. Marletto, Proceedings of Royal Society A, 471:20140540, 2014.
C. Marletto, Proc. R. Soc. A 472:20150883, 2016.

Defining 'non-classicality' within the superinformation framework

A system is 'non-classical' if it has at least two incompatible variables X and Z.

'Incompatible' means that it is impossible that X and Z are copied simultaneously to perfect accuracy (generalises the idea of non-commutativity)

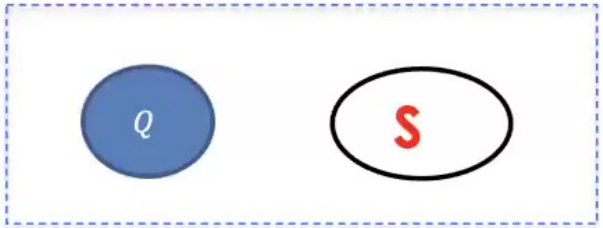
An information-theoretic argument for the totalitarian property of QT

Assume three general principles:

1. Locality (no action at a distance)
2. Interoperability of information
3. Interactions are logically reversible

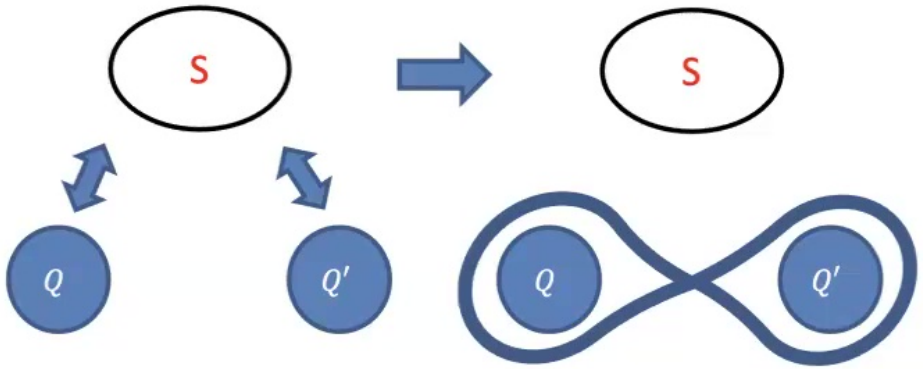
Testing the non-classicality of M

Witness of Non-Classicality: a protocol where a quantum probe Q interacts with the system S, to establish that S is non-classical by measuring Q only, under minimal assumptions.



Marletto, C. and Vedral, V. Phys. Rev. D, 102(8):086012, 2020

Entanglement-based witness of non-classicality

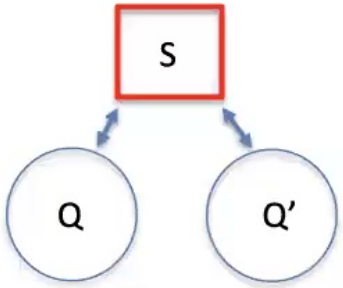


If S is can locally mediate entanglement
between two quantum systems Q and Q', then S is non-classical.

C. Marletto, V. Vedral, npj Quantum Information, 2017.
C. Marletto, V. Vedral, Phys. Rev. D 102, 2020.

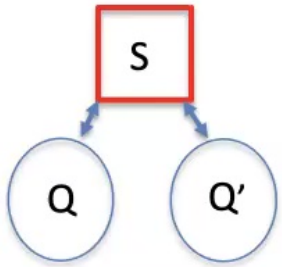
Dynamics-independent assumptions:
Locality
Interoperability of information

Gravitational Entanglement as a test of quantum gravity



If gravity can entangle two quantum masses locally, then gravity must be non-classical.

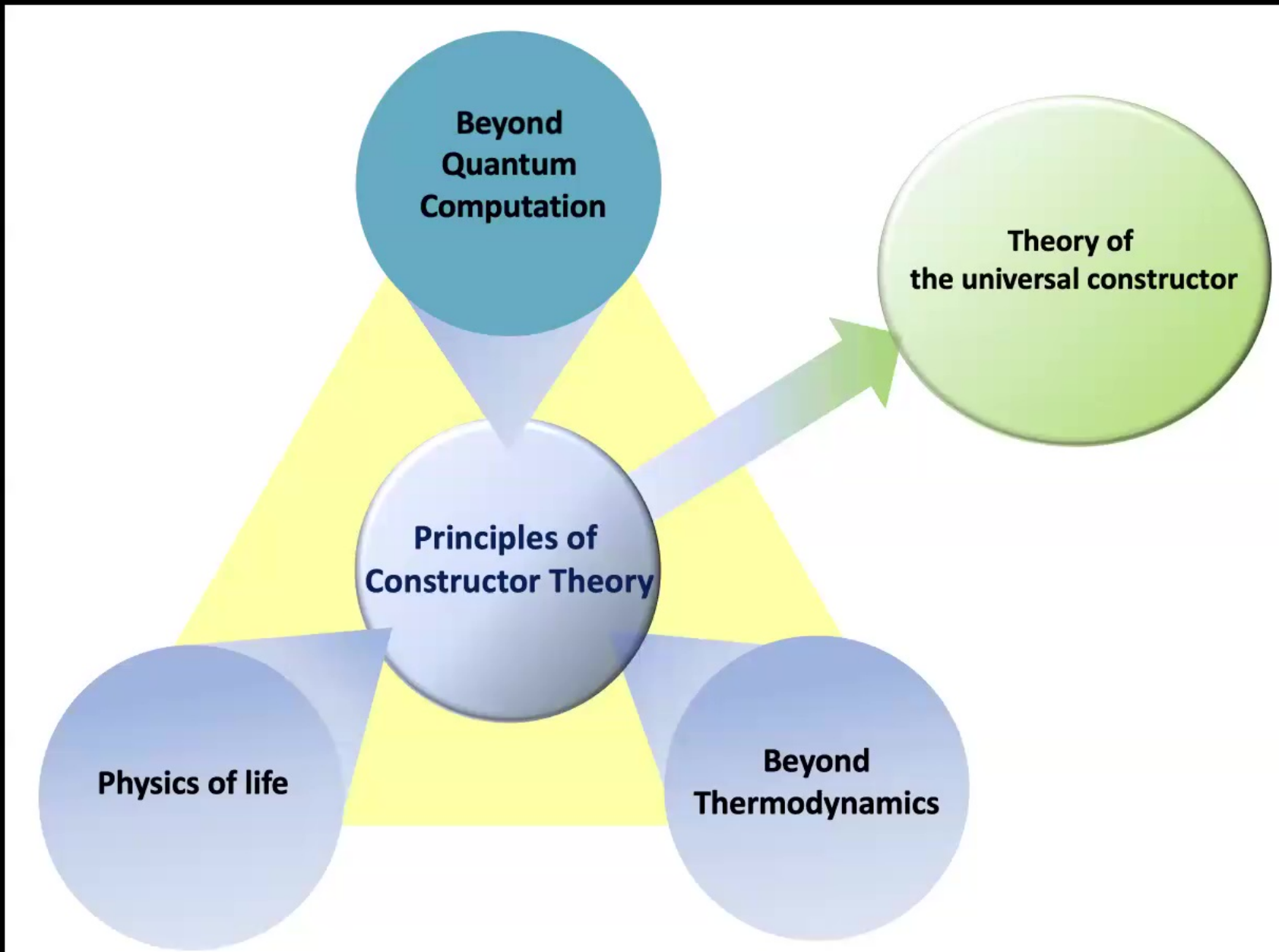
S. Bose et al., Phys. Rev. Lett. 119, 2017.
C. Marletto, V. Vedral , Phys. Rev. Lett. 119, 2017.



In summary:

1) The principles underlying the witness are expressed in constructor theory, independently of dynamics and scale.

2) Upon observing entanglement, the witness of non-classicality rules out all classical models (known and yet to be known) for S, that obey the two general principles of interoperability of information and locality. (cf. Bell's theorem)


Beyond
Quantum
Computation
Theory of
the universal constructor
Principles of
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