Title: Talk 29 - Any consistent coupling between classical gravity and quantum matter is fundamentally irreversible

Speakers: Flaminia Giacomini

Collection: It from Qubit 2023

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Abstract: When gravity is sourced by a quantum system, there is tension between its role as the mediator of a fundamental interaction, which is expected to acquire nonclassical features, and its role in determining the properties of spacetime, which is inherently classical. Fundamentally, this tension should result in breaking one of the fundamental principles of quantum theory or general relativity, but it is usually hard to assess which one without resorting to a specific model. Here, we answer this question in a theory-independent way using General Probabilistic Theories (GPTs). We consider the interactions of the gravitational field with a single matter system, and derive a no-go theorem showing that when gravity is classical at least one of the following assumptions needs to be violated: (i) Matter degrees of freedom are described by fully non-classical degrees of freedom; (ii) Interactions between matter degrees of freedom and the gravitational field are reversible; (iii) Matter degrees of freedom back-react on the gravitational field. We argue that this implies that theories of classical gravity and quantum matter must be fundamentally irreversible, as is the case in the recent model of Oppenheim et al. Conversely if we require that the interaction between quantum matter and the gravitational field are reversible, then the gravitational field must be non-classical.

DISCLAIMER

This is not just about gravity!

Also not about quantum/classical but classical/non-classical

WHY IS CLASSICAL-QUANTUM COUPLING (OFTEN) PROBLEMATIC?

$$H = H_{ho} + H_I$$

$$H_I = \kappa \hat{\sigma}_3 p$$

Diosi, Gisin, Strunz, Phys. Rev. A (2000)

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1. Classical system inherits quantum features
2. Quantum system inherits classical features
3. Genuine quantum-classical coupling?

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INCONSISTENCY

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2. **Quantum system inherits classical features**
3. **Genuine quantum-classical coupling?**

What is the most general consistent quantum-classical coupling?

Consistent: classical system stays classical, quantum system stays quantum under time evolution

Diosi, Gisin, Strunz, Phys. Rev. A (2000)

TENSION BETWEEN CLASSICAL GRAVITY AND QUANTUM MATTER?

GENERAL RELATIVITY

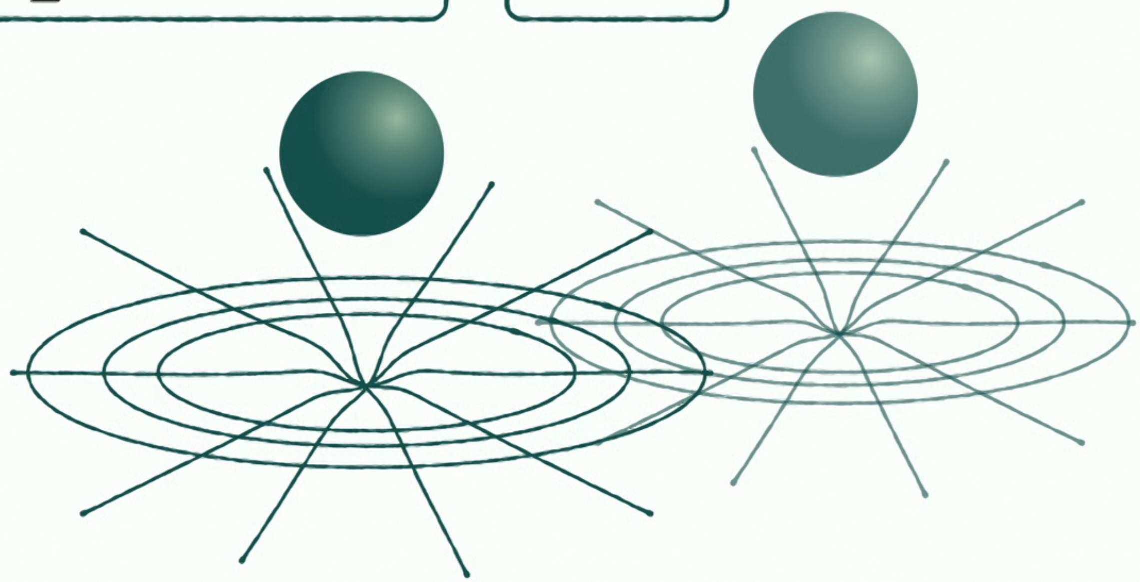
GRAVITY | CLASSICAL MATTER

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

QUANTUM THEORY

$$T_{\mu\nu} \rightarrow \hat{T}_{\mu\nu}$$

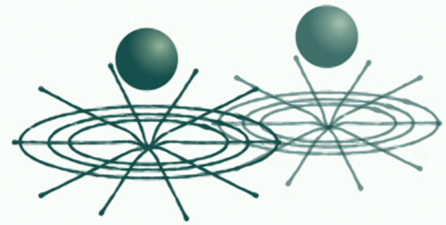
QUANTUM MATTER

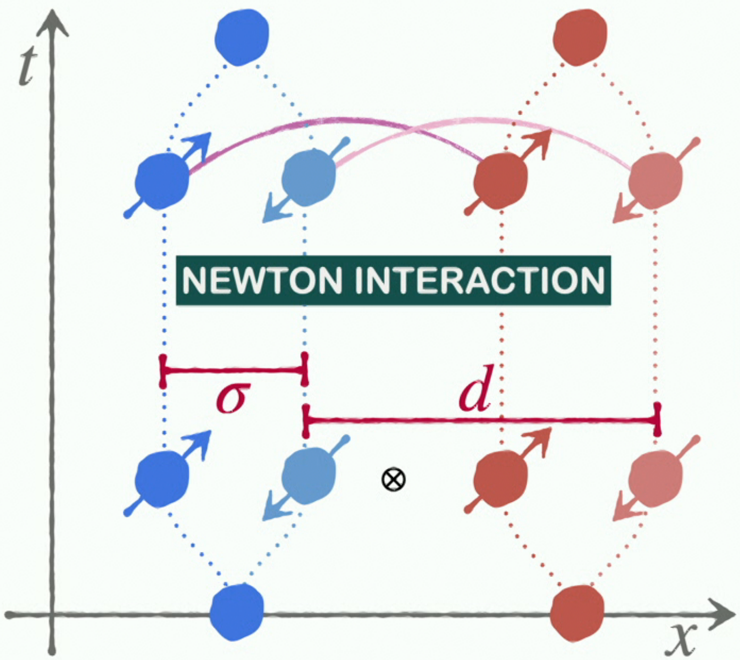


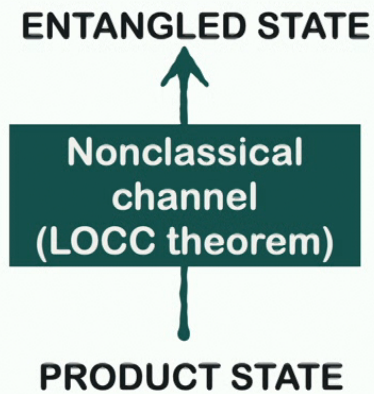
TESTING QUANTUM ASPECTS OF GRAVITY: GRAVITATIONALLY INDUCED ENTANGLEMENT

"If you believe in quantum mechanics up to any level then you have to believe in gravitational quantization in order to describe this experiment."

R. Feynman, Chapel Hill Conference (1957)







Bose et al. PRL (2017)
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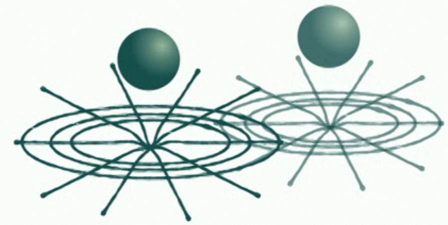

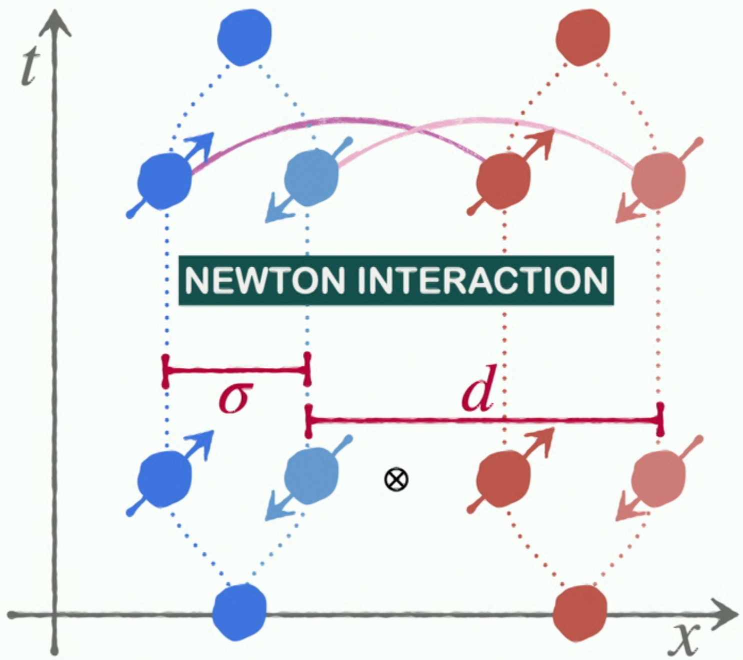

ENTANGLED STATE

Nonclassical channel (LOCC theorem)

PRODUCT STATE

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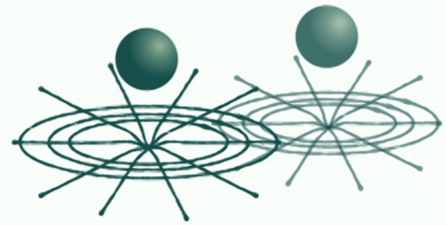

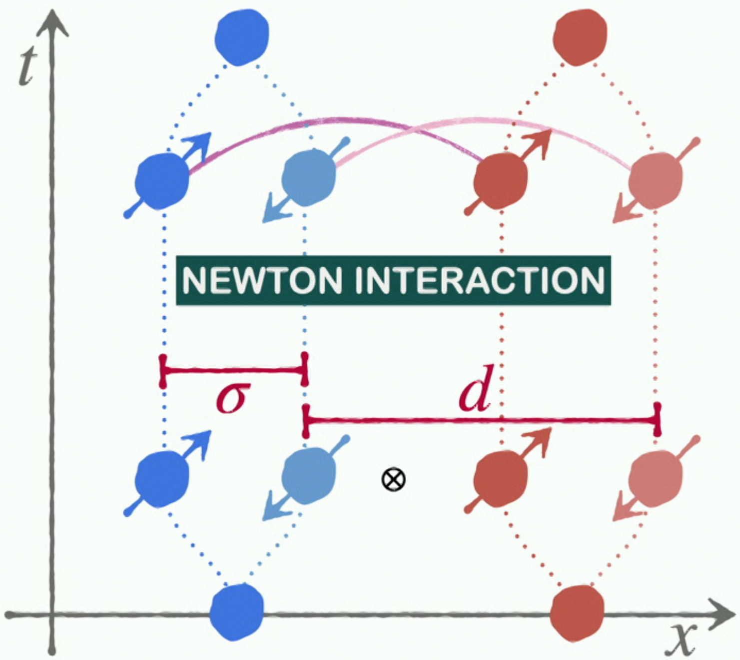

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ENTANGLEMENT RATE

$$\Gamma_{ent} = \frac{d}{dt}\Delta\phi = \frac{G}{\hbar}\frac{m^2\sigma^2}{d^3}$$

$$\begin{bmatrix} m \approx 10^{-5}\, g \\ d \approx 100\, \mu m \\ \sigma \approx 1\, nm \end{bmatrix}$$

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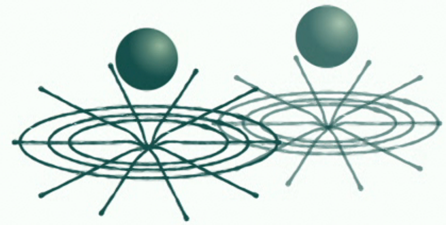

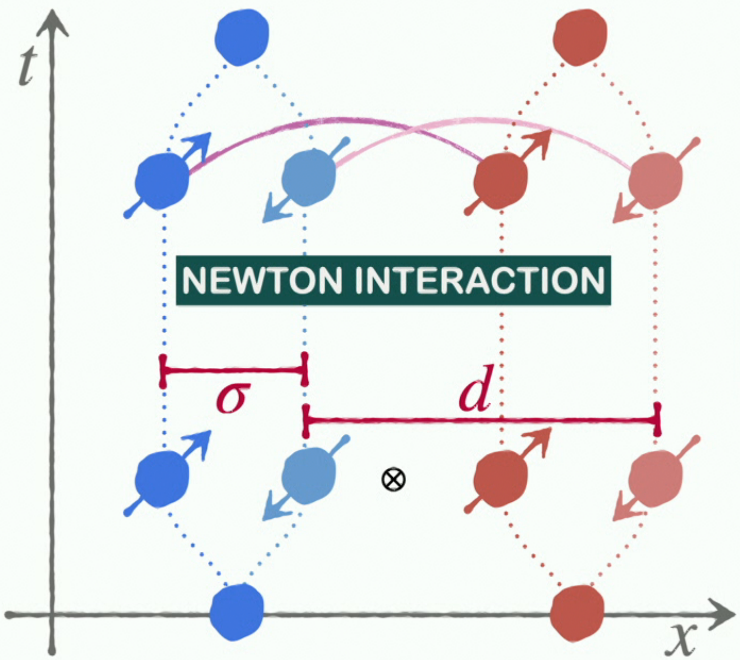

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$$\tau_{ent} = \Gamma_{ent}^{-1} \approx 0.1\, s$$

WHY IS THIS INTERESTING?

LEVEL 1: We do NOT know which quantum features of gravity we will be able to test in experiments
Good news: There will be experimental guidance!

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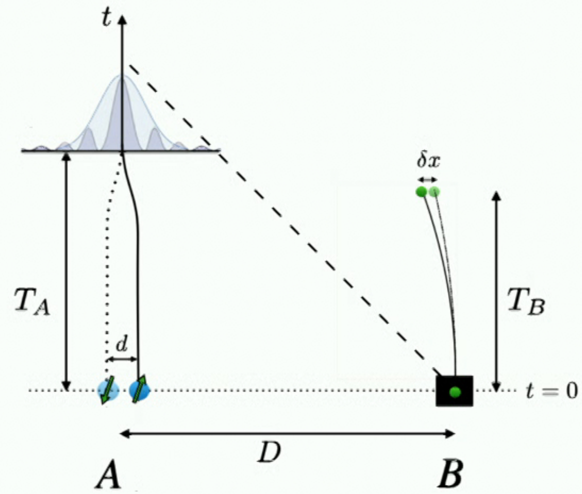
1. Newton interaction + no faster-than-light principle
$\Longrightarrow$ vacuum fluctuations and gravitational radiation in a quantum state

Belenchia, Wald, Giacomini, Castro-Ruiz, Brukner, Aspelmeyer, PRD (2018)

2. Modifying the theory may lead to nontrivial conclusions (see next)



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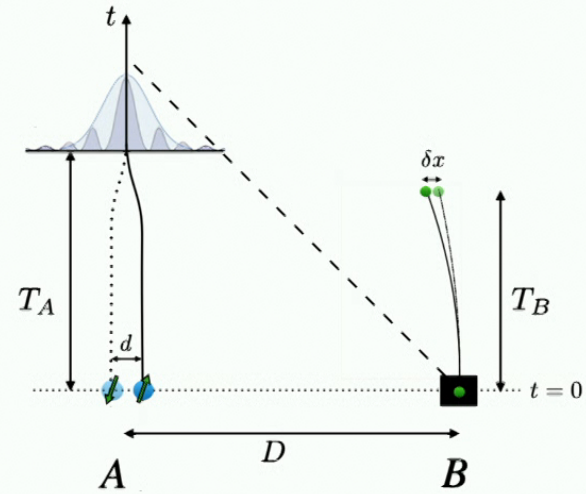
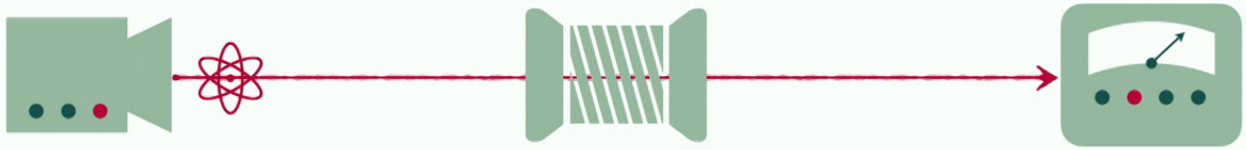


LEVEL 3: First-principle approach:
Internal consistency of GR and QT can be tested in thought experiments
NB: information theory is not tied to a specific regime

GENERALISED PROBABILISTIC THEORIES



PREPARATION
Knobs change the state

TRANSFORMATION
Device acting on system

MEASUREMENT
Obtain classical outcome

A theory is characterised by its probabilities.

L. Hardy, arXiv:0101012 (2001)
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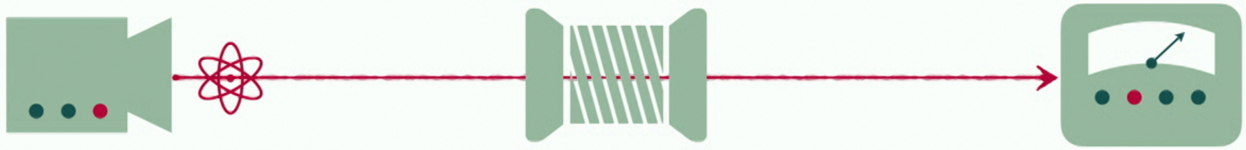

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Convex state space:
$\omega \in \Omega$

PURE STATES:
extremal states of the set

MIXED STATES:
convex combinations of pure states

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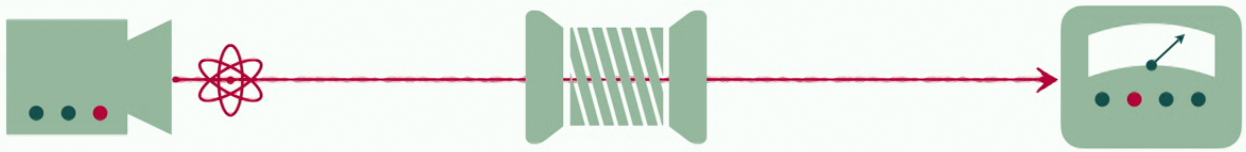

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TRANSFORMATIONS

$$\mathcal{T}\left(\sum_i p_i \omega_i\right) = \sum_i p_i \mathcal{T}(\omega_i)$$

MEASUREMENT

$$f_i \in \mathcal{F}$$

$$\sum_i f_i(\omega) = 1 \qquad \forall \omega \in \Omega$$

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CLASSICAL VS. QUANTUM

CLASSICAL SYSTEM

QUANTUM SYSTEM

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CLASSICAL SYSTEM

Set of states

$$\Omega_A = \left\{ \omega = (p_1, \cdots, p_n) \in \mathbb{R}^N \,|\, p_i \geq 0, \sum_i p_i = 1 \right\}$$

Set of measurements

$$\mathscr{F} = \{0 \leq f(\omega) \leq 1 \,|\, \omega \in \Omega_A\}$$

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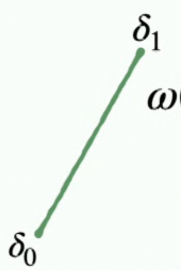

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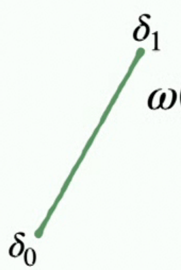

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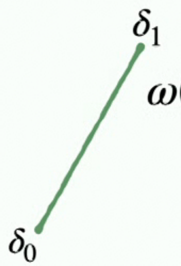

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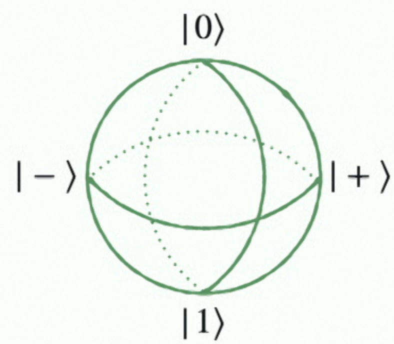

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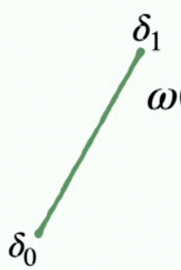

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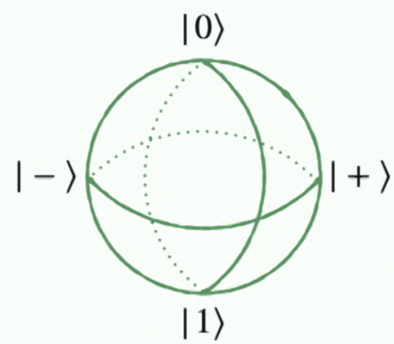

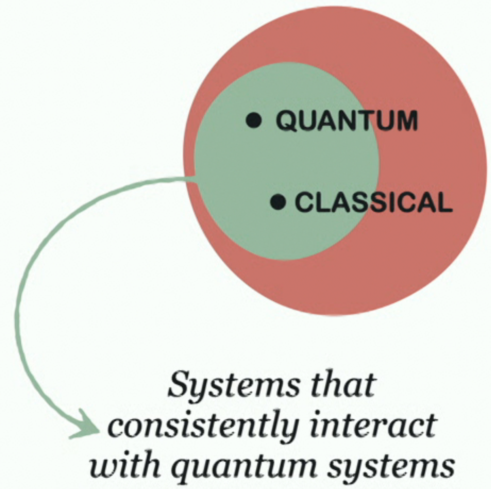

COUNTER-INTUITIVE CLASSICALITY: NONLINEAR QUANTUM MECHANICS

$$i\frac{\partial\psi}{\partial t} = -\nabla^2\psi + \epsilon f(|\psi|^2) + V\psi$$

e.g. Schrödinger-Newton equation

Arbitrary pure states (two-level system)

$$|\psi\rangle, |\phi\rangle$$

B. Mielnik (1980)

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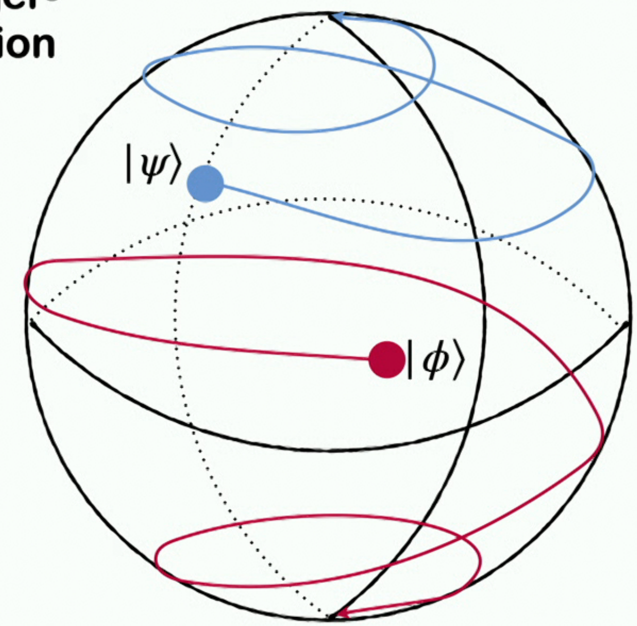

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It is possible to devise a procedure to distinguish perfectly any two states

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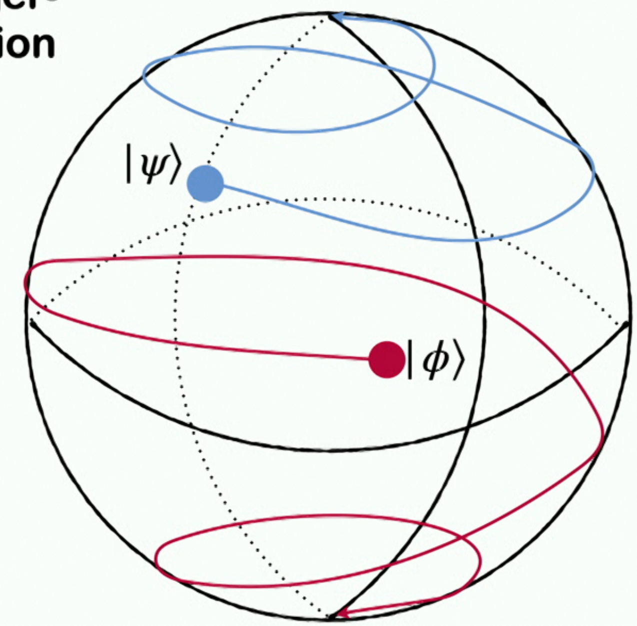

Arbitrary pure states (two-level system)

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It is possible to devise a procedure to distinguish perfectly any two states

The theory acquires CLASSICAL FEATURES

B. Mielnik (1980)

MAIN RESULT: NO-GO THEOREM

Theorem: **Given two GPT systems S and G which interact via some interaction I then at least one of the following conditions must be violated:**

(i) The system S is fully non-classical

(ii) The interaction I is reversible

(iii) There is information flow from system S to system G

(iv) G is classical

FULLY NON-CLASSICAL SYSTEMS

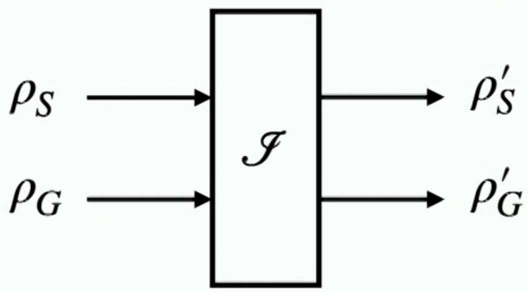
Non-classical systems which are not super-selected.

QUANTUM THEORY
super-selected systems
are block diagonal

$$\begin{pmatrix} \rho_1 & 0 \\ 0 & \rho_2 \end{pmatrix}$$

E.g. requirement of no superposition of different charge states.

REVERSIBLE INTERACTION



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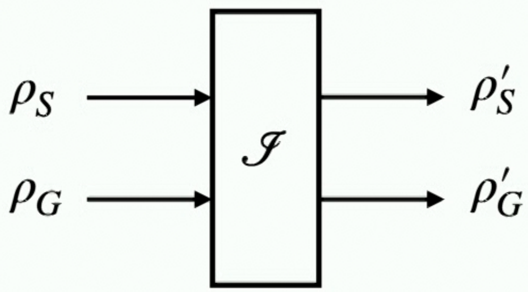

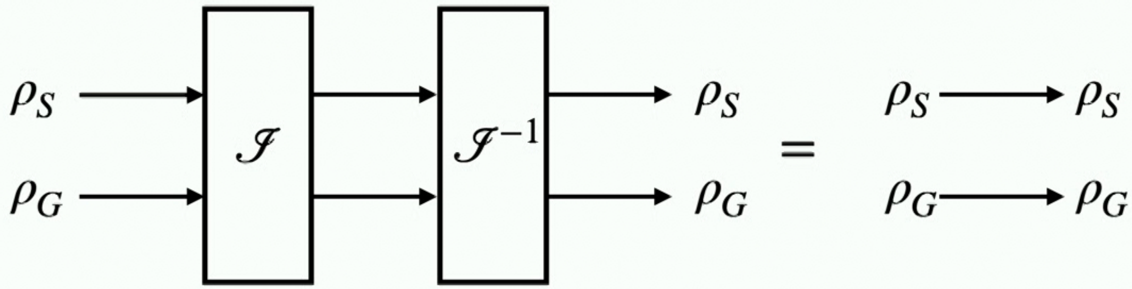

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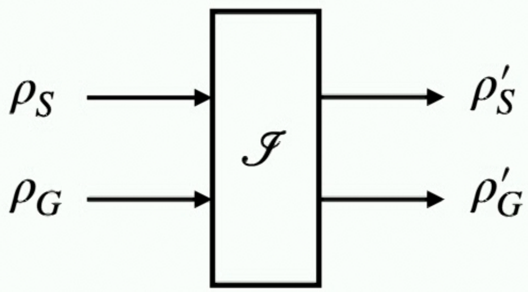

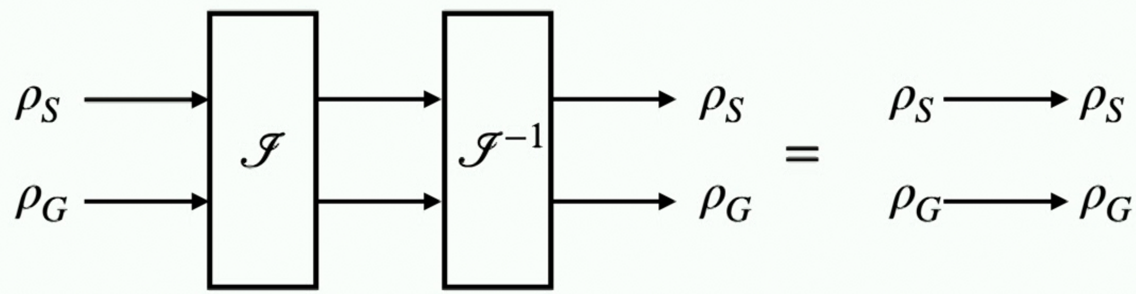

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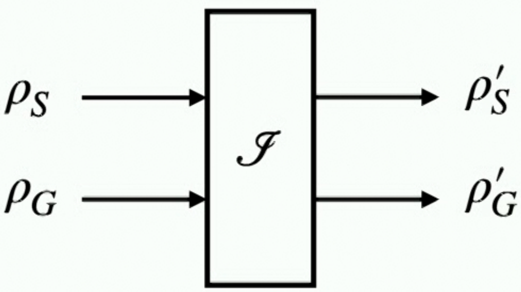
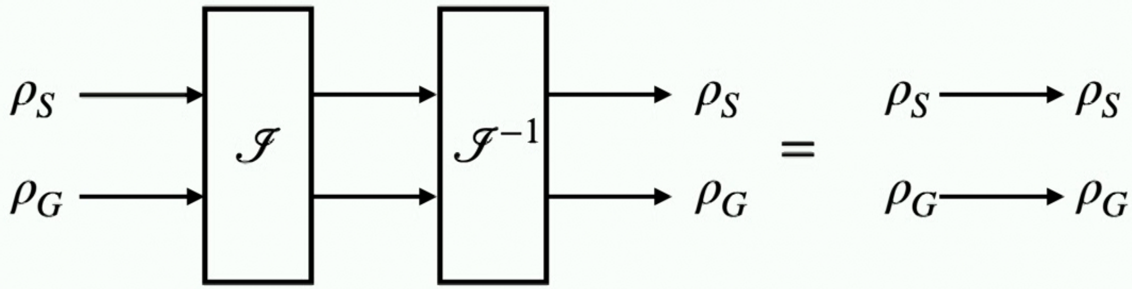
One-to-one
Deterministic
Reversible

REVERSIBLE INTERACTION





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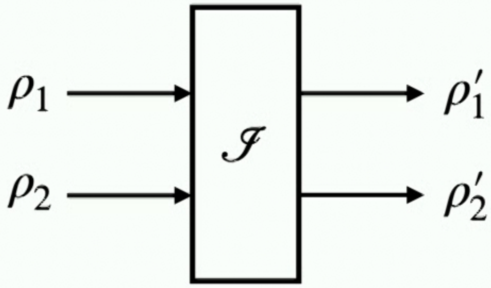
One-to-one
Deterministic
Reversible

$$|\psi\rangle\langle\psi| \mapsto |\alpha|^2|0\rangle\langle 0| + |\beta|^2|1\rangle\langle 1|$$

$|\psi\rangle\langle\psi| \mapsto |0\rangle\langle 0|$ **with prob** $|\alpha|^2$ **or** $|1\rangle\langle 1|$ **with prob** $|\beta|^2$

Many-to-one
Stochastic
Irreversible

INFORMATION FLOW FROM SYSTEM 1 TO SYSTEM 2



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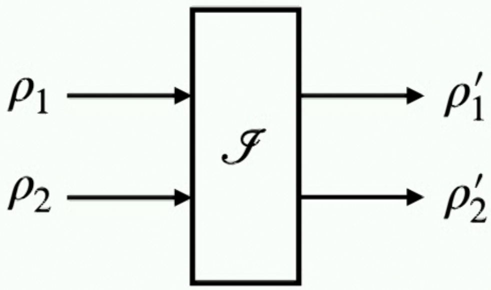

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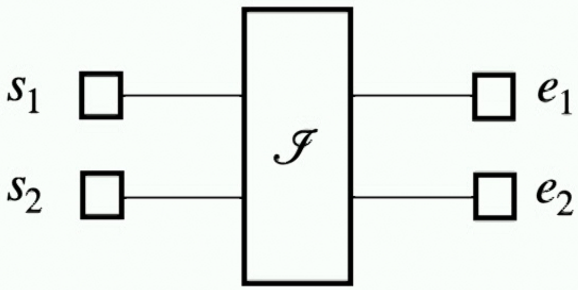
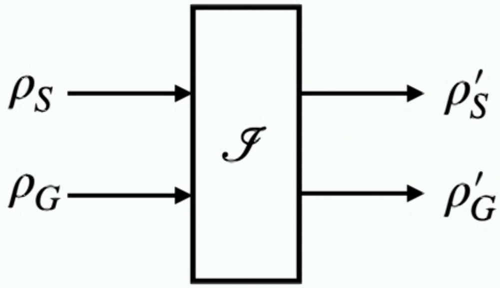


$p(e_2 \,|\, s_1, s_2, \mathscr{I})$ **depends non trivially on** s_1

Signalling from 1 to 2

INTUITION BEHIND PROOF

Assume S fully quantum, $\mathscr{I}$ reversible, back-reaction from S to G and G classical



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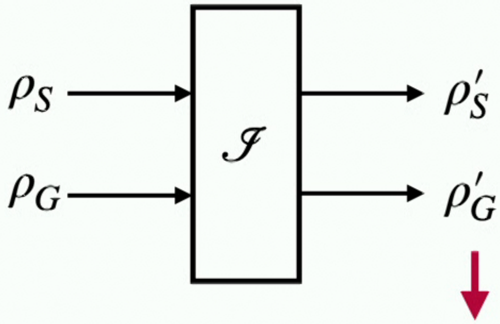

Extract some information about S from G (i.e measurement of S)

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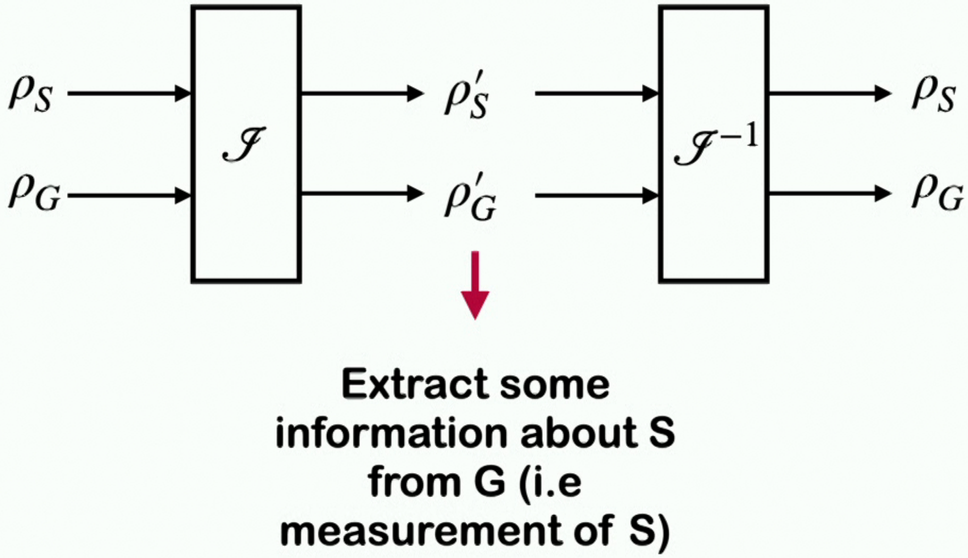

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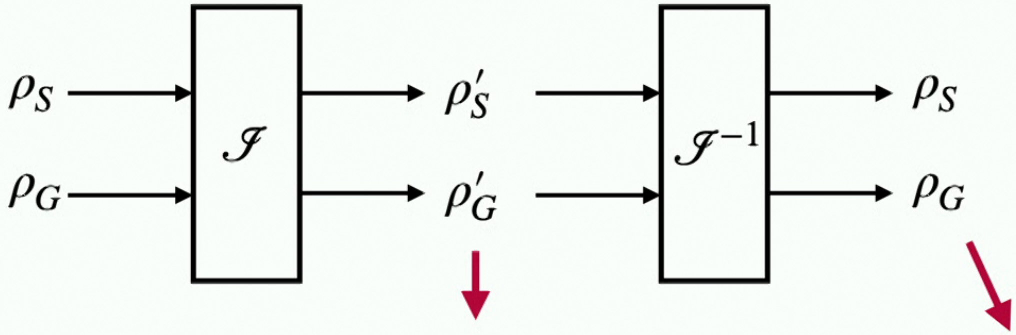

Non-disturbing measurement with information gain: impossible!

Extract some information about S from G (i.e measurement of S)

Return to initial state

OPTION 1: NONCLASSICALITY OF G

Theorem: Given two GPT systems S and G which interact via some interaction I then at least one of the following conditions must be violated:

(i) The system S is fully non-classical

(ii) The interaction I is reversible

(iii) There is information flow from system S to system G

(iv) G is classical

S: position degree of freedom of a quantum system

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In classical gravity matter back-reacts on G

(i) is satisfied ✓

(iii) is satisfied ✓

SUMMARY

If gravity is classical:

Reject condition	
i)	*Reject QT*
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EXAMPLE

A post-quantum theory of semiclassical gravity? (J. Oppenheim)

Consistent classical-quantum coupling

Has back-reaction

Not reversible (stochastic dynamical flow)

SUMMARY AND OUTLOOK

General Probabilistic Theories offer a tool to

- test the consistency of the theory (see NLSE: not really quantum)

-characterise the most general description from first principles

- rule out alternative descriptions based on solely laboratory operations

"Though it may be very difficult to quantize gravitation, it is even more difficult not to do it"

(Mielnik 1974)

(if the interaction is reversible)

Swiss National Science Foundation

ETH zürich

THANK YOU!

QISS | THE QUANTUM INFORMATION STRUCTURE OF SPACETIME

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QISS is an interdisciplinary initiative in Quantum Information and Quantum Gravity, bringing together theorists, experimentalists and philosophers.

Our research program aims to unravel the Quantum Information Structure of Spacetime.

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