No-Hypersignaling as a Physical Principle

Michele Dall'Arno,[1] Sarah Brandsen,[1] Alessandro Tosini,[2]
Francesco Buscemi,[3] Vlatko Vedral,[4,1]

[1] Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, 117543, Singapore

[2] QUIT group, Physics Dept., Pavia University, and INFN Sezione di Pavia, via Bassi 6, 27100 Pavia, Italy

[3] Graduate School of Information Science, Nagoya University, Chikusa-ku, 464-8601 Nagoya, Japan

[4] Atomic and Laser Physics, Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX13PU, United Kingdom

A paramount topic in quantum foundations, rooted in the study of the EPR paradox and Bell inequalities, is that of characterizing quantum theory in terms of the space-like correlations it allows. Here we show that to focus only on space-like correlations is not enough: we explicitly construct a toy model theory that, though being perfectly compatible with classical and quantum theories at the level of space-like correlations, displays an anomalous behavior in its time-like correlations. We call this anomaly, quantified in terms of a specific communication game, the "hypersignaling" phenomena. We hence conclude that the "principle of quantumness," if it exists, cannot be found in space-like correlations alone: nontrivial constraints need to be imposed also on time-like correlations, in order to exclude hypersignaling theories. These results are published in Ref. `https://arxiv.org/pdf/1609.09237.pdf`

One of the main tenets in modern physics is that if two space-like separated events are correlated, then such correlations must not carry any information [1]. This assumption, constituting the so-called *no-signaling principle*, was the starting point used by Bell [2] to quantify and compare space-like correlations of different theories on even grounds—an idea of vital importance for his argument about the EPR paradox [3] and the derivation of his famous inequality. Subsequently, due to seminal works by Tsirelson (Cirel'son) [4] and Popescu and Rohrlich [5], it became clear that the no-signaling principle alone is not enough to characterize "physical" space-like correlations: non-signaling space-like correlations allowed by quantum theory form a *strict* subset within the set of all non-signaling correlations [6].

A natural question is then to try to identify additional principles that, together with the no-signaling principle, may be able to rule out all super-quantum non-signaling correlations at once. Various ideas have been proposed, ranging from complexity theory, e.g. the collapse of the complexity tower [7] to information theory, e.g. the information causality principle [8]. However, none of these has been able to characterize the quantum/super-quantum boundary in full. In particular, an outstanding open question is whether quantum theory can be characterized in terms of the space-like correlations it allows [6].

In this work, we show that this cannot be done: any approach to characterize quantum theory based only on space-like correlations is necessarily incomplete unless it also takes into account time-like correlations as well. Our approach considers the elementary resource of noiseless communication and the input/output correlations that can be so established. By analogy with the no-signaling principle, we operationally introduce what we call the "no-hypersignaling principle," which roughly states that any input/output correlation that can be obtained by transmitting a composite system should also be obtainable by independently transmitting its constituents. As obvious as this may look (it is indeed so in classical and quantum theories), the fact that quantum theory obeys the no-hypersignaling principle (as we define it) is in fact a highly nontrivial consequence of a recent result by Frenkel and Weiner [9].

We then construct a toy model theory, denoted the HS Model, which violates the no-hypersignaling principle, but only possesses classical space-like correlations. As such, this theory (and other analogous

Submitted to:
QPL 2017

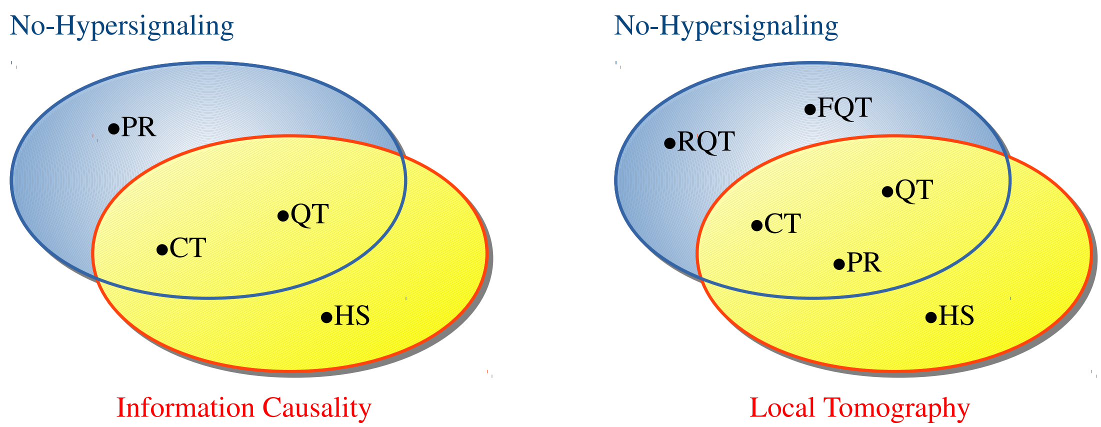

Figure 1: **No-Hypersignaling vs Information Causality and vs Local Tomography**. Left: the diagram compares theories satisfying information causality (yellow set) and the no-hypersignaling principle (blue set): CT (classical theory), QT (quantum theory), PR Model (the toy model theory for PR-boxes), and HS Model (the locally classical, hypersignaling theory constructed in this work). Right: comparison between local tomography and no-hypersignaling as two features of general probabilistic theories. Examples of theories that are non-hypersignaling but violate local tomography are provided by real quantum theory (RQT) and fermionic quantum theory (FQT). The HS Model is locally tomographic but hypersignaling. Finally CT, QT, and the PR Model lie in the intersection, as they obey both local tomography and the no-hypersignaling principle.

theories) would go undetected in any test involving only space-like correlations, despite displaying the anomalous effect of hypersignaling. On the technical side, our model is closely related to the standard implementation [11, 12, 13] of Popescu–Rohrlich [5] super-quantum non-signaling space-like correlations (or "PR-boxes," for short). However, while the PR-box model theory relies on entangled states to outperform quantum *space*-like correlations, our hypersignaling model relies on *entangled measurements* to outperform quantum *time*-like correlations. Nonetheless, since in our model only separable states are available, no super-quantum space-like correlation can be obtained. Therefore, while the standard PR-box model theory can be ruled out on the basis of its super-quantum space-like correlations, the model proposed here can only be ruled out by the principle of no-hypersignaling.

It is now relevant to observe that hypersignaling is logically unrelated to other possible "anomalies," such as the violation of local tomography or the violation of information causality. If any hypersignaling theory necessarily violates also other principles concerning space-like correlations, then one could rightly argue that the phenomenon of hypersignaling might be ruled out just by looking at space-like correlations. However, the point of this work is to argue the opposite: that time-like correlations require a new *independent* principle.

We show that hypersignaling and information causality are independent. The HS Model obeys information causality, despite allowing hypersignaling; vice versa, the PR-boxes model violates information causality but it cannot display any form of hypersignaling. The situation is depicted in Left Fig. 1.

Hypersignaling is also logically independent of local tomography. The HS Model is locally tomographic, despite being hypersignaling. Vice versa, there exist consistent theories that obey the no-hypersignaling principle and yet are not locally tomographic, e.g. the fermionic and the real quantum theory (these can be regarded as superselections of quantum theory, as introduced in Ref. [14]). The situation is summarized in Right Fig. 1.

We Finally notice that the no-hypersignaling principle can be violated by theories that do not show superadditivity of classical capacities (as the theories considered in Ref. [15]).

The last question we address in this contribution is the following. On the one hand, the HS Model has classical space-like correlations and super-quantum time-like correlations. On the other hand, the PR-boxes model has super-quantum space-like correlations and classical time-like correlations. May it be that a theory can be super-quantum only with respect to either space-like or time-like correlations, but not both? The answer is no, and an example is explicitly provided.

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