Title: Relativistic causality principles in QFT

Speakers: Doreen Fraser

Series: Quantum Foundations, Quantum Information

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Abstract: In QFT, one aspect of relativistic causality is the principle of microcausality, which requires that observables associated with spacelike separated regions commute. But this principle is not by itself sufficient to rule out superluminal signalling, as examples of â€˜impossibleâ€™ measurements demonstrate. Representations of the dynamics that respect relativity also play a necessary role in upholding relativistic causality in QFT. This talk will focus on the important role that principles of relativistic dynamics play in representations of local measurement in QFT.

Relativistic causality principles in QFT

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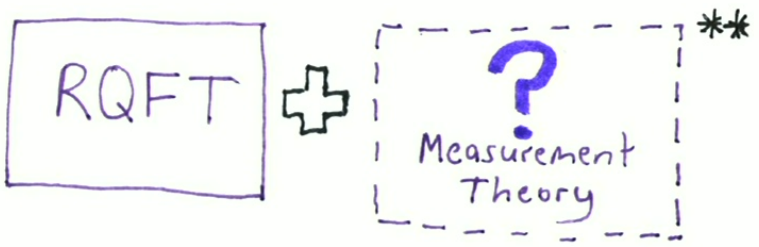
Causalworlds
September 19, 2024

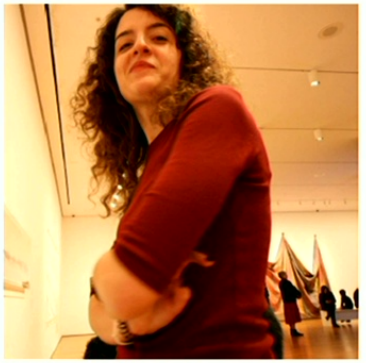
Why (as a philosopher and historian) I am excited about recent work on measurement in QFT



Review article (Foundations): MP and DF, "Eliminating the 'Impossible': Recent Progress on Local Measurement Theory for Quantum Field Theory," *Found Phys* 2024

History for physics: DF and MP, "Note on episodes in the history of modeling measurements in local spacetime regions using QFT," *EJPH* 2023

For philosophers:
DF, "The Measurement Problem in QFT" *(coming soon)*



Maria Papageorgiou
(IQOQI Vienna)

Outline

1. Three approaches to Microcausality
2. Sorkin's 'impossible measurements' problem
3. How Sorkin's 'impossible measurements' problem has been addressed in QFT

Three Approaches to Microcausality *(Without Measurement Theory)*

Microcausality: If algebras of observables $\mathcal{A}$ and $\mathcal{B}$ are associated with spacelike separated regions, then $[A, B] = 0$ for $A \in \mathcal{A}$ and $B \in \mathcal{B}$

Non-relativistic QM

- does not include *Microcausality*
- *Microcausality* can be added to the theory

Galilean QFT (Lévy-Leblond 1967 Comm Math Phys)

- Causal principle: If two regions of spacetime are causally disjoint, then the algebras of observables associated with these regions are mutually commuting.
- *Local commutativity*: At equal times, two field operators commute (for non-zero spatial separation)

Axiomatic QFT for Minkowski spacetime

- Causal principle: If two regions of spacetime are causally disjoint, then the algebras of observables associated with these regions are mutually commuting.
- *Microcausality* follows from this causal principle

Two Approaches to Investigating Consequences of Relativistic Principles in Quantum Theory

Galilean QFT does not allow consistent addition of relativistic principles

1. **Abstract version of NRQM + relativistic principles (e.g., Microcausality)**

   Is this a consistent framework?

   If an inconsistent set of principles is found, does this indicate an inconsistency between quantum theory and relativity theory? Or an inconsistency between relativity and underlying non-relativistic assumptions?

2. **Axiomatic QFT (+ other principles that are not considered axioms)**

   Is this a consistent framework?

   (If not, then revise the axioms)

Big Questions: Are these convergent research programs? What belongs in the general framework *quantum theory* (for all fixed spacetime backgrounds)?

No Superluminal Signalling: Definitions

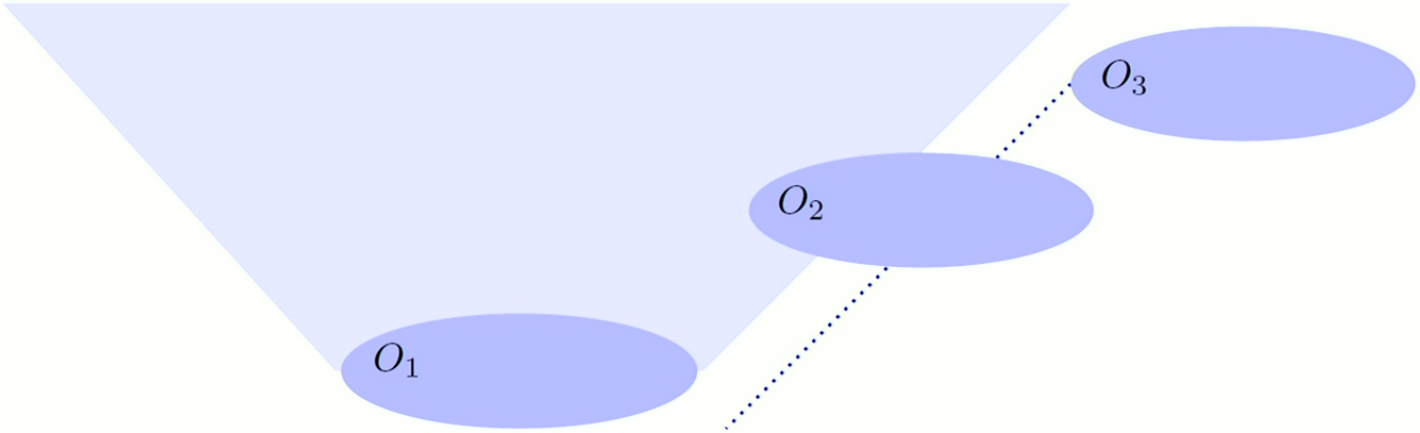
What conditions in *relativistic quantum theory* are sufficient to prohibit superluminal signalling?[1]

Superluminal signalling (general): Alice can perform a local operation in region O_A that affects the expectation values of observables that Bob can locally measure in spacelike separated region O_B.

[1] In contrast with Alejandro Pozas-Kerstjens' talk

Sorkin-Borsten-Jubb-Kells example of an 'impossible measurement' for relativistic quantum theory

Sorkin 1993 *Directions in General Relativity*; Borsten, Jubb & Kells 2021 Phys Rev D (Papageorgiou & DF 2024 Found Phys)



Key Assumptions: Microcausality + Lüders' state update rule for non-selective measurement (QMT) + relativistic temporal ordering relation ($O_1 \prec O_2 \prec O_3$) + unitary time evolution between local operations

Result: Alice can perform a local unitary operation in O_1 that affects the expectation values of Bob's local observables in O_3

No Superluminal Signalling: Definitions

Superluminal signalling (general): Alice can perform a *local operation* in region O_A that affects the expectation values of observables that Bob can locally measure in spacelike separated region O_B.

Superluminal signalling (non-selective measurement): Alice can perform a *non-selective measurement* in region O_A that affects the expectation values of observables that Bob can locally measure in spacelike separated region O_B.

How the Sorkin problem is addressed in QFT with Relativistic QMT

- replace non-relativistic QMT with relativistic QMT
- the relativistic dynamics is important

1. **Detector model approach** (Polo-Gómez, Garay & Martín-Martínez 2022 Phys Rev D):
   - retain NRQM and Lüders' rule for the detector (e.g. Unruh-DeWitt detector) and use QFT to model the system
   - introduce state update rules for QFT system
   - use detector models in regimes in which calculations *rule out superluminal signalling for all practical purposes* (de Ramón Rivera, Papageorgiou & Martín-Martínez 2021 Phys Rev D)
2. **Fewster-Verch (FV) measurement framework for AQFT** (Fewster & Verch 2020 Comm Math Phys):
   - use AQFT to describe both probe and system
   - in place of Lüders' rule (and QMT), derive new state update rules
   - additional principles of AQFT (especially Time-Slice Property dynamical axiom) can be used to *rule out superluminal signalling in principle* (Bostelmann, Fewster, Ruep 2021 Phys Rev D)

Relativistic dynamics in FV AQFT

Time-slice property axiom: If open, causally convex region N contains a Cauchy surface for M, then $\mathcal{A}(N) = \mathcal{A}(M)$. That is, there is a local embedding isomorphism $\alpha_{M;N}$: $\mathcal{A}(N) \to \mathcal{A}(M)$.

The dynamics is not represented in terms of unitary time evolution; does not depend on choice of a foliation of Cauchy surfaces

(and similarly for histories-based formulations of quantum theory)

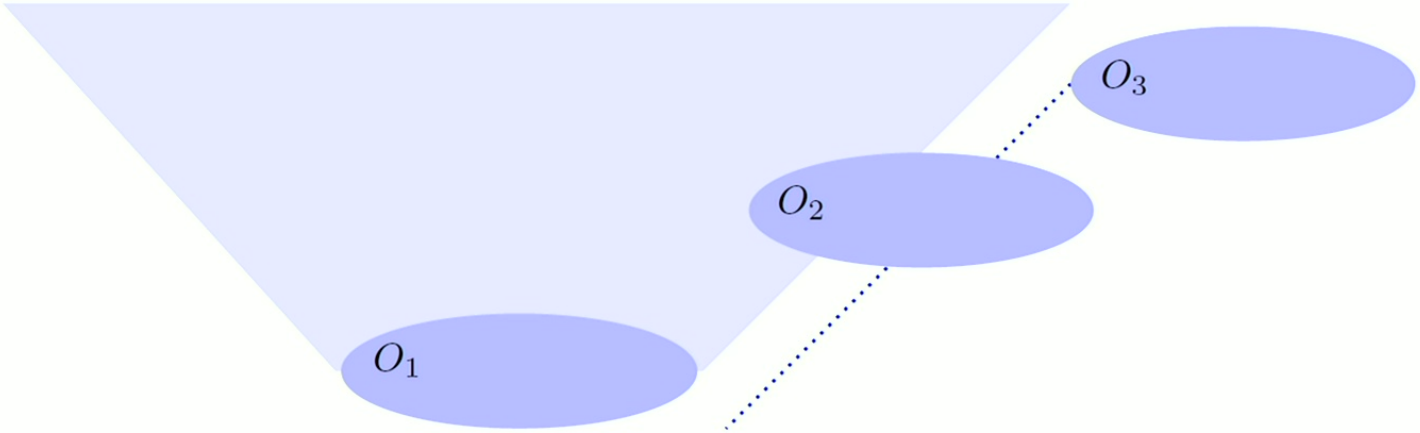
A question for quantum causal modelers: How do representations of relativistic dynamics that do not take the form of unitary time evolution fit into the framework?

Conclusions

- What belongs in the general framework *quantum theory* for all fixed spacetime backgrounds?
  - this is not a straightforward question
  - one proposal (of many!): FV measurement framework for QFT (more generally locally covariant AQFT (Fewster & Verch 2015)
- *Microcausality* is not by itself sufficient to rule out superluminal signalling in a relativistic quantum theory
- In QFT, relativistic QMT and dynamics are also relevant factors in the prohibition of superluminal signalling by non-selective measurements.
  - *A question for quantum causal modelers*: How do representations of relativistic dynamics that do not take the form of unitary time evolution fit into the framework?

Sorkin-Borsten-Jubb-Kells example of an 'impossible measurement' for relativistic quantum theory

Sorkin 1993 *Directions in General Relativity*; Borsten, Jubb & Kells 2021 Phys Rev D (Papageorgiou & DF 2024 Found Phys)



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