Quantum field measurements with(out) superluminal signalling

Jason Pye

work with José de Ramón, Eduardo Martín-Martínez

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Theory of measurements/operations for QFT

How to do quantum operations in a relativistic spacetime?

- i.e. how to introduce agents
- finite times (push beyond S-matrix)

Contexts:

- Time machine paradoxes, BH entropy, …
- QI experiments in relativistic regime (q. optics, cQED, …)
- Foundational question: What can be measured in principle?

QM operations → QFT?

Naively, can use standard idealised measurements from QM

- PVMs: projectors $\rho \to P_a \rho P_a$

  e.g., from self-adjoint $A = \sum_a a P_a \to \langle A \rangle$

- POVMs: $\rho \to M_i \rho M_i^\dagger$

  s.t. $\sum_i M_i^\dagger M_i = 1$

- Channels (CPTP maps):

$$\rho \to \sum_i M_i \rho M_i^\dagger$$

Does relativity impose further requirements?

Impossible Measurements on Quantum Fields*

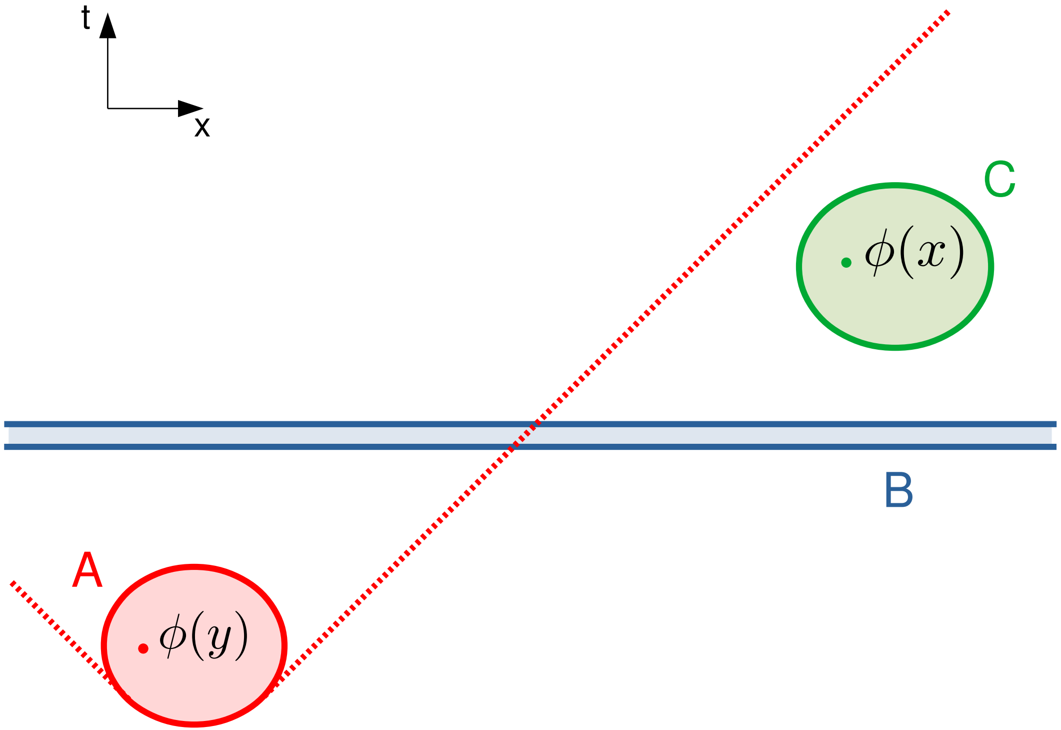
RAFAEL D. SORKIN

Department of Physics, Syracuse University, Syracuse NY 13244-1130

Abstract

It is shown that the attempt to extend the notion of ideal measurement to quantum field theory leads to a conflict with locality, because (for most observables) the state vector reduction associated with an ideal measurement acts to transmit information faster than light. Two examples of such information-transfer are given, first in the quantum mechanics of a pair of coupled subsystems, and then for

Sorkin's Impossible Measurement



- Initial state $\rho_0 = |0\rangle\langle 0|$
- Operation in A

$$U = e^{i\lambda\phi(y)} \qquad (\lambda \in \mathbb{R})$$
$$\rho = U\rho_0 U^\dagger$$

- Measurement in B (unconditional)

$$P = |\psi\rangle\langle\psi|$$

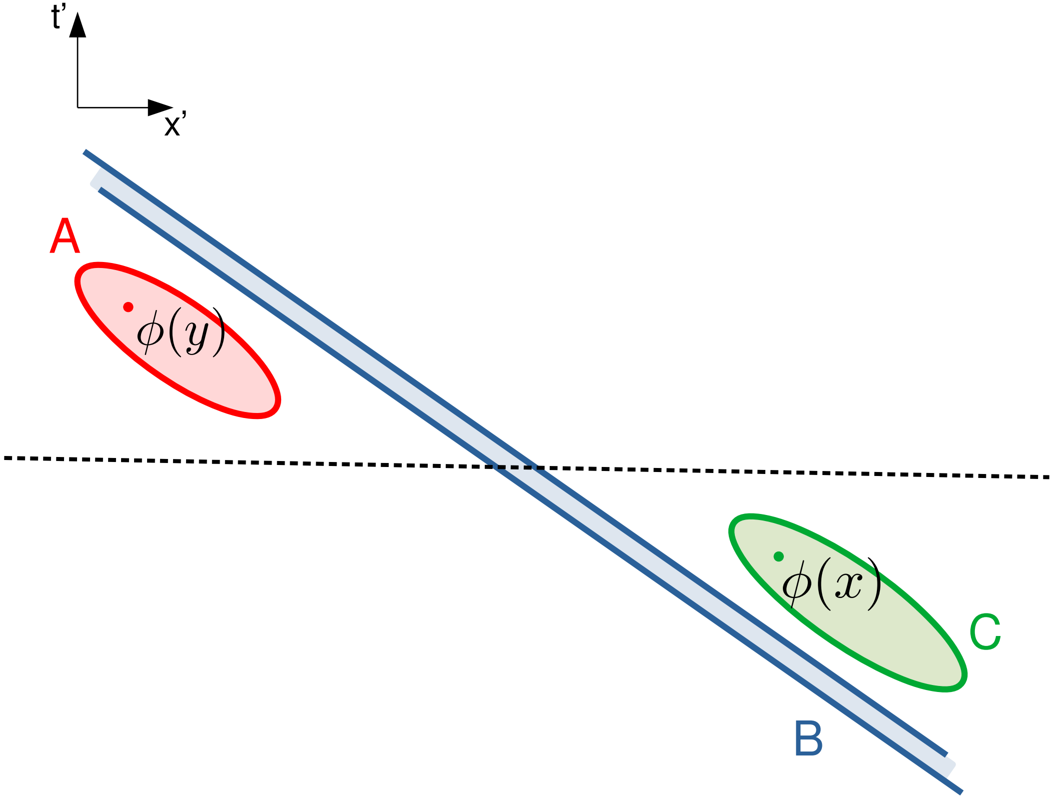
with $|\psi\rangle := \alpha|0\rangle + \beta|1\rangle \quad (|1\rangle \in \mathcal{H}_1)$

$$\rho' = P\rho P + (1-P)\rho(1-P)$$

- Expectation value in C

$\langle\phi(x)\rangle_{\rho'}$ depends on λ!

Sorkin's Impossible Measurement



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Implications

Assuming theory should not admit superluminal signalling of this kind…

- Sorkin's quantum measure (path integral); OR
- (Operator framework): not every idealized quantum operation is admissible
  - Measurement postulates vs. Relativistic spacetime structure

$$A = \sum_a a P_a$$
$$p_a = \mathrm{tr}(\rho P_a)$$
$$\rho \to P_a \rho P_a$$

vs.

$$[\phi(x), \phi(y)] = 0,$$
$$\text{for } (x-y)^2 > 0 \text{ (spacelike)}$$

  - Counterexample to: self-adjoint $\Longrightarrow$ observable

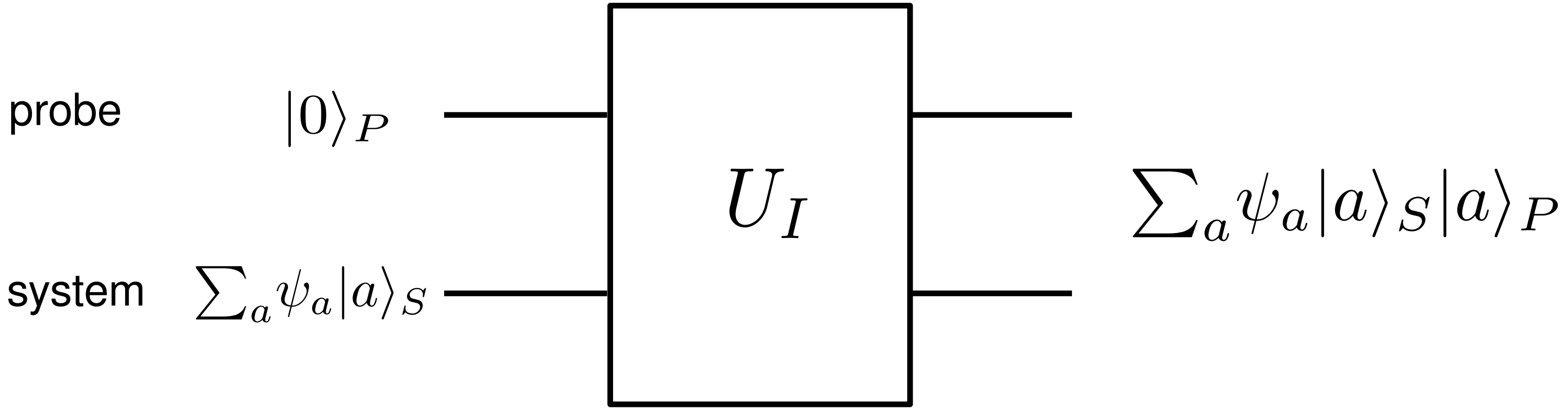
Aim

- What measurements are/are not allowed?
  - What precisely is the issue with Sorkin's measurement?

- Would like:
  - List of observables, e.g., $H, P, N, \phi(f), \phi(f)^2, \ldots?$
  - Characterization of allowable PVMs/POVMs, channels

How would these measurements be performed?

- Measurements via interactions
  - Idealized von Neumann measurement



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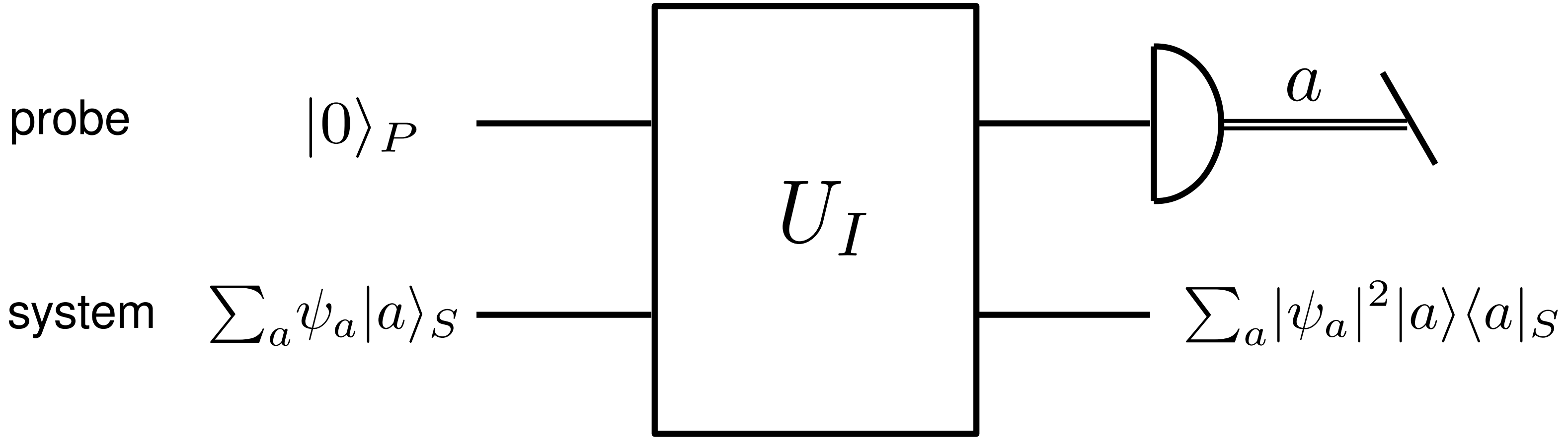
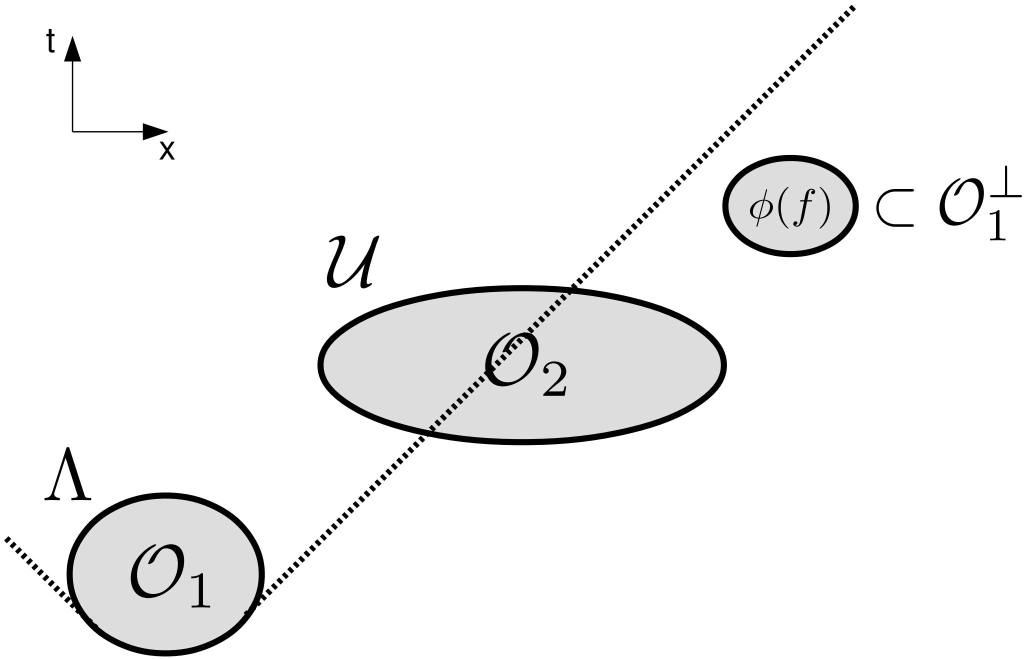


<u>channel on system</u> $\mathcal{U} : \rho \mapsto \sum_a P_a \rho P_a$

Causality condition

Formulate condition that operations should satisfy:



- For any map in (any) $\mathcal{O}_1$

  $$\Lambda : \mathcal{A}(\mathcal{O}_1) \to \mathcal{A}(\mathcal{O}_1)$$

- Operation (CP, unital) in $\mathcal{O}_2$

  $$\mathcal{U} : \mathcal{A}(\mathcal{O}_2) \to \mathcal{A}(\mathcal{O}_2)$$

should be s.t.

- any state $\omega : \mathcal{A}(\mathcal{M}) \to \mathbb{C}$
- any $A \in \mathcal{A}(\mathcal{O}_1^\perp)$

$$\omega(\Lambda \circ \mathcal{U}(A)) \stackrel{!}{=} \omega(\mathcal{U}(A))$$

Measurements via interactions with probes

- Sorkin-type impossible measurement

$$H_I(t) = \lambda\, \mu(t) \otimes \phi(f)^2$$
$$= \lambda\, \mu(t) \otimes \int d\mathbf{x} d\mathbf{y}\, f(t,\mathbf{x}) f(t,\mathbf{y}) \phi(t,\mathbf{x}) \phi(t,\mathbf{y})$$

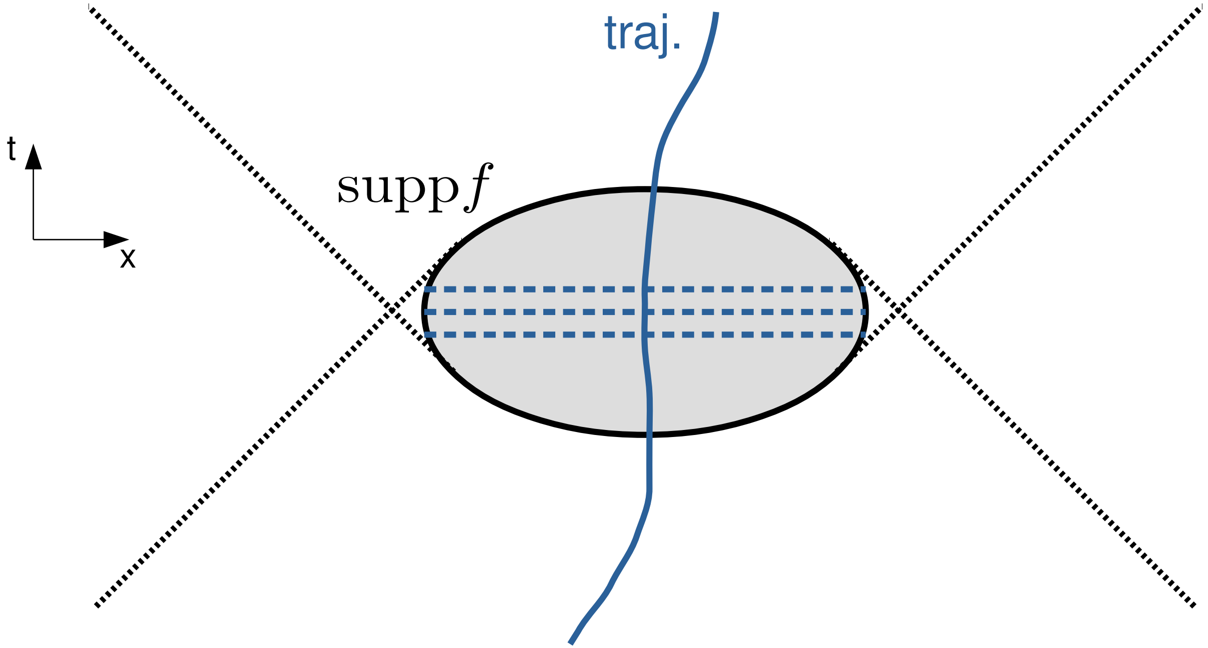
- Allowed, e.g., Weyl channels

$$\rho \to \sum_a p_a e^{-ia\phi(f)} \rho\, e^{ia\phi(f)}$$

Issues with internal dynamics

- Non-relativistic probes highly constrained

$$H = H_F \otimes 1 + 1 \otimes H_D + H_I$$



Unruh-deWitt-like model

$$H_I = \lambda \, p(t) \otimes \phi(f)$$

Towards a general characterization

- Non-relativistic probes generate examples of allowable measurements/operations
- May not exhaust set of allowable idealized operations
  - (If not, some kind of dilation theorem?)

- Source in the classical interaction?

- Eventually should take axiomatic approach to avoid proving existence of general classes of models

Summary

- Gained insight into issues causing superluminal signalling for idealized measurements
  - Non-local interaction terms, internal probe dynamics, …
- Simple class (Weyl channels) of allowable operations generated by non-relativistic probes

- **Message:** be careful when performing quantum measurements/operations on relativistic spacetime!