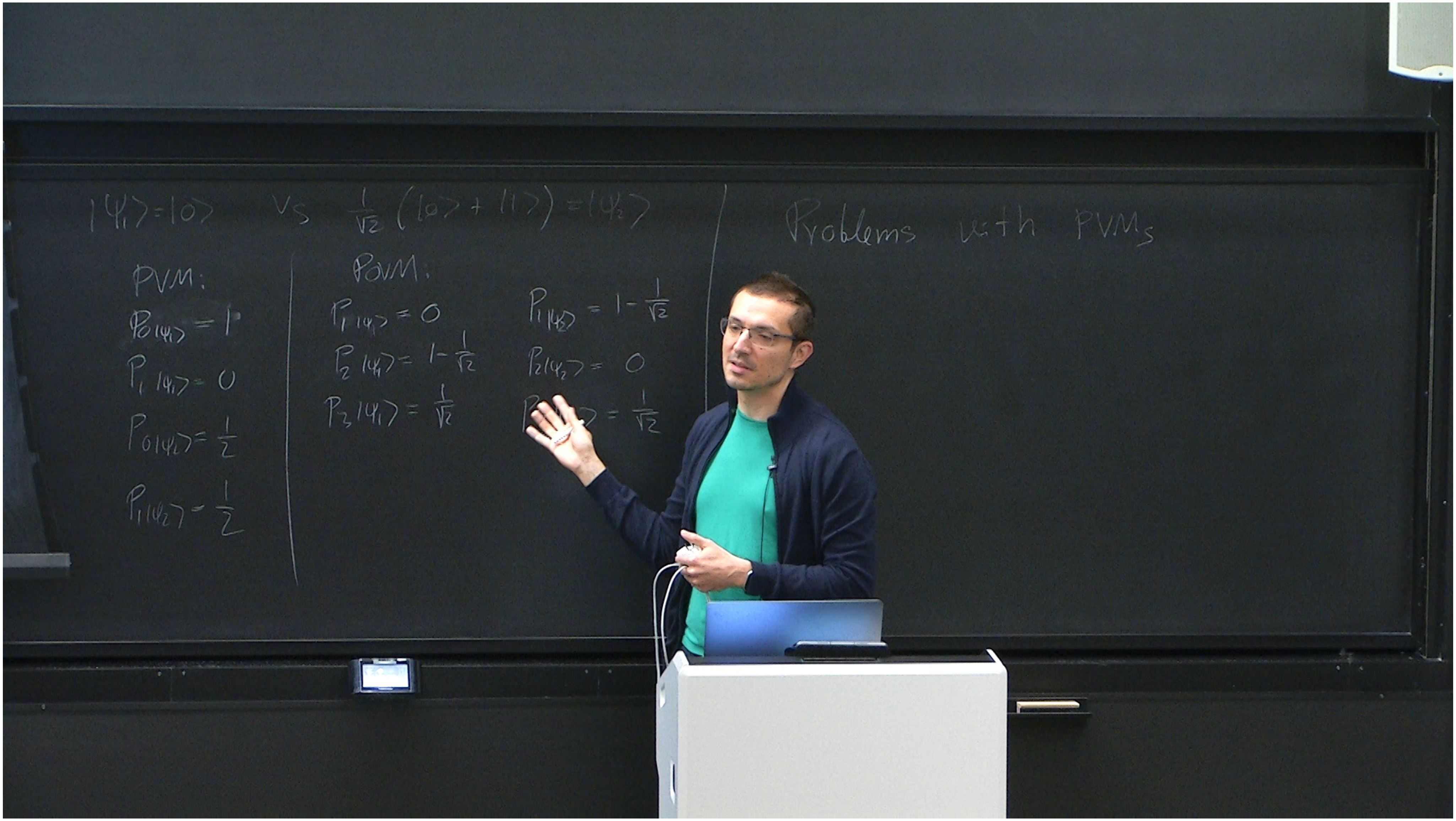
Title: Quantum Information Lecture - 230320

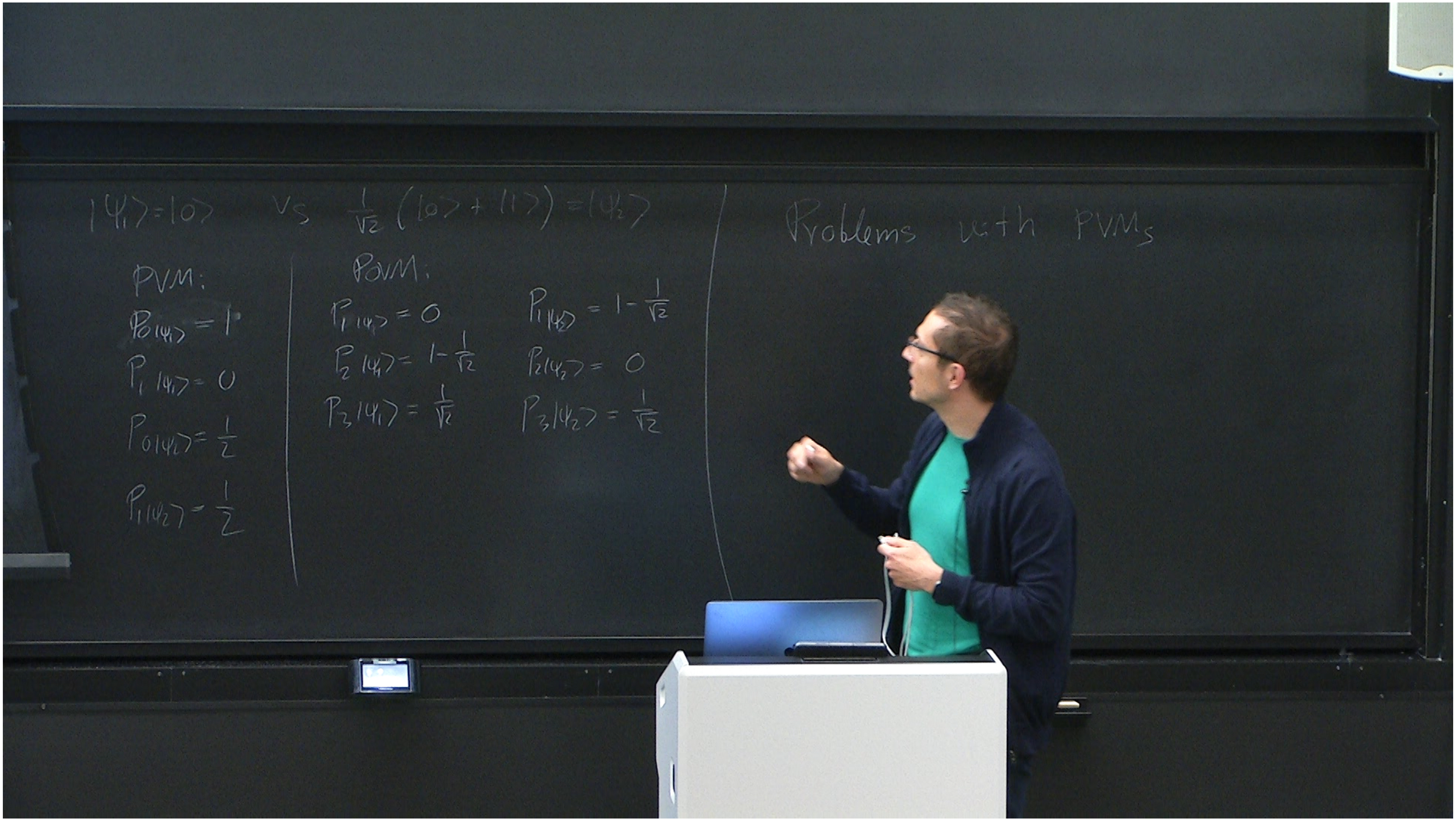
Speakers: Eduardo Martin-Martinez

Collection: Quantum Information (2022/2023)

Date: March 20, 2023 - 9:00 AM

URL: https://pirsa.org/23030009


|ψ1> = |0> vs 1/√2 (|0> + |1>) = |ψ2>
Problems with PVMs
PVM:
P0 |ψ1> = 1
P1 |ψ1> = 0
P0 |ψ2> = 1/2
P1 |ψ2> = 1/2
POVM:
P1 |ψ1> = 0
P2 |ψ1> = 1 - 1/√2
P3 |ψ1> = 1/√2
P1 |ψ2> = 1 - 1/√2
P2 |ψ2> = 0


|ψ₁⟩=|0⟩ vs 1/√2 (|0⟩+|1⟩)=|ψ₂⟩
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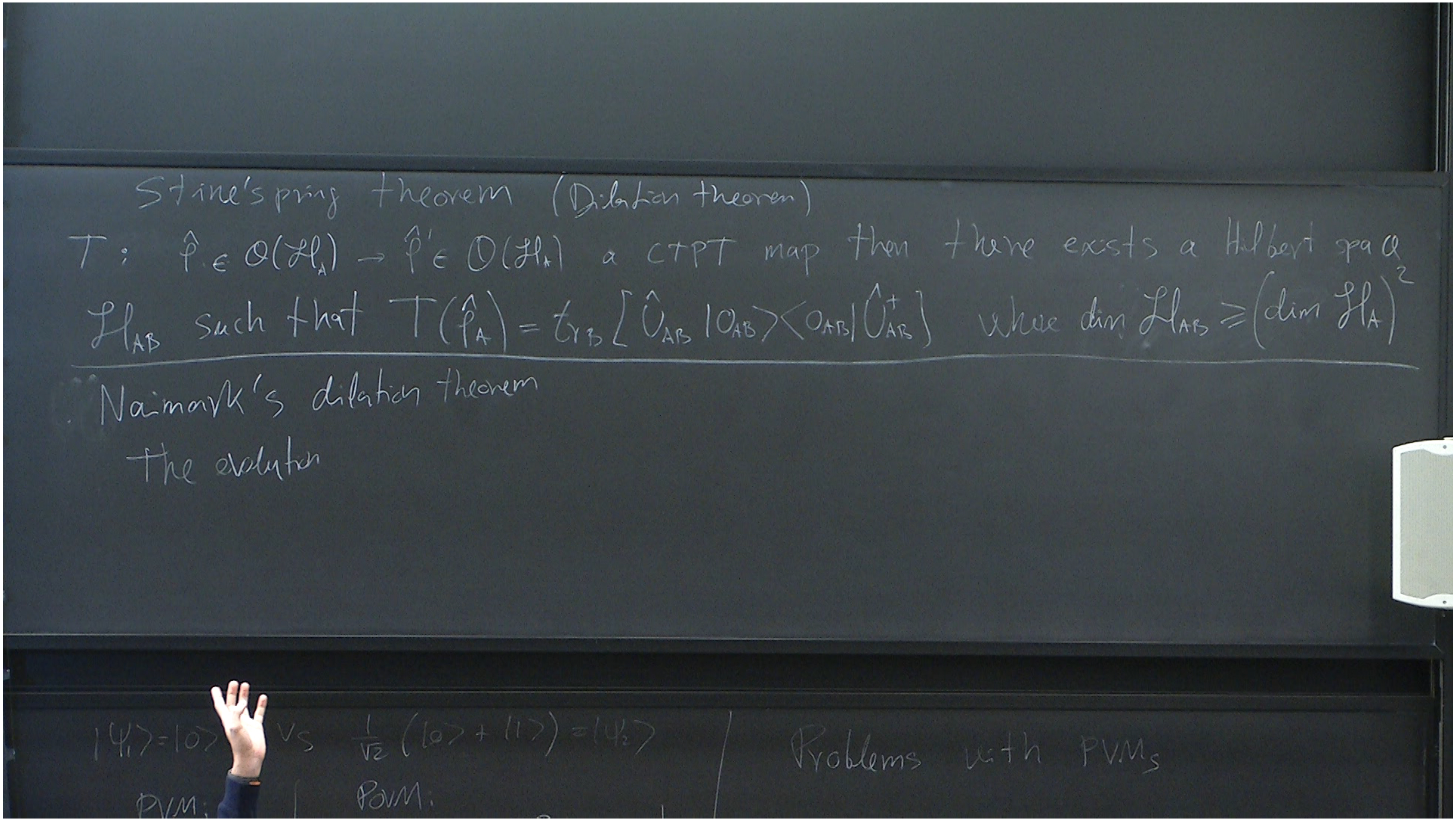
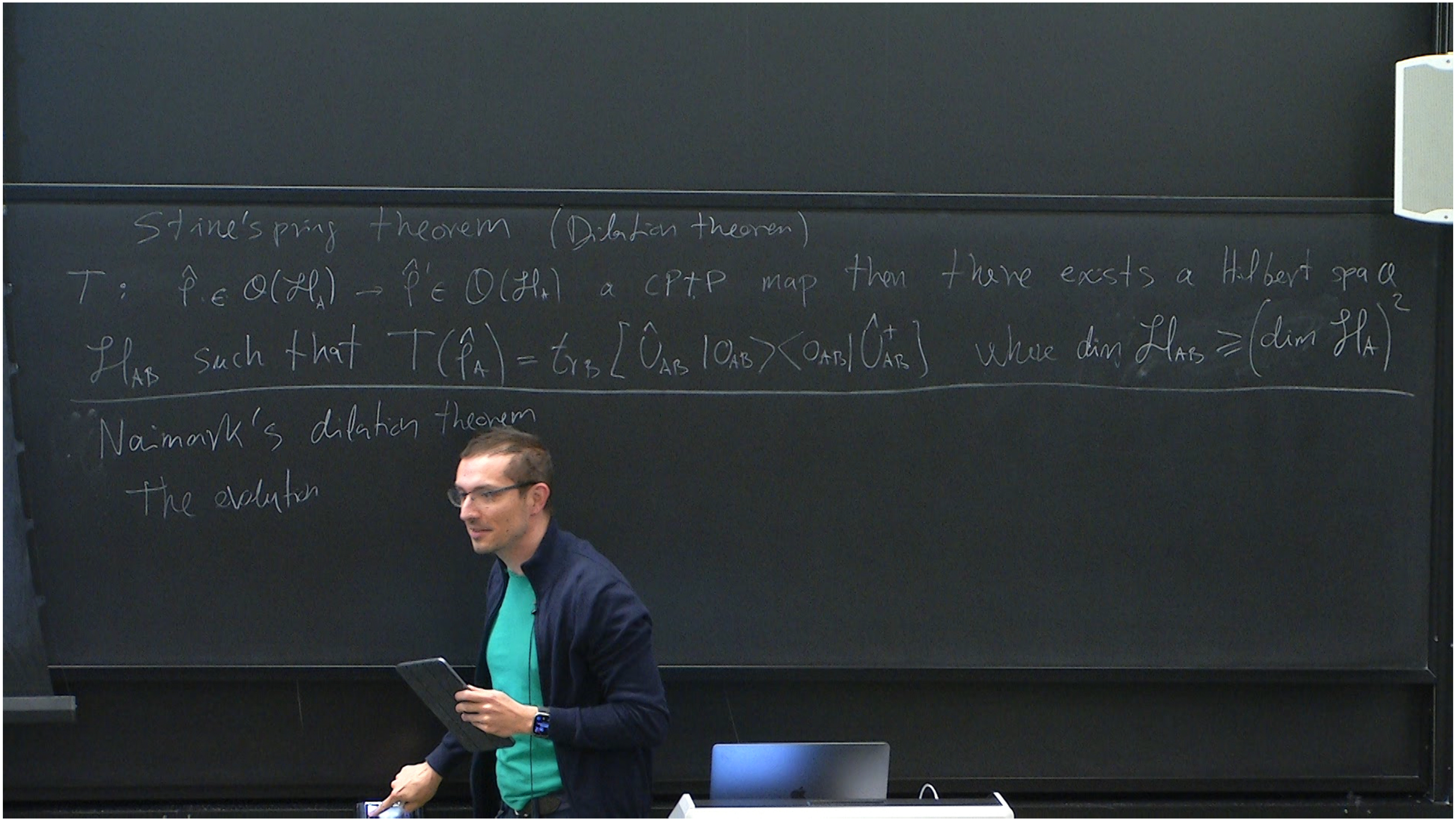
Problems with PVMs


Stinespring theorem (Dilation theorem)
$T: \hat{\rho} \in \mathcal{O}(\mathcal{H}_A) \to \hat{\rho}' \in \mathcal{O}(\mathcal{H}_A)$ a CTPT map then there exists a Hilbert space
$\mathcal{H}_{AB}$ such that $T(\hat{\rho}_A) = tr_B[\hat{U}_{AB} |0_{AB}\rangle\langle 0_{AB}| \hat{U}^{\dagger}_{AB}]$ where $\dim \mathcal{H}_{AB} \geq (\dim \mathcal{H}_A)^2$
Naimark's dilation theorem
The evolution
$|\psi_1\rangle = |0\rangle$ vs $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) = |\psi_2\rangle$
PVM:
POVM:
Problems with PVMs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Naimark's dilation theorem
the evolution

3.5 An application of entanglement: Quantum Teleportation

Entanglement is known to be a resource for quantum computing, cryptography and communication. In particular, we are going to see a protocol of quantum communication known as 'quantum teleportation'. Quantum teleportation is a protocol by which quantum information (e.g. the exact quantum state of an atom, photon, etc) can be transmitted from one location to another, with the help of classical communication and previously shared quantum entanglement between the sending and receiving location. It was first proposed in 1993 by Bennet, Brassard, Crepeau, Jozsa, Peres and Wootters [?], and first experimentally tested in 1997 [?].

Let us analyze the protocol step by step for qubits:

Step 0 - A and B share a Bell pair, for example

$$|\Phi^+\rangle_{A_2B_3} = \frac{1}{\sqrt{2}}\Big[|00\rangle_{A_2B_3} + |11\rangle_{A_2B_3}\Big]. \tag{3.5.1}$$

A and B prepare this bell pair and then B goes away. After that Alice is given a qubit $|\varphi\rangle_{A_1}$ that she wants to send to Bob:

$$|\varphi\rangle_{A_1} = \alpha_0|0\rangle + \alpha_1|1\rangle. \tag{3.5.2}$$

Step 1- Alice will make a joint measurement of her two qubits (the one she wants to teleport, A_1, and her own half of the entangled pair, A_2) in a Bell basis. For that we first write the tripartite system of the three qubits:

$$\begin{aligned}
|\psi\rangle_{A_1A_2B_3} &= |\varphi\rangle_{A_1} \otimes |\Phi^+\rangle_{A_2B_3} \\
&= \Big(\alpha_0|0\rangle_{A_1} + \alpha_1|1\rangle_{A_1}\Big) \otimes \frac{1}{\sqrt{2}}\Big[|00\rangle_{A_2B_3} + |11\rangle_{A_2B_3}\Big] \\
&= \frac{\alpha_0}{\sqrt{2}}\Big(|000\rangle_{A_1A_2B_3} + |011\rangle_{A_1A_2B_3}\Big) + \frac{\alpha_1}{\sqrt{2}}\Big(|100\rangle_{A_1A_2B_3} + |111\rangle_{A_1A_2B_3}\Big).
\end{aligned} \tag{3.5.3}$$

If we factor out explicitly Alice's two qubits we get

$$|\psi\rangle_{A_1A_2B_3} = \frac{\alpha_0}{\sqrt{2}}\Big(|00\rangle_{A_1A_2} \otimes |0\rangle_{B_3} + |01\rangle_{A_1A_2} \otimes |1\rangle_{B_3}\Big)$$

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As mentioned in the previous section, the four Bell pairs form an orthonormal basis of the space of two qubits. We can rewrite Alice's two qubits in the Bell basis, noticing that

$$|00\rangle = \frac{1}{\sqrt{2}}\Big(|\Phi^+\rangle + |\Phi^-\rangle\Big), \qquad |11\rangle = \frac{1}{\sqrt{2}}\Big(|\Phi^+\rangle - |\Phi^-\rangle\Big), \tag{3.5.5}$$

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$$|\Phi^+\rangle_{A_2B_3} = \frac{1}{\sqrt{2}}\Big[|00\rangle_{A_2B_3} + |11\rangle_{A_2B_3}\Big]. \tag{3.5.1}$$

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and use it to rewrite (3.5.4) as

$$
\begin{aligned}
|\psi\rangle_{A_1A_2B_3} = &\frac{1}{2}|\Phi^+\rangle_{A_1A_2}\otimes\Big(\alpha_0|0\rangle_{B_3}+\alpha_1|1\rangle_{B_3}\Big)\\
&+\frac{1}{2}|\Phi^-\rangle_{A_1A_2}\otimes\Big(\alpha_0|0\rangle_{B_3}-\alpha_1|1\rangle_{B_3}\Big)\\
&+\frac{1}{2}|\Psi^+\rangle_{A_1A_2}\otimes\Big(\alpha_0|1\rangle_{B_3}+\alpha_1|0\rangle_{B_3}\Big)\\
&+\frac{1}{2}|\Psi^-\rangle_{A_1A_2}\otimes\Big(\alpha_0|1\rangle_{B_3}-\alpha_1|0\rangle_{B_3}\Big).
\end{aligned}
\tag{3.5.7}
$$

If Alice measures her states in the Bell basis, Bob's states get projected with equal probability to one of the following four states (given in matrix representation):

$$
|\varphi\rangle_{B_3} = \begin{pmatrix}\alpha_0\\ \alpha_1\end{pmatrix}, \begin{pmatrix}\alpha_0\\ -\alpha_1\end{pmatrix}, \begin{pmatrix}\alpha_1\\ \alpha_0\end{pmatrix}, \begin{pmatrix}-\alpha_1\\ \alpha_0\end{pmatrix}. \tag{3.5.8}
$$

They are related with the original qubit that Alice wanted to teleport $|\varphi\rangle_{A_1}$ by simple local operations.

Step 3- Alice announces the result of her measurement to Bob through a classical channel (2 classical bits). With the obtained information, Bob can recover, through local unitary operations, the quantum state that Alice wanted to teleport. In particular

Local

$$|\varphi\rangle_{B_3} = \begin{pmatrix} \alpha_0 \\ \alpha_1 \end{pmatrix}, \begin{pmatrix} \alpha_0 \\ -\alpha_1 \end{pmatrix}, \begin{pmatrix} \alpha_1 \\ \alpha_0 \end{pmatrix}, \begin{pmatrix} -\alpha_1 \\ \alpha_0 \end{pmatrix}. \quad (3.5.8)$$

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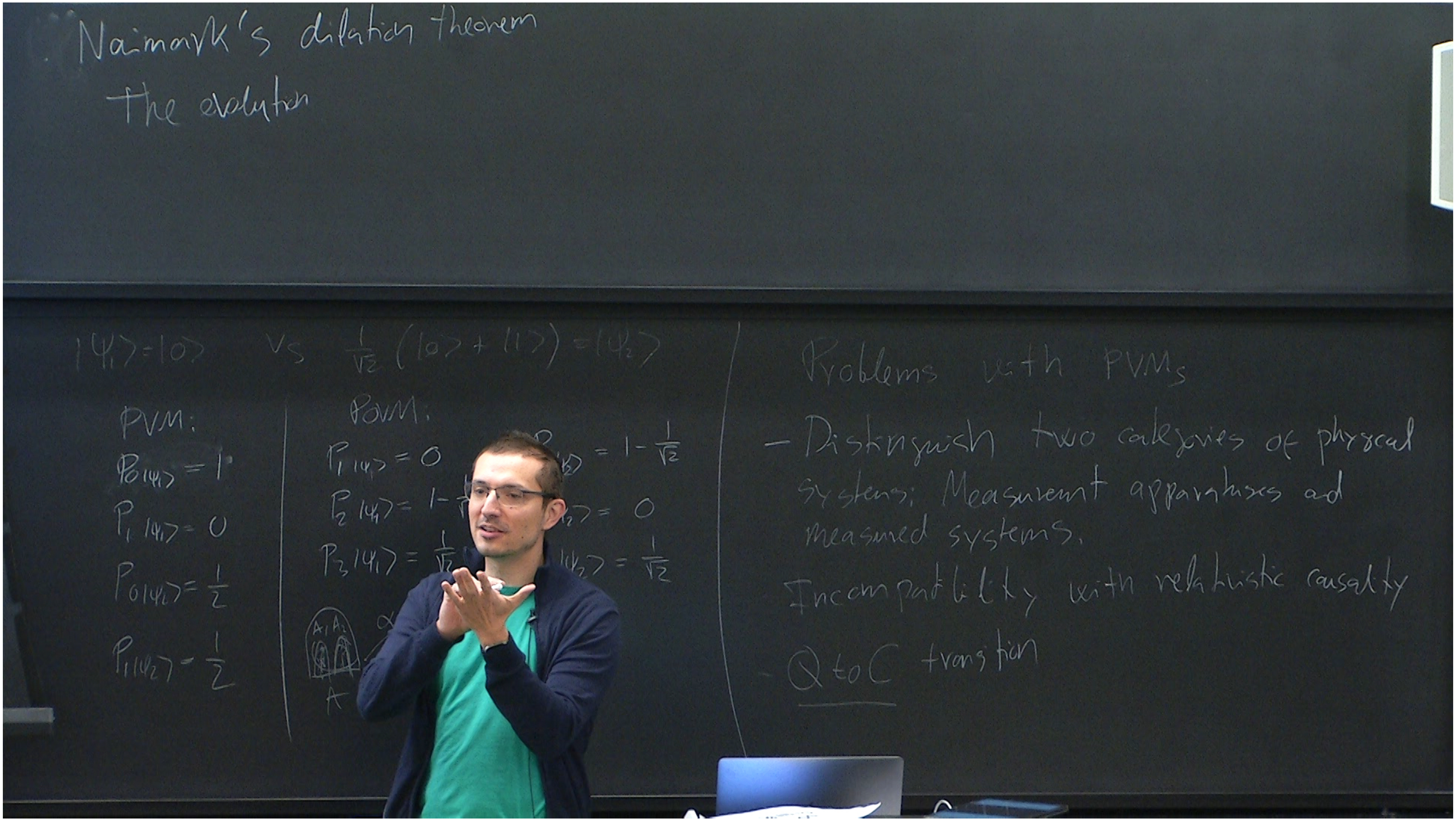
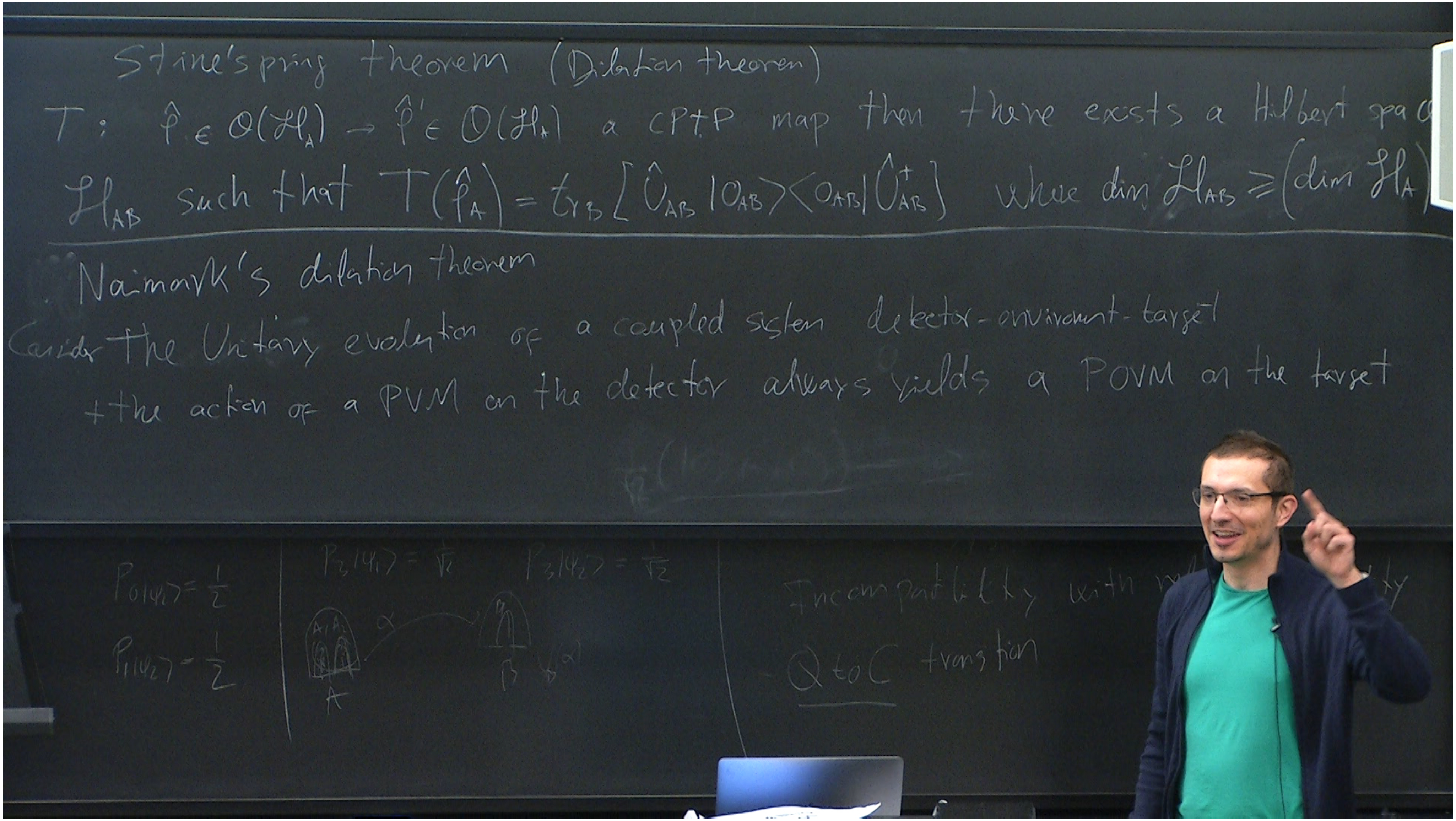
A measured	B has	B does	Local operation used
$\lvert\Phi^+\rangle$	$\lvert\varphi\rangle_{B_3} = \begin{pmatrix} \alpha_0 \\ \alpha_1 \end{pmatrix}$	$\lvert\varphi'\rangle_{B_3} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} \alpha_0 \\ \alpha_1 \end{pmatrix} = \begin{pmatrix} \alpha_0 \\ \alpha_1 \end{pmatrix} = \lvert\varphi\rangle_{A_1}$	$\mathbb{1}$
$\lvert\Phi^-\rangle$	$\lvert\varphi\rangle_{B_3} = \begin{pmatrix} \alpha_0 \\ -\alpha_1 \end{pmatrix}$	$\lvert\varphi'\rangle_{B_3} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} \alpha_0 \\ -\alpha_1 \end{pmatrix} = \begin{pmatrix} \alpha_0 \\ \alpha_1 \end{pmatrix} = \lvert\varphi\rangle_{A_1}$	σ_z
$\lvert\Psi^+\rangle$	$\lvert\varphi\rangle_{B_3} = \begin{pmatrix} \alpha_1 \\ \alpha_0 \end{pmatrix}$	$\lvert\varphi'\rangle_{B_3} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} \alpha_1 \\ \alpha_0 \end{pmatrix} = \begin{pmatrix} \alpha_0 \\ \alpha_1 \end{pmatrix} = \lvert\varphi\rangle_{A_1}$	σ_x
$\lvert\Psi^-\rangle$	$\lvert\varphi\rangle_{B_3} = \begin{pmatrix} -\alpha_1 \\ \alpha_0 \end{pmatrix}$	$\lvert\varphi'\rangle_{B_3} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}\begin{pmatrix} -\alpha_1 \\ \alpha_0 \end{pmatrix} = \begin{pmatrix} \alpha_0 \\ \alpha_1 \end{pmatrix} = \lvert\varphi\rangle_{A_1}$	$i\sigma_y$

At the end of the protocol, Bob ends up with a state which is identical to the state of A_1 that Alice initially had. What happened is that the subsystem B_3 has acquired the state A_1. The Bell state that Alice and Bob shared is destroyed applying this protocol, as it is the state of A_1. Causality is preserved by the fact that Bob needs the information input about the outcome of Alice, or otherwise he is unable to know which operation to perform to recover the original qubit. Also, it is very simple to prove that it is impossible to clone quantum states (for further reference, see the no-cloning theorem [?]), so to teleport one has first to destroy the original.


Naimark's dilation theorem
The evolution
Problems with PVMs
- Distinguish two categories of physical systems: Measurement apparatuses and measured systems.
Incompatibility with relativistic causality
- Q to C transition
PVM:
POVM: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T : ρ̂ ∈ O(H_A) → ρ̂' ∈ O(H_A) a CPTP map then there exists a Hilbert space
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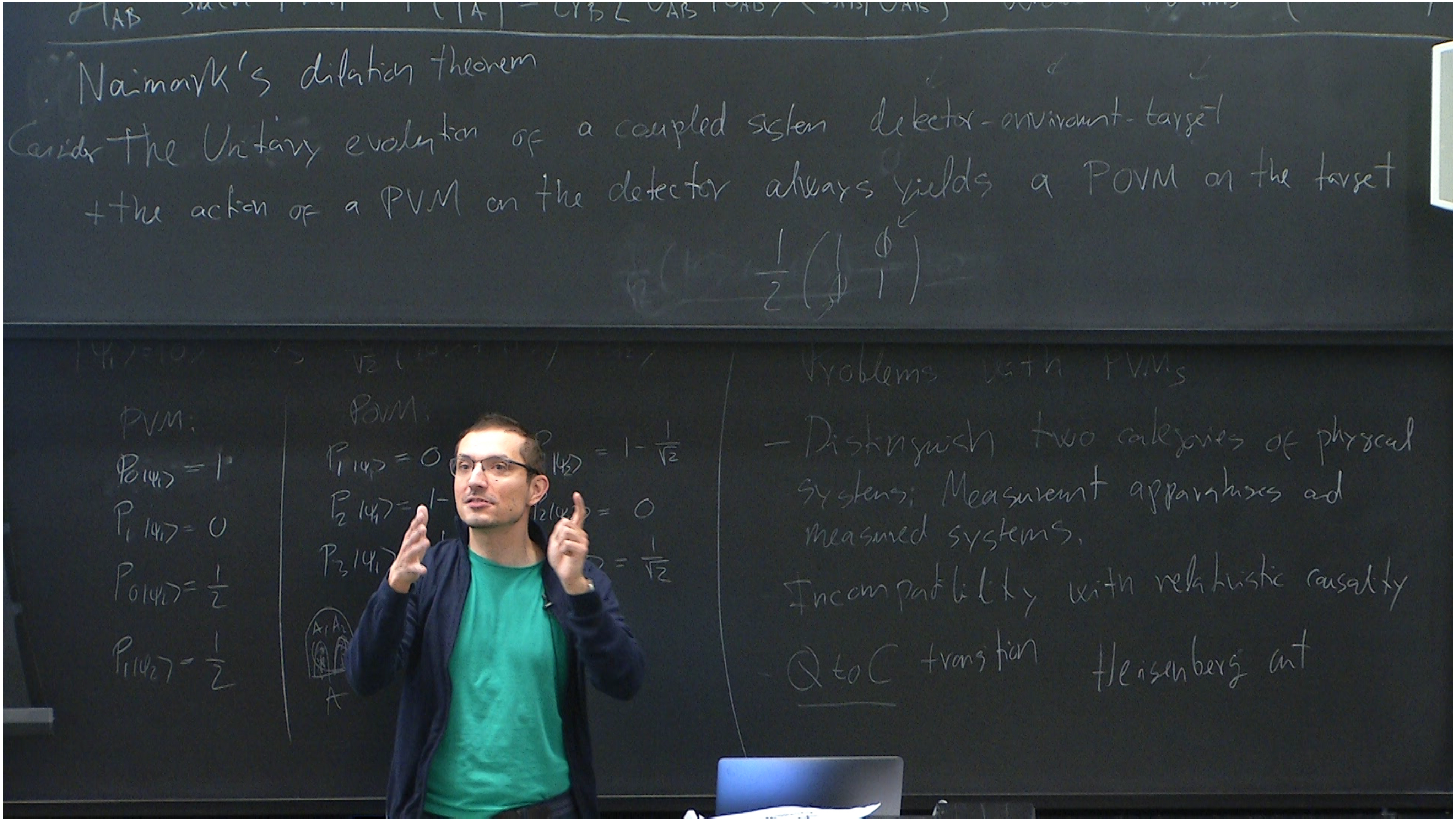
Naimark's dilation theorem
Consider the Unitary evolution of a coupled system detector-environment-target
+ the action of a PVM on the detector always yields a POVM on the target
Q to C transition



Naimark's dilation theorem
Consider the Unitary evolution of a coupled system detector-environment-target
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PVM:
POVM:
Problems with PVMs
- Distinguish two categories of physical systems: Measurement apparatuses and measured systems.
Incompatibility with relativistic causality
Q to C transition
Heisenberg cut

Measurements in Quantum Theory

Still an open problem!

Proposal: At least some Measurements can give values (e.g., 42) that we can write on a notepad

In QM, we model that with idealized measurements

Idealized measurements of non-degenerate observables update states through a rank-1 projector on the spectrum of the measured observables

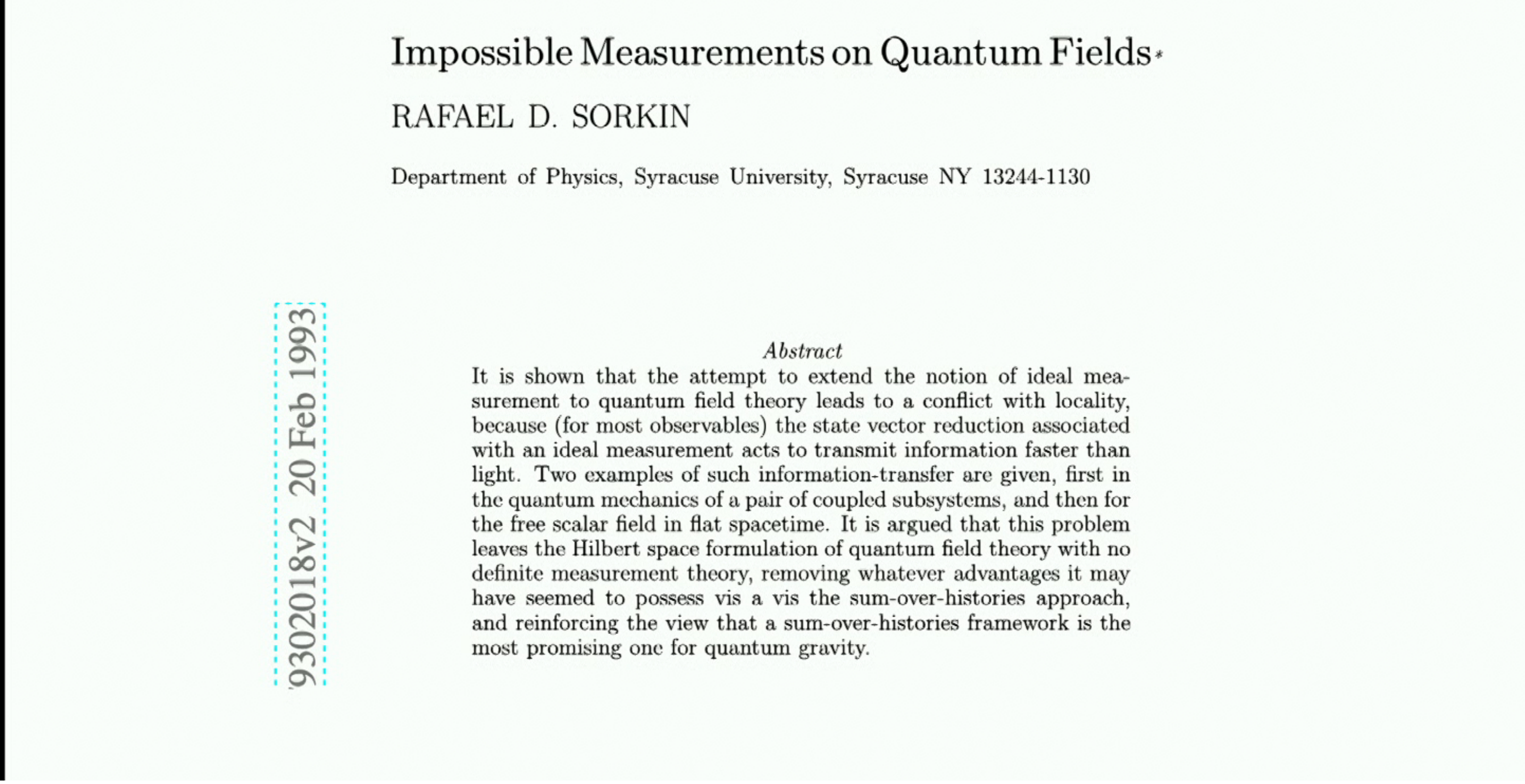
But Quantum to Classical transition? Interpretation?

You could "not care"! And still get rich and famous

No idealized measurements?

Rafael Sorkin (1992):

No idealized measurements in QFT?



Impossible Measurements on Quantum Fields*

RAFAEL D. SORKIN

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

9302018v2 20 Feb 1993

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 the free scalar field in flat spacetime. It is argued that this problem leaves the Hilbert space formulation of quantum field theory with no definite measurement theory, removing whatever advantages it may have seemed to possess vis a vis the sum-over-histories approach, and reinforcing the view that a sum-over-histories framework is the most promising one for quantum gravity.

No idealized measurements?

Rafael Sorkin (1992):

No idealized measurements in QFT?

Argues that idealized measurements are incompatible with causality

Two examples:

Example 1: Two-Qubit system

Consider a state: $|0_A 0_B\rangle$

1-Perform local Unitary on A

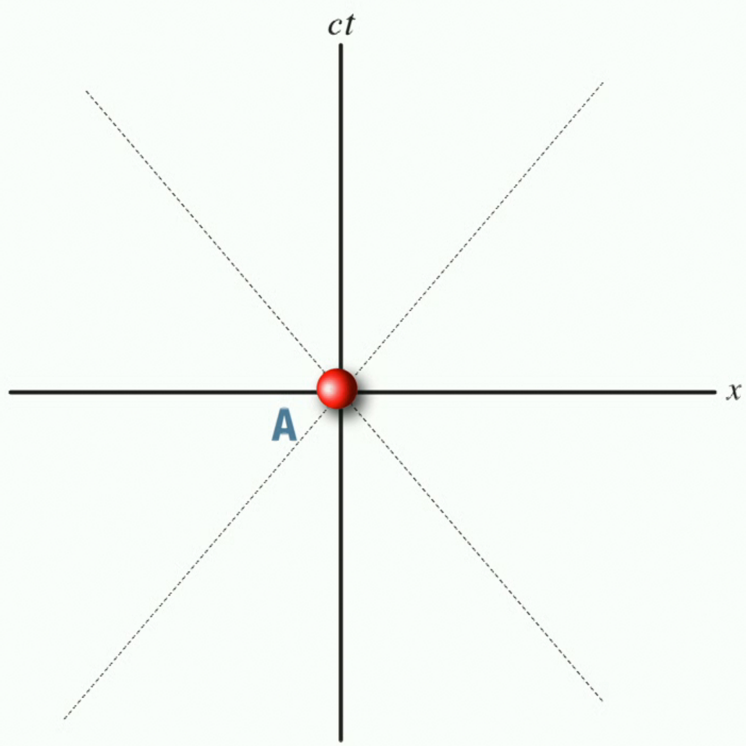
2-Make an idealized Bell measurement projecting on to $\frac{1}{\sqrt{2}}(|0_A 0_B\rangle + |1_A 1_B\rangle)$

3-Expectation of observable on B gains information about the unitary on A

Surprised?

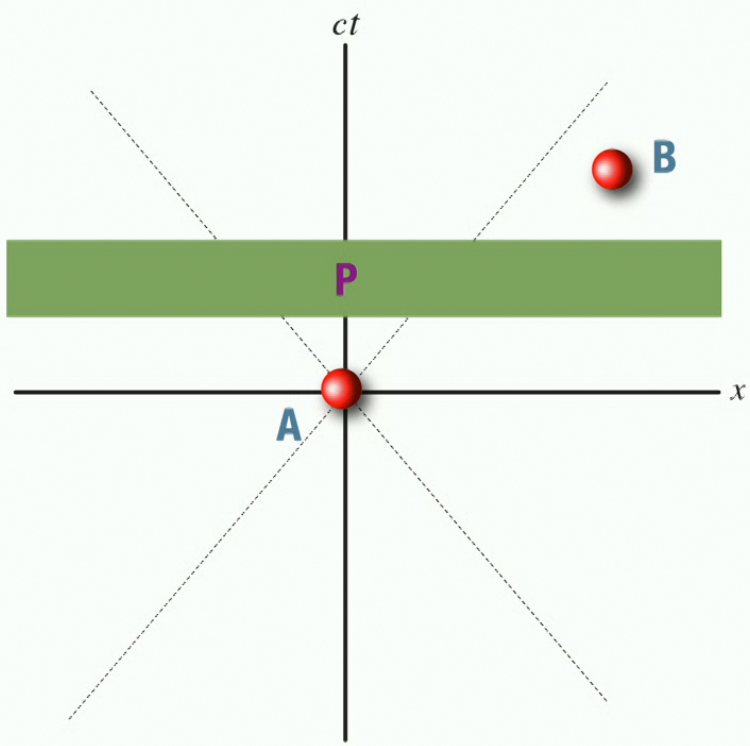
No idealized measurements?

1-Perform local Unitary on a field observable localized around A



No idealized measurements?

3-Expectation of local observables on B gains information about the unitary on A



So what's the plan?

People kept using such idealized measurements (actively and by assumption)

People in RQI followed two paths:

Particle detectors

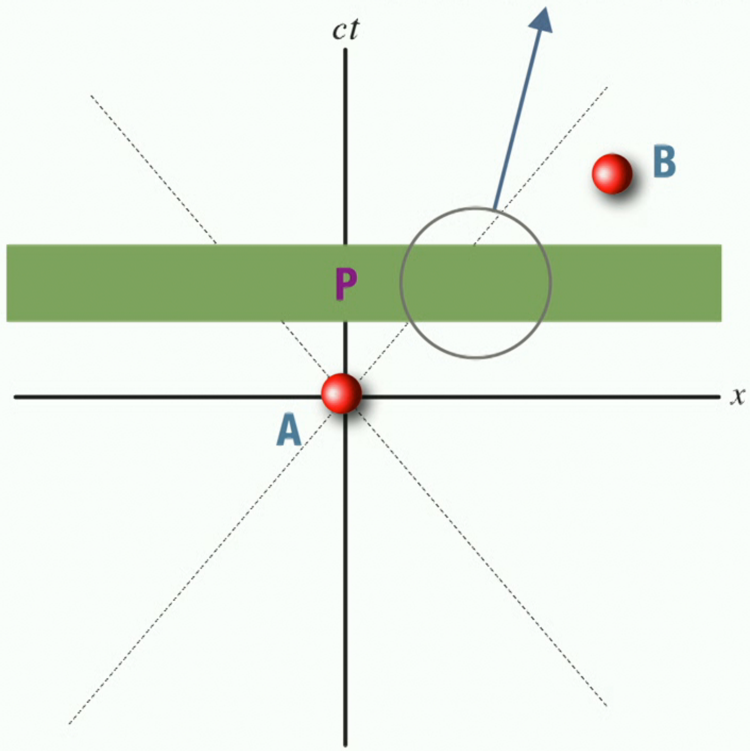
More on this later!

Localized idealized measurements

Is this okay?

Localized idealized measurements

This seems to be the problem!

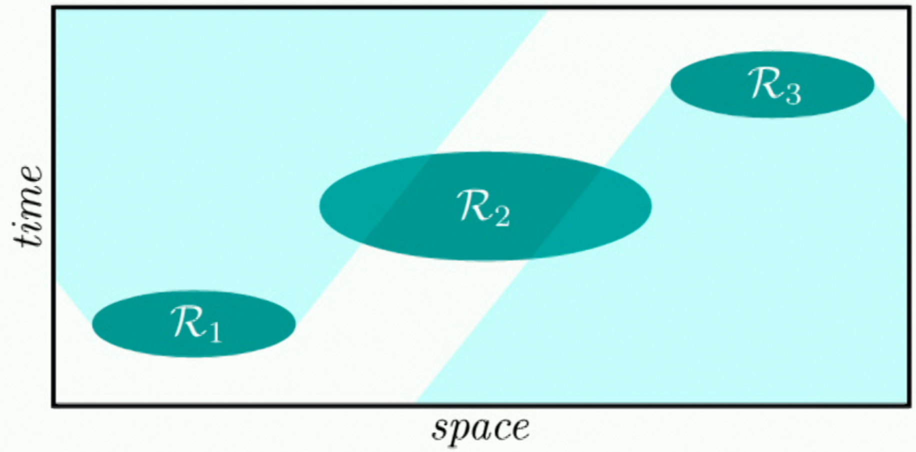


A naive read of Sorkin's paper may suggest so....

Localized idealized measurements

Impossible measurements revisited

L. Borsten,* I. Jubb,† and G. Kells‡
School of Theoretical Physics, Dublin Institute for Advanced Studies, 10 Burlington Road, Dublin 4, Ireland
(Dated: December 16, 2019)



Localized idealized measurements?

Foundations of Physics, Vol. 25, No. 1, 1995

More Ado about Nothing

Michael Redhead[1]

Received February 9, 1994

In this paper questions about vacuum fluctuations in local measurements, and the correlations between such fluctuations, are discussed. It is shown that maximal correlations always exist between suitably chosen local projection operators associated with spacelike separated regions of space-time, however far apart these regions may be. The connection of this result with the well-known Fregenhagen bound showing exponential decay of correlations with distance is explained, and the relevance of the discussion to the question "What do particle detectors detect?" is addressed.

Localized idealized measurements?

Foundations of Physics, Vol. 25, No. 1, 1995

Theorem 1. If $P \in R(O)$, then P is an infinite-dimensional projector.

Proof. This follows directly from the result of Driessler[7] which states that the quasi-local algebra associated with an unbounded wedge of space-time is a type III factor. Now any bounded region is internal to some wedge, so by isotony $R(O)$ is a subalgebra of some wedge algebra. So the projectors in $R(O)$ are identified with some of the projectors in the wedge algebra. But in a type III factor *all* the projectors are infinite-dimensional. So all the projectors in $R(O)$ are infinite-dimensional.

A PVM over a bounded region of spacetime cannot be finite-rank!

Measurements in Quantum Theory

What do I want from a measurement theory in QFT?

1-Capable of producing definite values

2-Provides an update rule

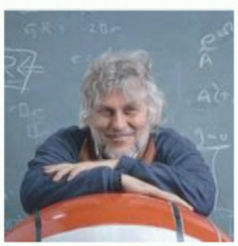
3-Consistent with the theory
(e.g., respect causality in a relativistic theory)

4-Reproduces experiments!!!

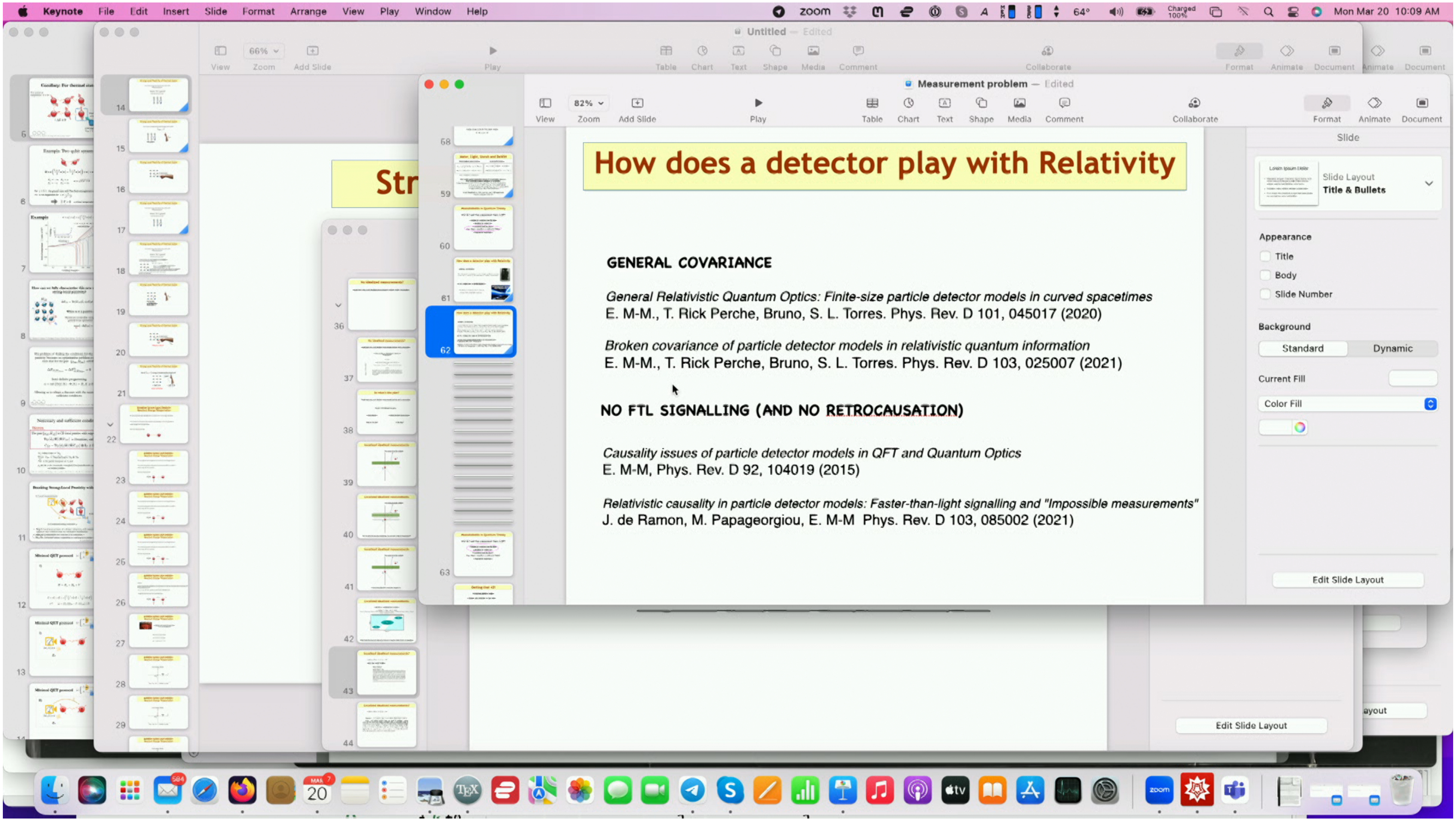
Measuring fields: Particle detectors

How do we measure quantum fields?

Particle detectors: Non-relativistic quantum systems coupling 'locally' to the field



Particles are what particle detectors detect


How does a detector play with Relativity
GENERAL COVARIANCE
General Relativistic Quantum Optics: Finite-size particle detector models in curved spacetimes
E. M-M., T. Rick Perche, Bruno, S. L. Torres. Phys. Rev. D 101, 045017 (2020)
Broken covariance of particle detector models in relativistic quantum information
E. M-M., T. Rick Perche, Bruno, S. L. Torres. Phys. Rev. D 103, 025007 (2021)
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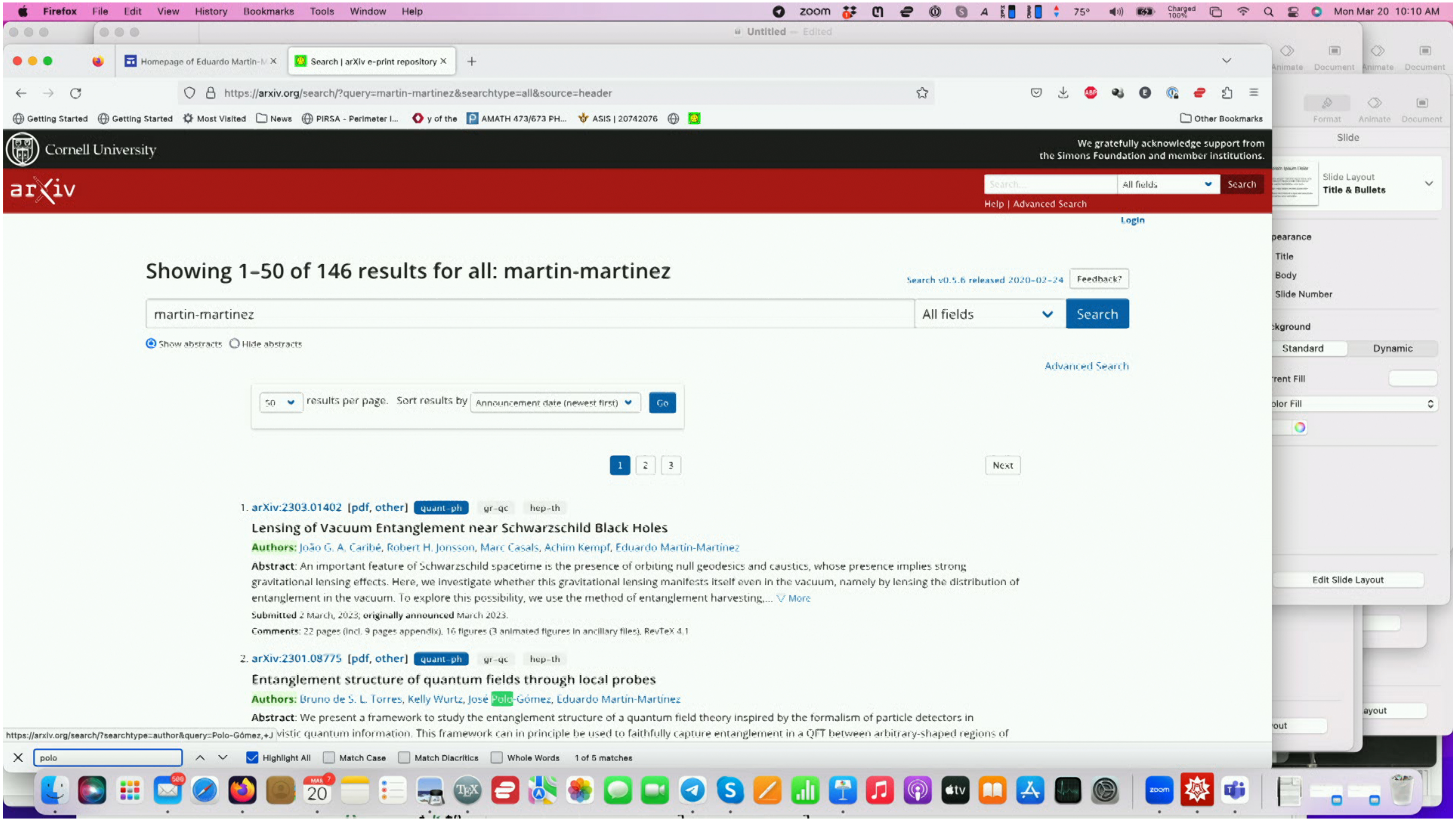

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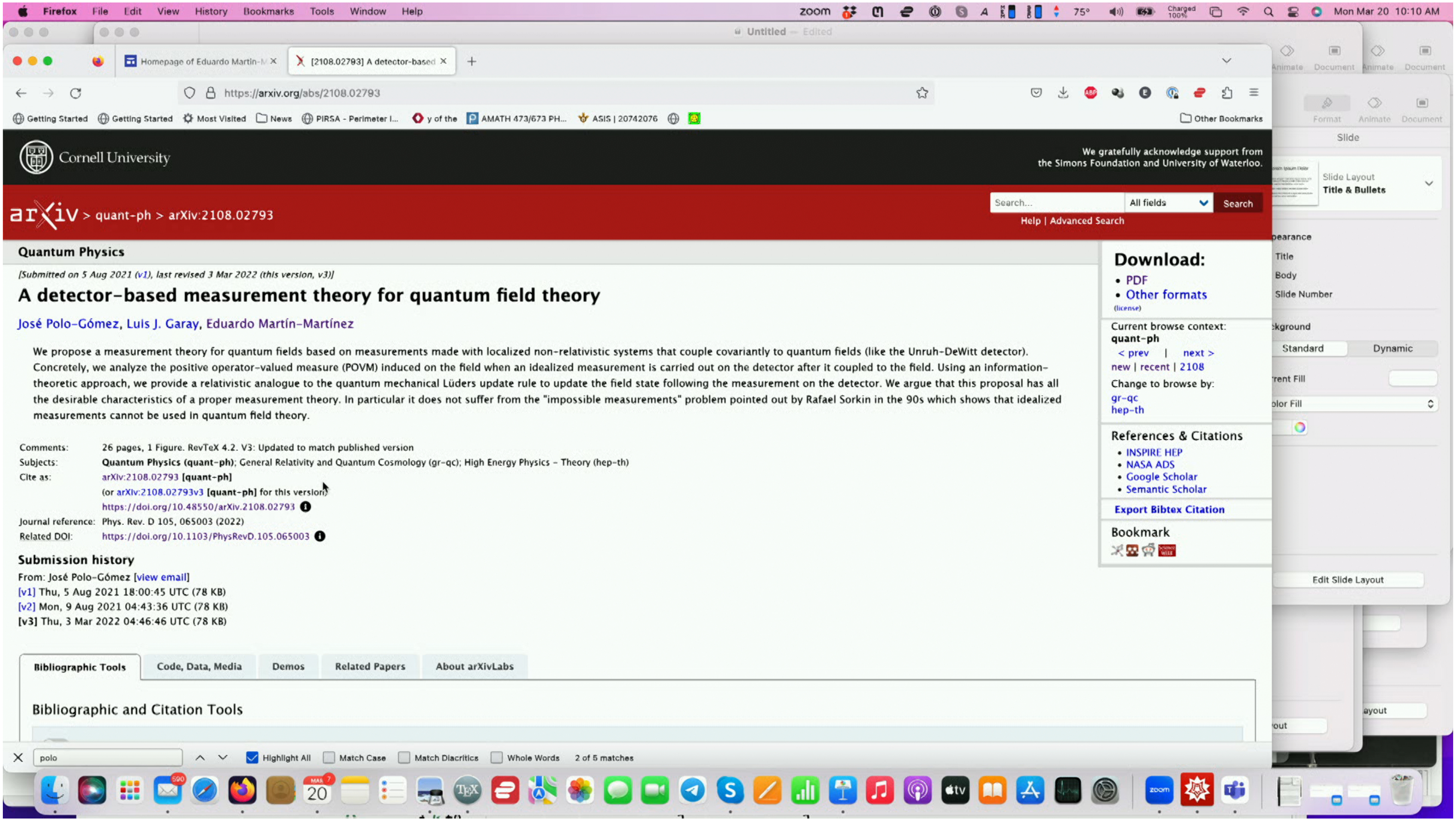
1. arXiv:2303.01402 [pdf, other] quant-ph gr-qc hep-th
Lensing of Vacuum Entanglement near Schwarzschild Black Holes
Authors: João G. A. Caribé, Robert H. Jonsson, Marc Casals, Achim Kempf, Eduardo Martin-Martinez
Abstract: An important feature of Schwarzschild spacetime is the presence of orbiting null geodesics and caustics, whose presence implies strong gravitational lensing effects. Here, we investigate whether this gravitational lensing manifests itself even in the vacuum, namely by lensing the distribution of entanglement in the vacuum. To explore this possibility, we use the method of entanglement harvesting,... More
Submitted 2 March, 2023; originally announced March 2023.
Comments: 22 pages (incl. 9 pages appendix), 16 figures (3 animated figures in ancillary files), RevTeX 4.1
2. arXiv:2301.08775 [pdf, other] quant-ph gr-qc hep-th
Entanglement structure of quantum fields through local probes
Authors: Bruno de S. L. Torres, Kelly Wurtz, José Polo-Gómez, Eduardo Martin-Martinez
Abstract: We present a framework to study the entanglement structure of a quantum field theory inspired by the formalism of particle detectors in ...vistic quantum information. This framework can in principle be used to faithfully capture entanglement in a QFT between arbitrarily-shaped regions of



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We gratefully acknowledge support from the Simons Foundation and University of Waterloo.

arXiv > quant-ph > arXiv:2108.02793

Quantum Physics

[Submitted on 5 Aug 2021 (v1), last revised 3 Mar 2022 (this version, v3)]

A detector-based measurement theory for quantum field theory

José Polo-Gómez, Luis J. Garay, Eduardo Martín-Martínez

We propose a measurement theory for quantum fields based on measurements made with localized non-relativistic systems that couple covariantly to quantum fields (like the Unruh-DeWitt detector). Concretely, we analyze the positive operator-valued measure (POVM) induced on the field when an idealized measurement is carried out on the detector after it coupled to the field. Using an information-theoretic approach, we provide a relativistic analogue to the quantum mechanical Lüders update rule to update the field state following the measurement on the detector. We argue that this proposal has all the desirable characteristics of a proper measurement theory. In particular it does not suffer from the "impossible measurements" problem pointed out by Rafael Sorkin in the 90s which shows that idealized measurements cannot be used in quantum field theory.

Comments: 26 pages, 1 Figure. RevTeX 4.2. V3: Updated to match published version
Subjects: **Quantum Physics (quant-ph)**; General Relativity and Quantum Cosmology (gr-qc); High Energy Physics - Theory (hep-th)
Cite as: arXiv:2108.02793 **[quant-ph]**
(or arXiv:2108.02793v3 **[quant-ph]** for this version)
https://doi.org/10.48550/arXiv.2108.02793
Journal reference: Phys. Rev. D 105, 065003 (2022)
Related DOI: https://doi.org/10.1103/PhysRevD.105.065003

Submission history

From: José Polo-Gómez [view email]
[v1] Thu, 5 Aug 2021 18:00:45 UTC (78 KB)
[v2] Mon, 9 Aug 2021 04:43:36 UTC (78 KB)
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