Title: PSI 2019/2020 - Relativistic Quantum Information Part 1 - Lecture 1

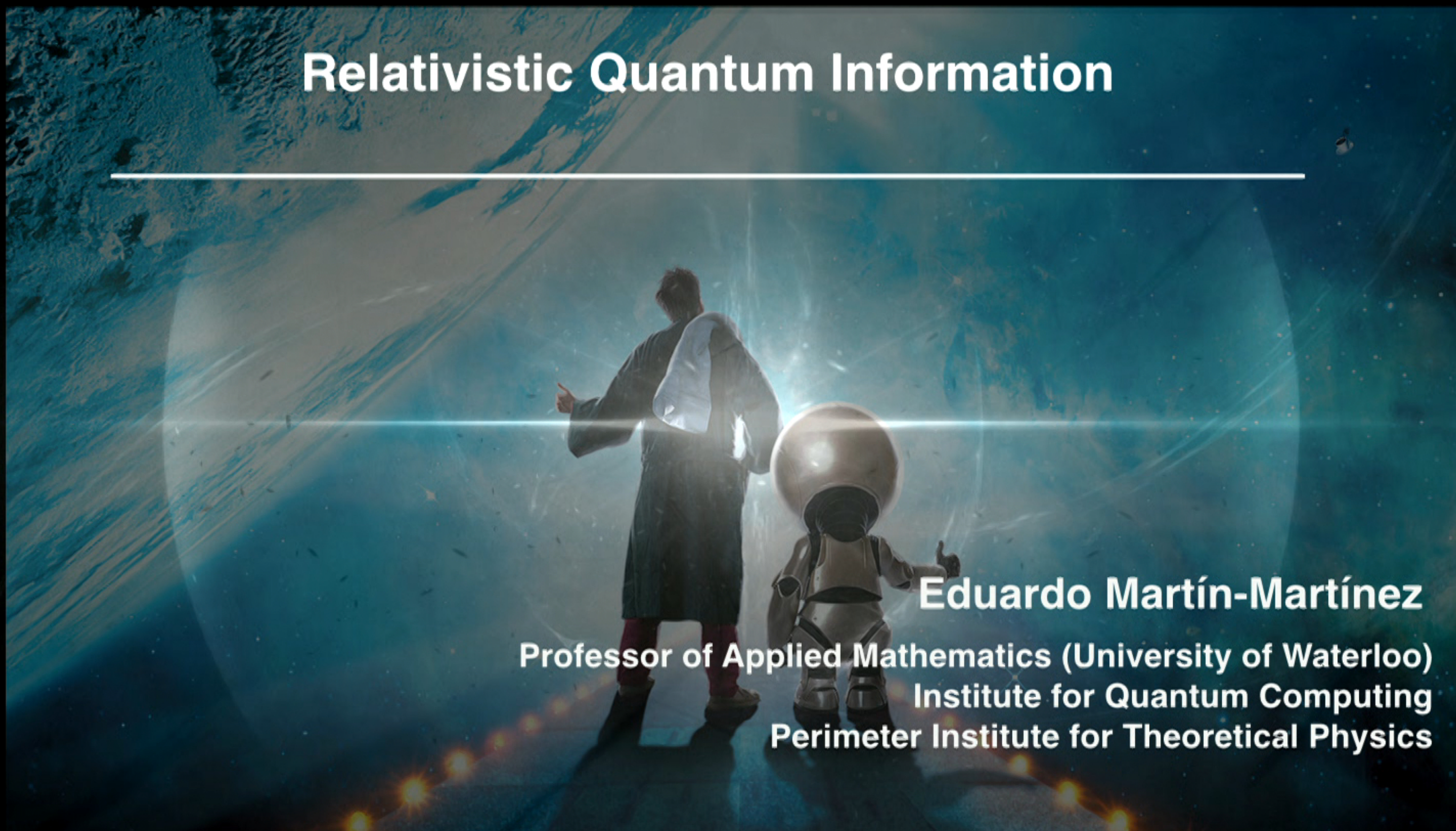
Speakers: Eduardo Martin-Martinez

Collection: PSI 2019/2020 - Relativistic Quantum Information Part 1

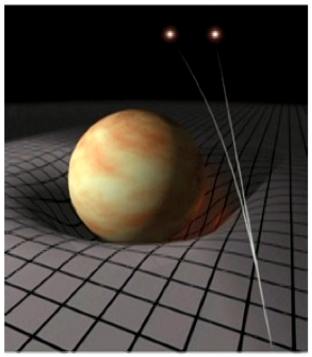
Date: March 02, 2020 - 9:00 AM

URL: http://pirsa.org/20030043

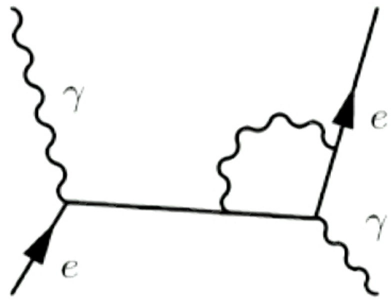
PSI - Exploration Course



Relativistic Quantum Information



General relativity

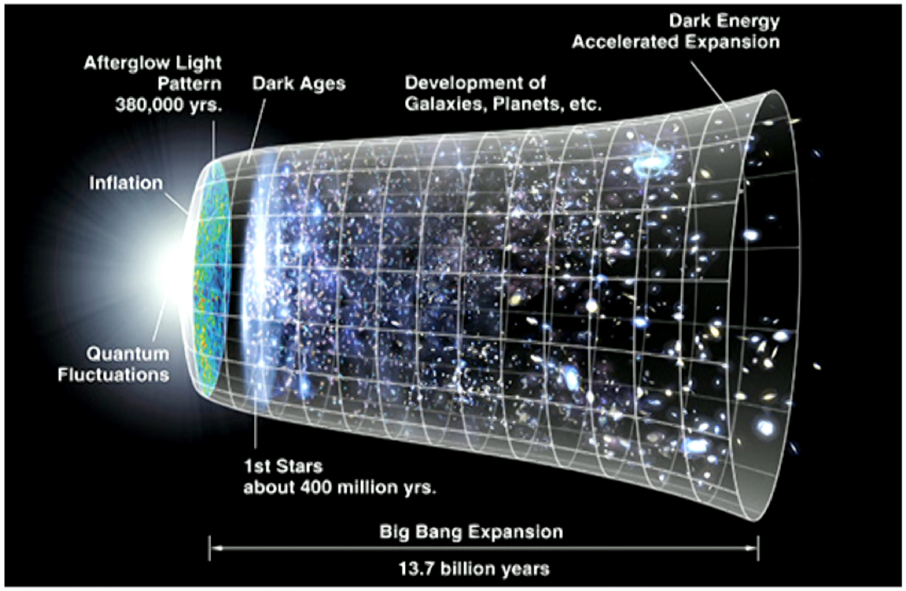


Quantum field theory

Quantum information

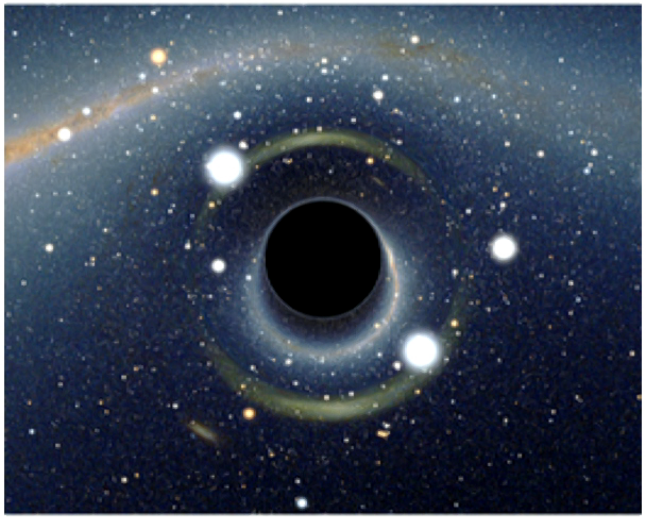
- Harness relativistic approaches to "do more" in quantum information processing.
- Study the structure of spacetime and the quantum nature of gravity via quantum informational tools

Fundamental Topics: Cosmology



How much can we learn about the Early Universe nowadays?

Fundamental Topics: Black Hole Information Loss Problem

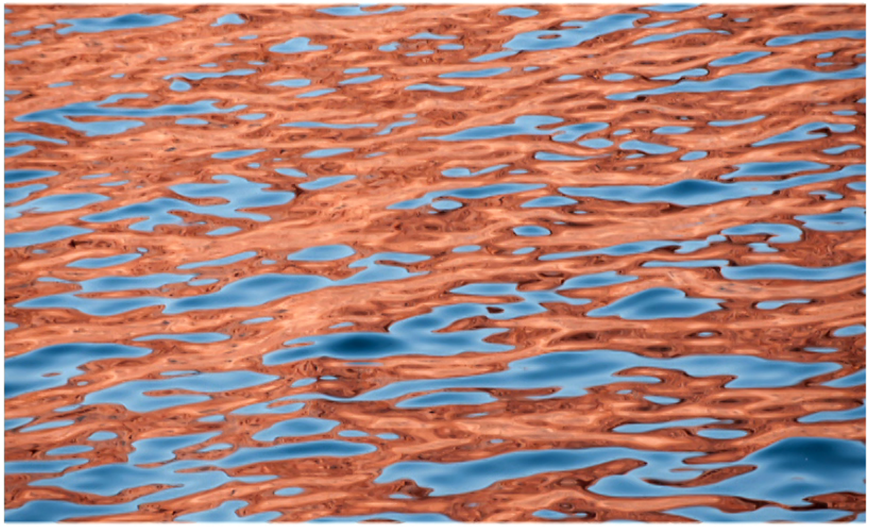


Quantum Mechanics preserves information.

Black Holes: Does Nature destroy information?

Or does the information escape in the form of Hawking Radiation?

Fundamental Topics: Vacuum Fluctuations

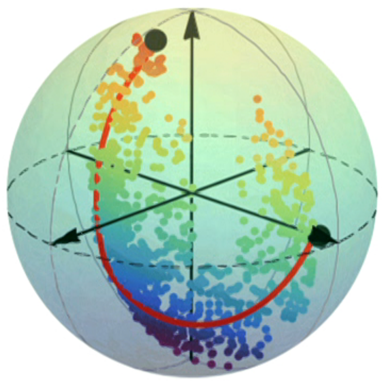


In Nature, the vacuum is not empty. Only on average.

Vacuum Fluctuations contain Information about curvature of spacetime.

Quantum noise is special: It can assist communication!

Fundamental Topics: Quantum Measurements and Localization



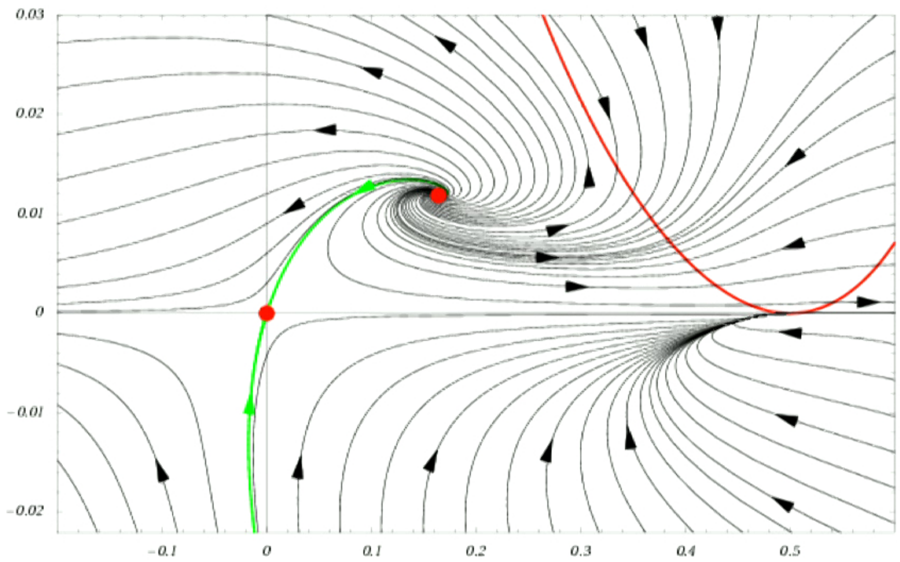
Quantum Theory is a probabilistic theory.

The measurement problem in QFT.

Quantum-to-Classical transition.

Relativistic considerations in the localization of Information

Fundamental Topics: Thermodynamics in QFT



The problem of equilibration in Quantum Theory and in Gravity.

Quantum Thermodynamics.

Fundamental Topics: Quantum Gravity

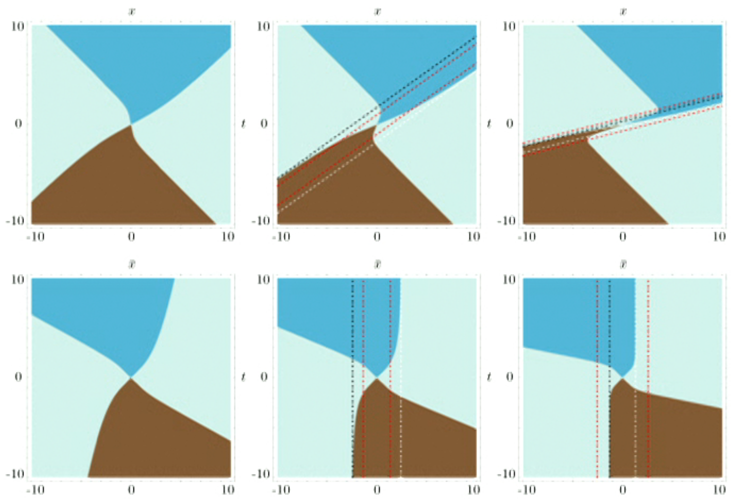
One of the most important challenges of modern Mathematical Physics:

Quantum Theory for Gravitation

Fundamental Topics: "Spacetime Engineering"

Consequences of Violation of energy conditions:

-Warp drives?
-Wormholes?



Applications

Development of Mathematical tools that can be applied to experiments and technologies:

-Quantum Entanglement and Quantum Resources

-Communication

-Metrology

-Quantum Control and Simulations

Getting Familiar with Spacetime

Relativity Matters for Quantum Information

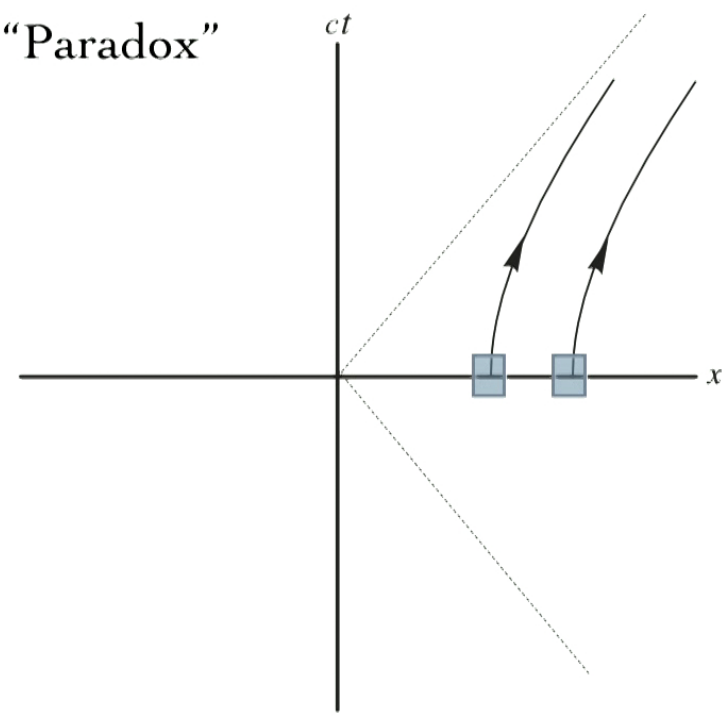
Same Physics, Different Descriptions

Bell Rocket "Paradox"

Does the rope break or not?? Why??

Same Physics, Different Descriptions

Bell Rocket "Paradox"

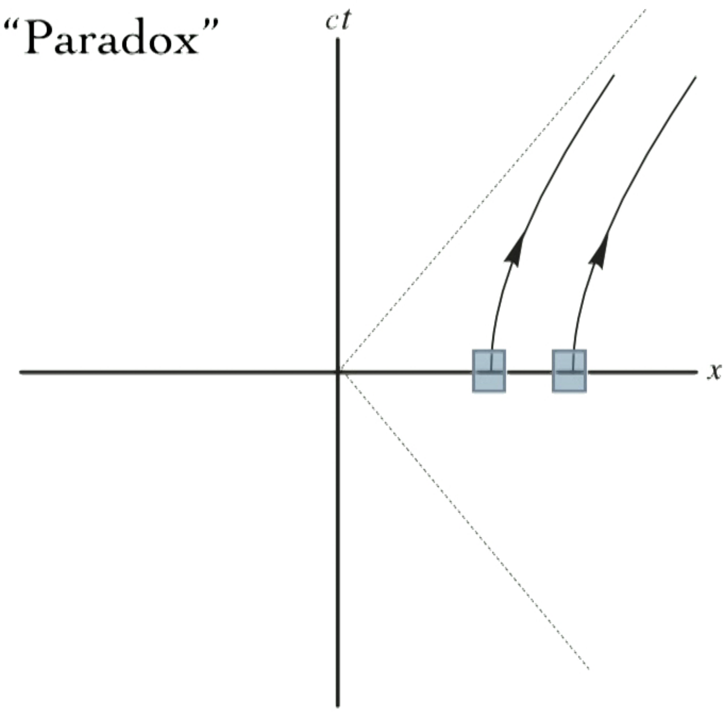


Does the rope break or not??

Why??

Same Physics, Different Descriptions

Bell Rocket "Paradox"

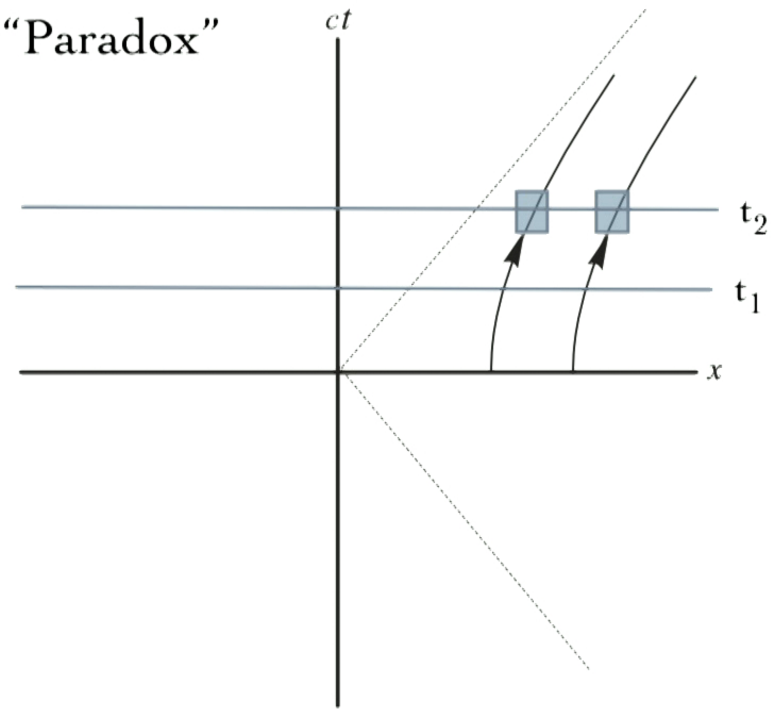


Does the rope break or not??

Why??

Same Physics, Different Descriptions

Bell Rocket "Paradox"



Does the rope break or not??

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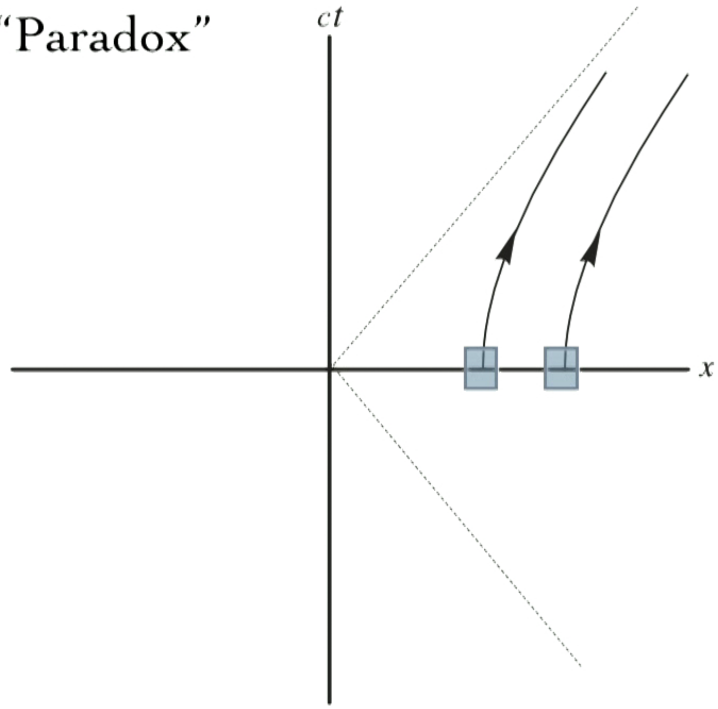
Bell Rocket "Paradox"

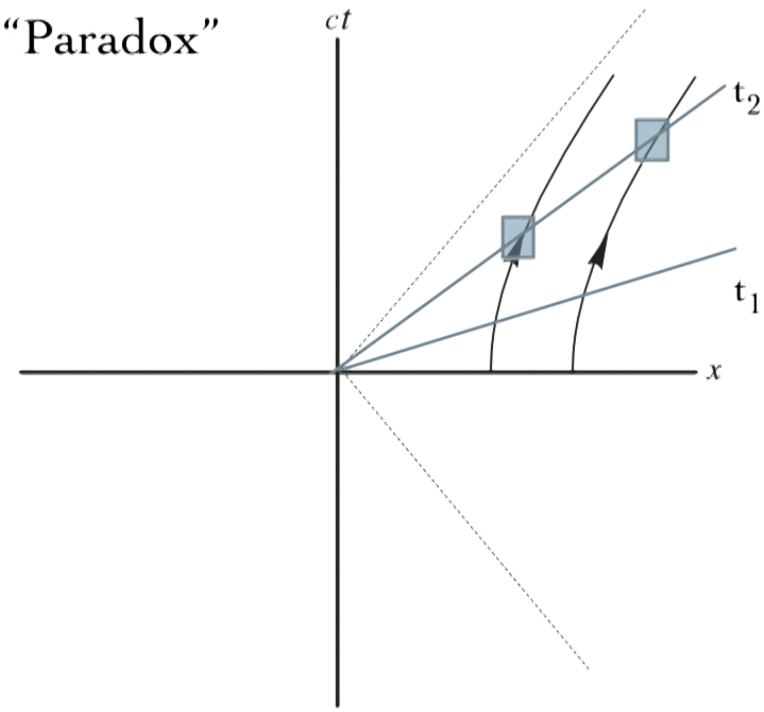


Does the rope break or not??

Why??

Same Physics, Different Descriptions

Bell Rocket "Paradox"



Does the rope break or not??

Why??

Same Physics, Different Descriptions

PHYSICS:

The rope breaks, all right!

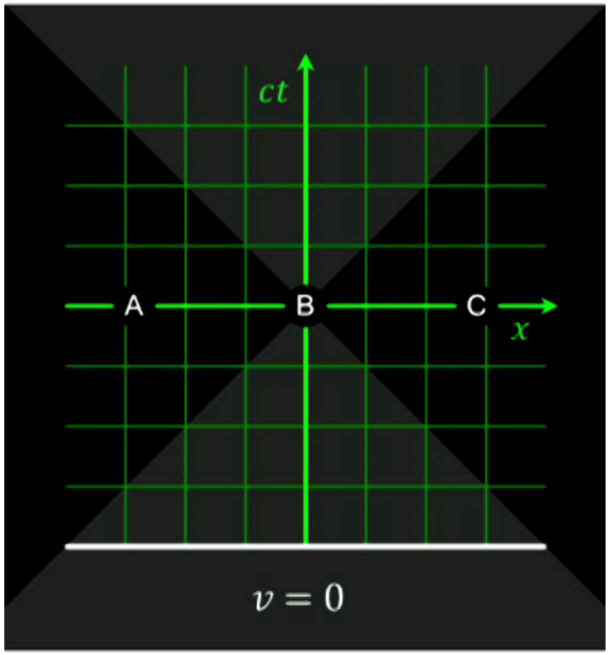
PHENOMENOLOGY:

For the accelerated observer A: Because rocket B is faster than us!

For the observer on the ground: Because both rockets go equally faster and faster, the length of the rope Lorentz-contracts!

Getting Familiar with Spacetime

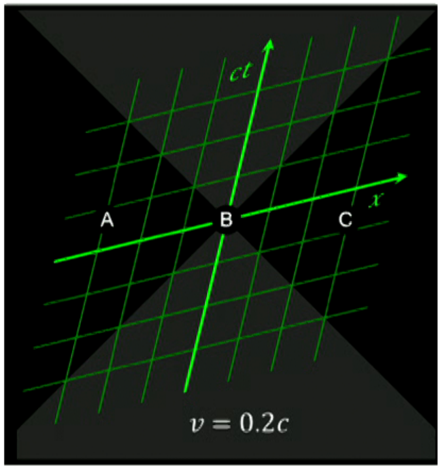
Simultaneity is Relative!



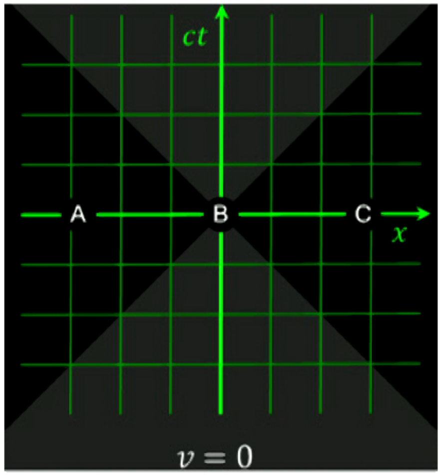
Two observers in different states of motion would not agree about what happens first

Getting Familiar with Spacetime

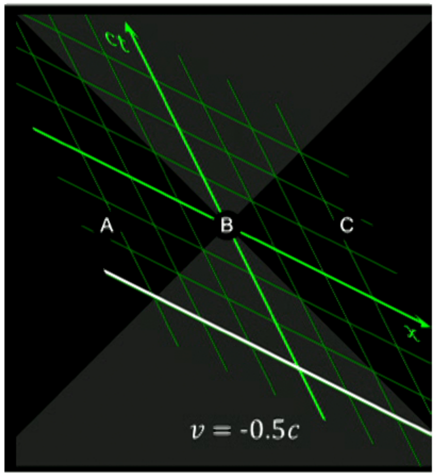
Simultaneity is Relative!



A happens after C



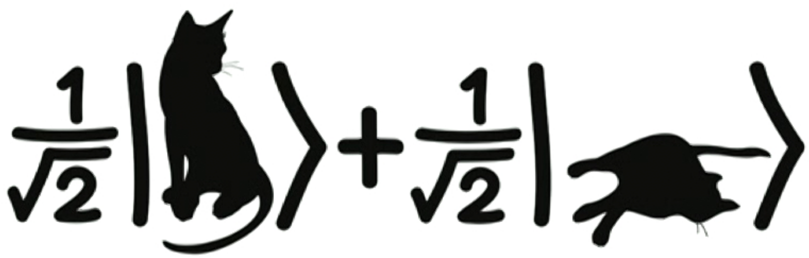
A and C are simultaneous



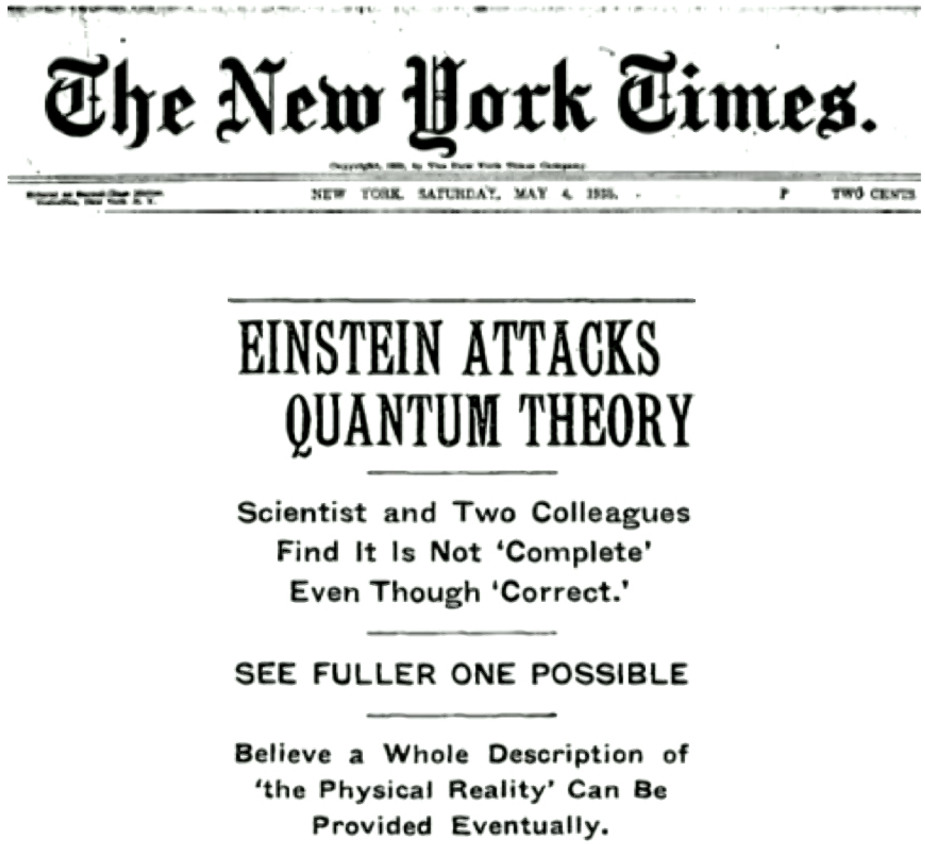
A happens before C

Getting Familiar with Quantum Mechanics

Schrödinger's cat



Quantum Entanglement



The New York Times.

NEW YORK, SATURDAY, MAY 4, 1935. TWO CENTS

EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.

Quantum Entanglement Vs Classical Correlations

Quantum Entanglement Vs Classical Correlations

I pick one ball at random… It's white!

I know the one inside is black!

Quantum Entanglement Vs Classical Correlations

Quantum Entanglement Vs Classical Correlations

I pick one set of dice at random…
I throw it and it gives 10!

Classically: I don't know anything about what would be the result of throwing the other set

Quantum Entanglement

What if the dice are in an entangled state?

Alice: I pick one set of dice at random…
I roll it and it gives 8!

I know what Bob's roll is going to be! (or was)

What entanglement is not

POPULAR SCIENCE SUBSCRIBE

The Race To Prove 'Spooky' Quantum Connection May Have a Winner

Entanglement breakthrough could lead to unhackable Internet

By **Devin Powell** August 29, 2015

Particles don't obey the same rules as people. Poke a particle, and another one far away can instantly respond the touch -- without any messages passing through the space between, as if the two particles were one. "Entanglement" is what quantum physics calls the intimate connection.

Einstein called it "spooky." To his dying day, he refused to believe that nature could be so unreasonable.

From http://www.popsci.com

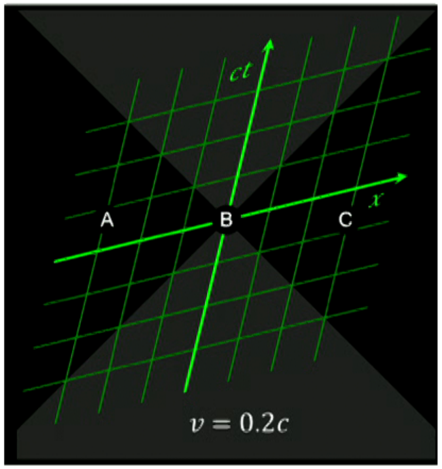
Quantum Entanglement

Alice: I pick one set of dice at random…
I roll it and it gives 8!

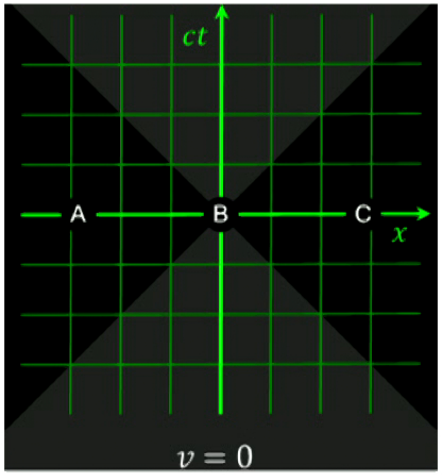
But Remember Einstein!

Getting Familiar with Spacetime

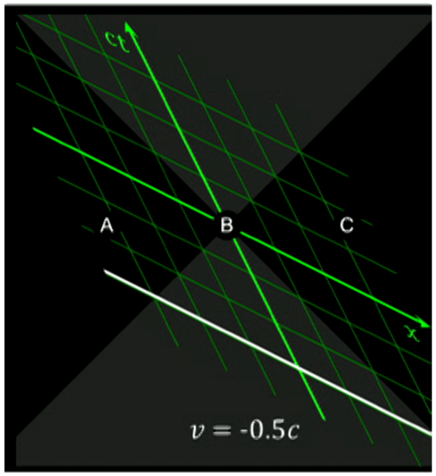
Simultaneity is Relative!
Who collapses what??
Who pokes what??



A happens after C

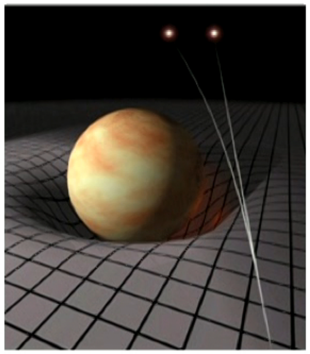


A and C are simultaneous

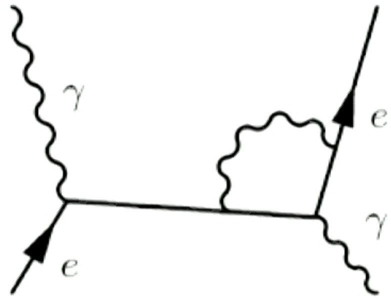


A happens before C

Relativistic Quantum Information



General relativity



Quantum field theory

Quantum information

- Harness relativistic approaches to "do more" in quantum information processing.

Quantum Information and Relativity

Can we take advantage of relativistic effects to do better in Quantum information?

-Quantum information processing.

-Generation of Quantum resources.

-Quantum Communication.

-Quantum non-demolition measurements. Relativistic Quantum Metrology.

-Quantum simulations.

Can we learn something about spacetime using quantum informational approaches?

-The Early Universe and Cosmology

-QFT in curved spacetimes: Unruh and Hawking radiation. Black hole information paradox.

-Quantum correlations and the structure of spacetime.

-Relativistic Quantum Foundations: The Casimir effect, The problem of localization, measurement…

-Quantum Gravity. Causal Structure.

Course Topics

2-Thermality in QFT. The Unruh effect and the Hawking effect: A Quantum Information perspective

-The Unruh effect and the Hawking effect: What's common, what's not common

-Thermality: What is a thermal state of a quantum field

-Thermality: The role of measurement in the Unruh effect

-Thermality: The Gibbons-Hawking effect

-Vacuum entanglement structure.

Course Topics

3-Entanglement harvesting:

-Entangling spacelike separated systems: Is that possible? How??

-A simple setup on entanglement harvesting: Harvesting entanglement from a scalar field.

-Some comments on harvesting entanglement from electromagnetic vacuum.

-Entanglement Farming: Growing entanglement from the vacuum

-“Quantum seismology”: How to reverse engineer entanglement farming for metrology.

Course Topics

4-Quantum Collect Calling:

-Information flows not carried by energy flows. Is that possible? How??

-A simple setup of Quantum Collect Calling

-Applications in curved spacetime: How much information from the Early Universe survives nowadays

-How much information survives a cosmological cataclysm?

Course Topics

5-Quantum Energy Teleportation:

-Minimal QET model: transmitting energy without energy travelling from sender to receiver

-A bit of quantum thermodynamics: Breaking Strong Local Passivity.

-QET in quantum fields: designing negative stress-energy densities.

Course Topics

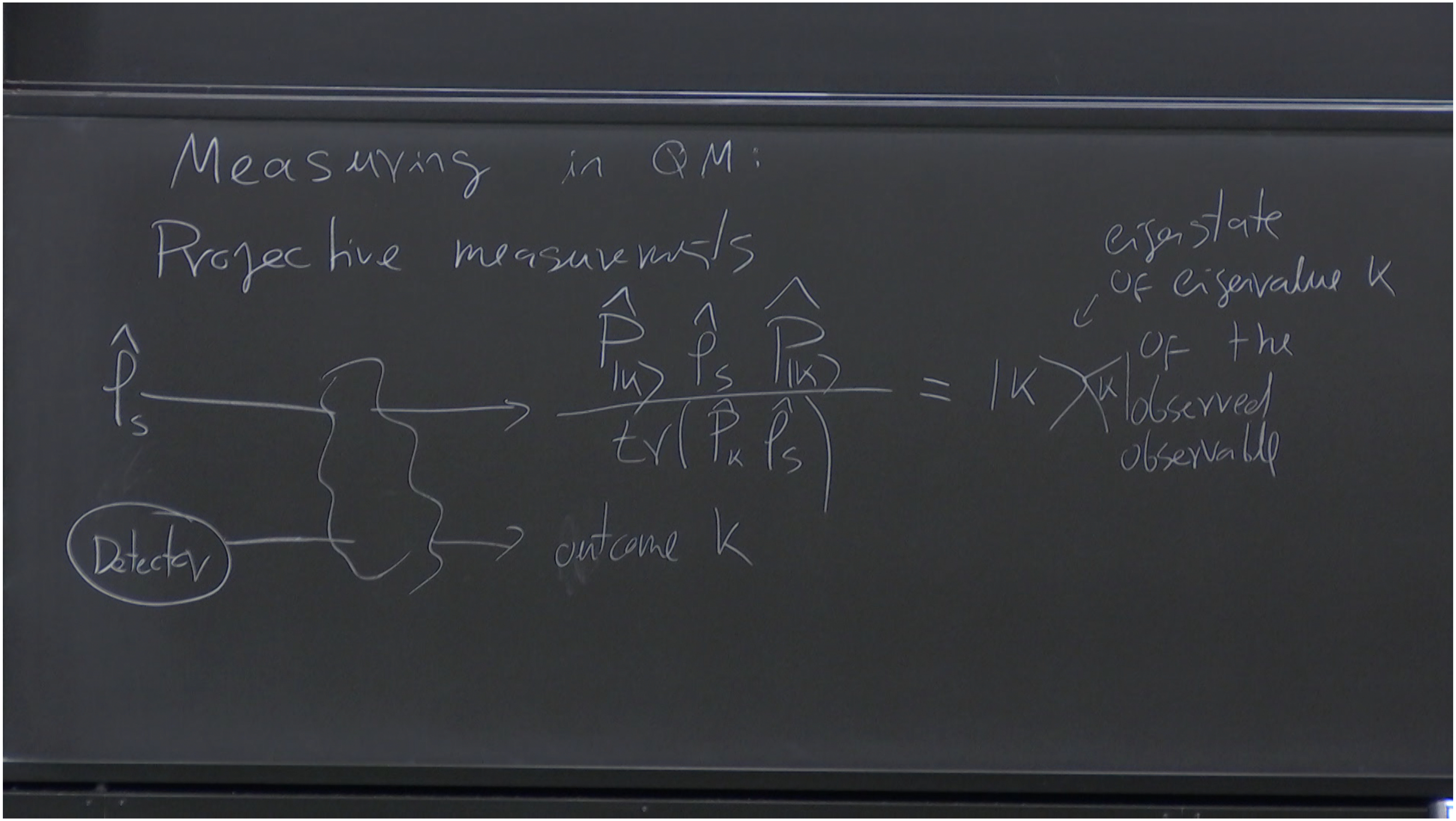
Second part of the course

-Non-perturbative measurements

-QFT thermodynamics

-Advanced aspects of the Unruh effect

-Advanced aspects of the relativistic study of the light-matter interaction

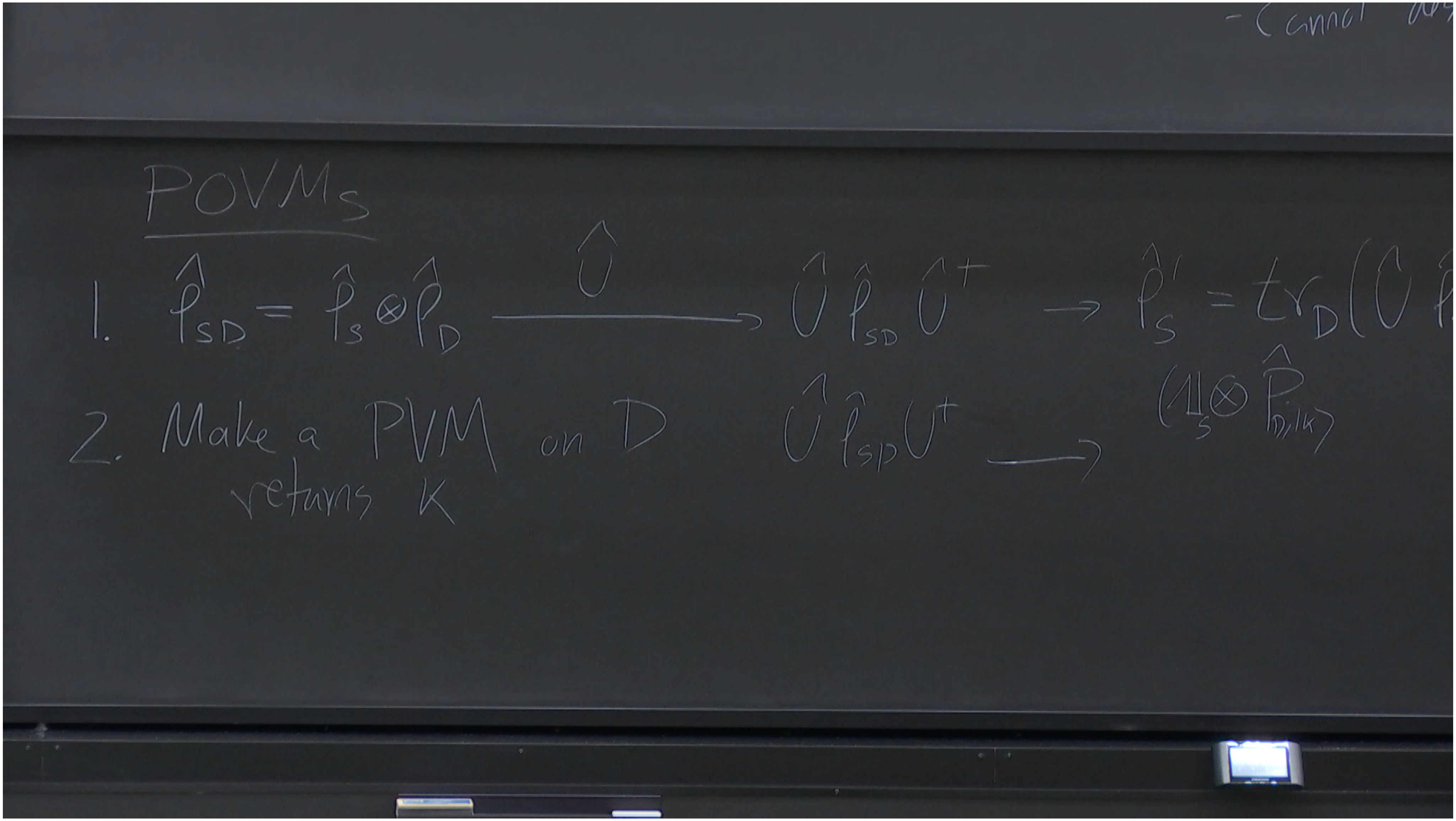

Measuring in QM:
Projective measurements
eigenstate of eigenvalue k of the observed observable
$\hat{\rho}_s$
Detector
outcome k
$\frac{\hat{P}_{|k\rangle}\,\hat{\rho}_s\,\hat{P}_{|k\rangle}}{tr(\hat{P}_k\,\hat{\rho}_s)} = |k\rangle\langle k|$

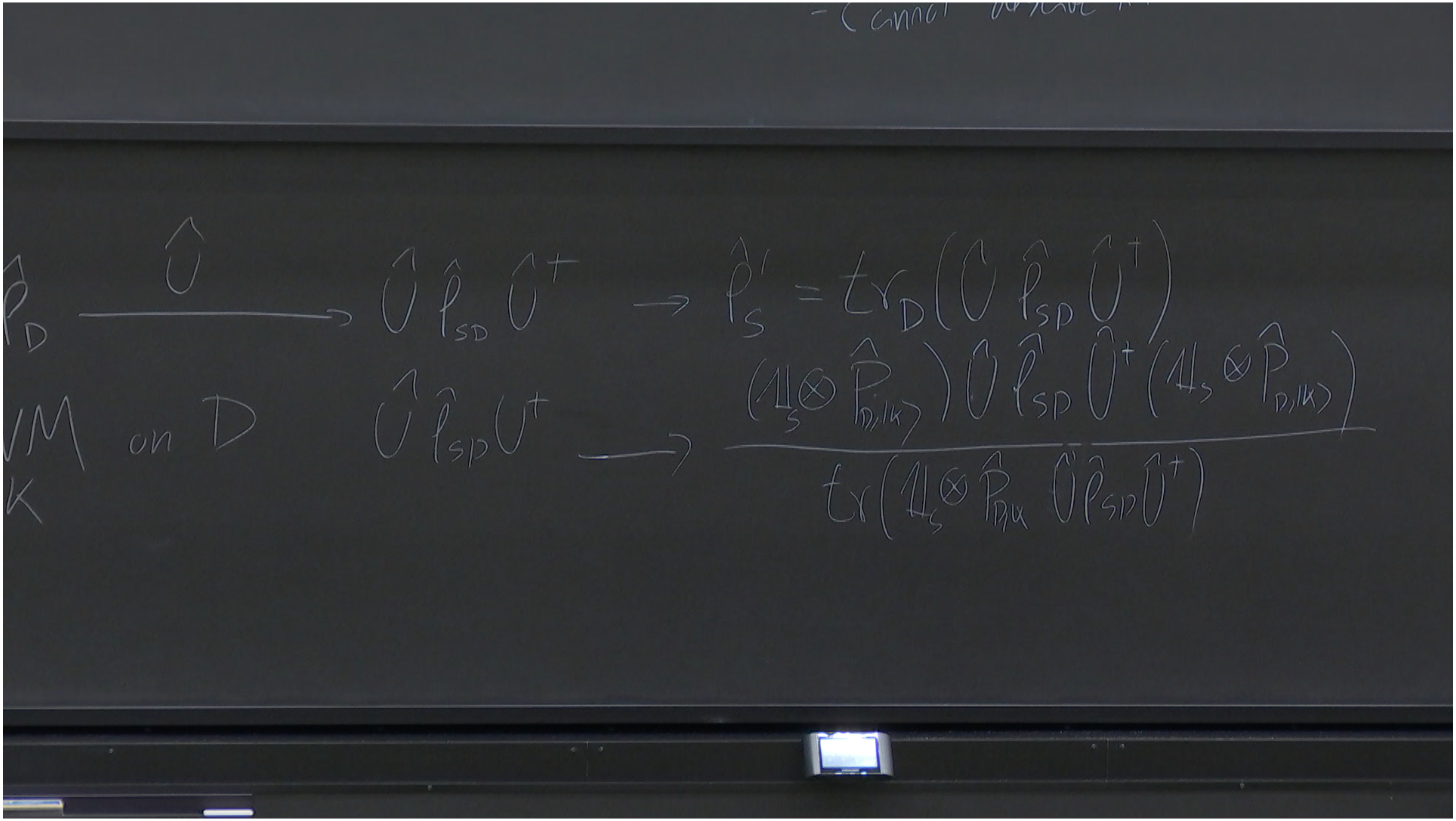
Pros

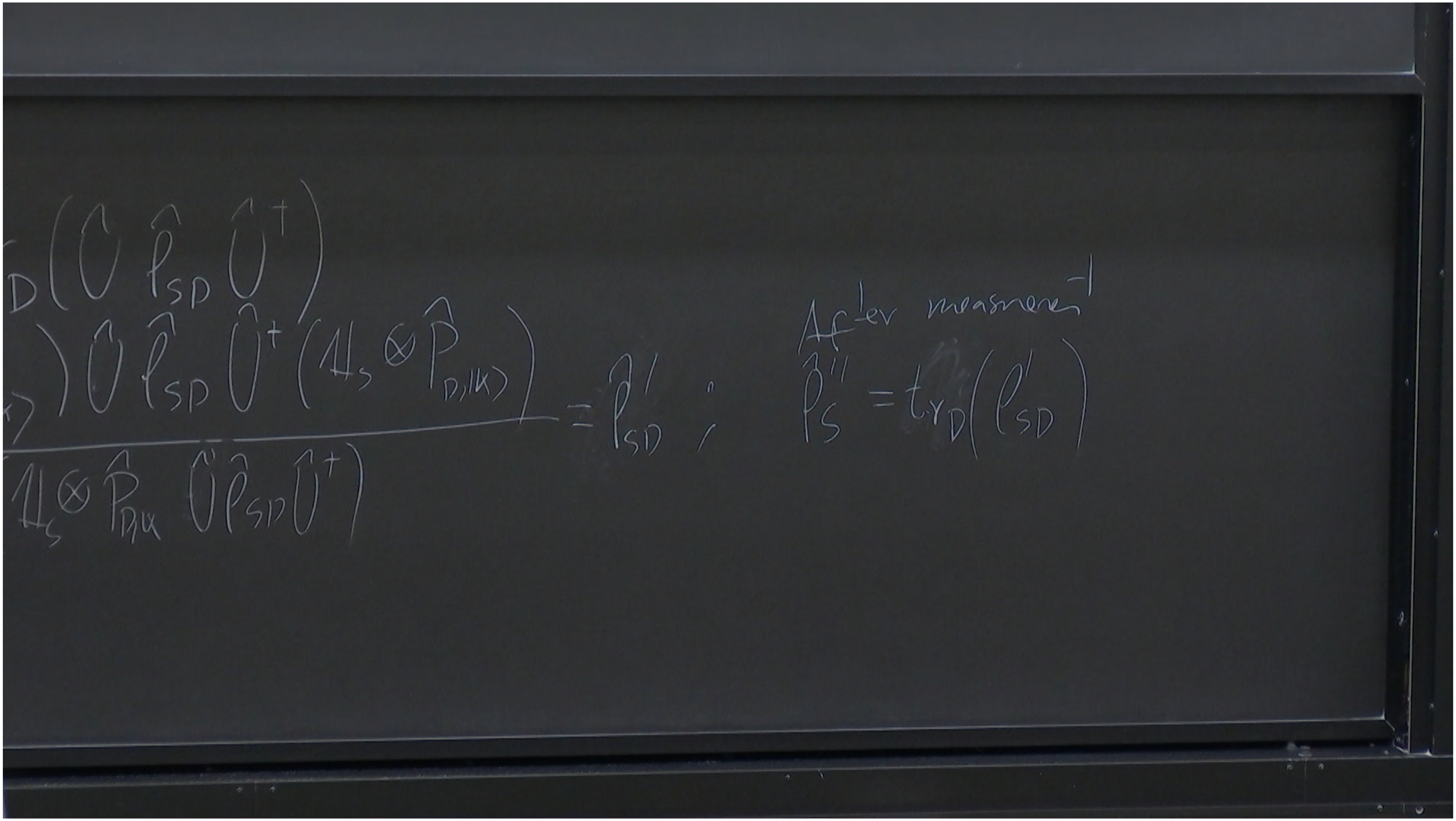
+ A way of getting def. answers out of single-shot exp.
+ Seems to work phenomenologically (most of the times)
+ It's crazy easy

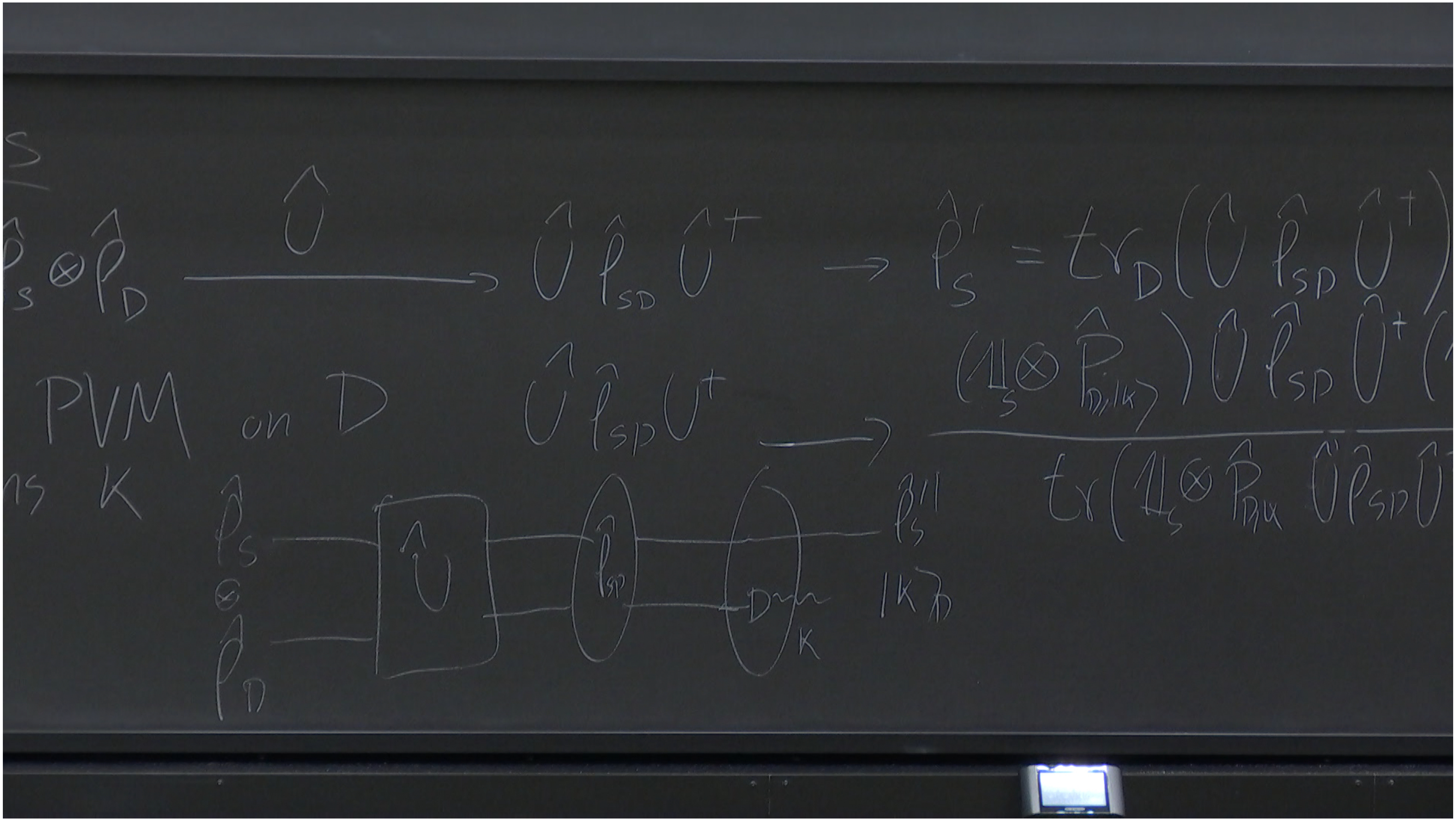
Cons

- Cannot describe interactions between detectors and system


- Cannot
POVMs
1. $\hat{\rho}_{SD} = \hat{\rho}_S \otimes \hat{\rho}_D \xrightarrow{\hat{U}} \hat{U}\hat{\rho}_{SD}\hat{U}^\dagger \rightarrow \hat{\rho}'_S = tr_D(\hat{U}$
2. Make a PVM on D
returns K
$\hat{U}\hat{\rho}_{SD}U^\dagger \longrightarrow$
$(\mathbb{1}_S \otimes \hat{P}_{D,|k\rangle}$


- Cannot
$\hat\rho_D \xrightarrow{\hat U} \hat U \hat\rho_{SD} \hat U^\dagger \to \hat\rho'_S = tr_D(\hat U \hat\rho_{SD} \hat U^\dagger)$
VM on D
K
$\hat U \hat\rho_{SD} \hat U^\dagger \to \frac{(1_S \otimes \hat P_{D,|k\rangle}) \hat U \hat\rho_{SD} \hat U^\dagger (1_S \otimes \hat P_{D,|k\rangle})}{tr(1_S \otimes \hat P_{D,|k\rangle} \hat U \hat\rho_{SD} \hat U^\dagger)}$


After measurement
$\hat{\rho}''_S = tr_D(\rho'_{SD})$


PVM on D

Measurements in Quantum Theory

Still an open problem!

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

In QM, we model that with idealized measurements

Idealized measurements 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

Measurements in Quantum Theory

How about QFT?

Maybe we want to measure localized observables of the field (e.g., the electric field in this room during the duration of my talk)

If you measure it, it is not unthinkable you get a definite reading (e.g., 42 V/m)

Can you become rich and famous with idealized measurements in QFT?

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

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?

Rafael Sorkin (1992):

No idealized measurements in QFT?

Argues that idealized measurements are incompatible with causality

Two examples:

Example 2: Quantum Field

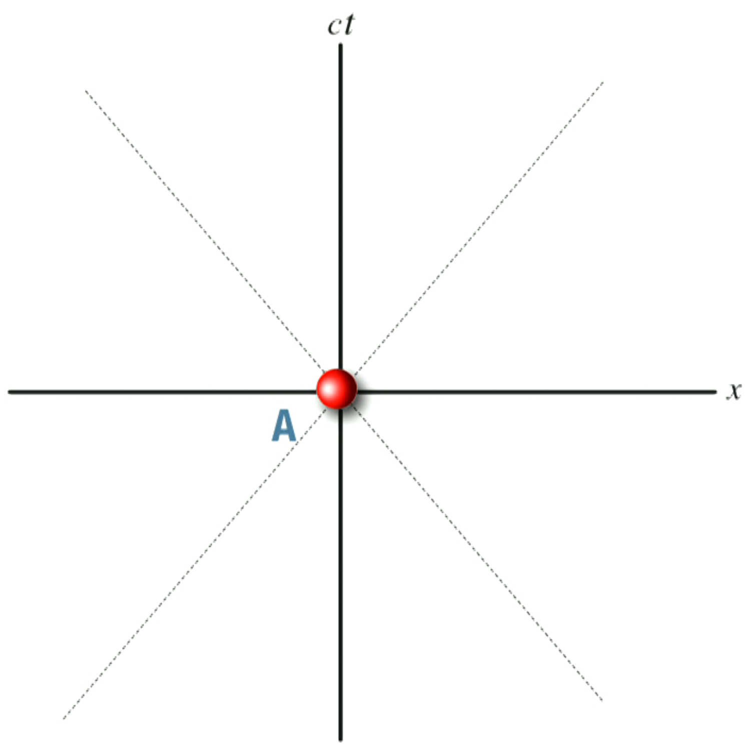
Consider a state: $\hat{\rho}$

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

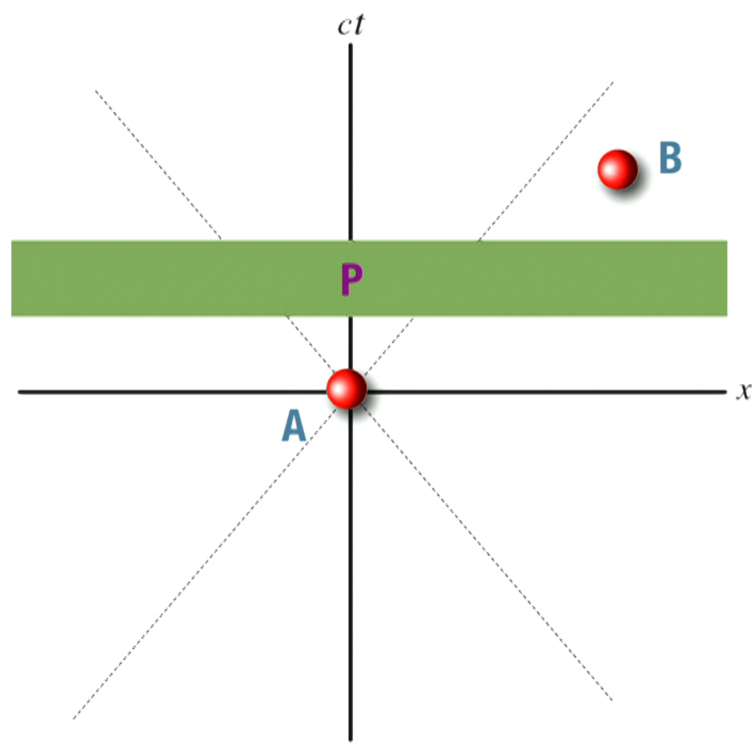
2-Make an idealized measurement (Non-local) on a spacetime "horizontal" slice

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

No idealized measurements?



No idealized measurements?



No idealized measurements?

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

Useless Qubits in "Relativistic Quantum Information"

Fay Dowker

Blackett Laboratory, Imperial College, London, SW7 2AZ, U.K.
and
Perimeter Institute, 39 Caroline St. N., Waterloo, ON N2L 2Y5, Canada

Abstract

I draw attention to previous work that shows that the observables corresponding to relativistic quantum field modes commonly employed in papers on "relativistic quantum information" cannot be measured by ideal measurements.

So what's the plan?

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

People in RQI followed two paths:

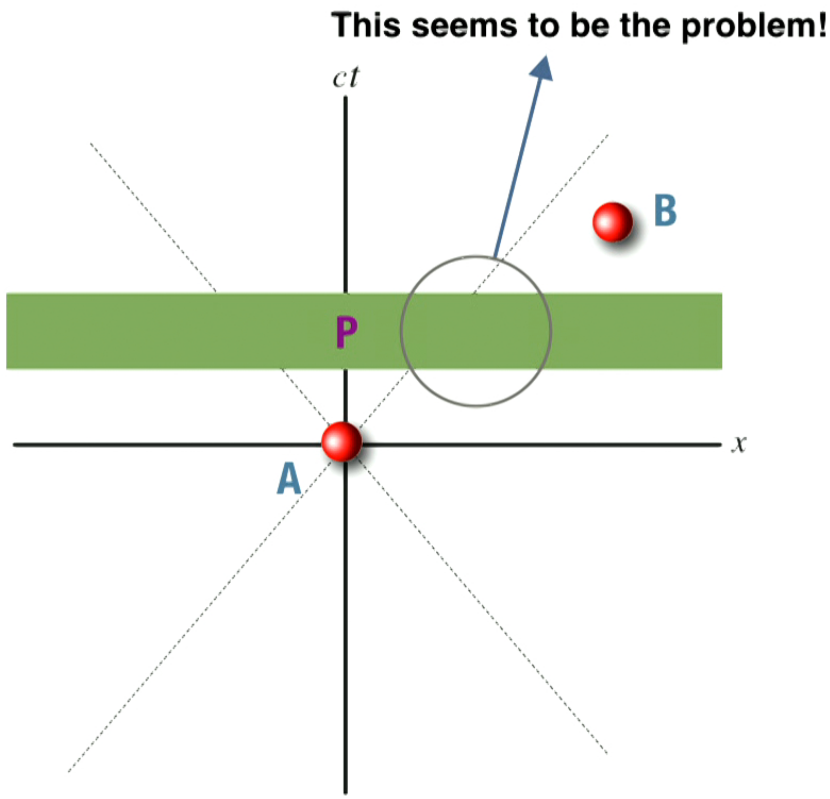
Particle detectors

Localized idealized measurements

More on this later!

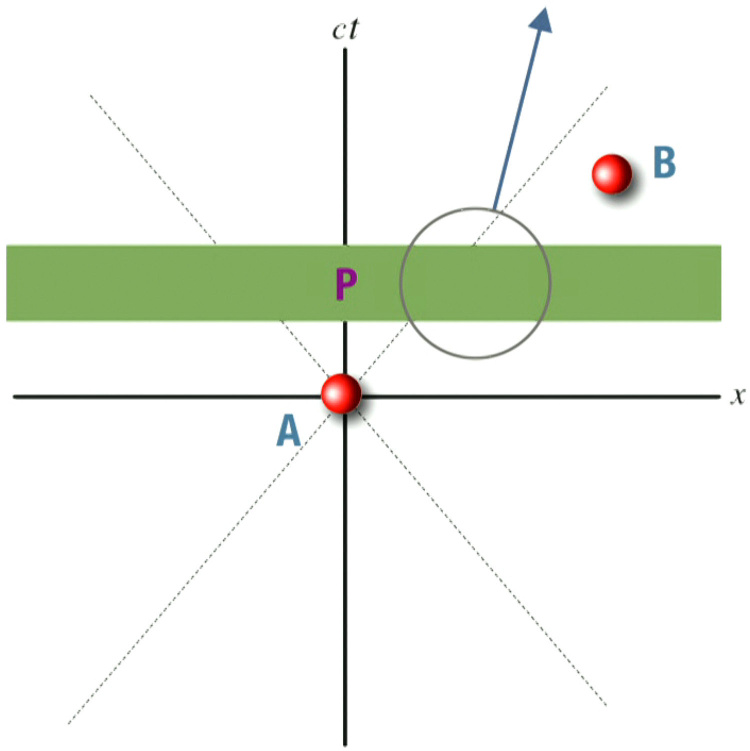
Is this okay?

Localized idealized measurements



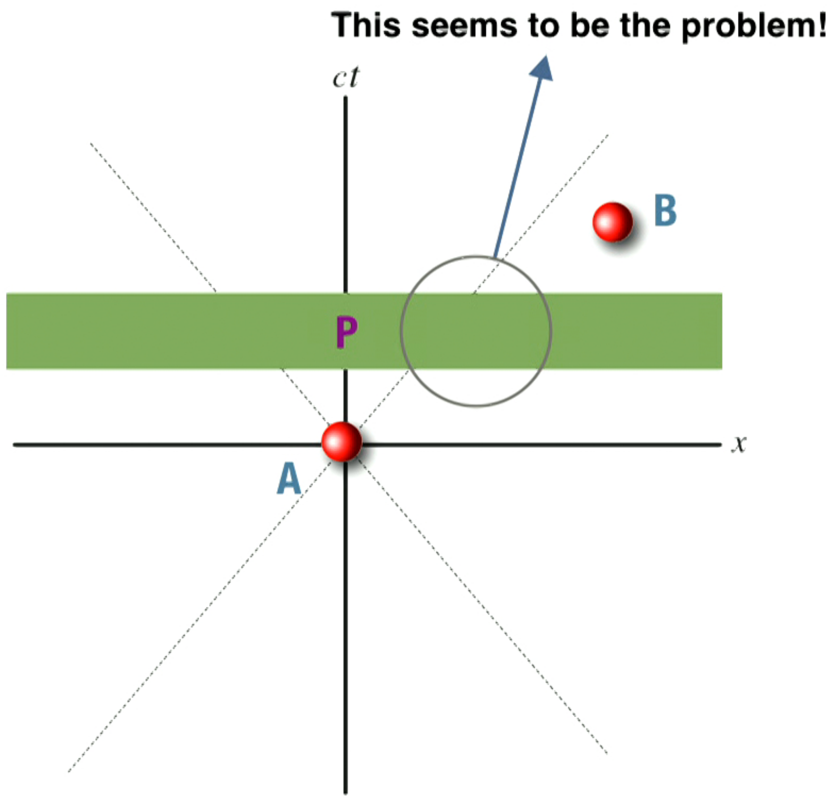
Localized idealized measurements

This seems to be the problem!



Can we solve the issue by disallowing 'too non-local' kinds of measurement?

Localized idealized measurements



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

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.

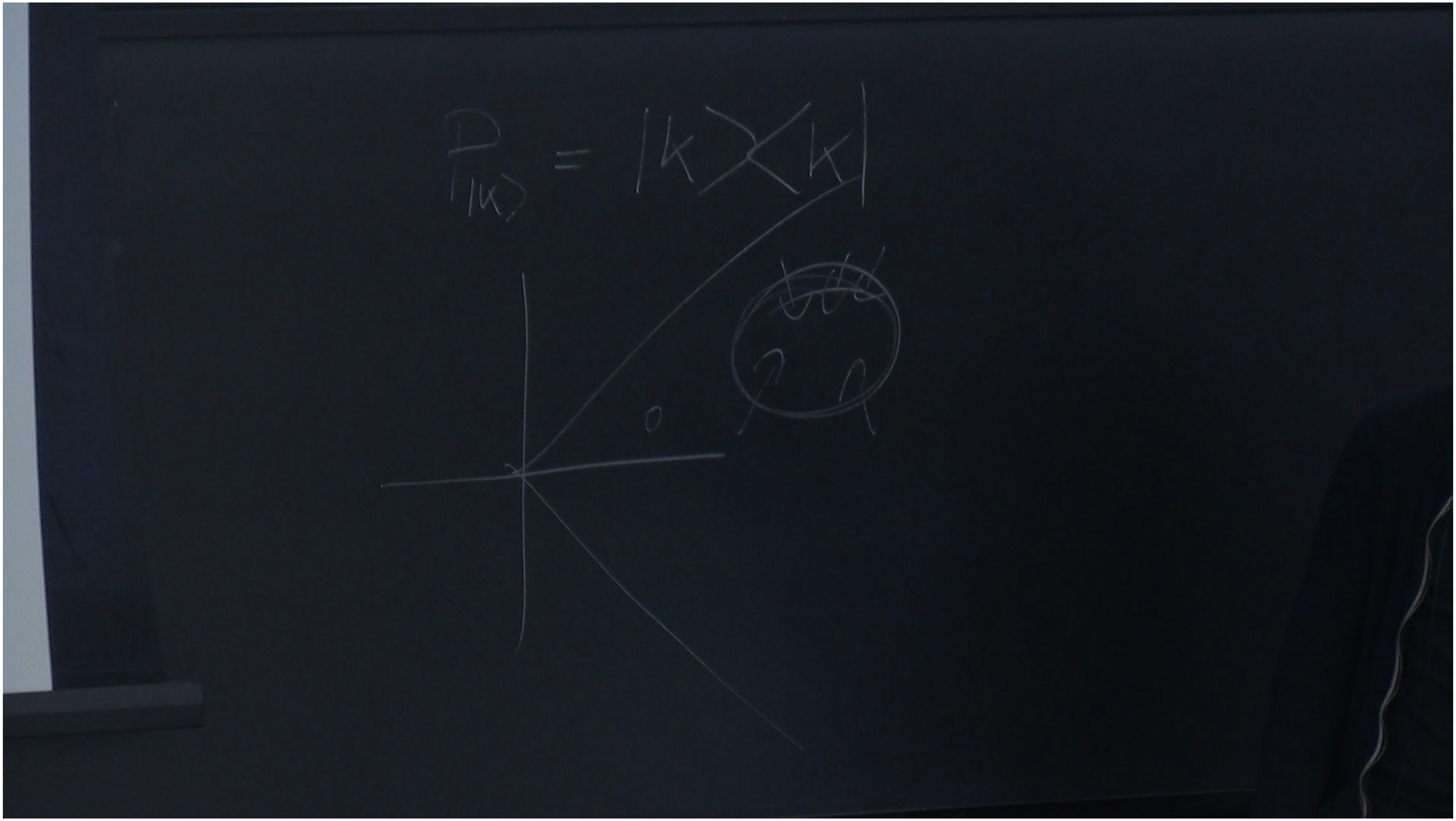
Localized idealized measurements?

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 projector over a bounded region of spacetime cannot be rank-1!


$P_{|k\rangle} = |k\rangle\langle k|$

Measurements in Quantum Theory

What do I want from a measurement theory?

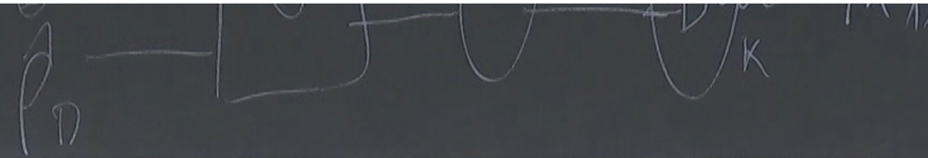
1-Capable of producing definite values

2-Provides an update rule

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

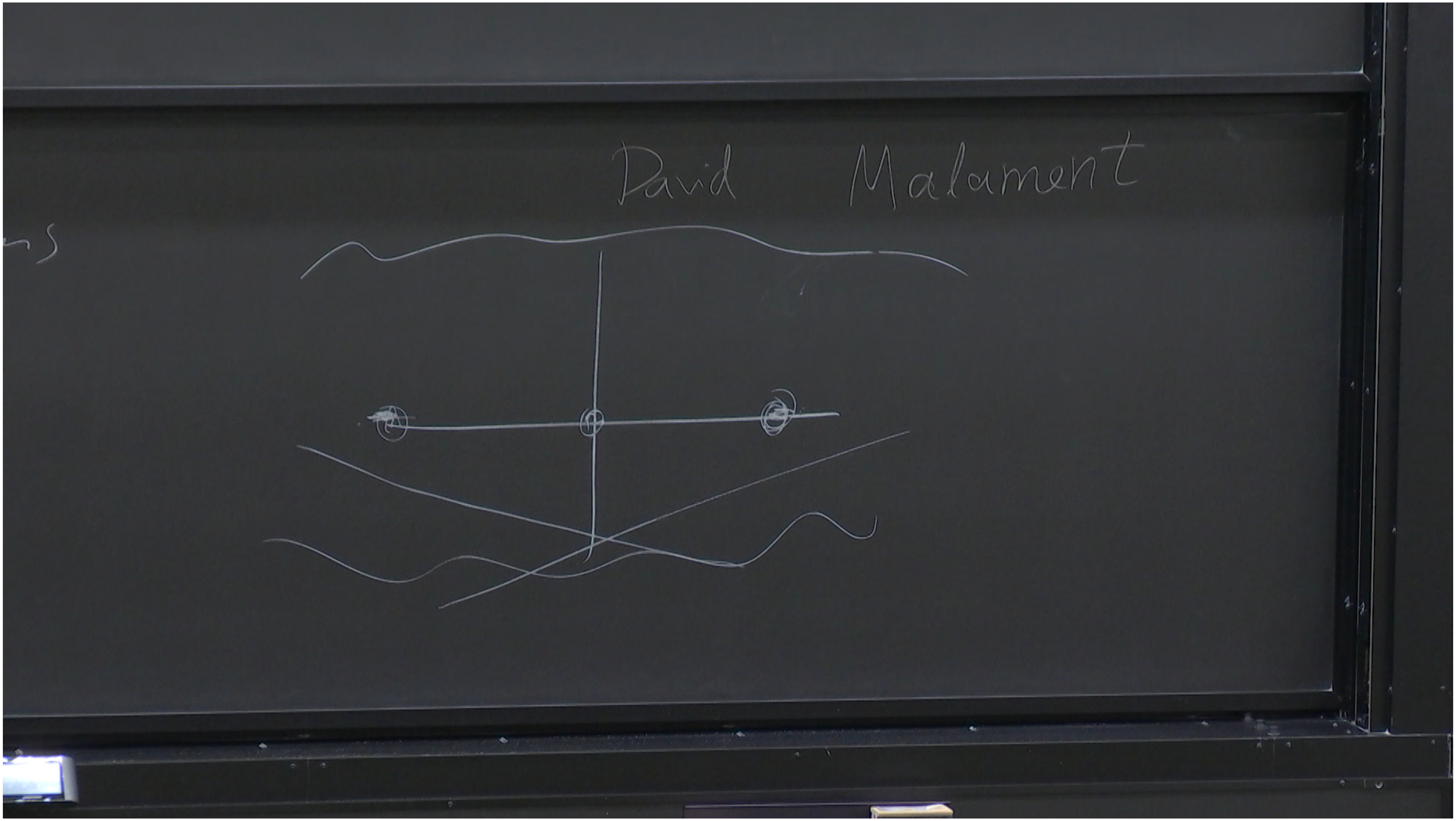
4-Reproduces experiments!!!

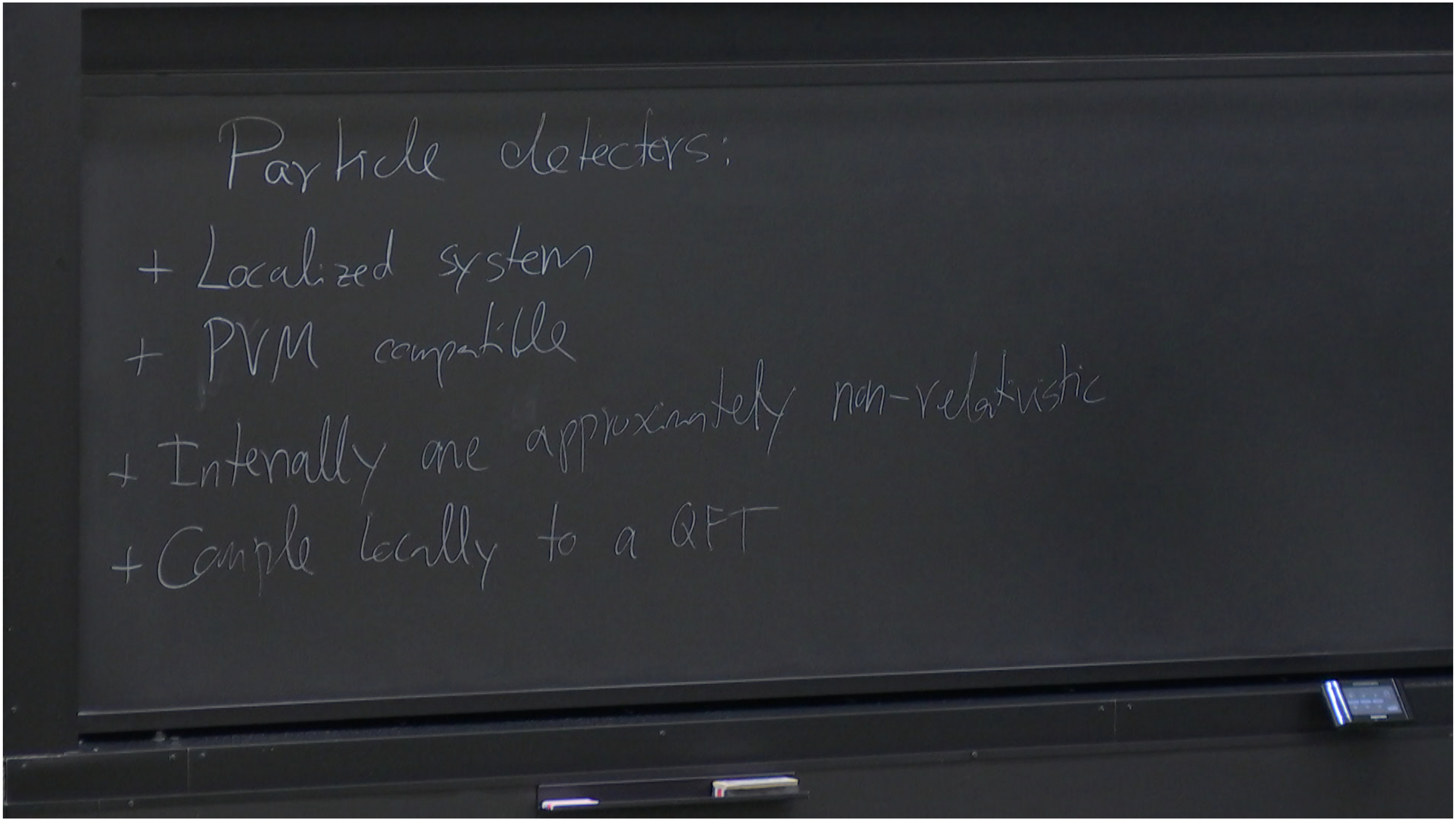
Is there an alternative to idealized measurements?

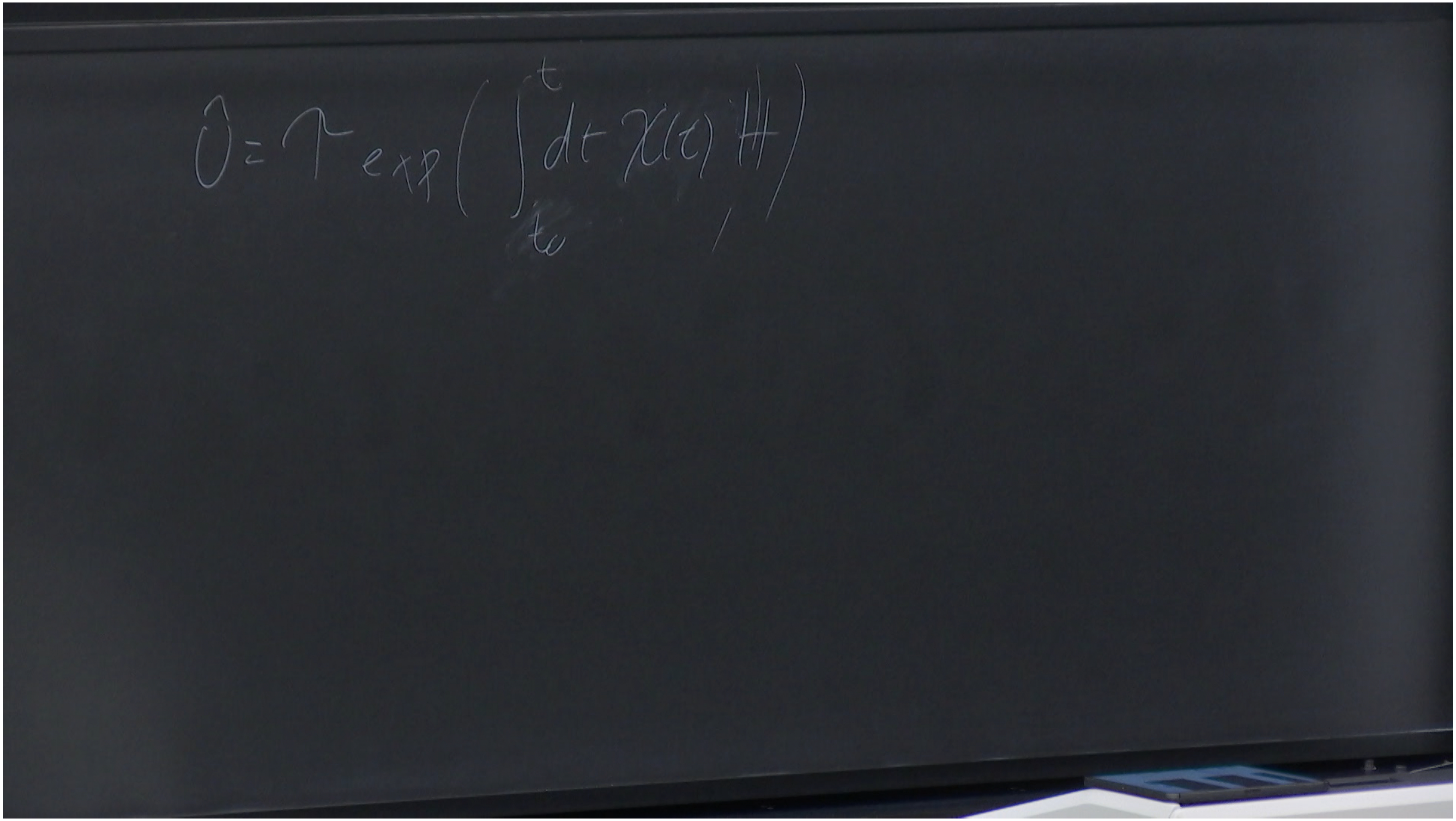


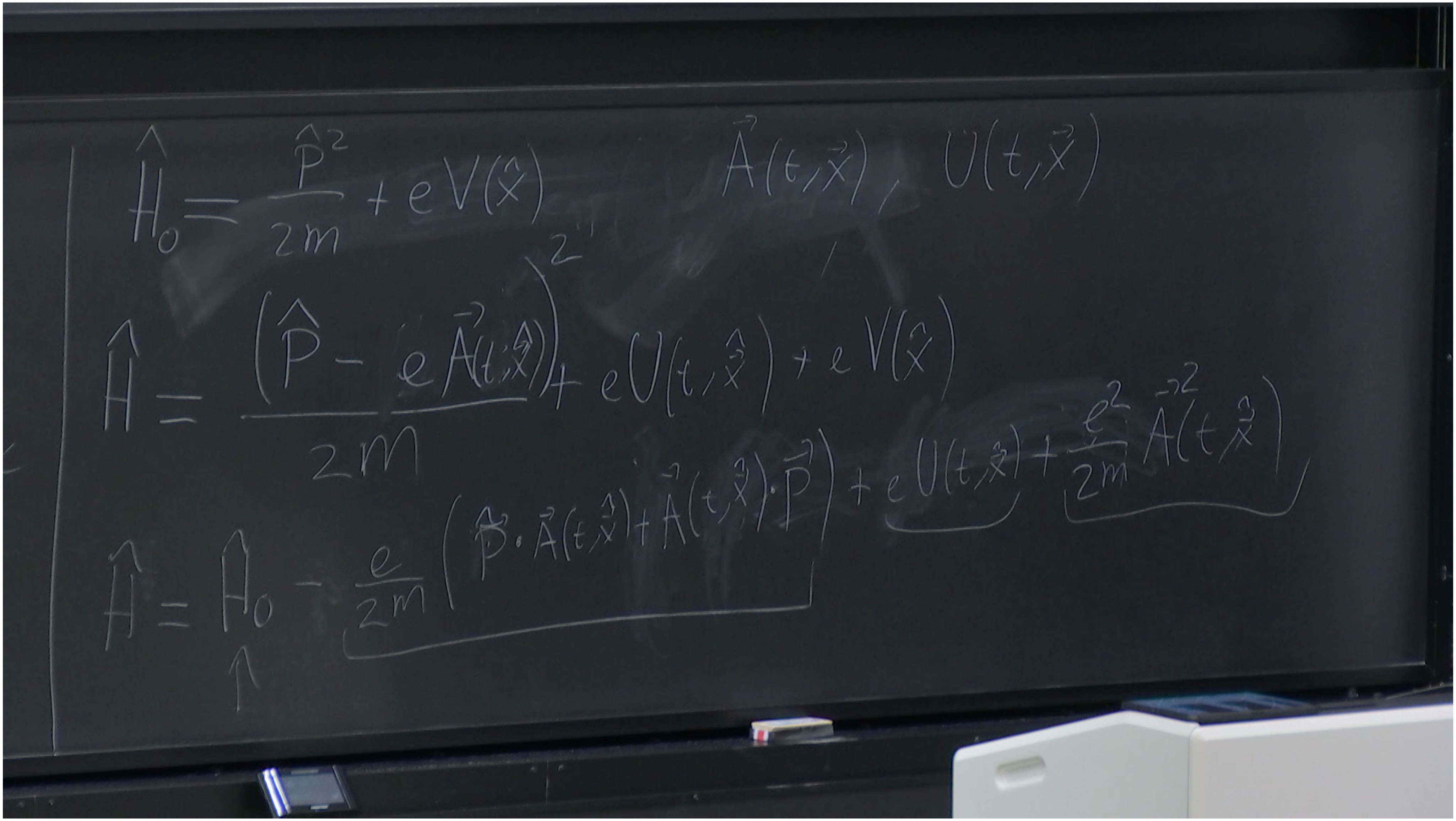
Pros

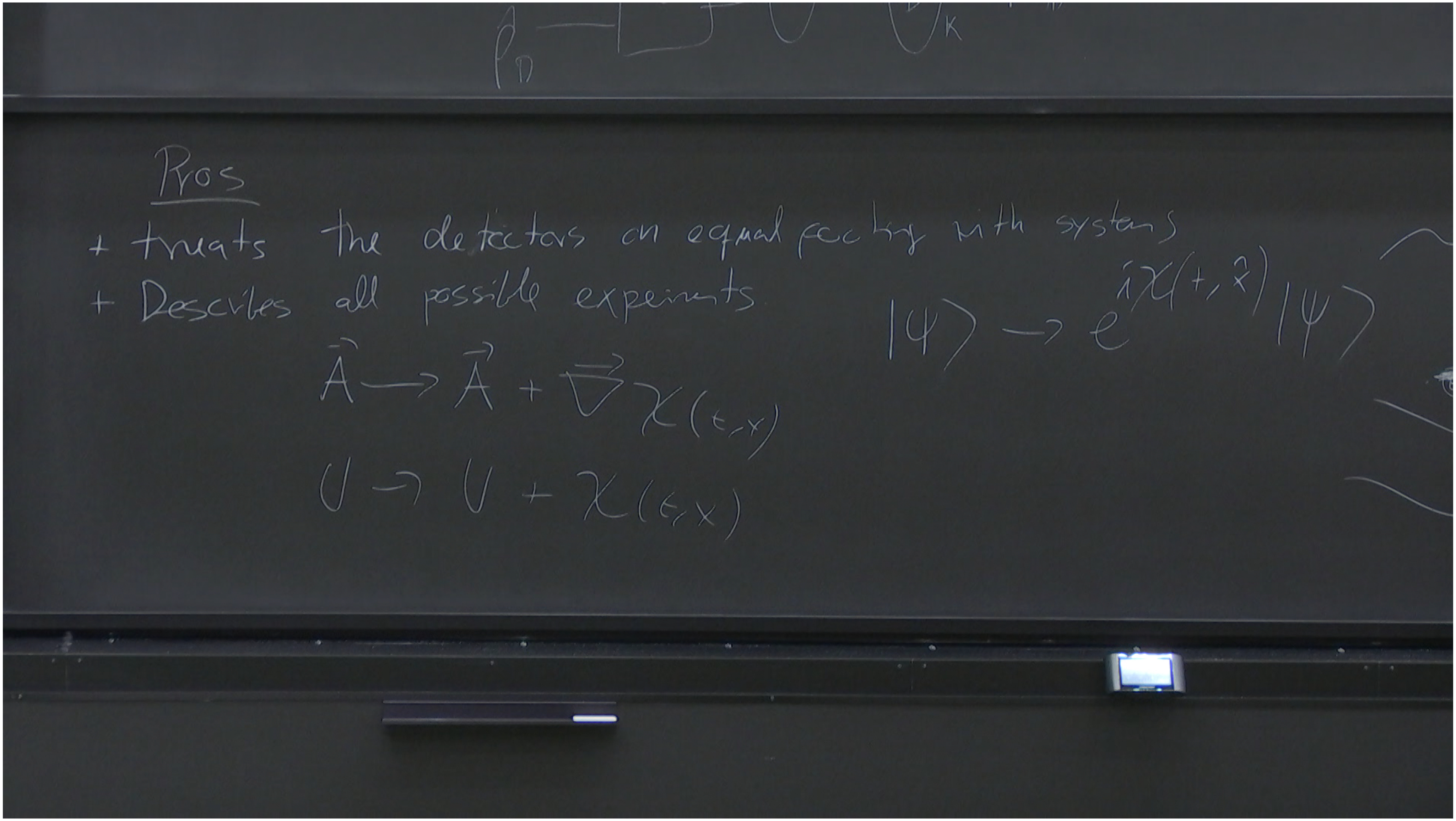
+ treats the detectors on equal footing with systems
+ Describes all possible experiments


David Malament


Particle detectors:
+ Localized system
+ PVM compatible
+ Internally are approximately non-relativistic
+ Couple locally to a QFT


$\hat{U} = T \exp\left(\int_{t_0}^{t} dt\, \chi(t)\, H \right)$


$\hat{H}_0 = \frac{\hat{p}^2}{2m} + eV(\hat{x})$
$\vec{A}(t,\vec{x}),\ U(t,\vec{x})$
$\hat{H} = \frac{(\hat{P} - e\vec{A}(t,\hat{x}))^2}{2m} + eU(t,\hat{x}) + eV(\hat{x})$
$\hat{H} = \hat{H}_0 - \frac{e}{2m}(\hat{P}\cdot\vec{A}(t,\hat{x}) + \vec{A}(t,\hat{x})\cdot\hat{P}) + eU(t,\hat{x}) + \frac{e^2}{2m}\vec{A}^2(t,\hat{x})$


Pros
+ treats the detectors on equal footing with systems
+ Describes all possible experiments
$\vec{A} \to \vec{A} + \vec{\nabla}\chi(t,x)$
$V \to V + \chi(t,x)$
$|\psi\rangle \to e^{i\chi(t,x)}|\psi\rangle$