Title: Operational Causality in Spacetime

Speakers: Michal Eckstein

Series: Quantum Foundations

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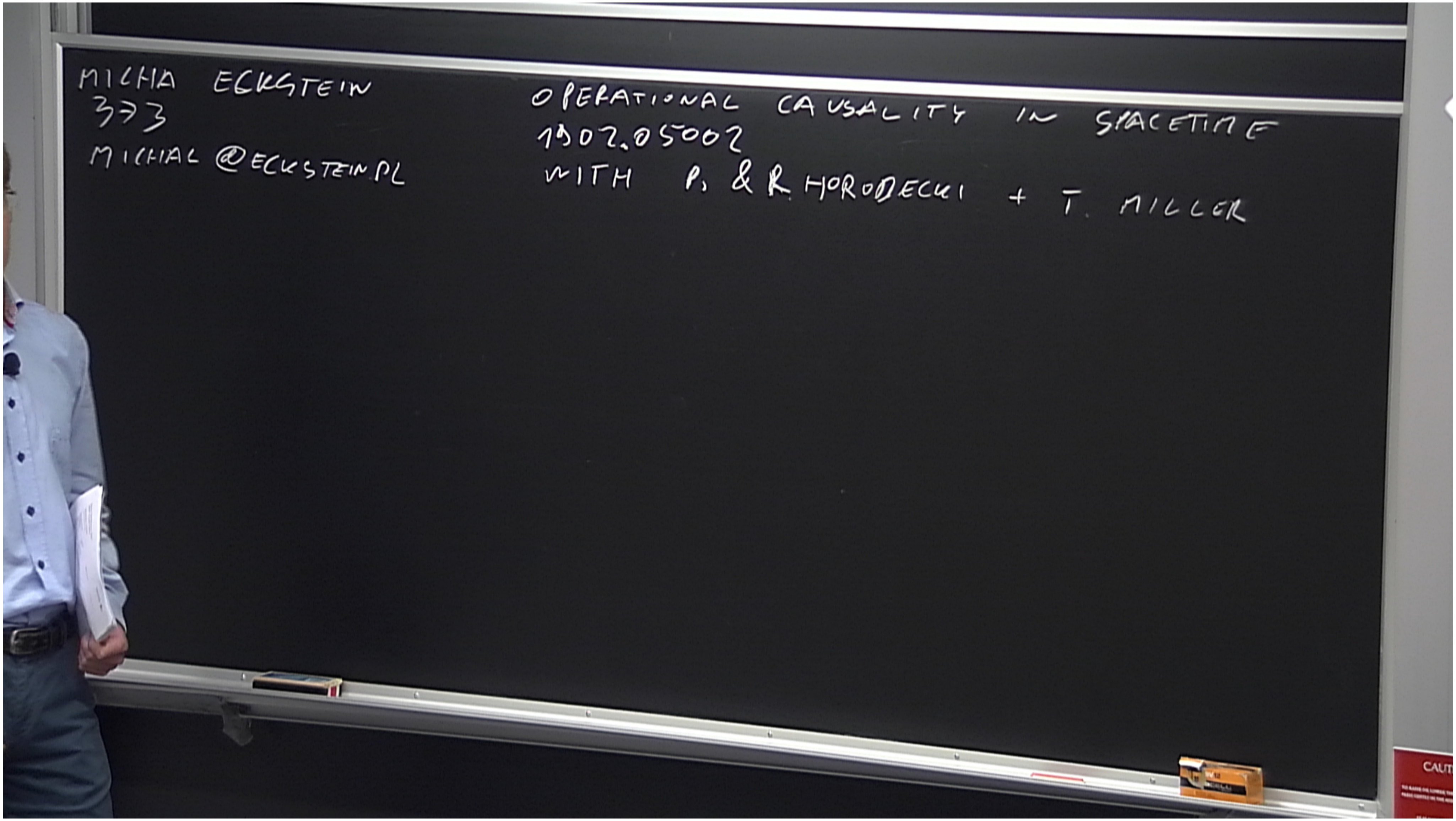
Abstract: The no-signalling principle, preventing superluminal communication and the consequent logical paradoxes, is typically formulated within the information-theoretic framework in terms of admissible correlations in composite systems. In my talk, I will present its complementary incarnation associated with dynamics of single systems subject to invasive measurements. The `dynamical no-signalling principle' applies to any theory with well defined rules of calculating detection statistics in spacetime. It thus offers a new framework, based on measure theory, for studying ``post-quantum" theories in spacetime. I will show that, strikingly, the `dynamical no-signalling' principle rules out some of the well know models of quantum wave dynamics.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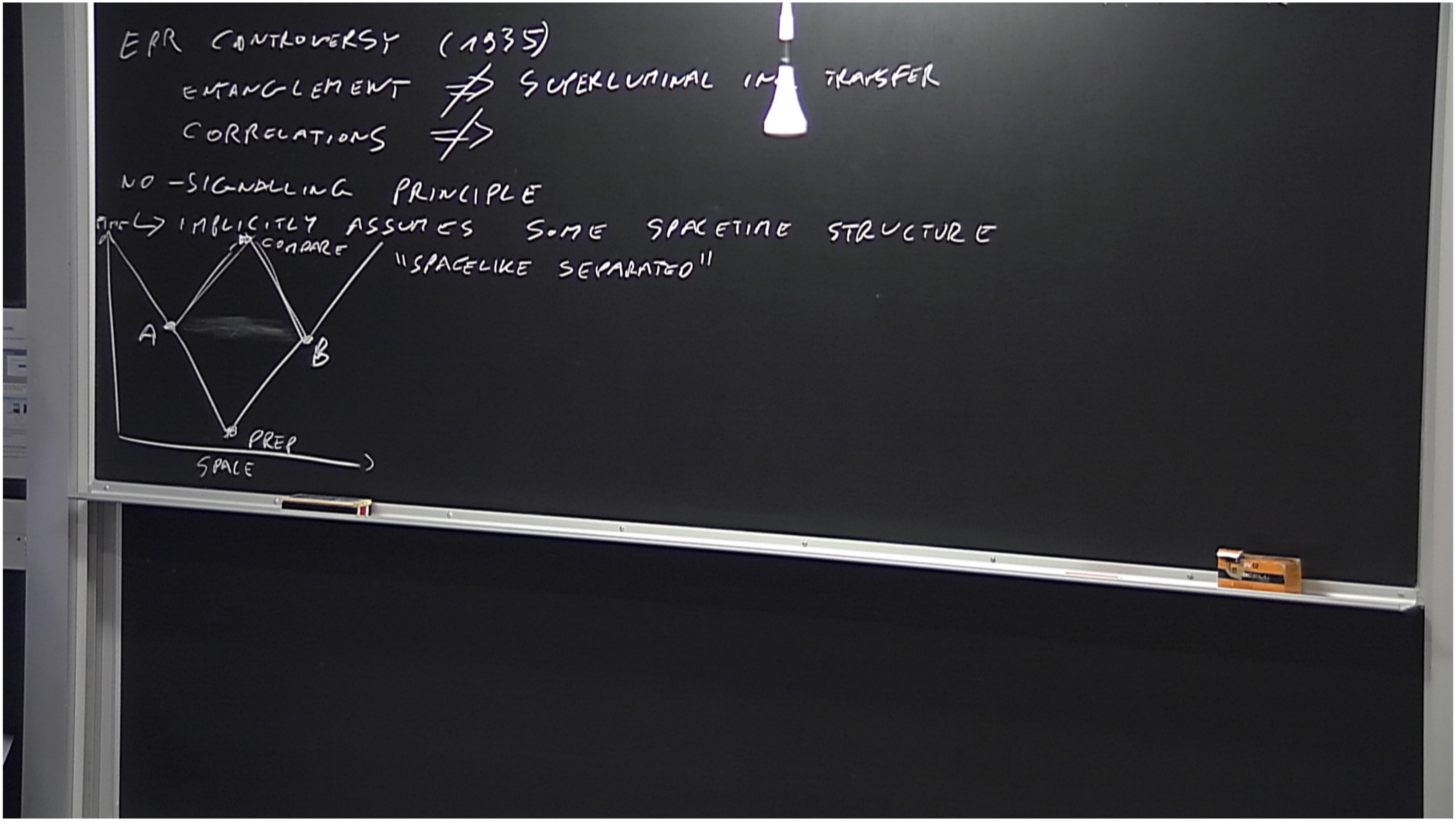
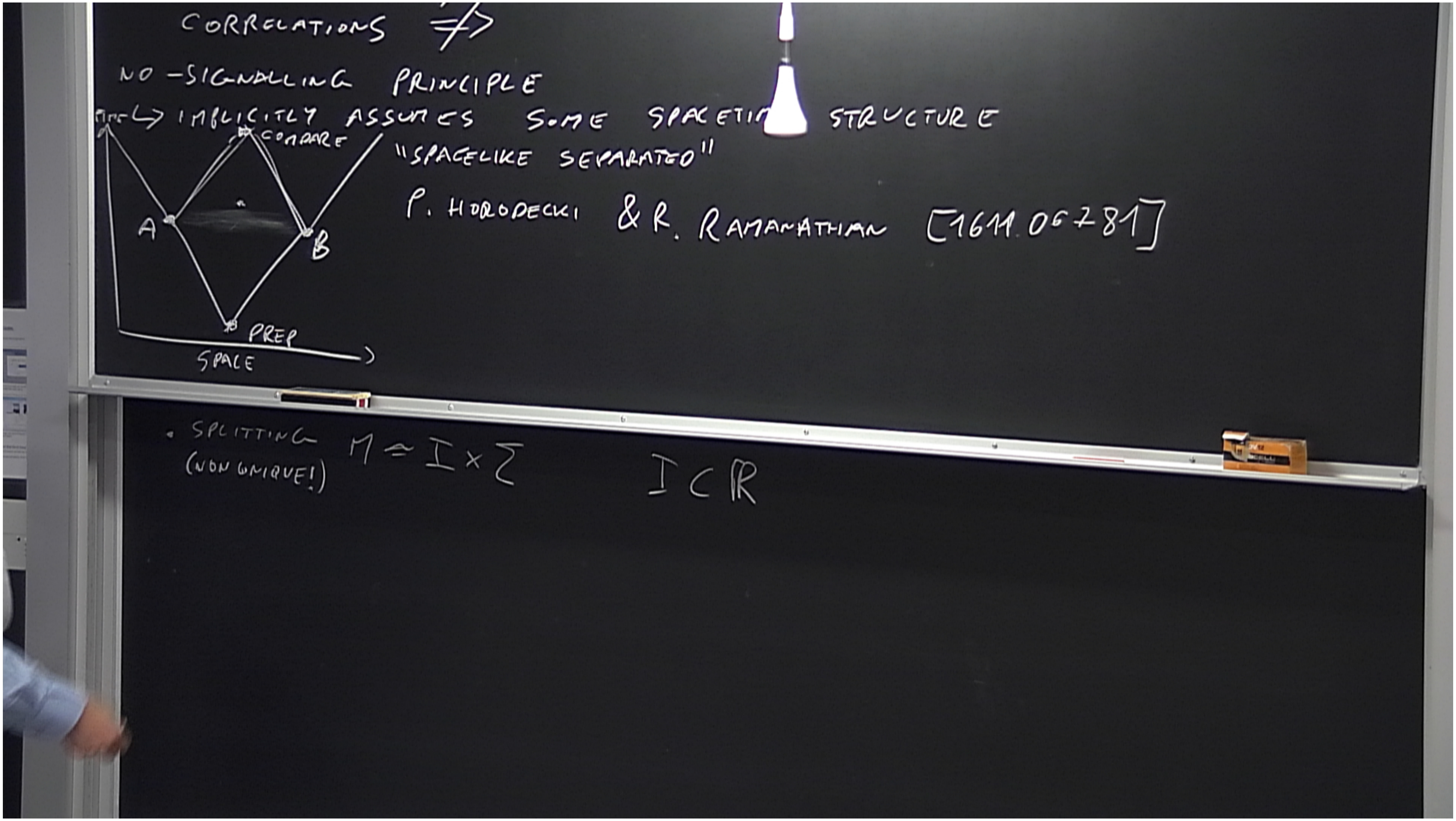
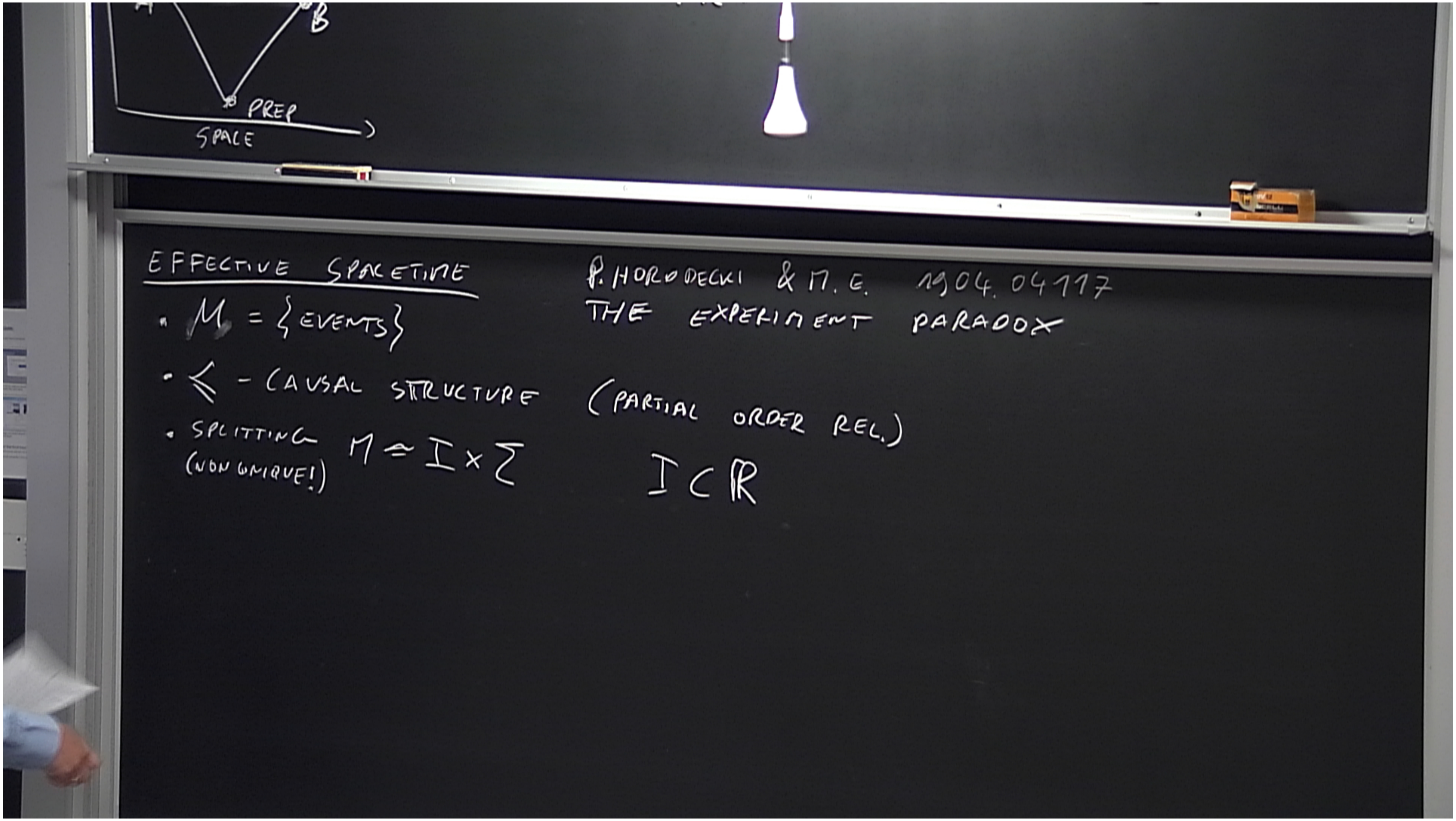
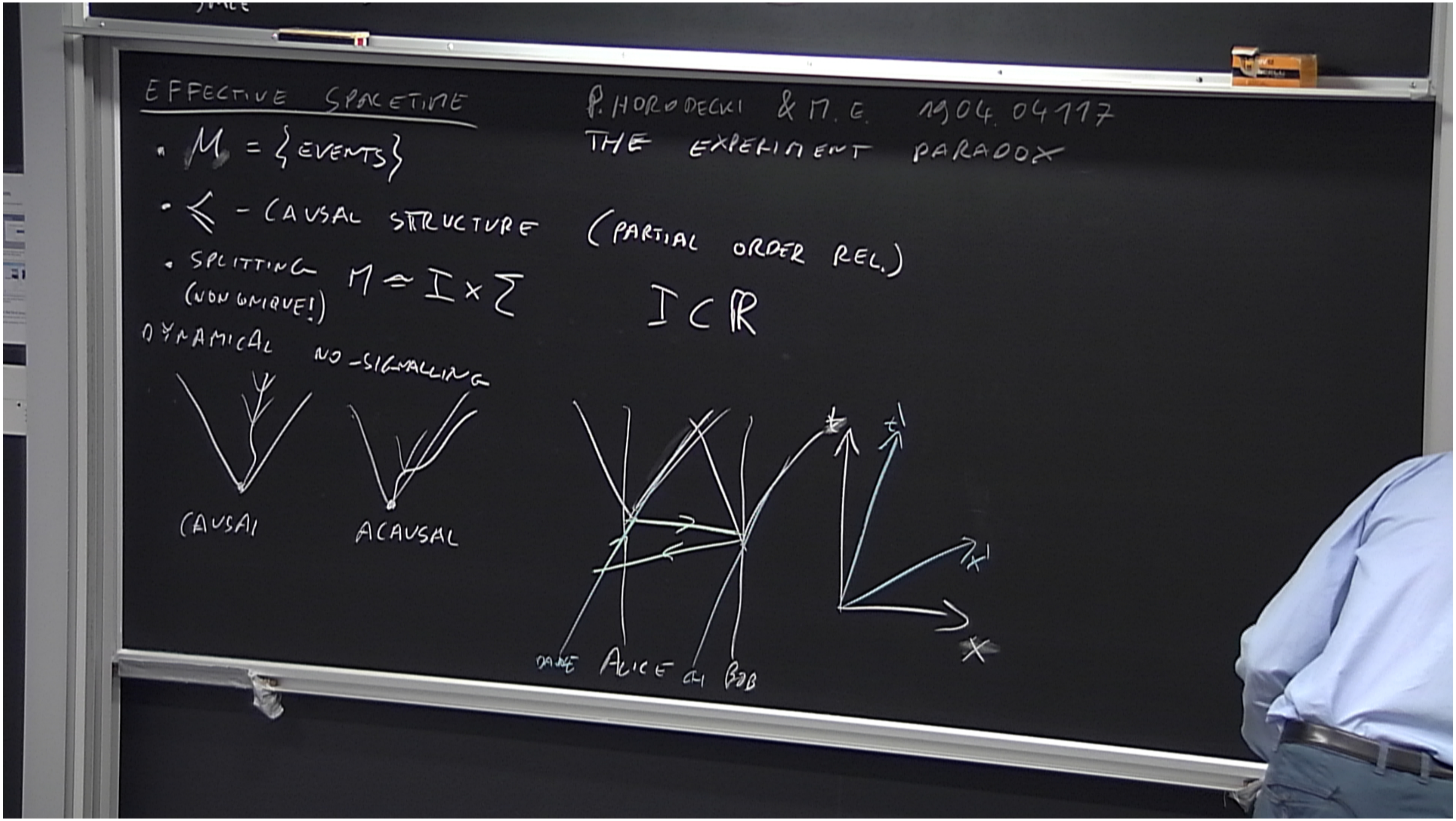
OPERATIONAL CAUSALITY IN SPACETIME
1902.05002
WITH P. & R. HORODECKI + T. MILLER

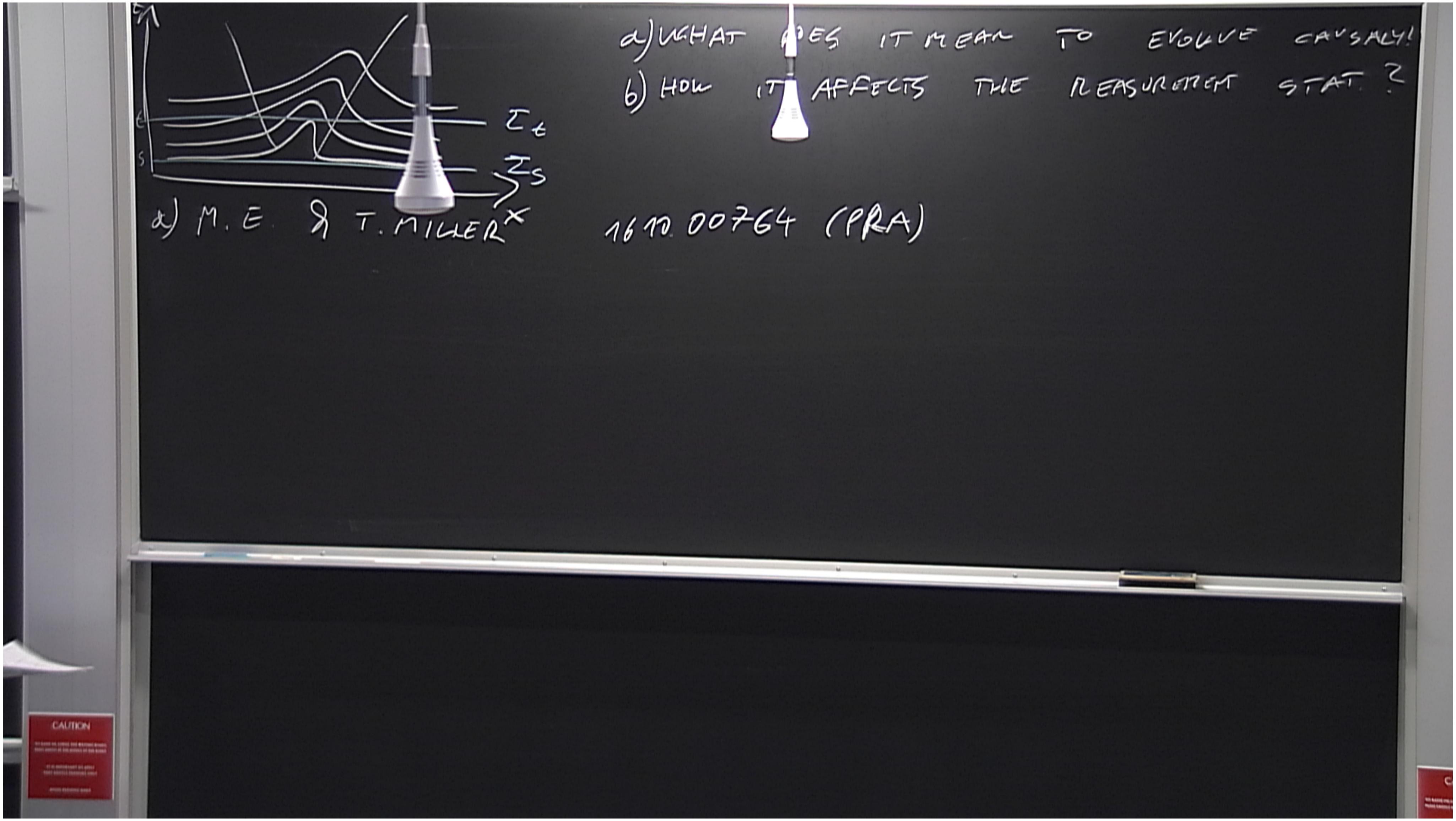

EPR CONTROVERSY (1935)
ENTANGLEMENT ⇏ SUPERLUMINAL IN TRANSFER
CORRELATIONS ⇏
NO-SIGNALLING PRINCIPLE
TIME ↳ IMPLICITLY ASSUMES SOME SPACETIME STRUCTURE
COMPARE
"SPACELIKE SEPARATED"
A
B
PREP
SPACE

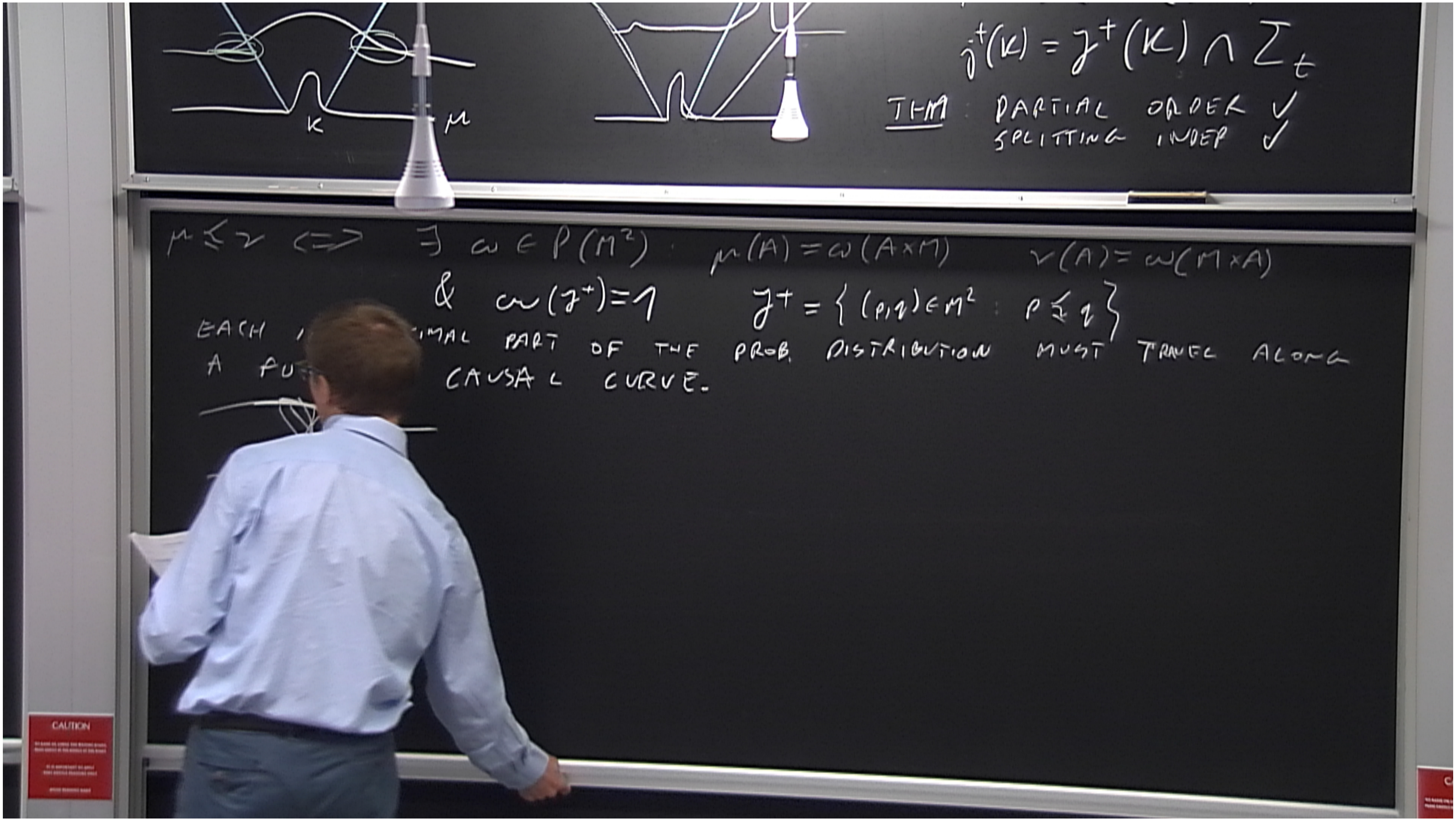

CORRELATIONS ⇏
NO-SIGNALLING PRINCIPLE
↳ IMPLICITLY ASSUMES SOME SPACETI STRUCTURE
"SPACELIKE SEPARATED"
P. HORODECKI & R. RAMANATHAN [1611.06781]
COMPARE
A
B
PREP
SPACE
• SPLITTING
(NON UNIQUE!)
M ≃ I × Σ
I ⊂ ℝ

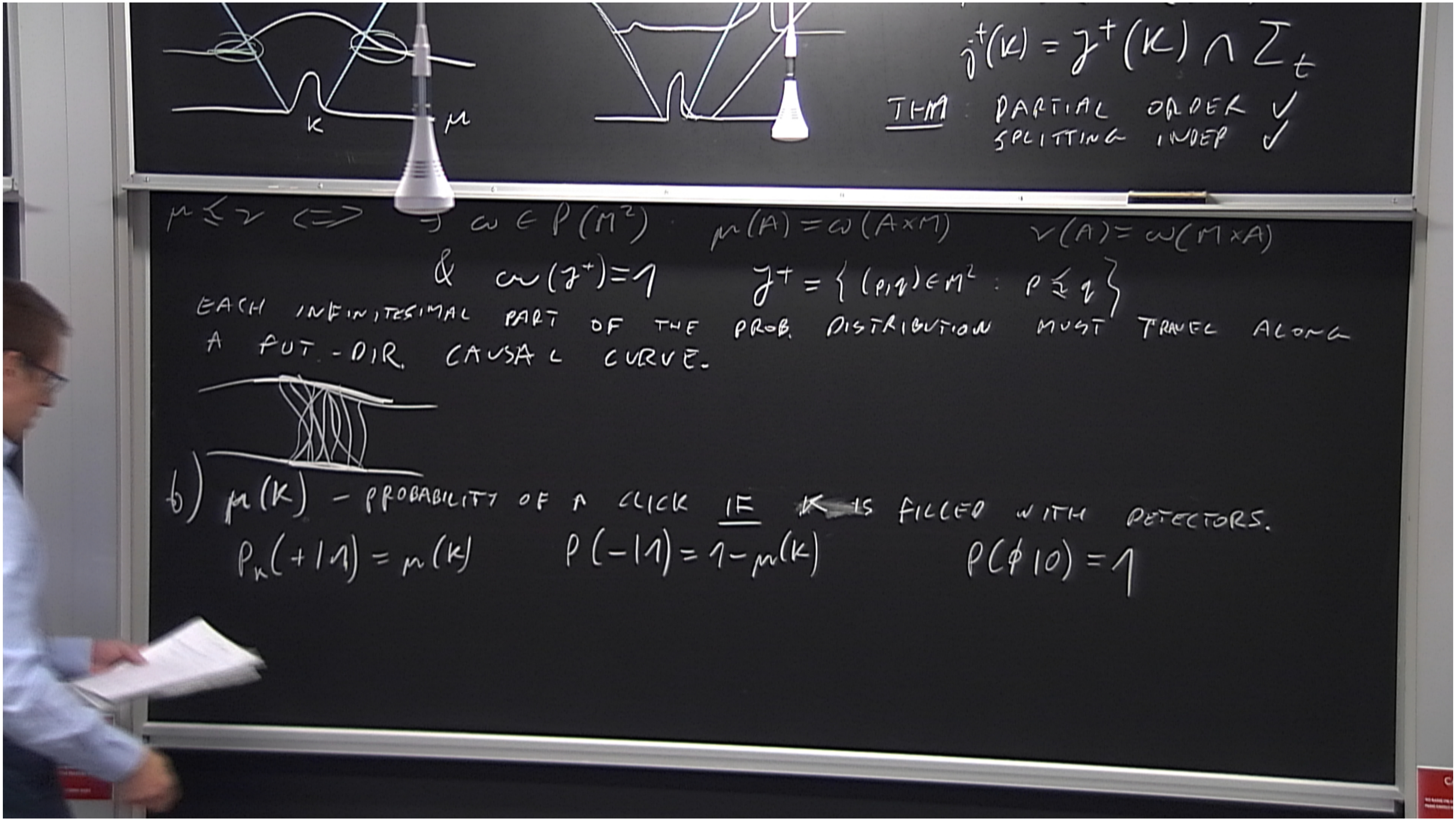

B
PREP
SPACE
EFFECTIVE SPACETIME
• M = {EVENTS}
• ≤ - CAUSAL STRUCTURE (PARTIAL ORDER REL.)
• SPLITTING (NON UNIQUE!) M ≃ I × Σ
I ⊂ ℝ
P. HORODECKI & M. E. 1904.04117
THE EXPERIMENT PARADOX



EFFECTIVE SPACETIME
P. HORODECKI & M. E. 1904.04117
THE EXPERIMENT PARADOX
• M = {EVENTS}
• ≤ - CAUSAL STRUCTURE
(PARTIAL ORDER REL.)
• SPLITTING
(NON UNIQUE!)
M ≃ I × Σ
I ⊂ ℝ
DYNAMICAL
NO-SIGNALLING
CAUSAL
ACAUSAL
ALICE
BOB
t
t'
x'
x


a) WHAT DOES IT MEAN TO EVOLVE CAUSALLY?
b) HOW IT AFFECTS THE MEASUREMENT STAT. ?
Σt
Σs
x
a) M. E & T. MILLER
1610.00764 (PRA)
CAUTION


K
μ
J⁺(K) = J⁺(K) ∩ Σ_t
THM: PARTIAL ORDER ✓
SPLITTING INDEP ✓
μ ≤ ν ⟺ ∃ ω ∈ P(M²): μ(A) = ω(A×M) ν(A) = ω(M×A)
& ω(J⁺) = 1 J⁺ = {(p,q) ∈ M² : p ≤ q}
EACH
IMAL PART OF THE PROB. DISTRIBUTION MUST TRAVEL ALONG
A
CAUSAL CURVE.



K
μ
$j^+(K) = J^+(K) \cap \Sigma_t$
THM: PARTIAL ORDER ✓
SPLITTING INDEP ✓
$\mu \preceq \nu \iff \exists\, \omega \in P(M^2)$: $\mu(A) = \omega(A \times M)$ $\nu(A) = \omega(M \times A)$
& $\omega(J^+) = 1$ $J^+ = \{(p,q) \in M^2 : p \preceq q\}$
EACH INFINITESIMAL PART OF THE PROB. DISTRIBUTION MUST TRAVEL ALONG A FUT.-DIR. CAUSAL CURVE.
b) $\mu(K)$ – PROBABILITY OF A CLICK IF ~~K~~ IS FILLED WITH DETECTORS.
$P_K(+|1) = \mu(K)$ $P(-|1) = 1 - \mu(K)$ $P(\phi|0) = 1$

$j^+(K) = J^+(K) \cap \Sigma_t$

THM: PARTIAL ORDER ✓
SPLITTING INDEP ✓

$\mu \preceq \nu \iff \exists\, \omega \in P(M^2)$: $\mu(A) = \omega(A \times M)$ $\quad \nu(A) = \omega(M \times A)$

& $\omega(J^+) = 1 \qquad J^+ = \{(p,q) \in M^2 : p \preceq q\}$

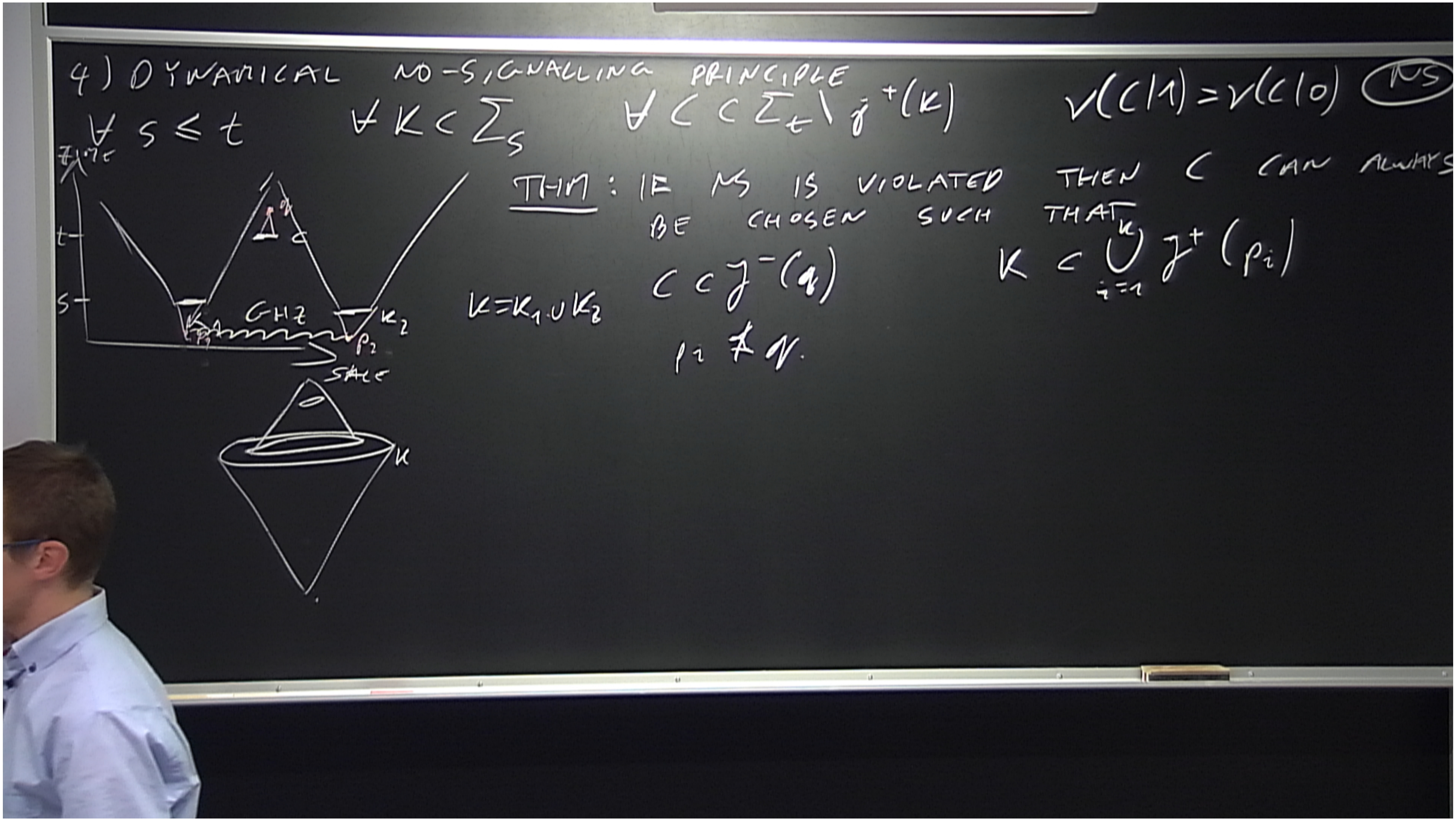
EACH INFINITESIMAL PART OF THE PROB. DISTRIBUTION MUST TRAVEL ALONG A FUT.-DIR. CAUSAL CURVE.

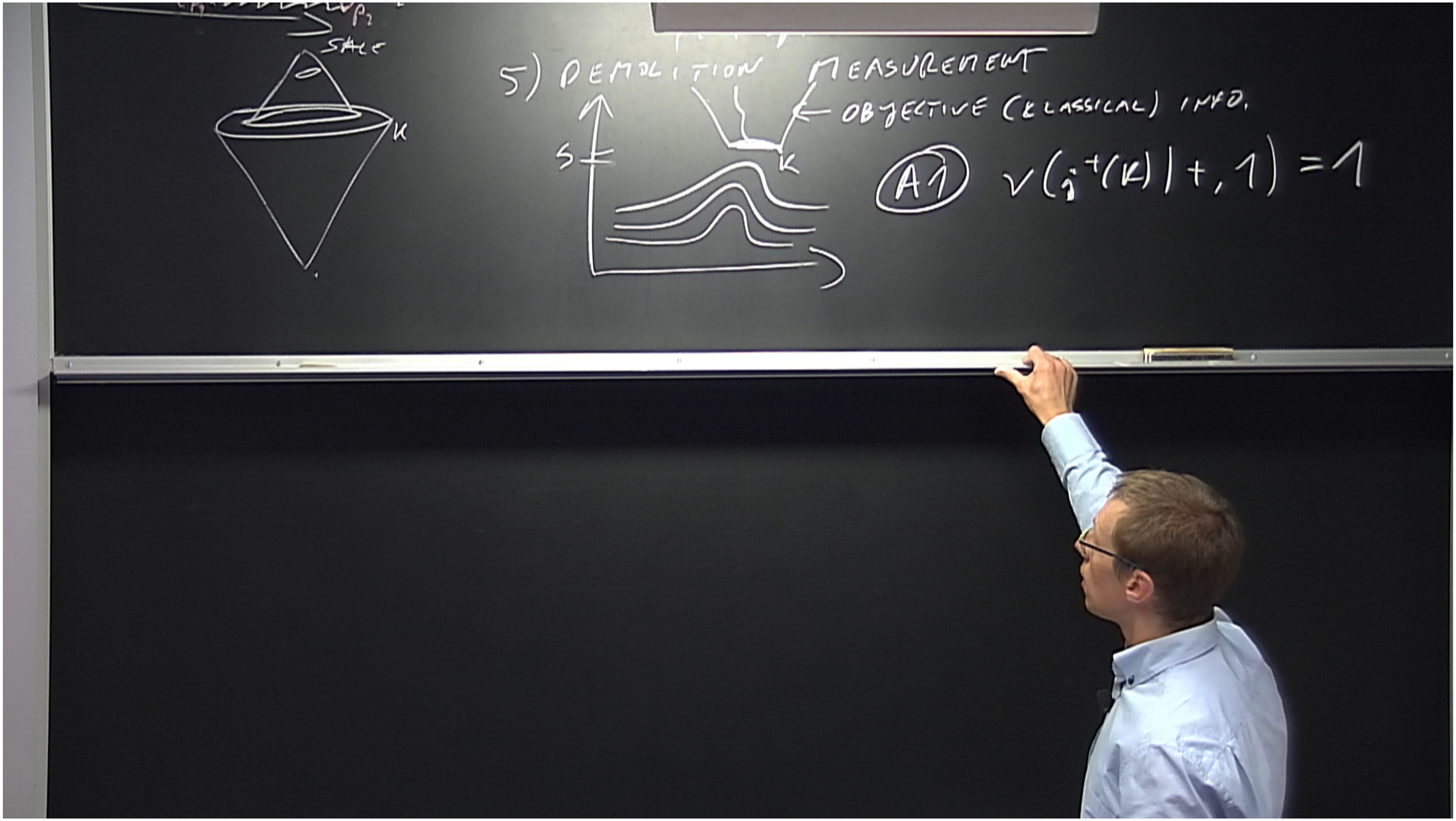
b) $\mu(K)$ – PROBABILITY OF A CLICK IF ~~K~~ IS FILLED WITH DETECTORS.

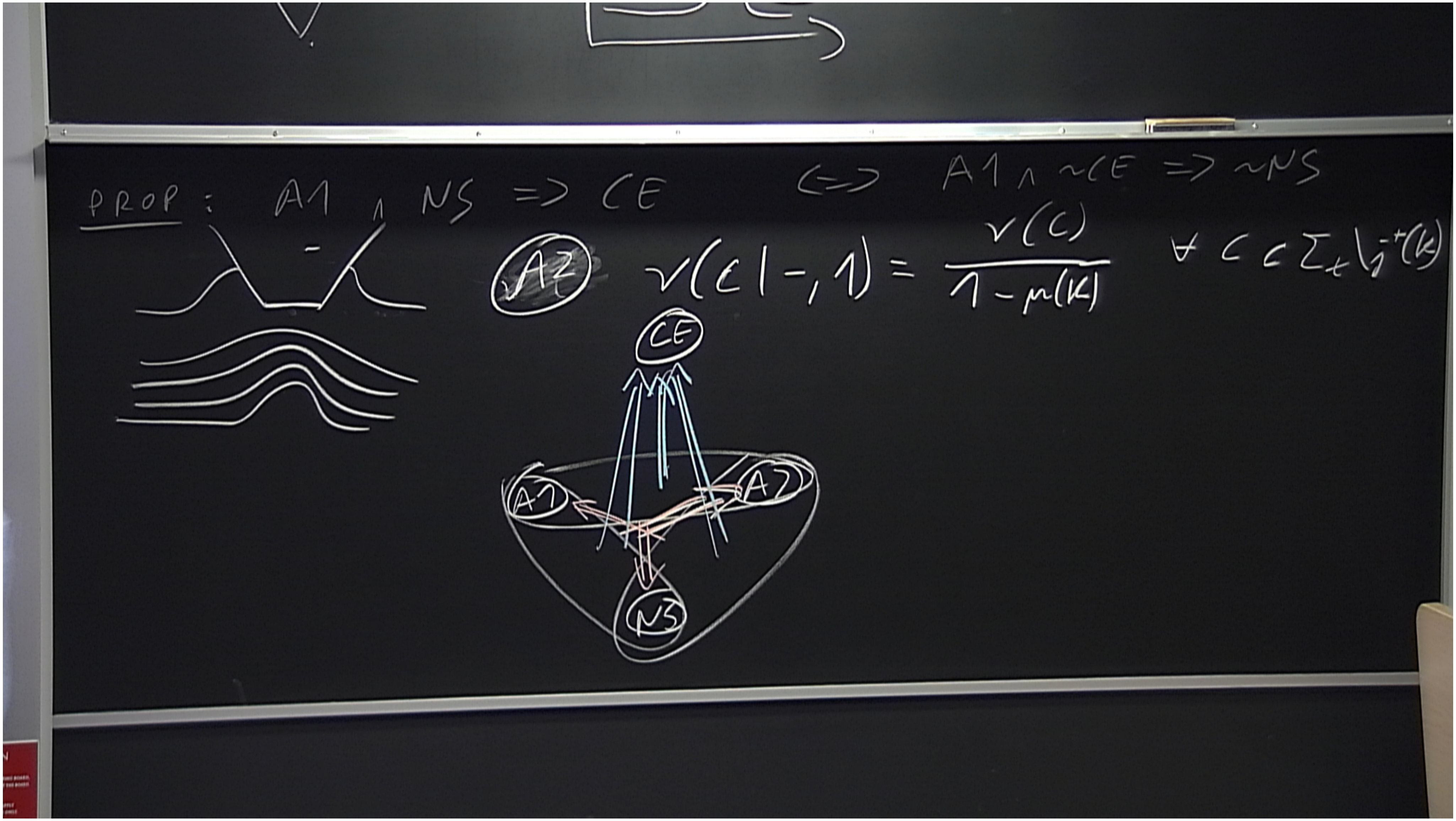
$P_K(+|1) = \mu(K) \qquad P(-|1) = 1 - \mu(K) \qquad P(\emptyset|0) = 1$

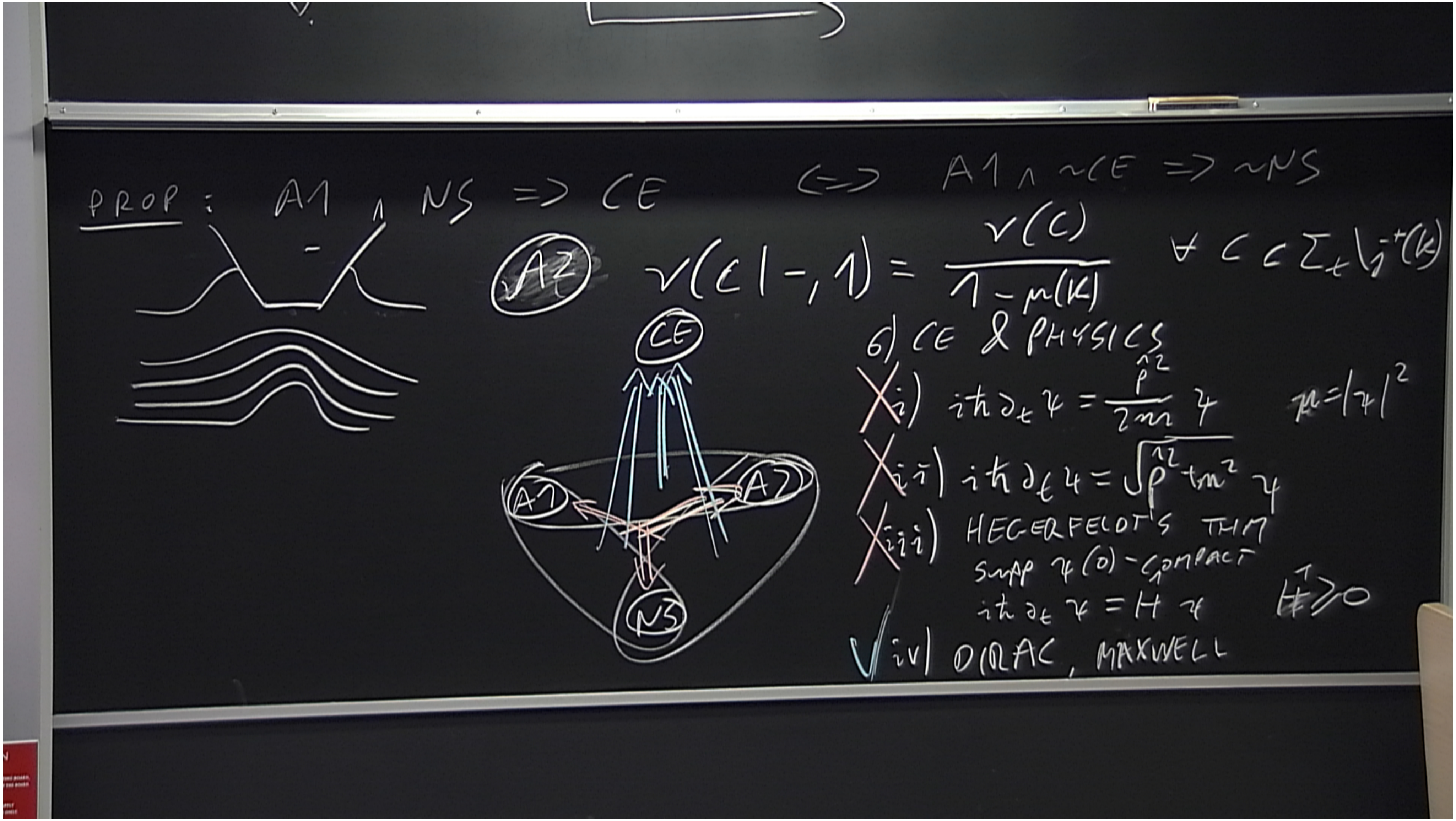
$\nu(\cdot|m_K)$ – PROBABILITY MEASURE AT t CONDITIONED BY MEASUREMENT IN K AT s

$\nu(\cdot|0) = \nu(\cdot) \qquad \| m_K$


4) DYNAMICAL NO-SIGNALLING PRINCIPLE
$\forall s \leq t \quad \forall K \subset \Sigma_s \quad \forall C \subset \Sigma_t \setminus J^+(K)$
$\nu(C|1) = \nu(C|0)$ NS
THM: IF NS IS VIOLATED THEN C CAN ALWAYS BE CHOSEN SUCH THAT
$C \subset J^-(q)$
$K \subset \bigcup_{i=1}^{k} J^+(p_i)$
$p_i \not< q$.
$K = K_1 \cup K_2$
TIME
t
s
GHZ
K_1
K_2
p_2
SPACE
K


SPACE
K
5) DEMOLITION MEASUREMENT
← OBJECTIVE (CLASSICAL) INFO.
S
K
A1 ν(j⁺(K) | +, 1) = 1


PROP: A1 ∧ NS => CE <=> A1 ∧ ~CE => ~NS
A2
v(c|-,1) = v(c) / (1 - μ(k)) ∀ c ∈ Σ_t \ j^{-+}(k)
CE
A1
A2
NS


PROP: A1 ∧ NS => CE <=> A1 ∧ ~CE => ~NS
A2 ν(c|−,1) = ν(c) / (1 − μ(K)) ∀ c ∈ Σ_t ∖ J⁻(K)
CE
A1
A2
NS
6) CE & PHYSICS
i) iħ∂_t ψ = p̂²/2m ψ
μ = |ψ|²
ii) iħ∂_t ψ = √(p̂² + m²) ψ
iii) HEGERFELDT'S THM
supp ψ(0) − compact
iħ∂_t ψ = Ĥ ψ
Ĥ ≥ 0
iv) DIRAC, MAXWELL