Title: Fundamental limits for realising quantum processes in spacetime

Speakers: Renato Renner

Series: Quantum Foundations, Quantum Information

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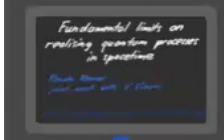
Abstract: Causality is a core concept in both General Relativity (GR) and Quantum Information Theory (QIT), yet it manifests differently in each domain. In GR, causal cones appear as a defining property of spacetime. Conversely, in QIT, causality relates to the abstract flow of information in quantum processes, independent of spacetime. This raises a crucial question: under what conditions can an abstract quantum process be realised within spacetime? The question is especially intriguing for quantum processes with indefinite causal structure, like the Quantum Switch, which resist classical causal descriptions. In this talk, I will present no-go theorems that reveal fundamental limitations on the realisability of such processes in spacetime and, thus, more generally, on the interplay between GR and QIT. This is based on joint work with V. Vilasini (Physical Review Letters, 133 080201, 2024).

FundamentalLimitsFinal.pdf
Page 1 of 19

Search

FundamentalLimitsF...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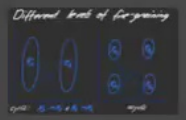
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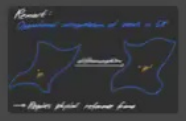
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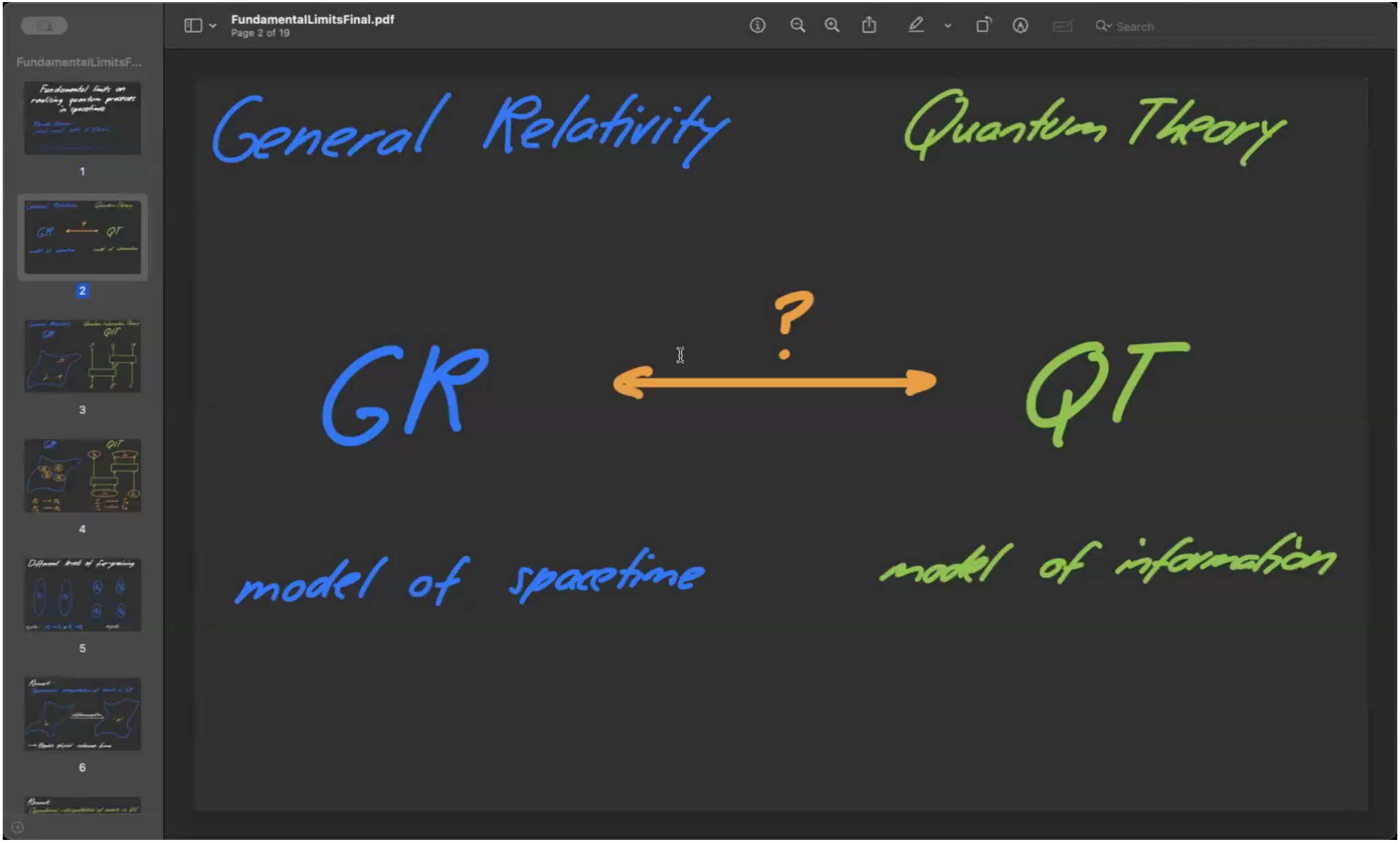
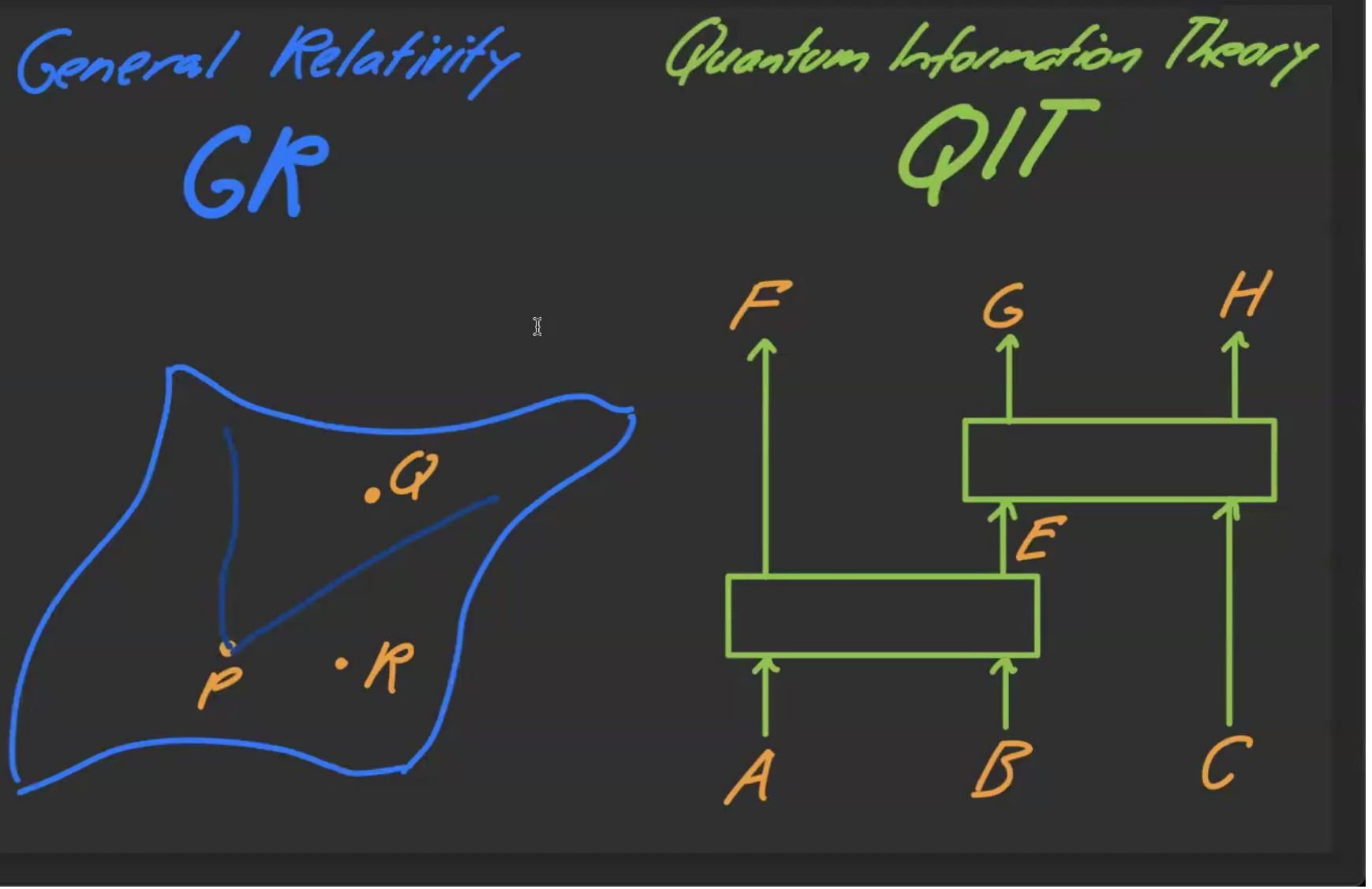
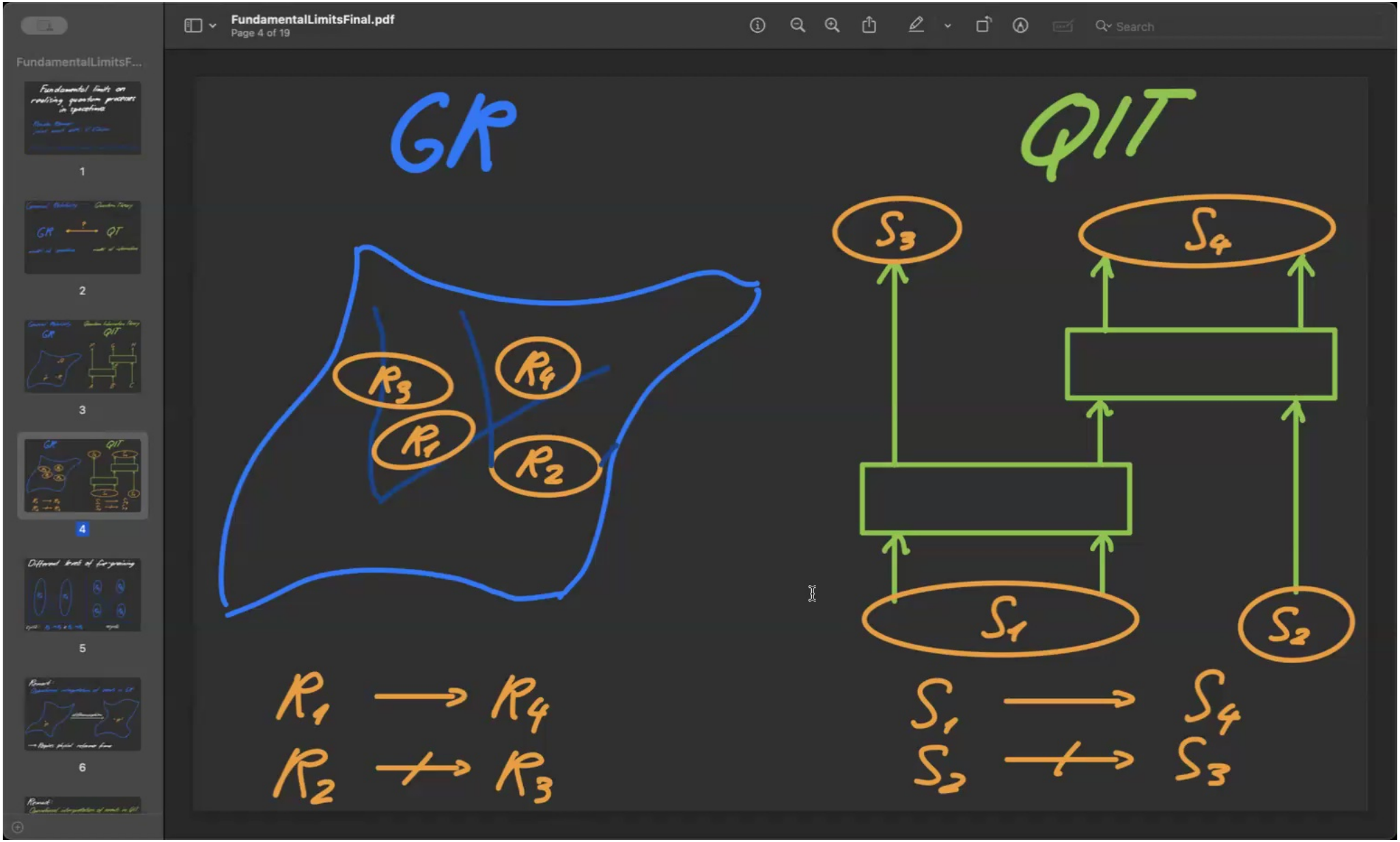
Fundamental limits on realising quantum processes in spacetime

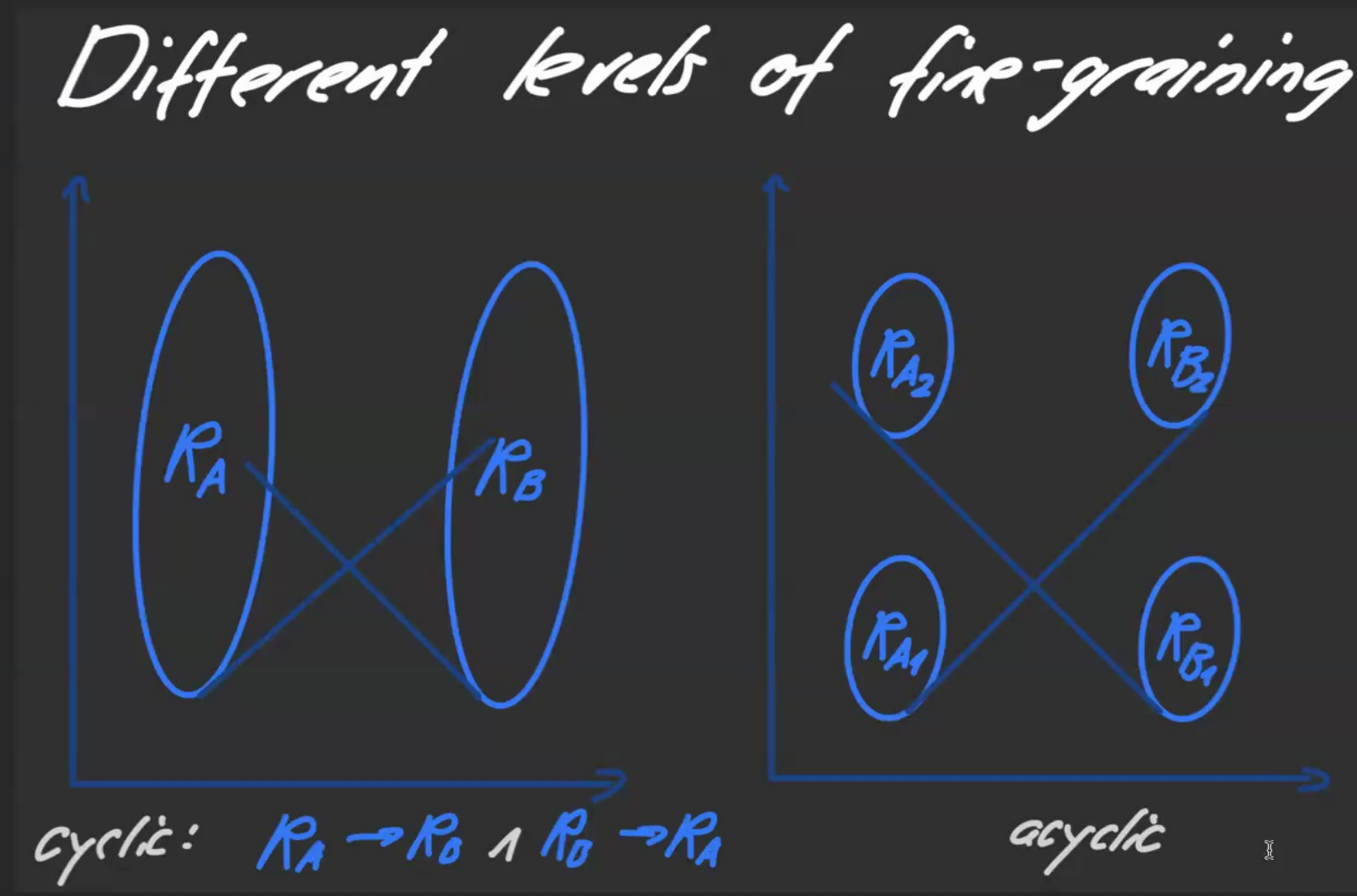
Renato Renner
joint work with V. Vilasini

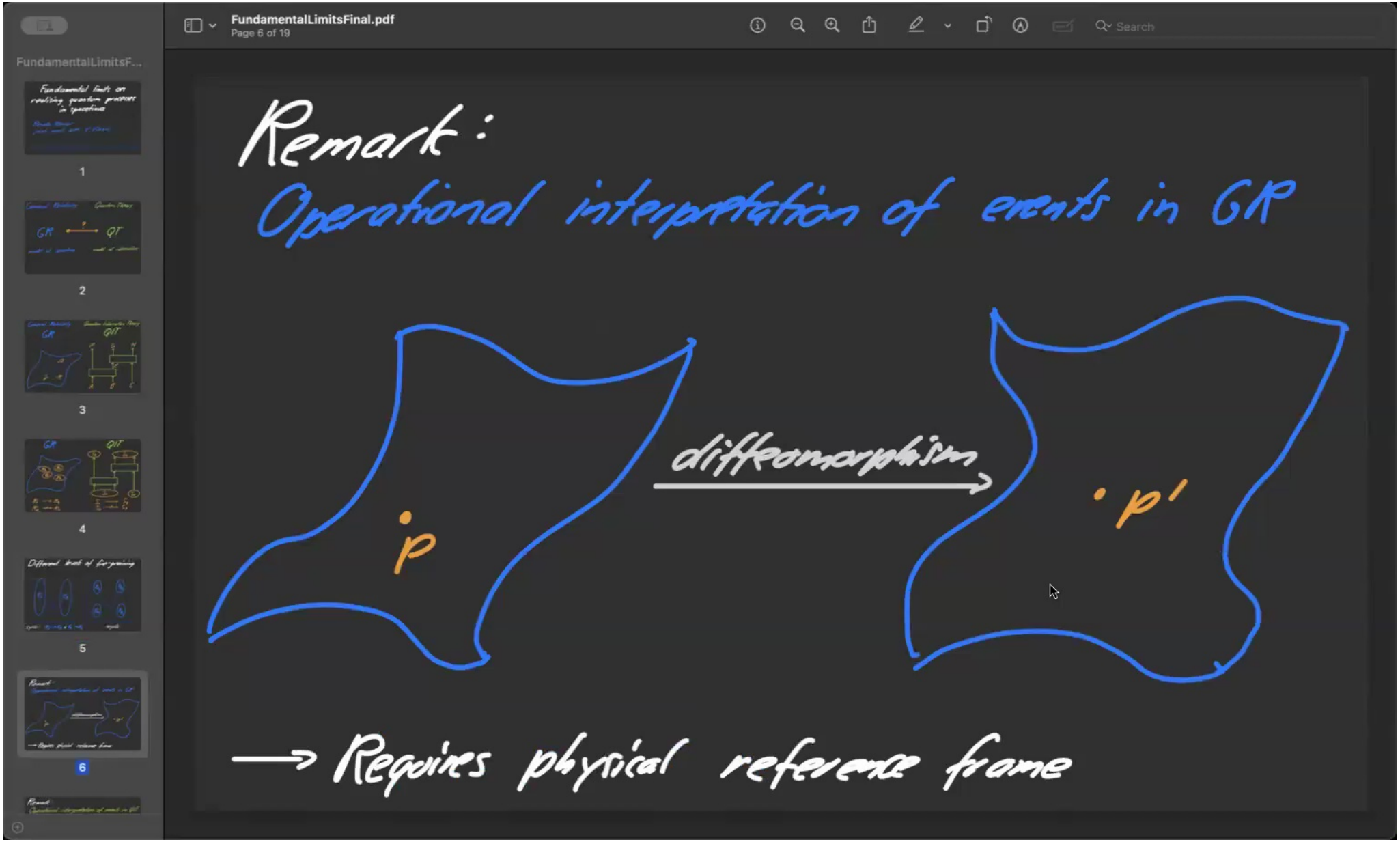
PRL 133, 080201, 2024 (arXiv:2408.13387)

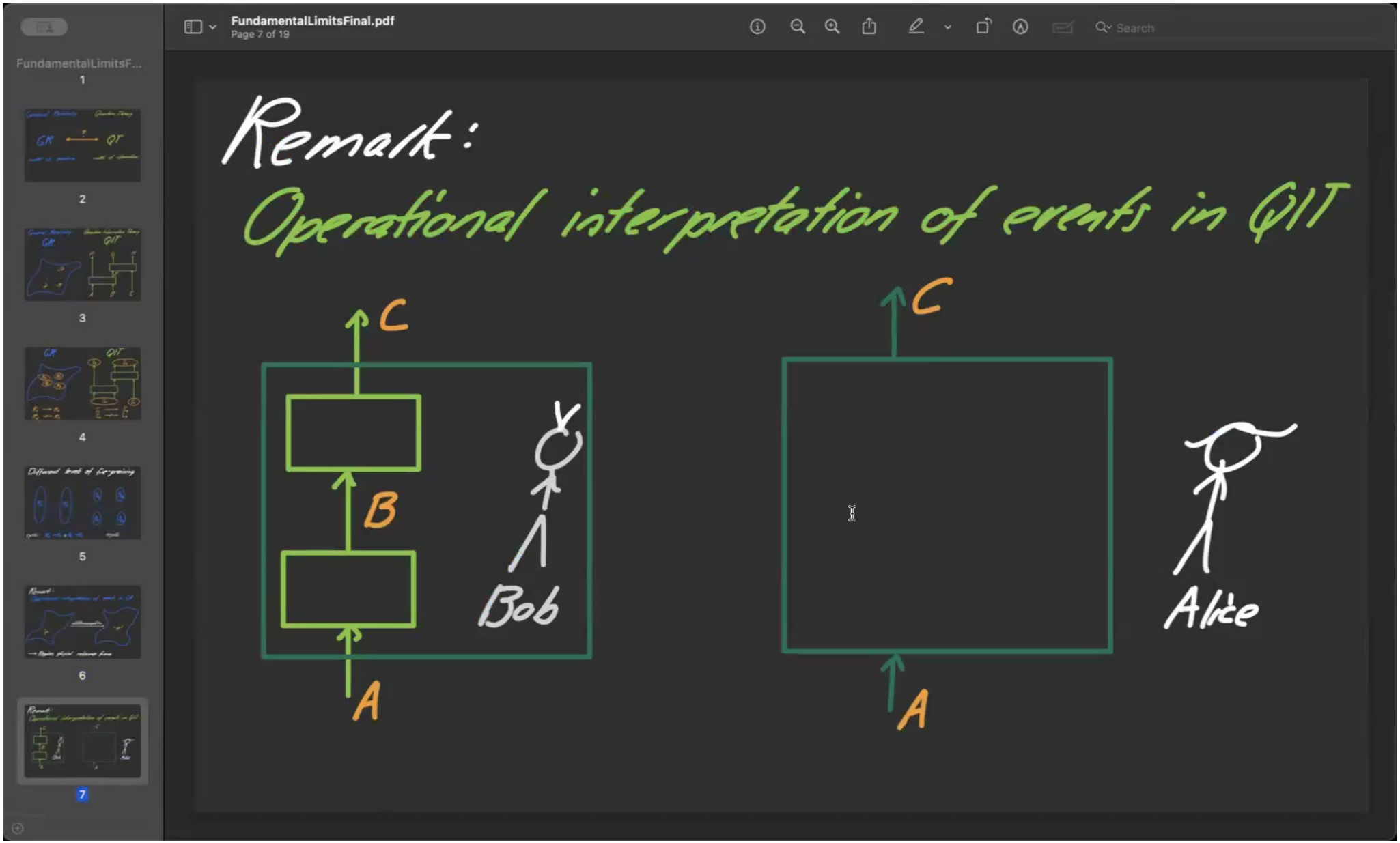

FundamentalLimitsFinal.pdf
Page 2 of 19
Search
General Relativity
Quantum Theory
GR
?
QT
model of spacetime
model of information

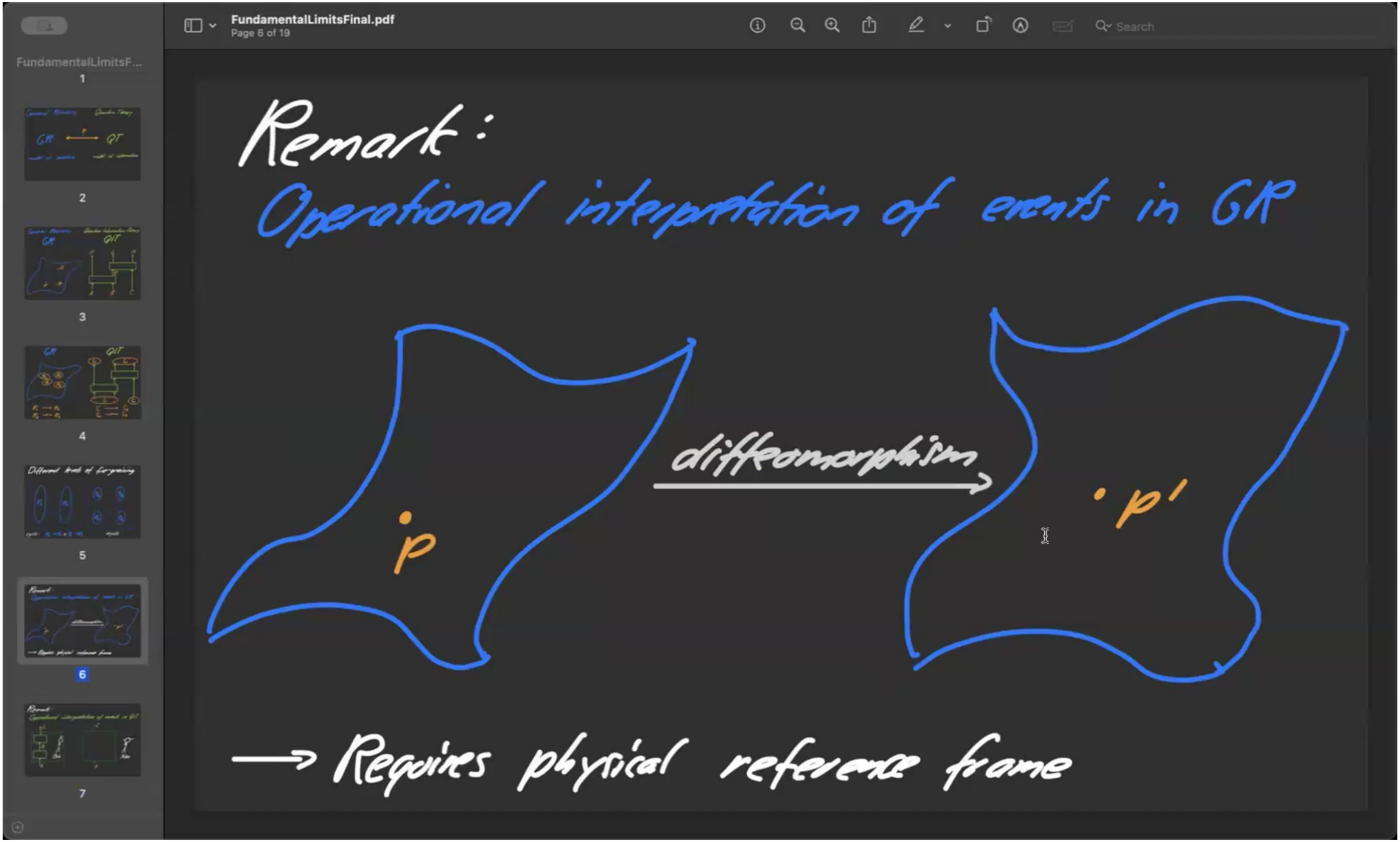

General Relativity
GR
Quantum Information Theory
QIT
Q
P
R
F
G
H
E
A
B
C

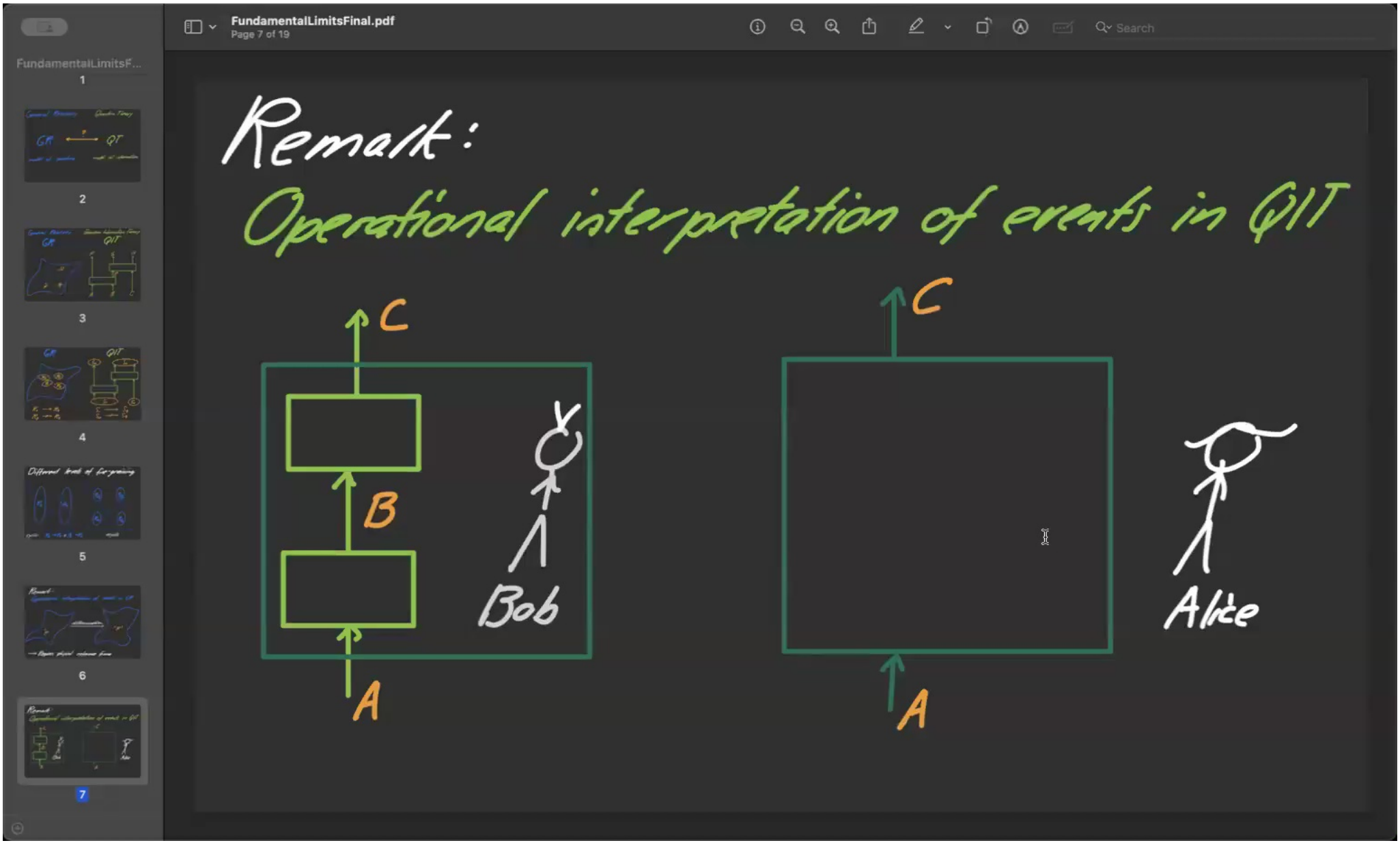

FundamentalLimitsFinal.pdf
Page 4 of 19
Search
FundamentalLimitsF...
1
2
3
4
5
6
GR
QIT
R_3
R_4
R_1
R_2
S_3
S_4
S_1
S_2
$R_1 \longrightarrow R_4$
$R_2 \not\longrightarrow R_3$
$S_1 \longrightarrow S_4$
$S_2 \not\longrightarrow S_3$

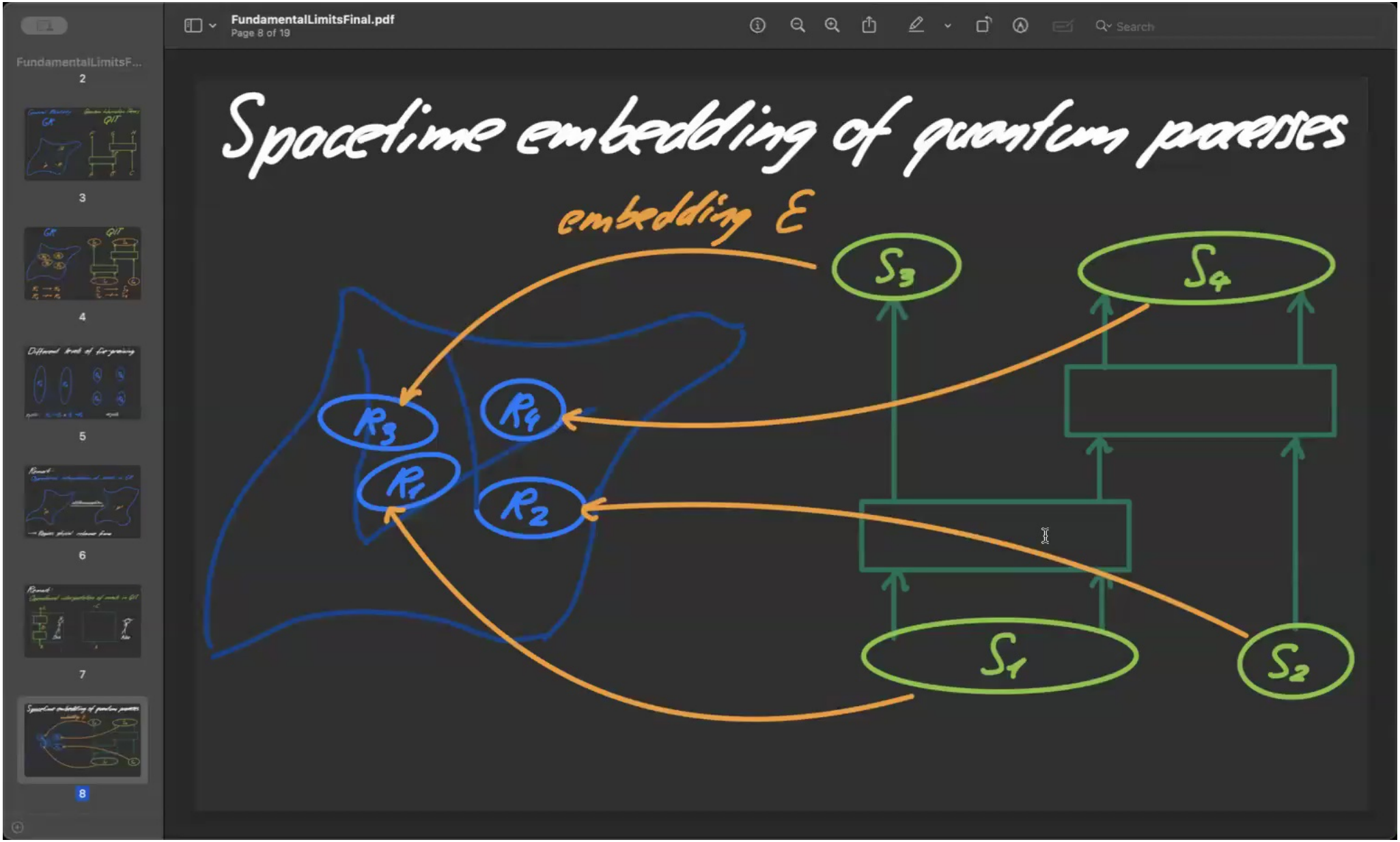

Different levels of fine-graining
R_A
R_B
R_{A_2}
R_{B_2}
R_{A_1}
R_{B_1}
cyclic: $R_A \to R_B$ & $R_B \to R_A$
acyclic

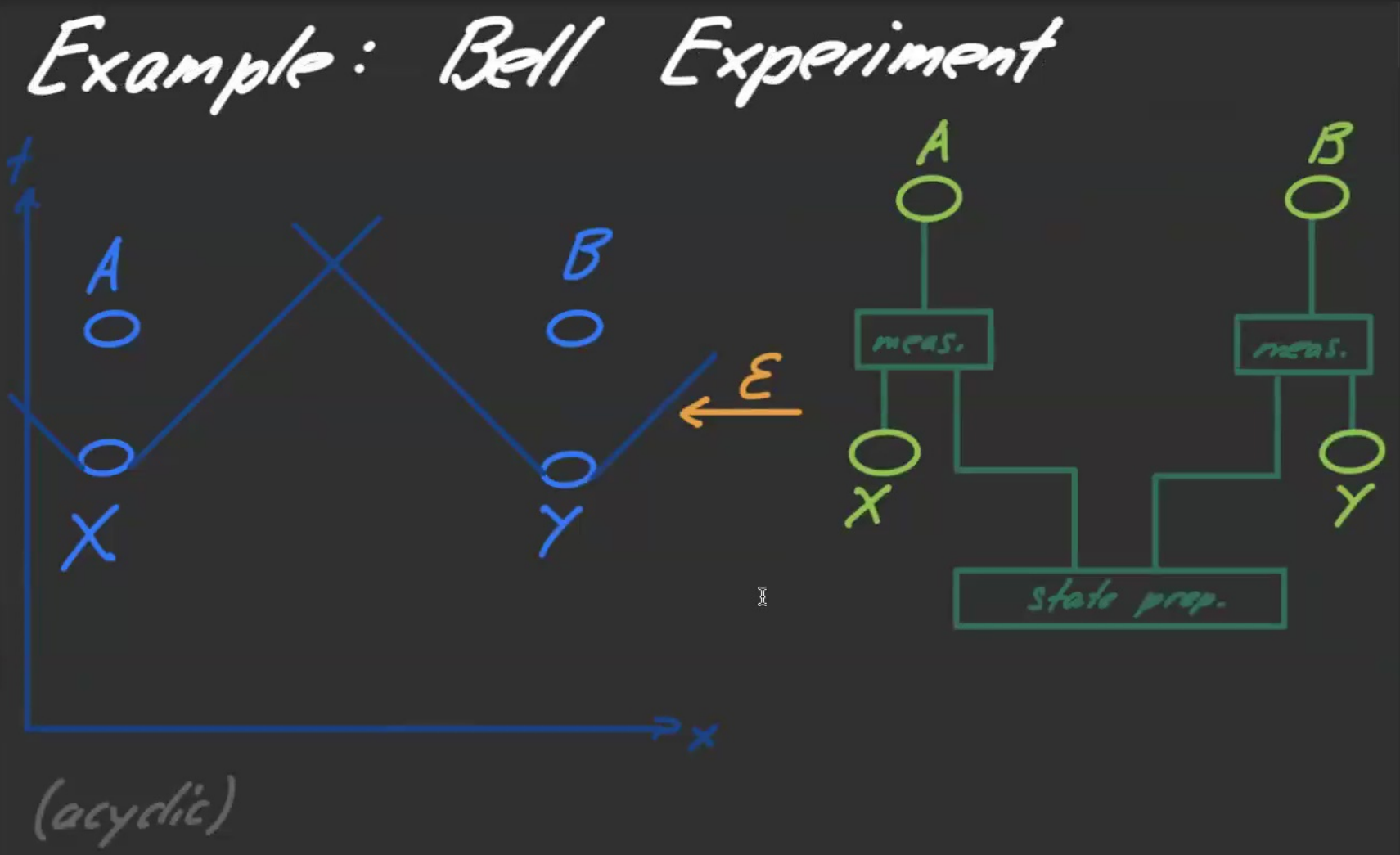

Remark:
Operational interpretation of events in GR
diffeomorphism
p
p'
→ Requires physical reference frame

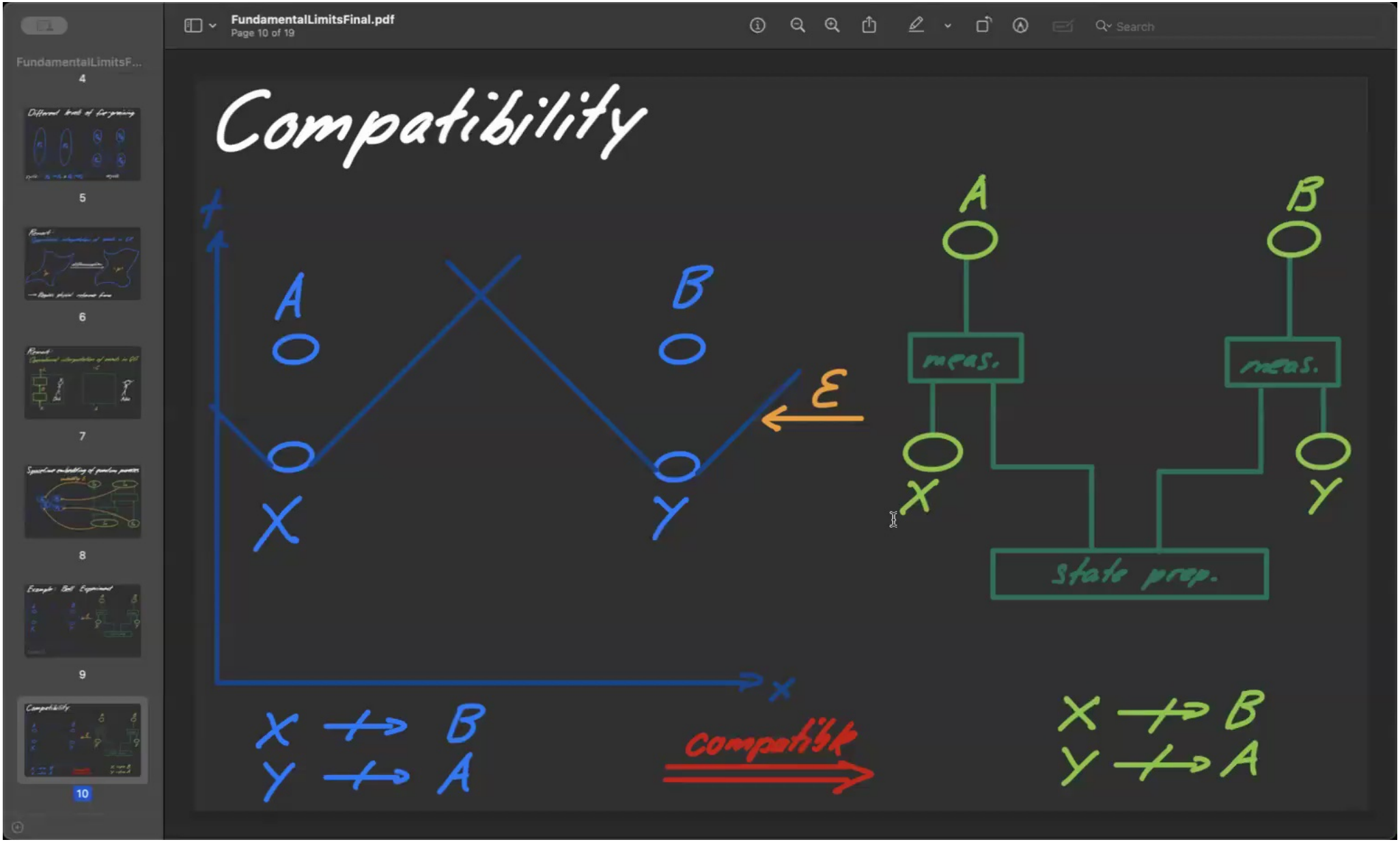

Remark:
Operational interpretation of events in QIT
C
B
A
Bob
C
A
Alice

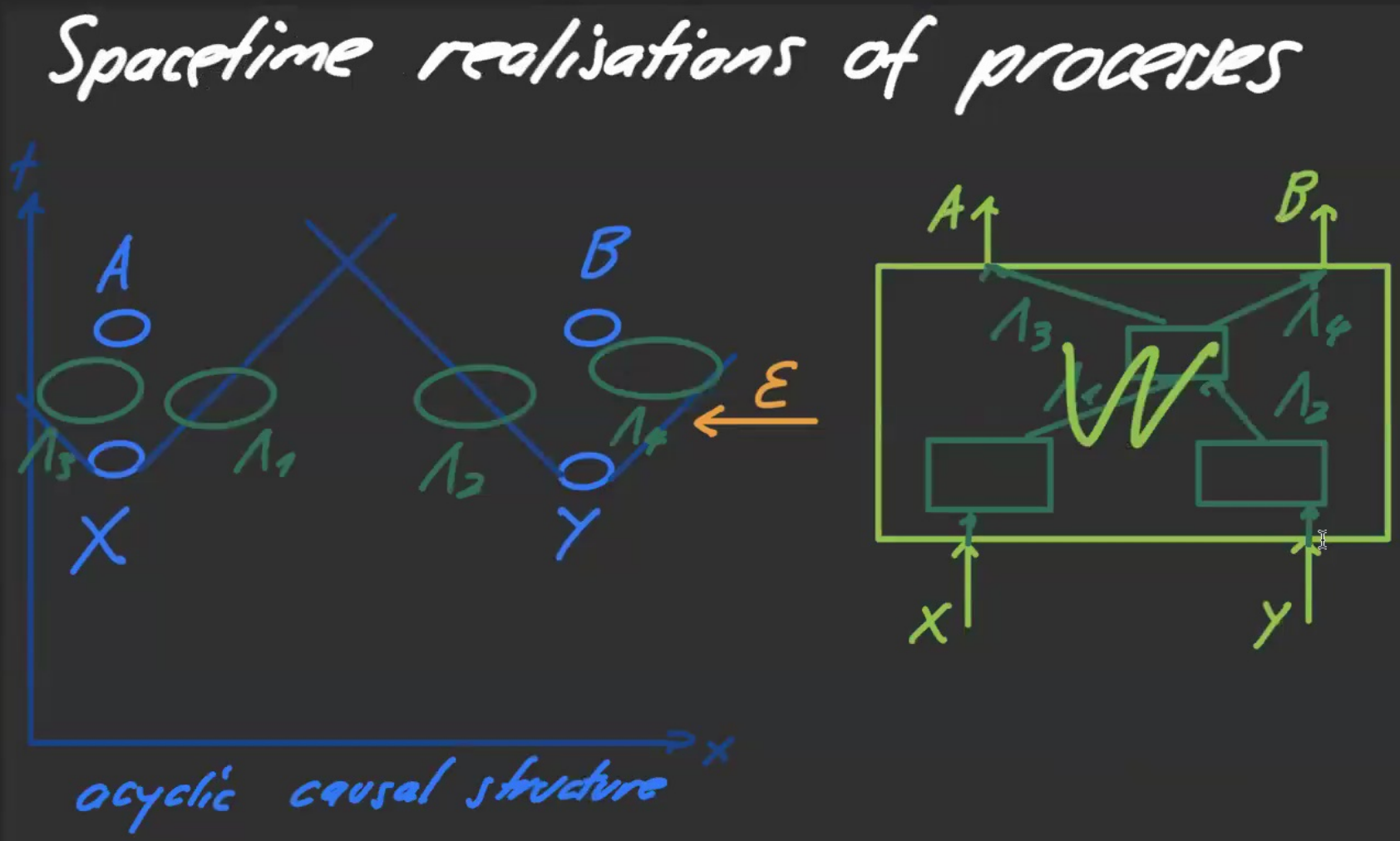

Remark:
Operational interpretation of events in GR
diffeomorphism
p
p'
→ Requires physical reference frame

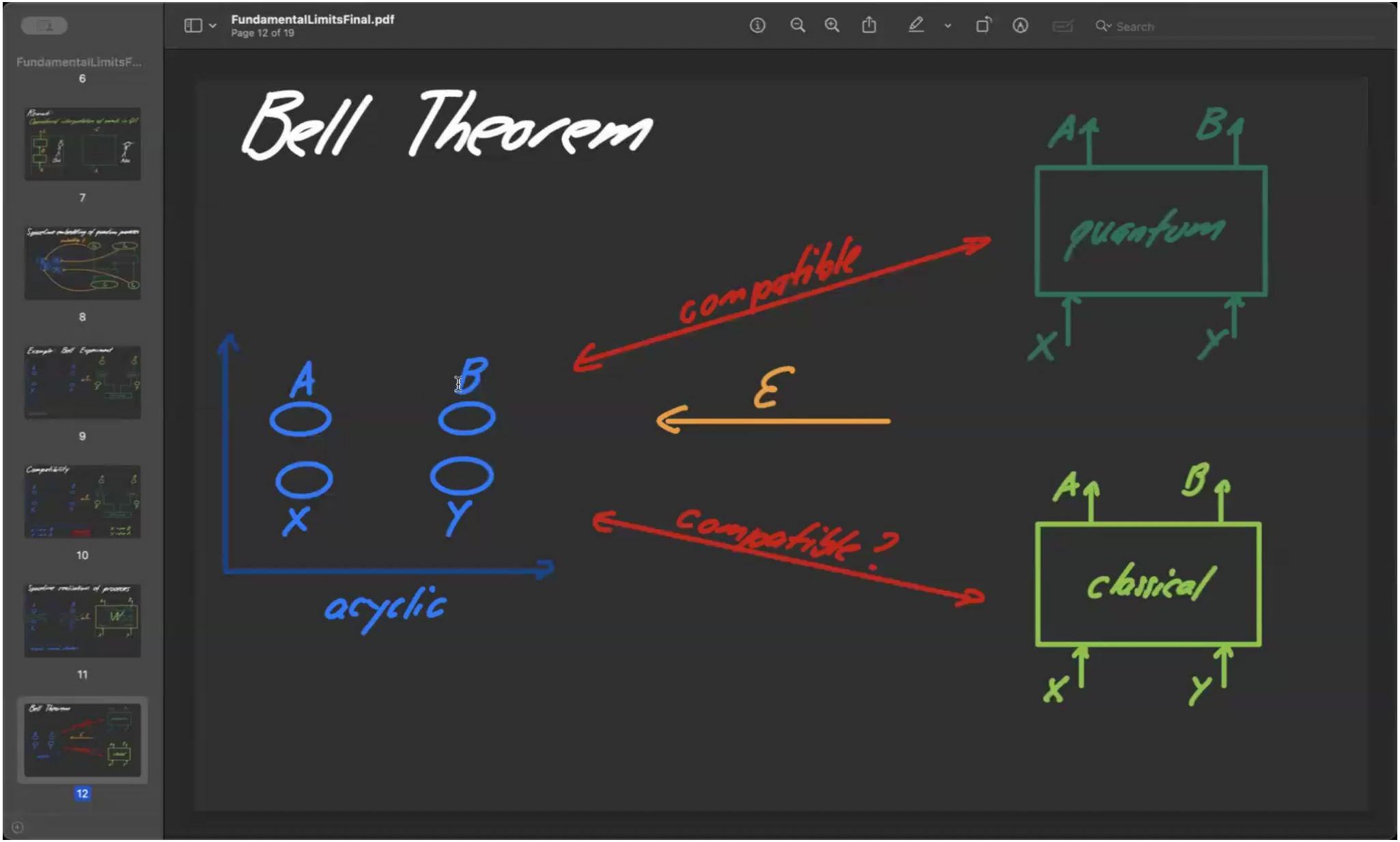

Remark:
Operational interpretation of events in QIT
C
B
A
Bob
C
A
Alice


FundamentalLimitsFinal.pdf
Page 8 of 19
Search
Spacetime embedding of quantum processes
embedding E
S_3
S_4
R_3
R_4
R_1
R_2
S_1
S_2

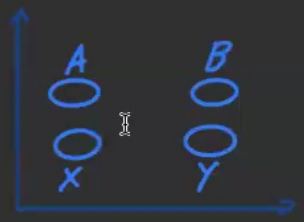

Example: Bell Experiment
t
A
B
X
Y
x
ε
(acyclic)
A
B
meas.
meas.
X
Y
state prep.

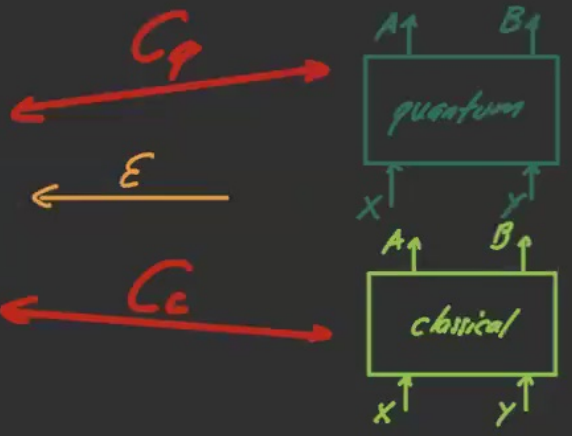

FundamentalLimitsFinal.pdf
Page 10 of 19
Search
FundamentalLimitsF...
4
5
6
7
8
9
10
Compatibility
t
A
B
X
Y
ε
x
meas.
meas.
state prep.
X ↦ B
Y ↦ A
compatible
X ↦ B
Y ↦ A


Spacetime realisations of processes
t
A
B
Λ_3
Λ_1
Λ_2
Λ_4
ε
X
Y
x
acyclic causal structure
A
B
Λ_3
Λ_4
W
Λ_1
Λ_2
x
y


FundamentalLimitsFinal.pdf
Page 12 of 19
Search
FundamentalLimitsF...
6
7
8
9
10
11
12
Bell Theorem
A
B
X
Y
acyclic
compatible
ε
Compatible ?
A
B
quantum
X
Y
A
B
classical
X
Y

Bell Theorem





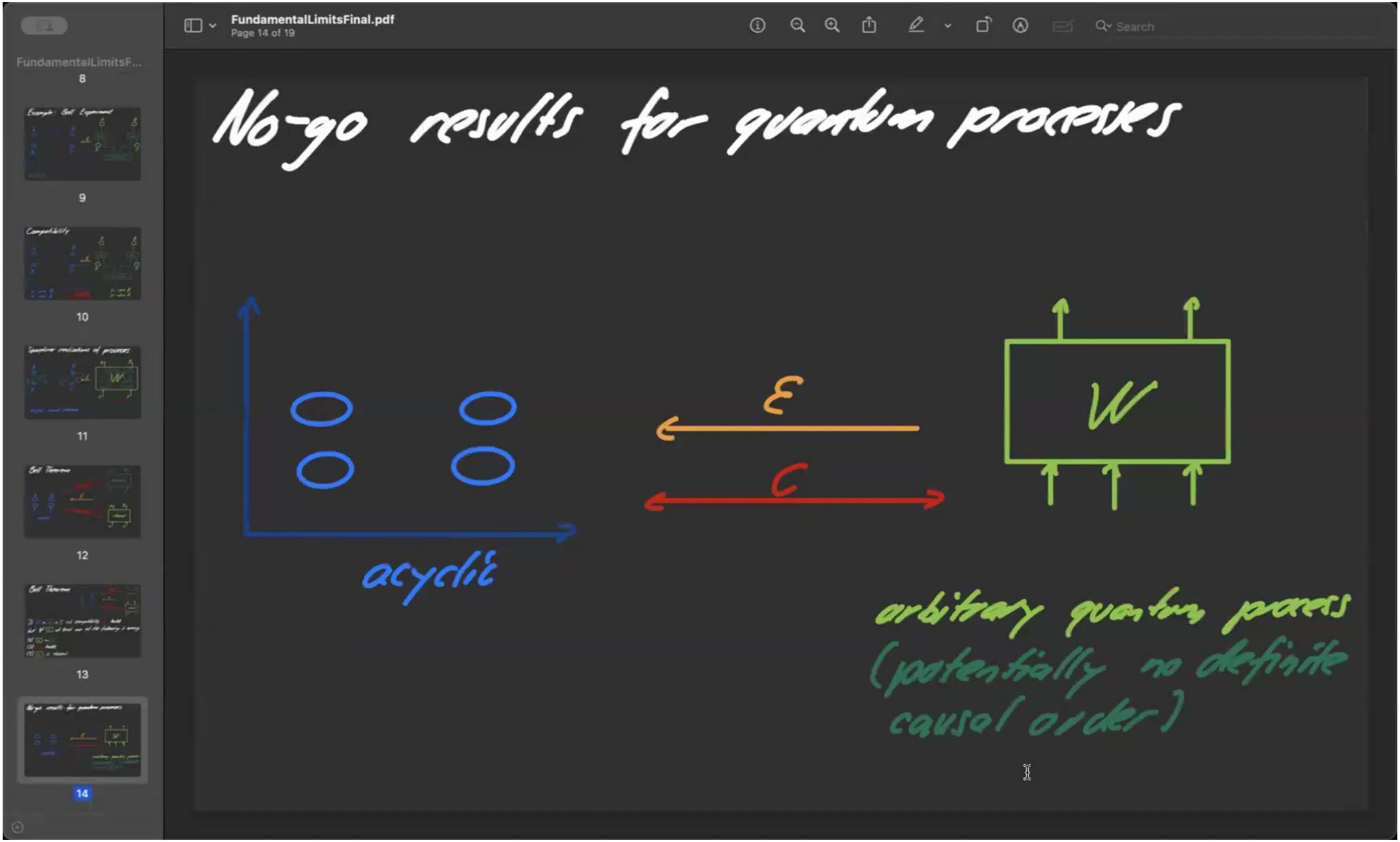
$\exists$ ρ $\wedge$ q $\wedge$ ε s.t. compatibility C_q holds

but if c at least one of the following is wrong

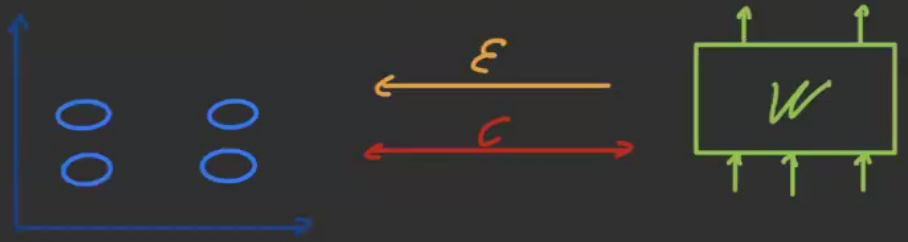
(1) $c \sim q$

(2) C_c holds

(3) c is classical


No-go results for quantum processes
acyclic
W
arbitrary quantum process
(potentially no definite
causal order)

First main result

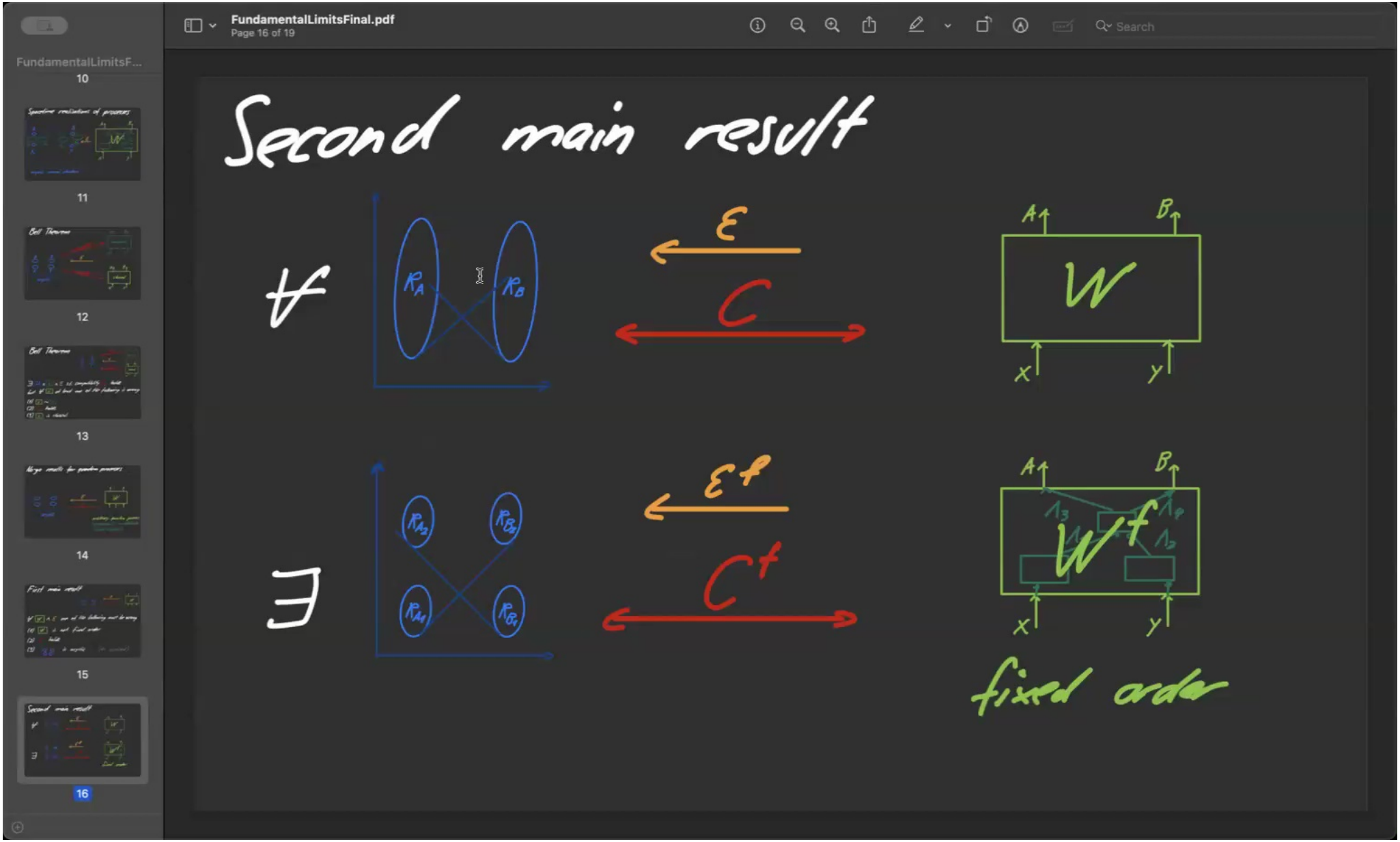


If W ∧ ε one of the following must be wrong

(1) W is not fixed order

(2) C holds

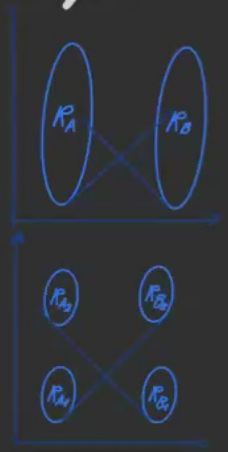
(3)  is acyclic (⇐ localised)

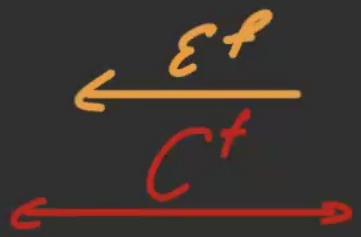

Second main result
∀
R_A
R_B
ε
C
A
B
W
x
y
∃
R_{A_2}
R_{B_2}
R_{A_1}
R_{B_1}
ε^f
C^f
W^f
fixed order

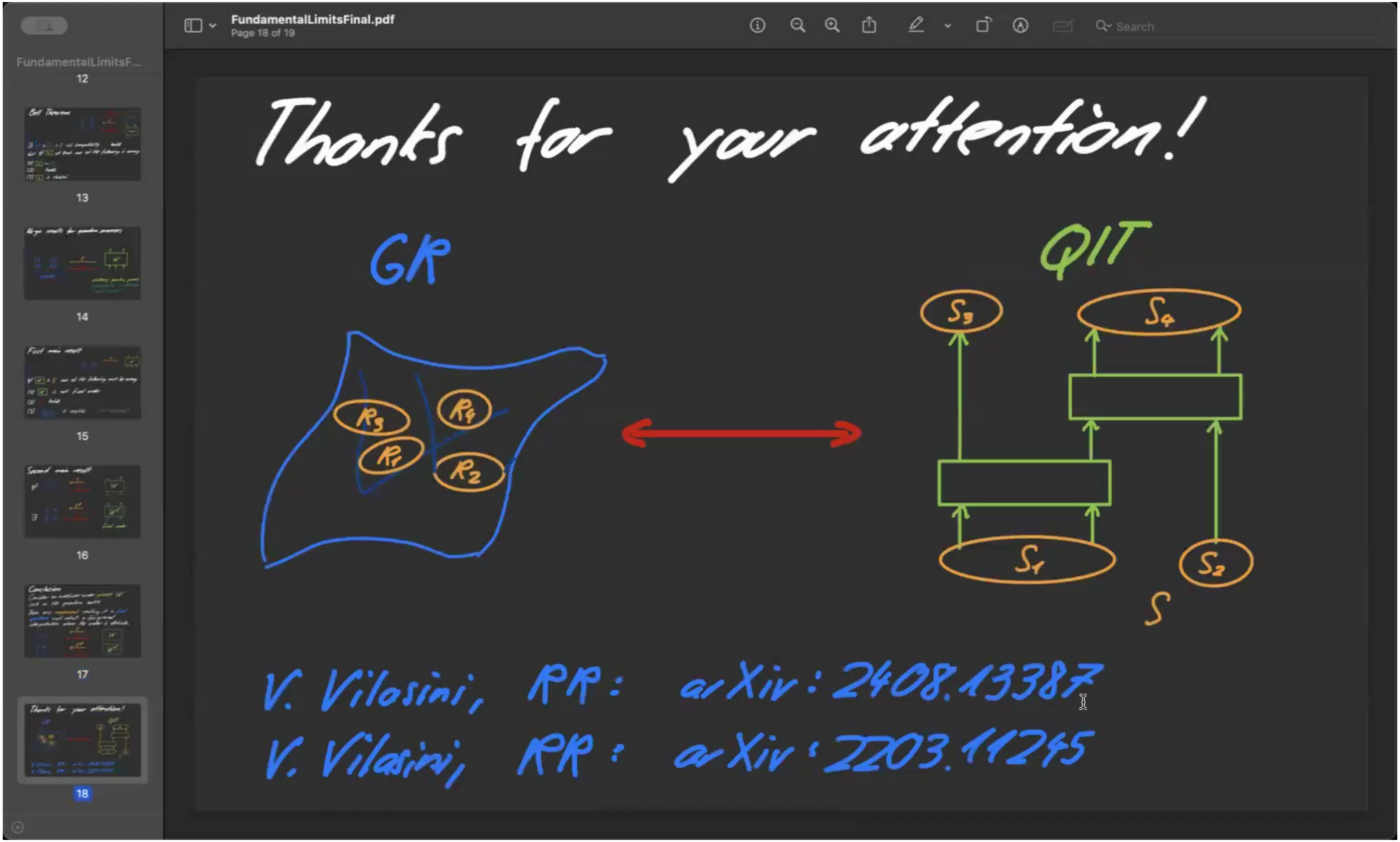
Conclusion

Consider an indefinite-order process W such as the quantum switch.

Then any experiment realising it in fixed spacetime must admit a fine-grained interpretation where the order is definite.






Thanks for your attention!
GR
QIT
S_3
S_4
S_1
S_2
S
V. Vilasini, RR: arXiv: 2408.13387
V. Vilasini, RR: arXiv: 2203.11245