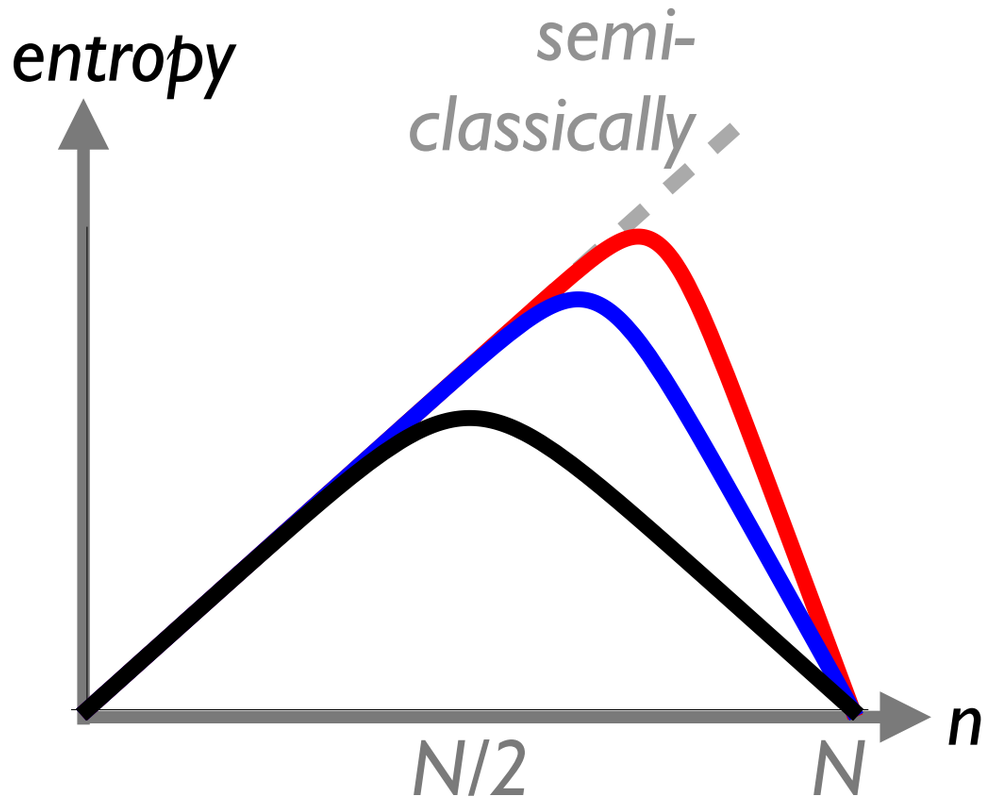
# The Page curve from less than the full quantum formalism

Markus P. Müller

Departments of Applied Mathematics and Philosophy, UWO

Perimeter Institute for Theoretical Physics, Waterloo




$r = 1$ : classical prob. theory

$r = 2$ : quantum theory

$r = 3$ : ???

$r = 4$ : ???

# Motivation

The black-hole information paradox has motivated
some people to consider modifications of quantum theory.

# Motivation

The black-hole information paradox has motivated some people to consider modifications of quantum theory.

**The black hole final state**

**Gary T. Horowitz**

*University of California at Santa Barbara*
*Santa Barbara, CA 93106, U.S.A.*
*E-mail:* gary@physics.ucsb.edu

**Juan Maldacena**

*Institute for Advanced Study*
*Princeton, New Jersey 08540, U.S.A.*
*E-mail:* malda@ias.edu

Abstract: We propose that in quantum gravity one needs to impose a final state boundary condition at black hole singularities. This resolves the apparent contradiction between string theory and semiclassical arguments over whether black hole evaporation is unitary.

Keywords: Black Holes in String Theory, AdS-CFT and dS-CFT Correspondence, Black Holes.

JHEP02(2004)008

# Motivation

The black-hole information paradox has motivated some people to consider modifications of quantum theory.

The bl

Gary T. H
Universit
Santa Ba
E-mail: g

Juan Mald
Institute
Princeto
E-mail: m

Abstract
condition a
string theo

Keyword
Black Hole

## Comment on "The black hole final state"

**Daniel Gottesman**

*Perimeter Institute*
*Waterloo ON N2V 1Z3, Canada*
*E-mail:* dgottesman@perimeterinstitute.ca

**John Preskill**

*Institute for Quantum Information, California Institute of Technology*
*Pasadena, CA 91125, U.S.A.*
*E-mail:* preskill@theory.caltech.edu

Abstract: Horowitz and Maldacena have suggested that the unitarity of the black hole $S$-matrix can be reconciled with Hawking's semiclassical arguments if a final-state boundary condition is imposed at the spacelike singularity inside the black hole. We point out that, in this scenario, departures from unitarity can arise due to interactions between the collapsing body and the infalling Hawking radiation inside the event horizon. The amount of information lost when a black hole evaporates depends on the extent to which these interactions are entangling.

JHEP03(2004)026

# Motivation

Ad-hoc modifications of QT's formalism have proven to be problematic in general…

ANNALS OF PHYSICS 194, 336–386 (1989)

## Testing Quantum Mechanics

STEVEN WEINBERG*

*Theory Group, Department of Physics,*
*University of Texas, Austin, Texas 78712*

Received March 6, 1989

This paper presents a general framework for introducing nonlinear corrections into ordinary quantum mechanics, that can serve as a guide to experiments that would be sensitive to such corrections. In the class of generalized theories described here, the equations that determine the time-dependence of the wave function are no longer linear, but are of Hamiltonian type. Also, wave functions that differ by a constant factor represent the same physical state and satisfy the same time-dependence equations. As a result, there is no difficulty in combining separated subsystems. Prescriptions are given for determining the states in which observables have definite values and for calculating the expectation values of observables for general states, but the calculation of probabilities requires detailed analysis

# Motivation

Ad-hoc modifications of QT's formalism have proven to be problematic in general…

ANN Volume 143, number 1,2 PHYSICS LETTERS A 1 January 1990

## WEINBERG'S NON-LINEAR QUANTUM MECHANICS AND SUPRALUMINAL COMMUNICATIONS

N. GISIN
*Group on Applied Physics, University of Geneva, 1211 Geneva 4, Switzerland*

Received 16 October 1989; accepted for publication 3 November 1989
Communicated by J.P. Vigier

We show with an example that Weinberg's general framework for introducing non-linear corrections into quantum mechanics allows for arbitrarily fast communications.

Recently Weinberg has proposed a general framework for introducing non-linear corrections into ordinary quantum mechanics [1,2]. Although we fully support his emphasis on the importance of testing quantum mechanics, we would like in this Letter to draw attention to the difficulty of modifying quantum mechanics without introducing arbitrarily fast actions at a distance. Below we show how to construct, within Weinberg's framework, an arbitrarily fast telephone line. In ordinary quantum mechanics

to know what such an apparatus is... do you know what is inside your phone?) In order to simplify we consider only a single-bit message. The two directions $z$ and $u$ are in the $xz$-plane orthogonal to the incoming flow of particles, and are 45° from each other. The way the inhomogeneous magnetic field acts on the particles is well-known from experimental evidence. After the apparatus there are two counters. For each particle one of the counters will click. This click will be amplified until all readers of

# Motivation

Ad-hoc modifications of QT's formalism have proven to be problematic in general…

ANN Volume 143, number 1,2 PHYSICS LETTERS A 1 January 1990

## WEINBERG'S NON-LINEAR QUANTUM MECHANICS

**Work on the level of physical principles, not of the formalism!**

Communicated by J.P. Vigier

We show with an example that Weinberg's general framework for introducing non-linear corrections into quantum mechanics allows for arbitrarily fast communications.

Recently Weinberg has proposed a general framework for introducing non-linear corrections into ordinary quantum mechanics [1,2]. Although we fully support his emphasis on the importance of testing quantum mechanics, we would like in this Letter to draw attention to the difficulty of modifying quantum mechanics without introducing arbitrarily fast actions at a distance. Below we show how to construct, within Weinberg's framework, an arbitrarily fast telephone line. In ordinary quantum mechanics

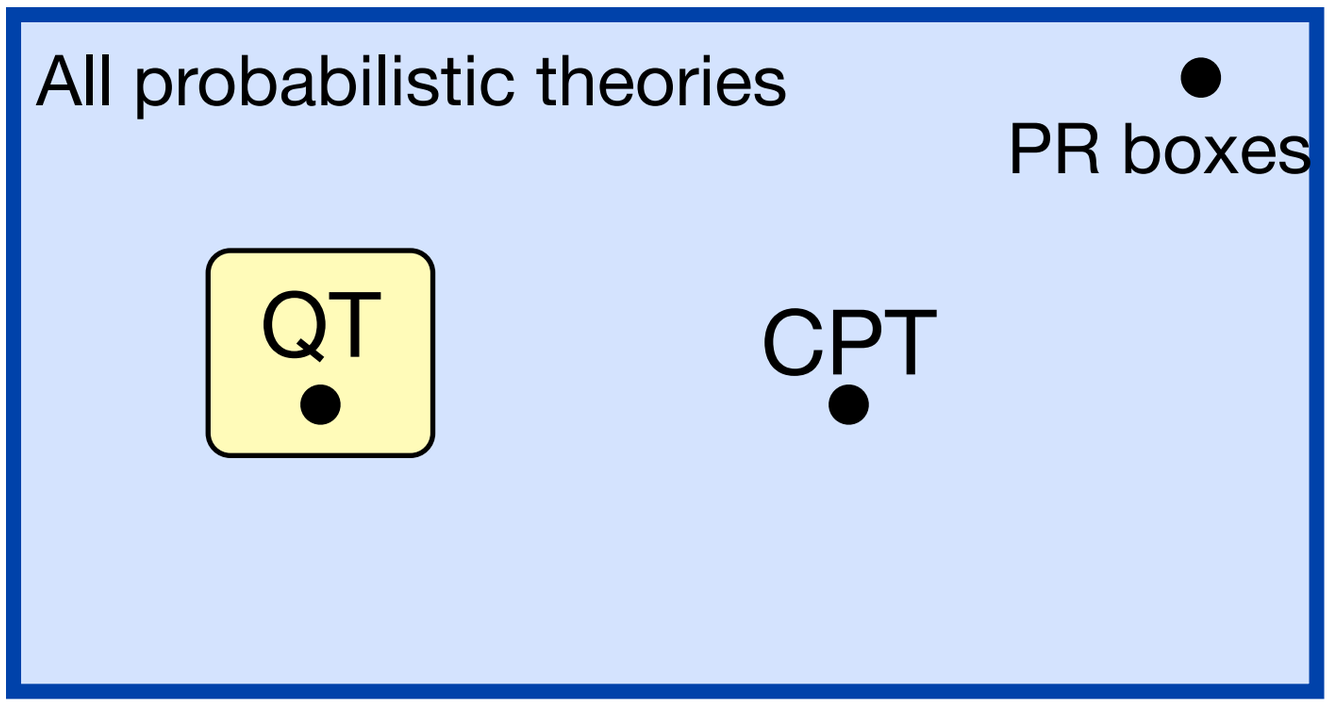
to know what such an apparatus is... do you know what is inside your phone?) In order to simplify we consider only a single-bit message. The two directions $z$ and $u$ are in the $xz$-plane orthogonal to the incoming flow of particles, and are 45° from each other. The way the inhomogeneous magnetic field acts on the particles is well-known from experimental evidence. After the apparatus there are two counters. For each particle one of the counters will click. This click will be amplified until all readers of

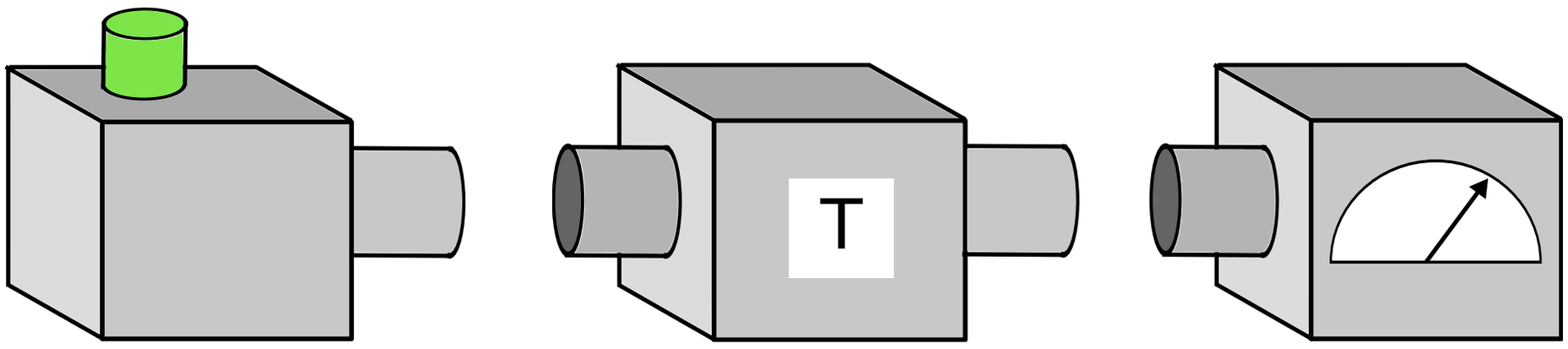
# Our approach

**MM**, J. Oppenheim, and O. Dahlsten, JHEP **09**, 116 (2012)

# Our approach

**MM**, J. Oppenheim, and O. Dahlsten, JHEP **09**, 116 (2012)

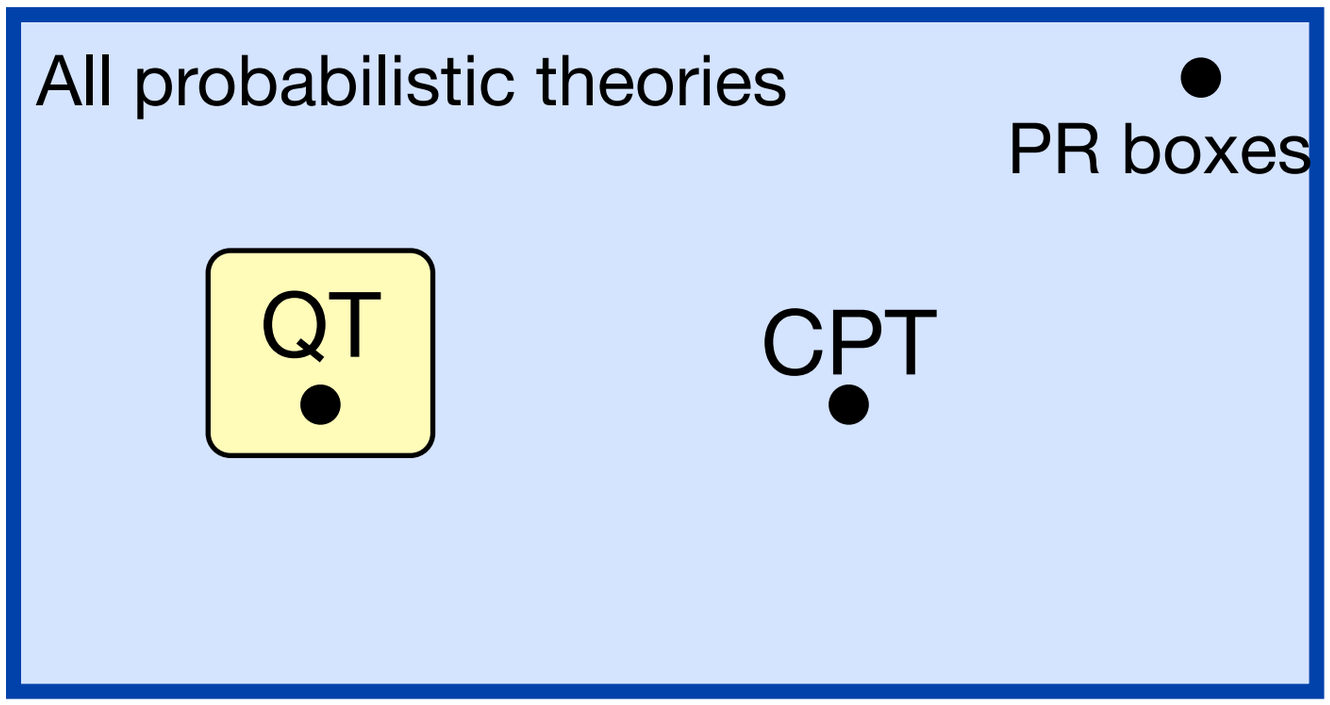


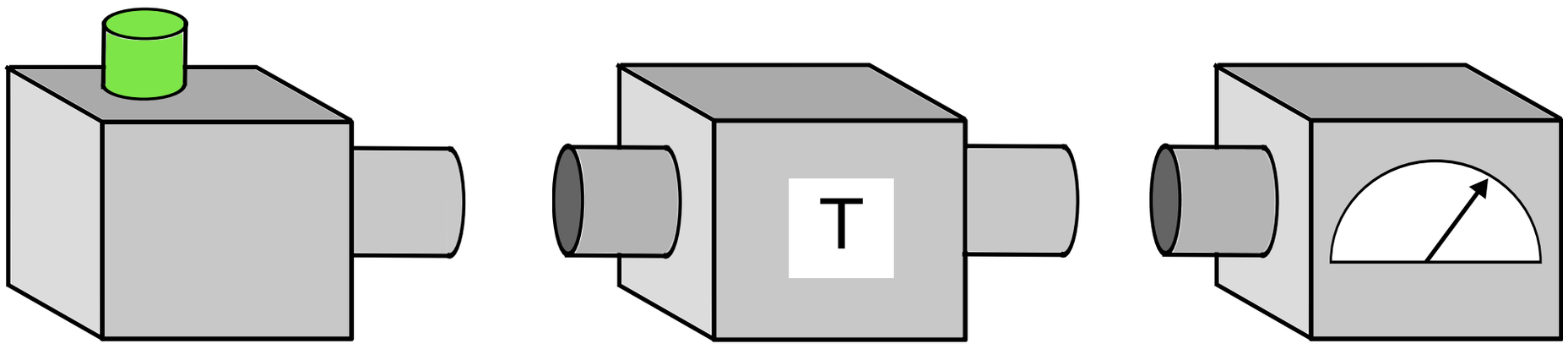

Preparation, transformation, measurement.

# Our approach

**MM**, J. Oppenheim, and O. Dahlsten, JHEP **09**, 116 (2012)



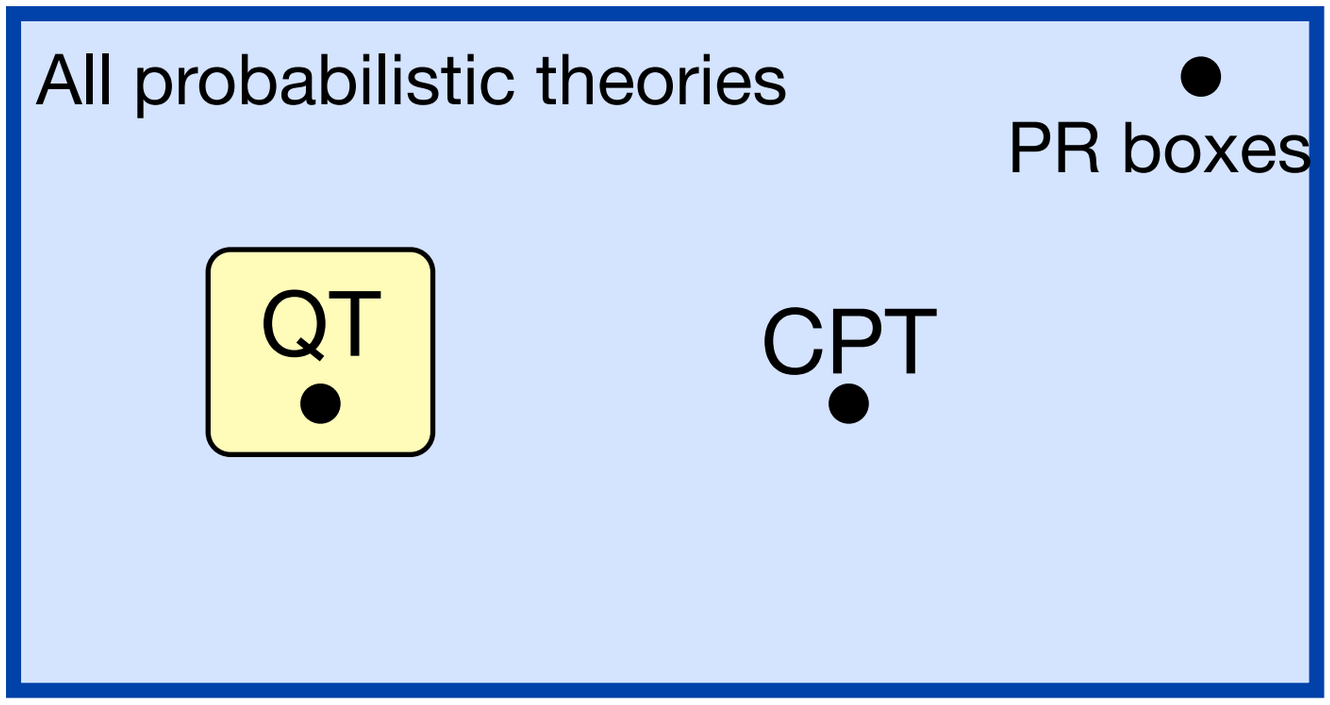

Consider BH information without assuming the full quantum formalism.




Preparation, transformation, measurement.

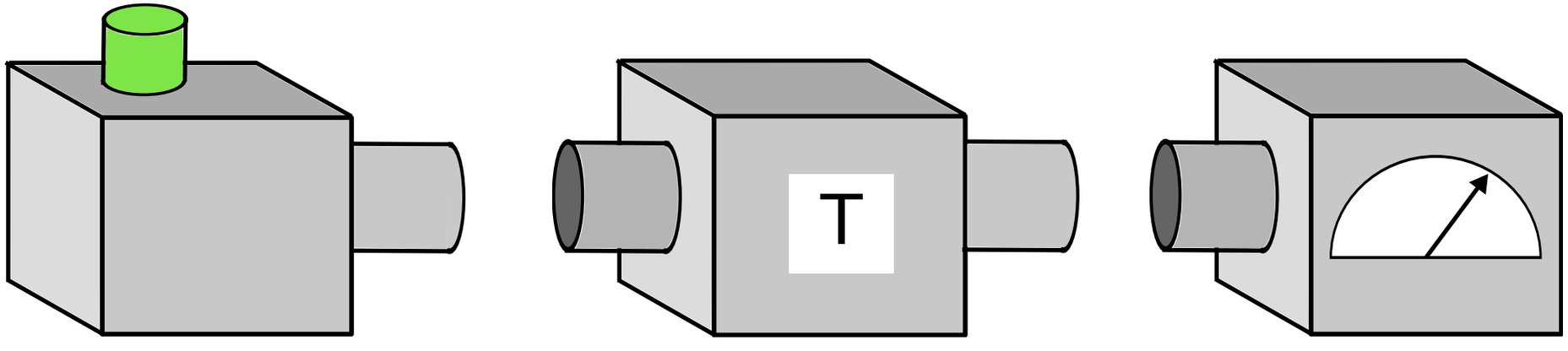
# Our approach

**MM**, J. Oppenheim, and O. Dahlsten, JHEP **09**, 116 (2012)




Consider BH information without assuming the full quantum formalism.

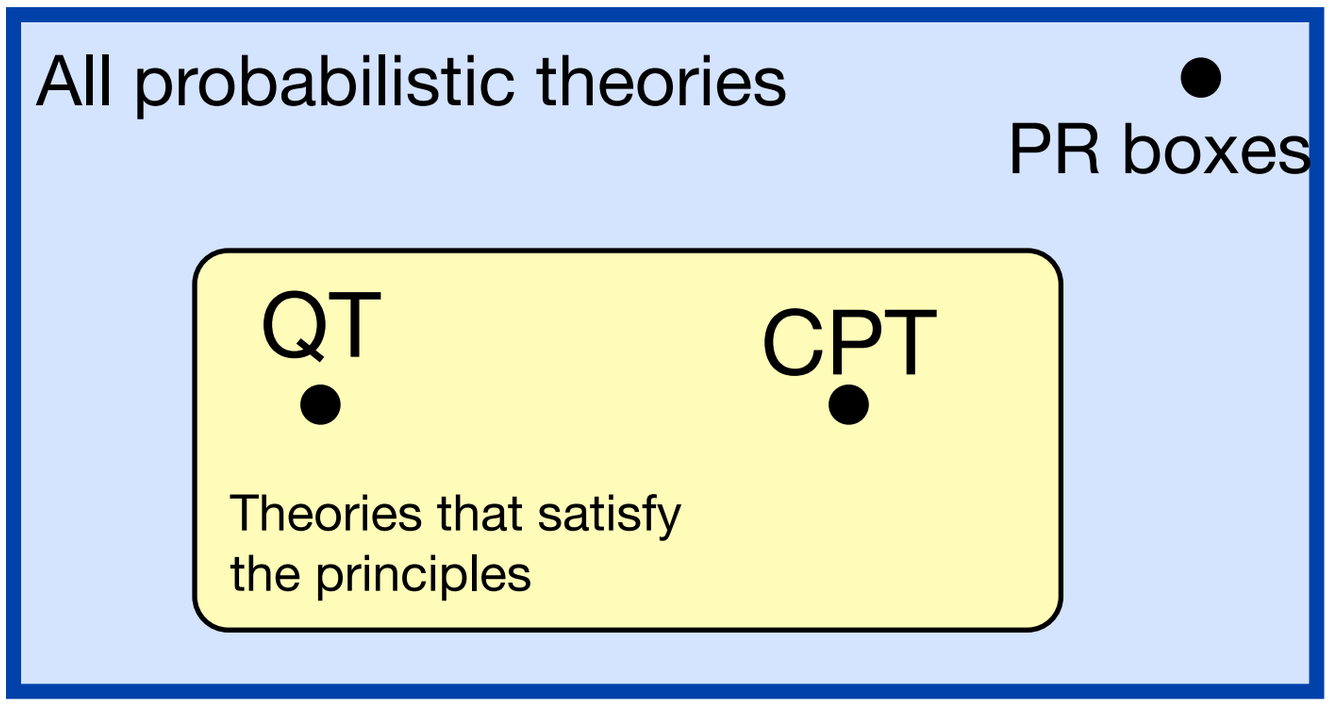
Assume only a few **principles**!




Preparation, transformation, measurement.

# Our approach

**MM**, J. Oppenheim, and O. Dahlsten, JHEP **09**, 116 (2012)

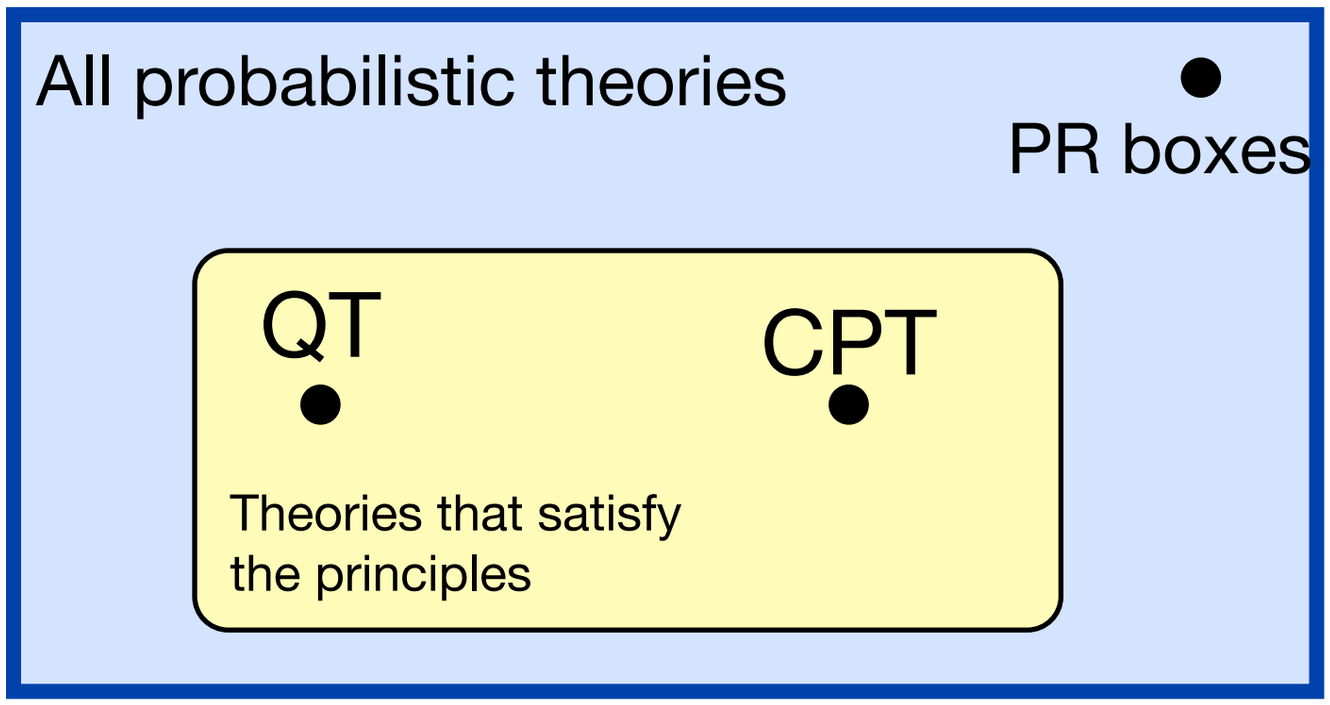



Consider BH information without assuming the full quantum formalism.

Assume only a few **principles**!

# Our approach

**MM**, J. Oppenheim, and O. Dahlsten, JHEP **09**, 116 (2012)




Consider BH information without assuming the full quantum formalism.

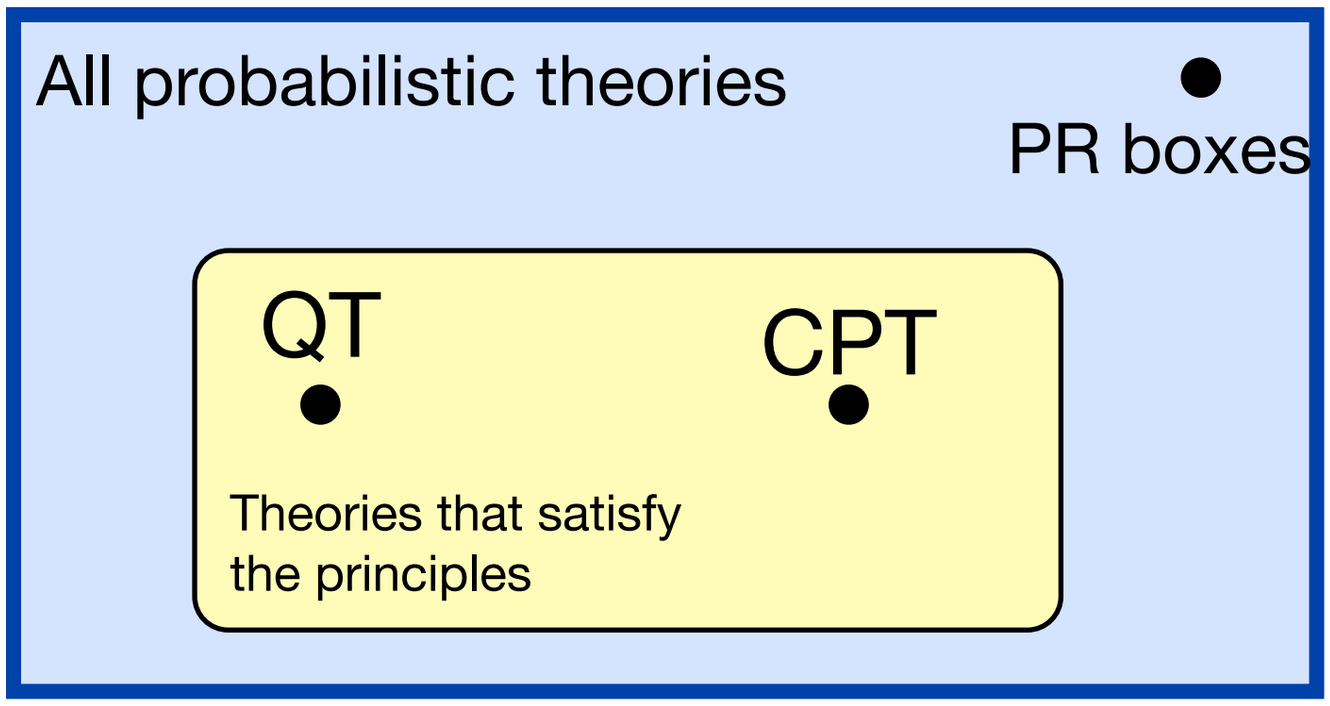
Assume only a few **principles**!

The **Principles** in a nutshell:

- Theories must allow decoherence to classical.
- Composition of systems satisfies "tomographic locality".
- Every two pure states are connected by reversible time evolution

# Our approach

**MM**, J. Oppenheim, and O. Dahlsten, JHEP **09**, 116 (2012)




Consider BH information without assuming the full quantum formalism.

Assume only a few **principles**!

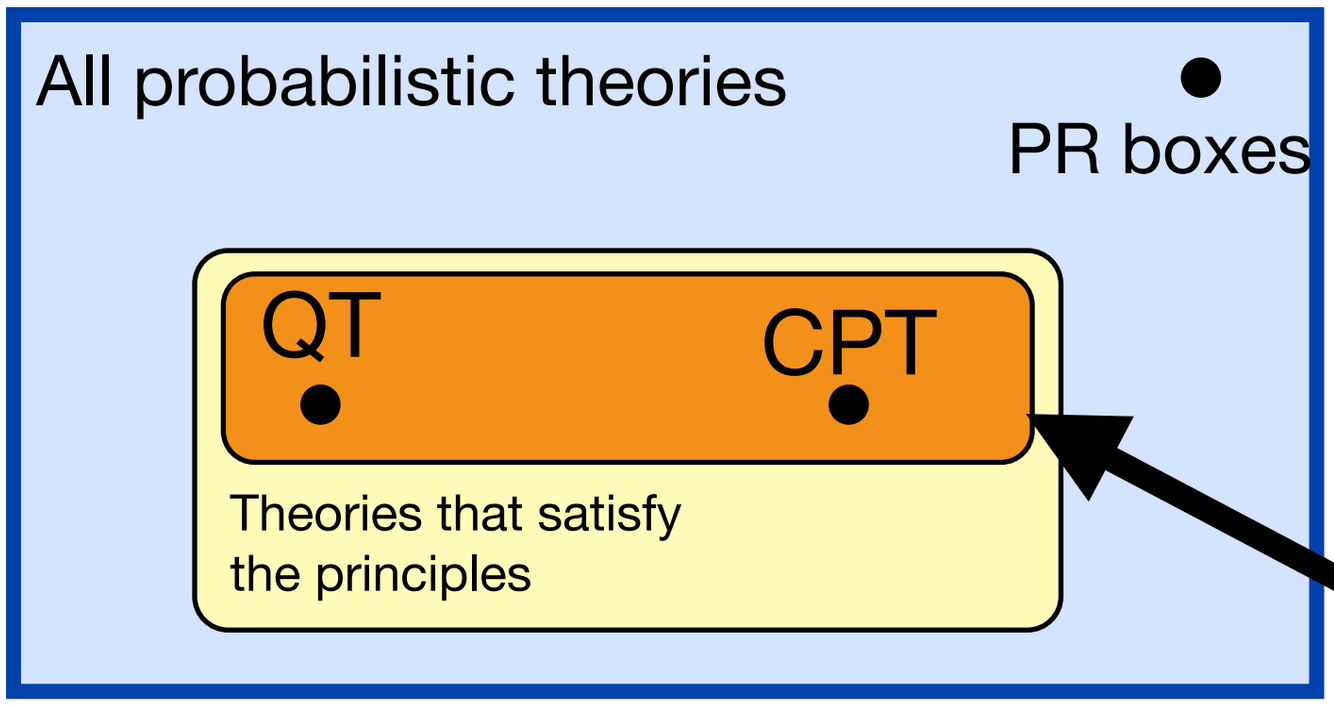
The **Principles** in a nutshell:

- Theories must allow decoherence to classical.
- Composition of systems satisfies "tomographic locality".
- Every two pure states are connected by reversible time evolution

→ Assumes less than full QT formalism, respecting "unitarity" (information preservation), causality, subsystem structure.

# Our approach

**MM**, J. Oppenheim, and O. Dahlsten, JHEP **09**, 116 (2012)




Consider BH information without assuming the full quantum formalism.

Assume only a few **principles**!

Subset of theories for which results look simple (will only talk about those)

The **Principles** in a nutshell:

- Theories must allow decoherence to classical.
- Composition of systems satisfies "tomographic locality".
- Every two pure states are connected by reversible time evolution

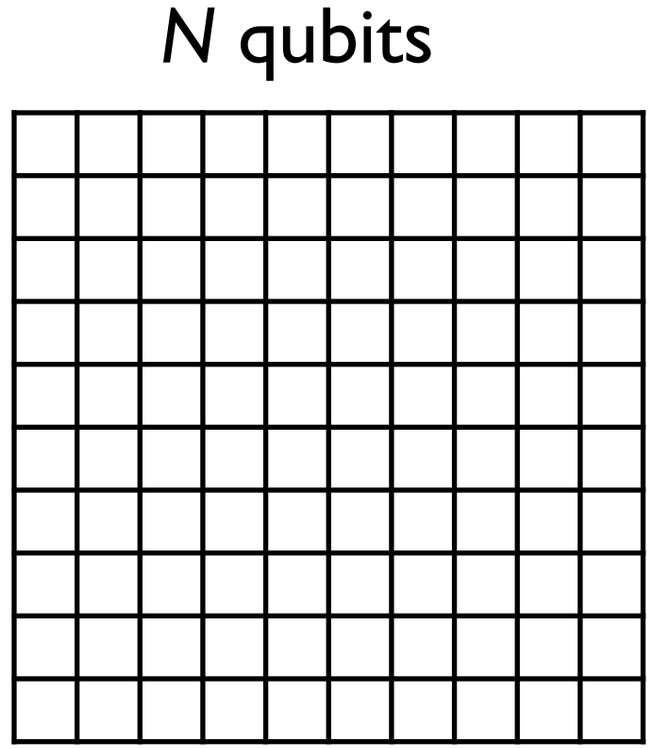
→ Assumes less than full QT formalism, respecting "unitarity" (information preservation), causality, subsystem structure.

# The Page curve

D. N. Page, *Information in Black Hole Radiation*, Phys. Rev. Lett. **71**, 3743 (1993)

# The Page curve

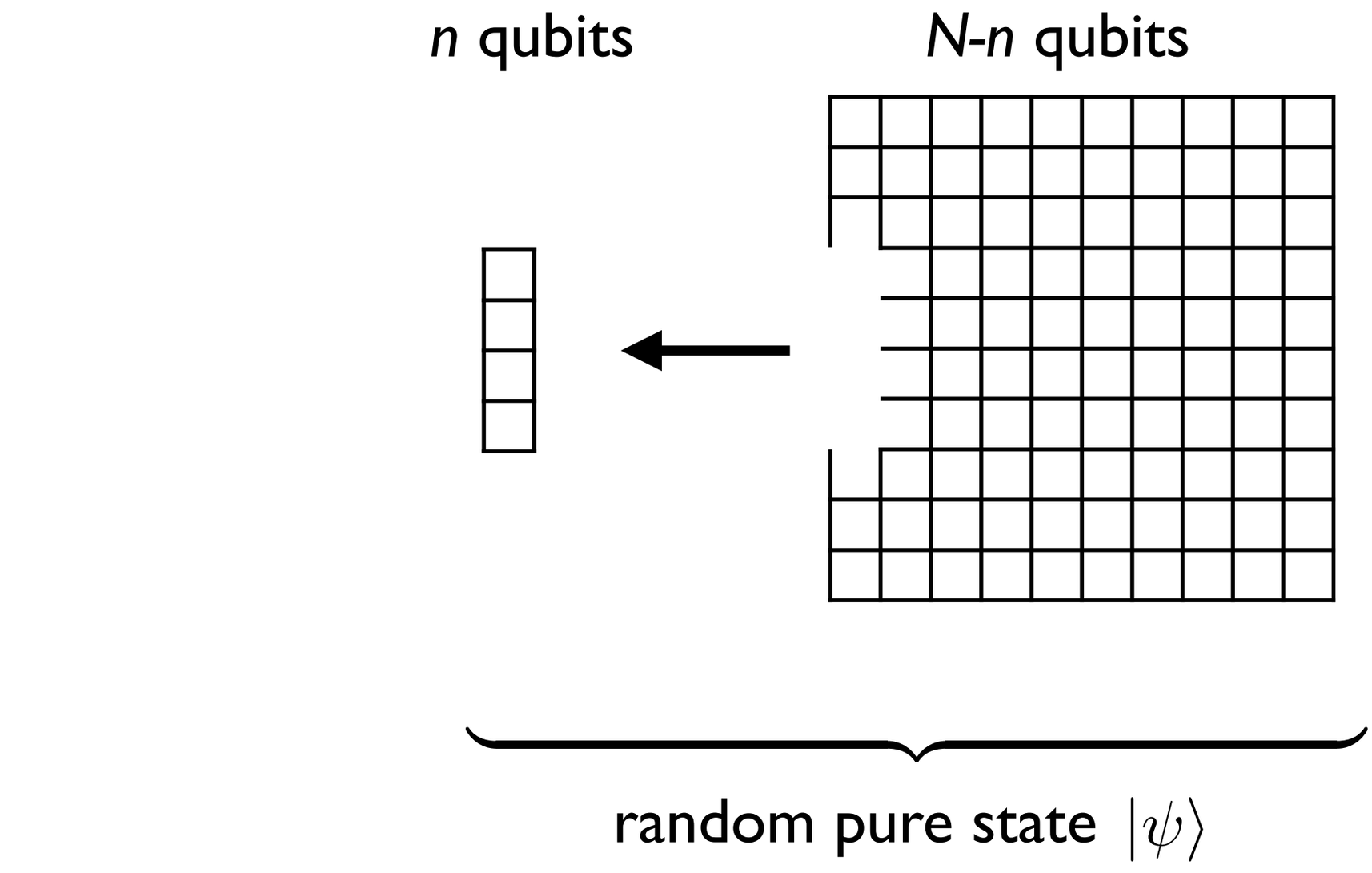
**MM**, O. C. O. Dahlsten, and V. Vedral, Commun. Math. Phys. **316** (2), 441-487 (2012)
**MM**, J. Oppenheim, and O. C. O. Dahlsten, JHEP **2012** (9), 116 (2012)




D. N. Page, *Information in Black Hole Radiation*, Phys. Rev. Lett. **71**, 3743 (1993)

# The Page curve

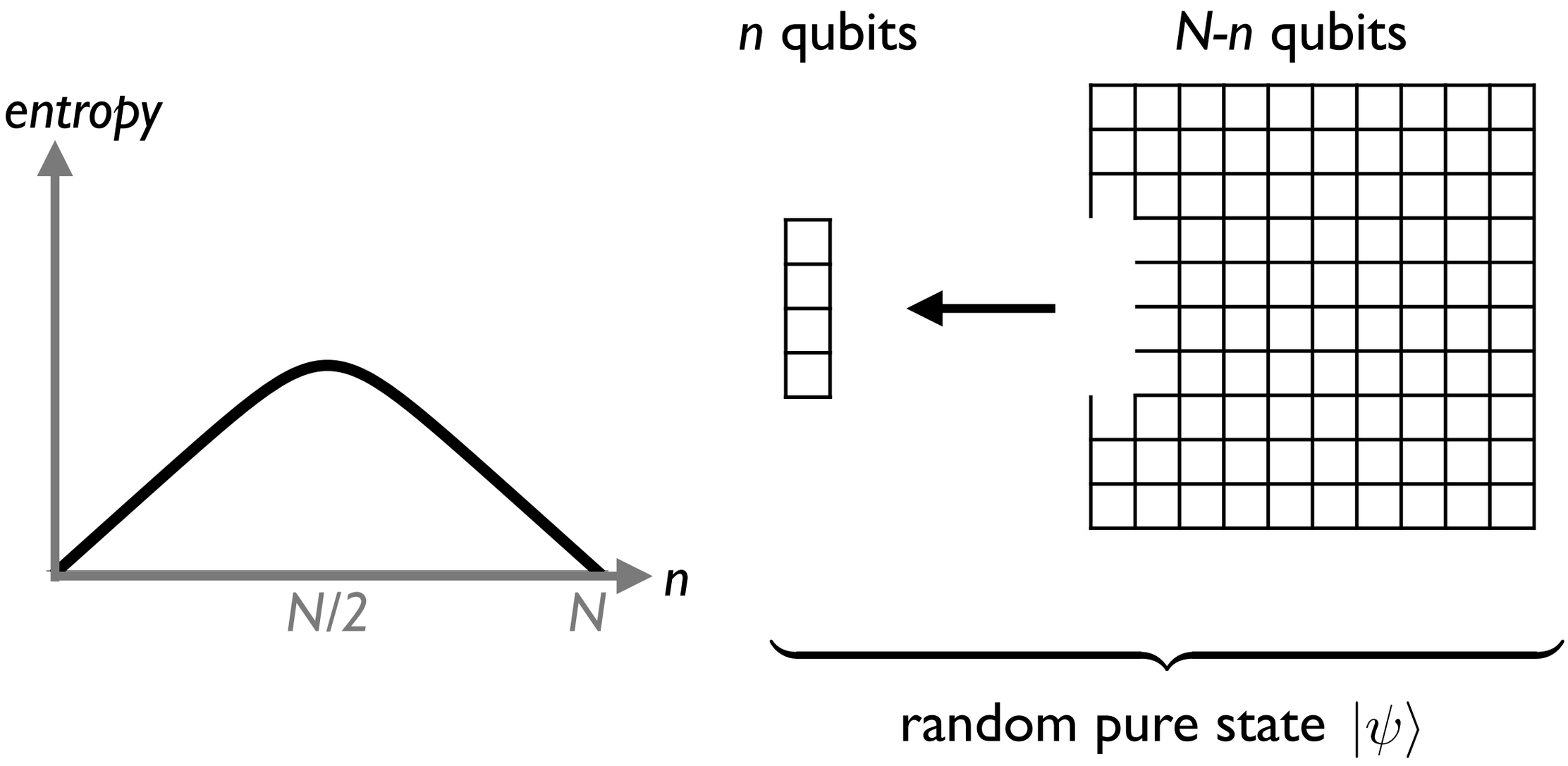
**MM**, O. C. O. Dahlsten, and V. Vedral, Commun. Math. Phys. **316** (2), 441-487 (2012)
**MM**, J. Oppenheim, and O. C. O. Dahlsten, JHEP **2012** (9), 116 (2012)




D. N. Page, *Information in Black Hole Radiation*, Phys. Rev. Lett. **71**, 3743 (1993)

# The Page curve

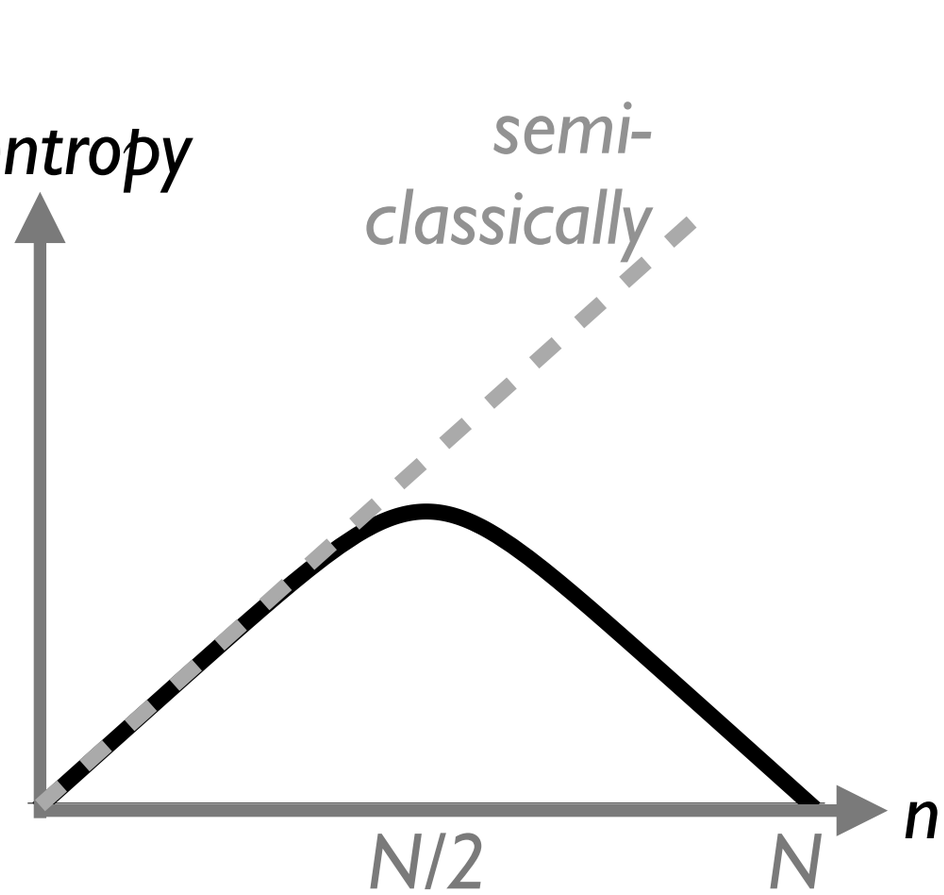
**MM**, O. C. O. Dahlsten, and V. Vedral, Commun. Math. Phys. **316** (2), 441-487 (2012)
**MM**, J. Oppenheim, and O. C. O. Dahlsten, JHEP **2012** (9), 116 (2012)

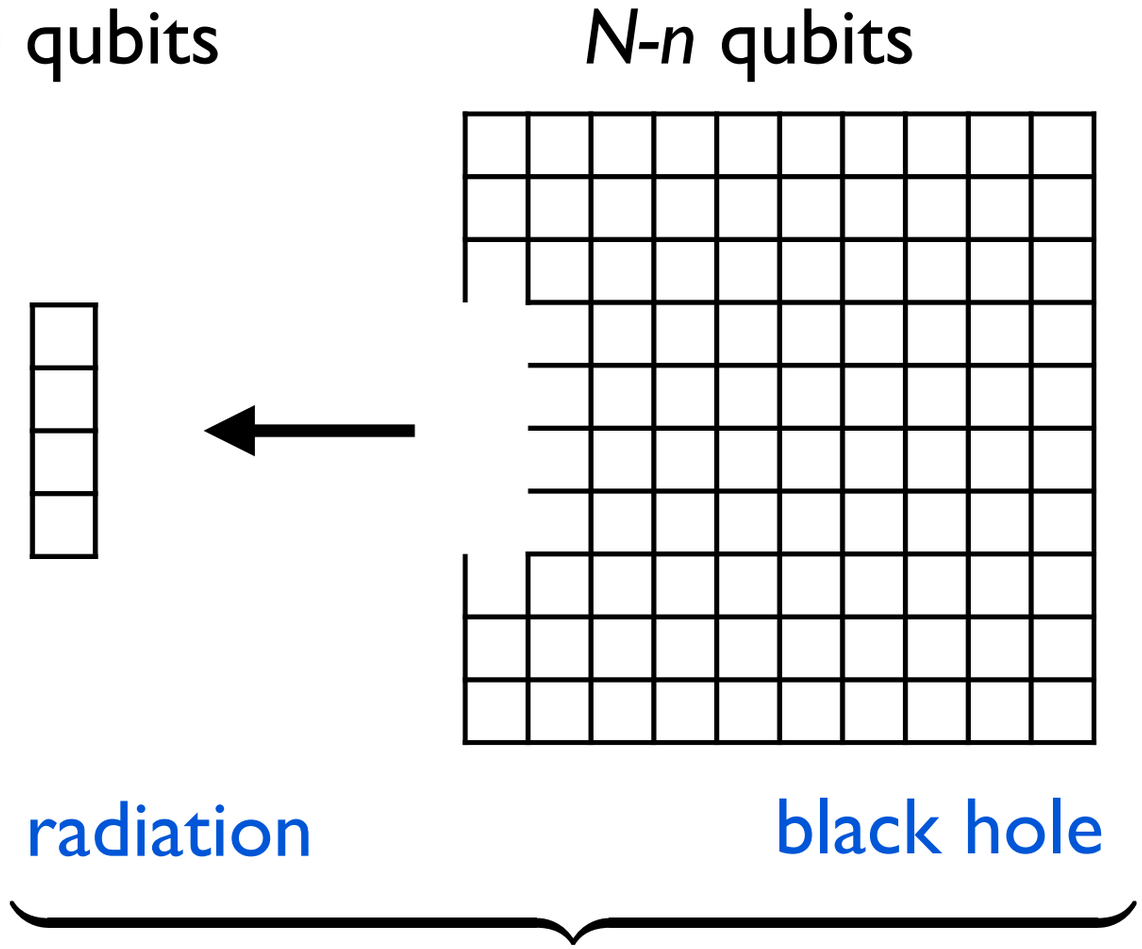



D. N. Page, *Information in Black Hole Radiation*, Phys. Rev. Lett. **71**, 3743 (1993)

# The Page curve

**MM**, O. C. O. Dahlsten, and V. Vedral, Commun. Math. Phys. **316** (2), 441-487 (2012)
**MM**, J. Oppenheim, and O. C. O. Dahlsten, JHEP **2012** (9), 116 (2012)

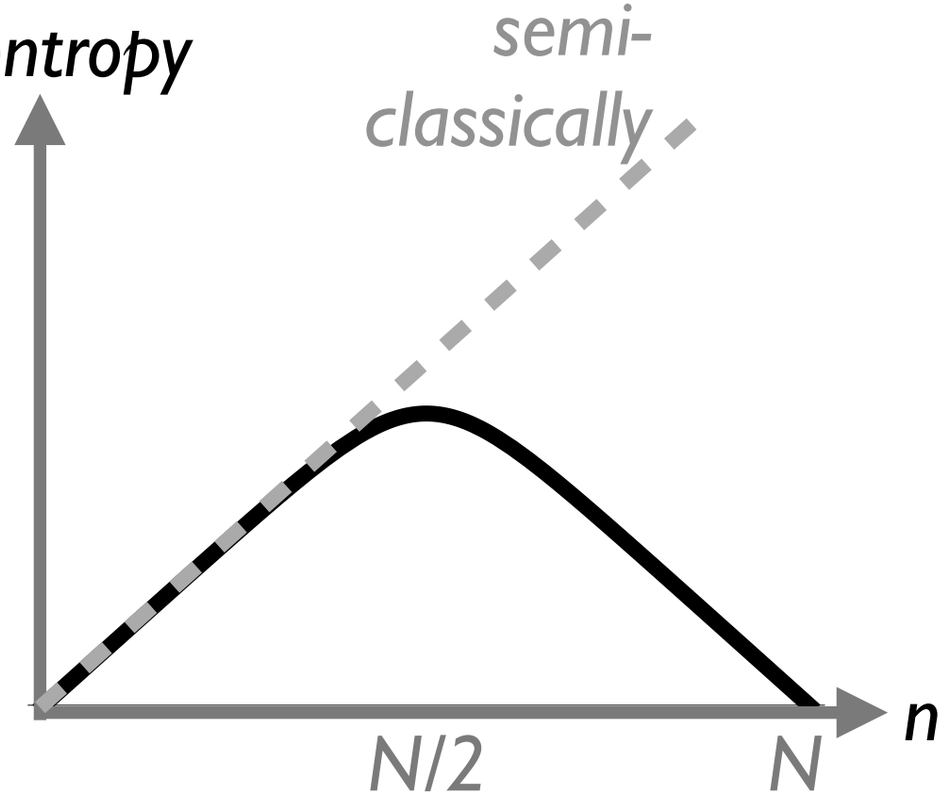


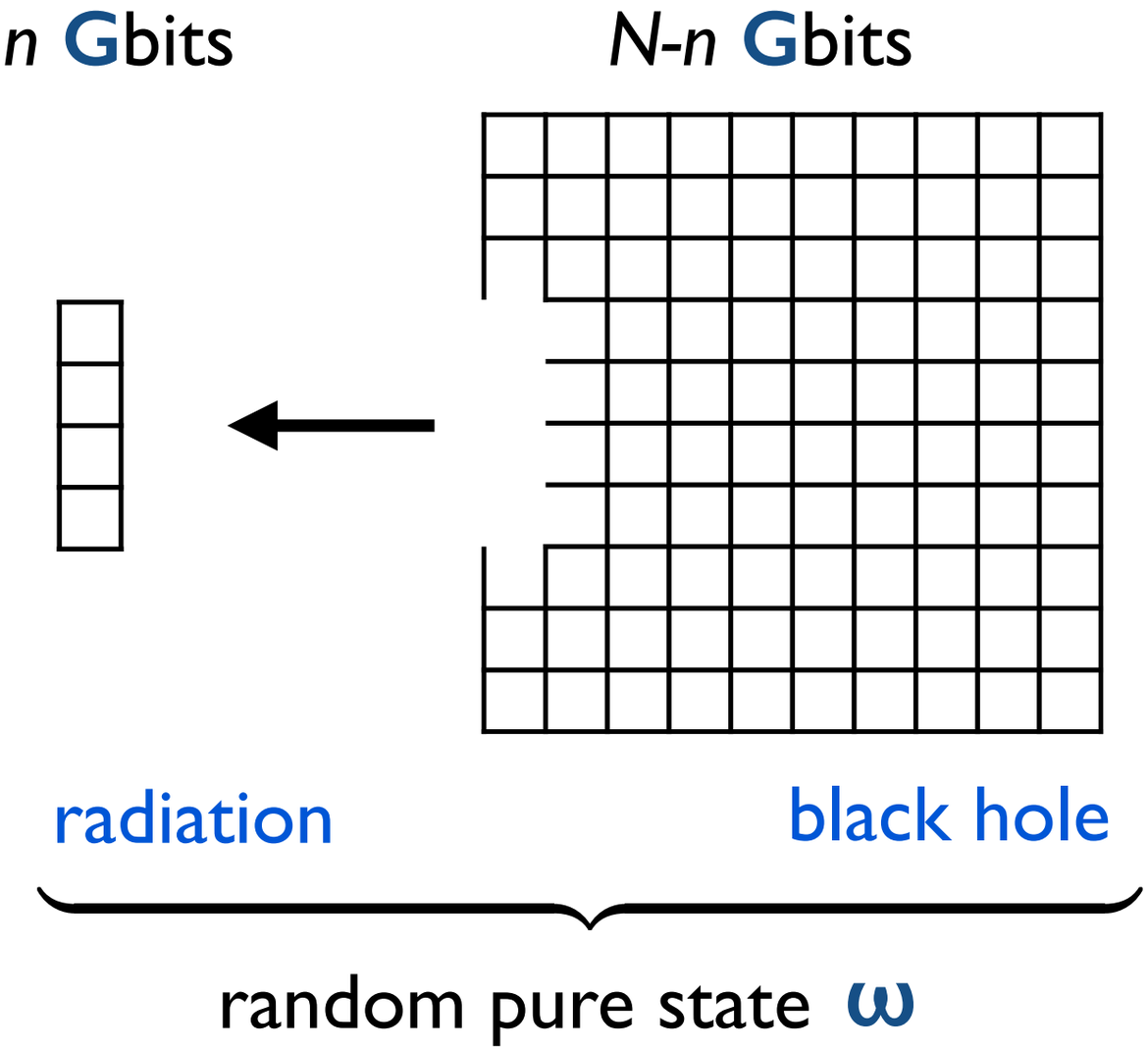




D. N. Page, *Information in Black Hole Radiation*, Phys. Rev. Lett. **71**, 3743 (1993)

# The Page curve

**MM**, O. C. O. Dahlsten, and V. Vedral, Commun. Math. Phys. **316** (2), 441-487 (2012)
**MM**, J. Oppenheim, and O. C. O. Dahlsten, JHEP **2012** (9), 116 (2012)

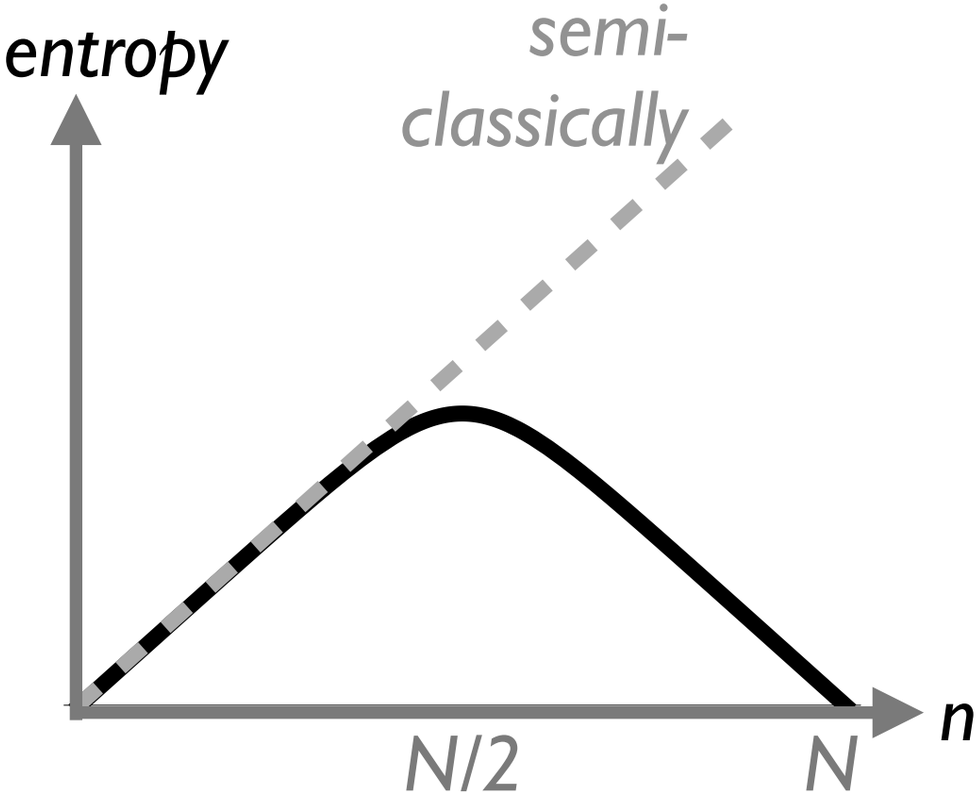



D. N. Page, *Information in Black Hole Radiation*, Phys. Rev. Lett. **71**, 3743 (1993)

# The Page curve

**MM**, O. C. O. Dahlsten, and V. Vedral, Commun. Math. Phys. **316** (2), 441-487 (2012)
**MM**, J. Oppenheim, and O. C. O. Dahlsten, JHEP **2012** (9), 116 (2012)

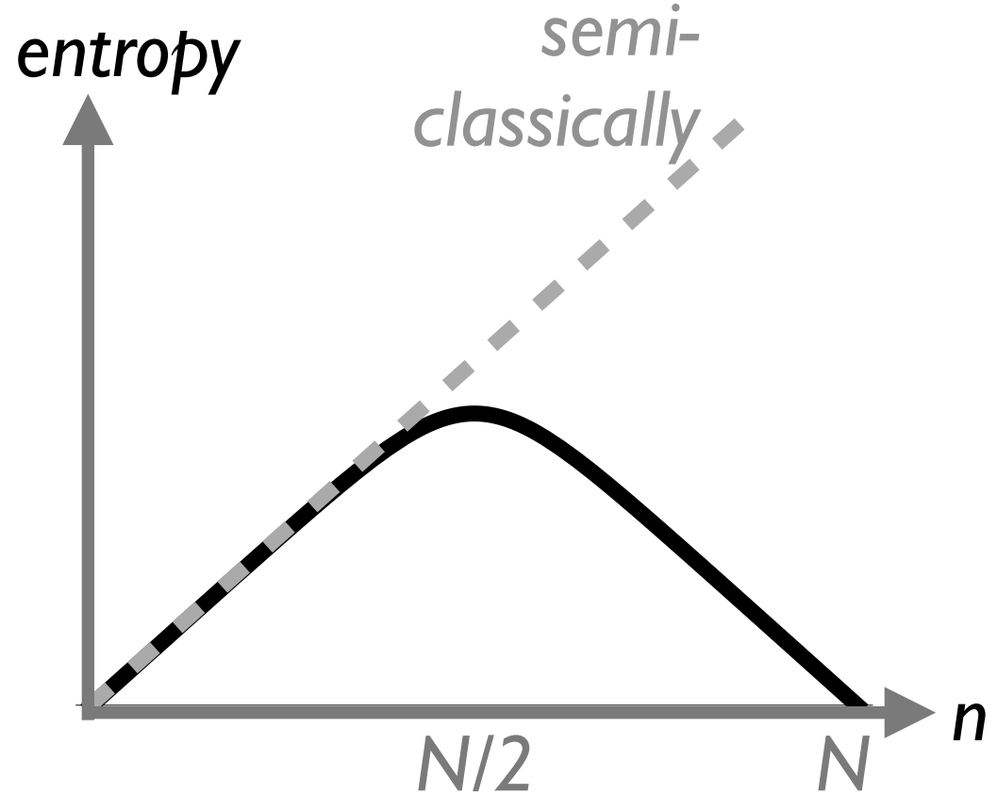


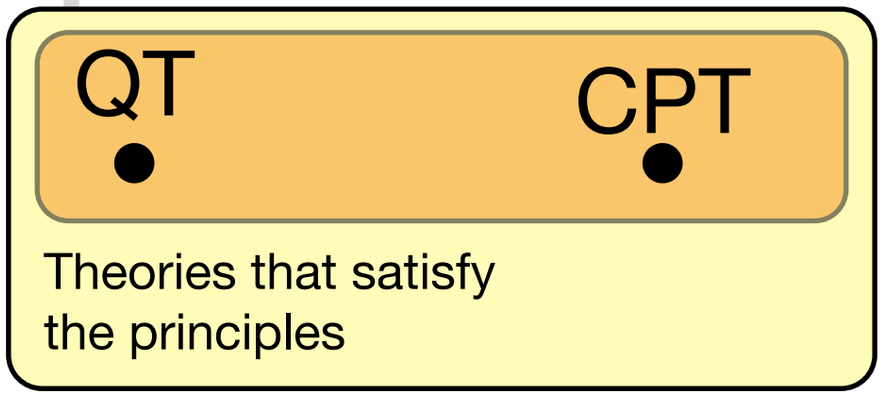

QT ● CPT ●

Theories that satisfy
the principles

# The Page curve

**MM**, O. C. O. Dahlsten, and V. Vedral, Commun. Math. Phys. **316** (2), 441-487 (2012)
**MM**, J. Oppenheim, and O. C. O. Dahlsten, JHEP **2012** (9), 116 (2012)



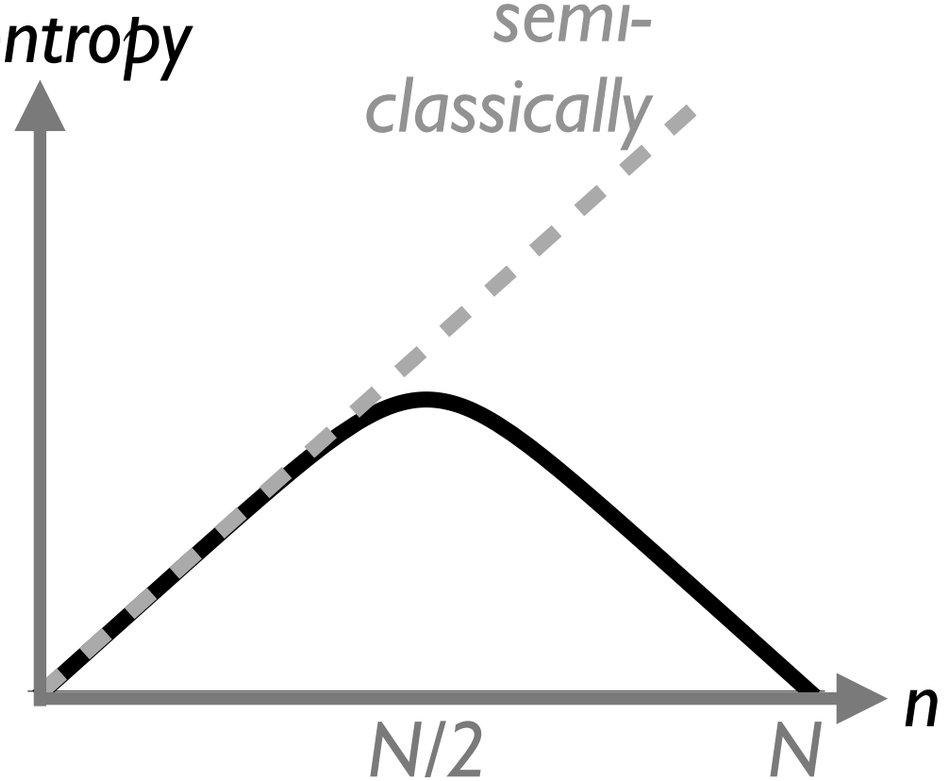



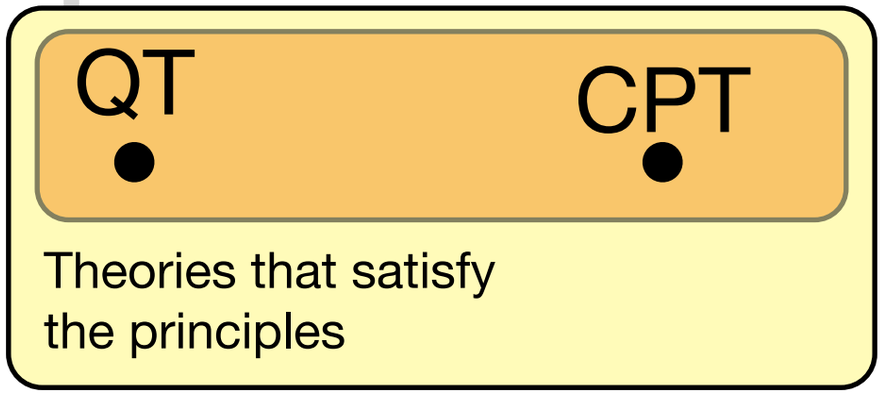

Result: "Interference parameter" $r \in \mathbb{N}$

- $r = 1:$ CPT
- $r = 2:$ QT

# The Page curve

**MM**, O. C. O. Dahlsten, and V. Vedral, Commun. Math. Phys. **316** (2), 441-487 (2012)
**MM**, J. Oppenheim, and O. C. O. Dahlsten, JHEP **2012** (9), 116 (2012)



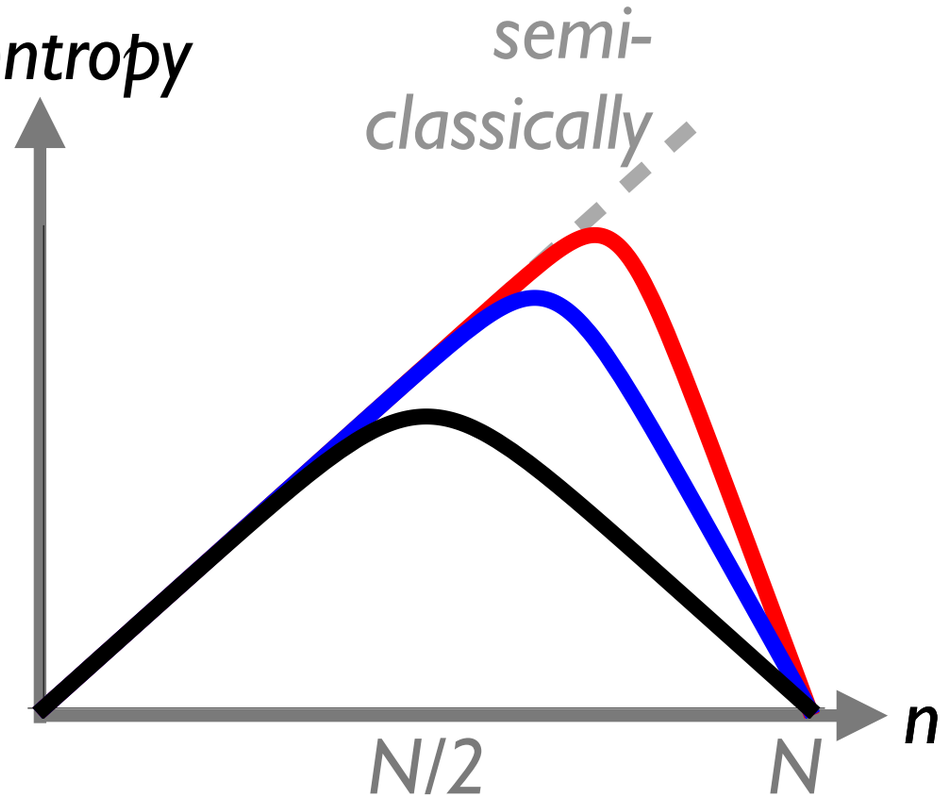




Result: "Interference parameter" $r \in \mathbb{N}$

- $r = 1$ : CPT
- $r = 2$ : QT
- $r = 3$ : ???
- $r = 4$ : ???

# The Page curve

**MM**, O. C. O. Dahlsten, and V. Vedral, Commun. Math. Phys. **316** (2), 441-487 (2012)
**MM**, J. Oppenheim, and O. C. O. Dahlsten, JHEP **2012** (9), 116 (2012)




QT CPT

Theories that satisfy the principles

Result: "Interference parameter" $r \in \mathbb{N}$

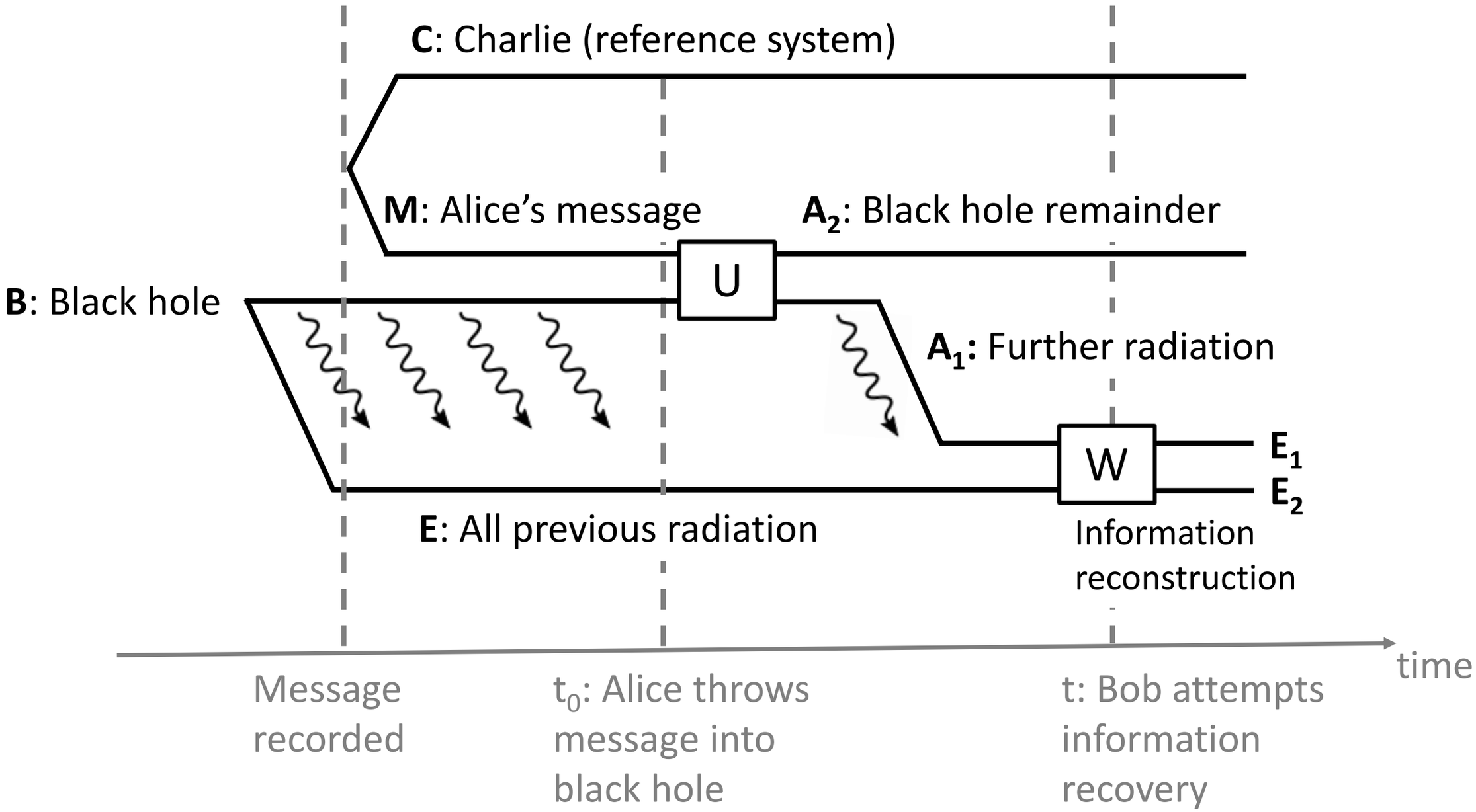
- $r = 1$ : CPT
- $r = 2$ : QT
- $r = 3$ : ???
- $r = 4$ : ???

Rényi-2 entropy of Hawking radiation:

$$H_2 = n - \log_2\left(1 + \frac{(2^{nr}-1)(2^N-1)}{2^{Nr}-1}\right).$$

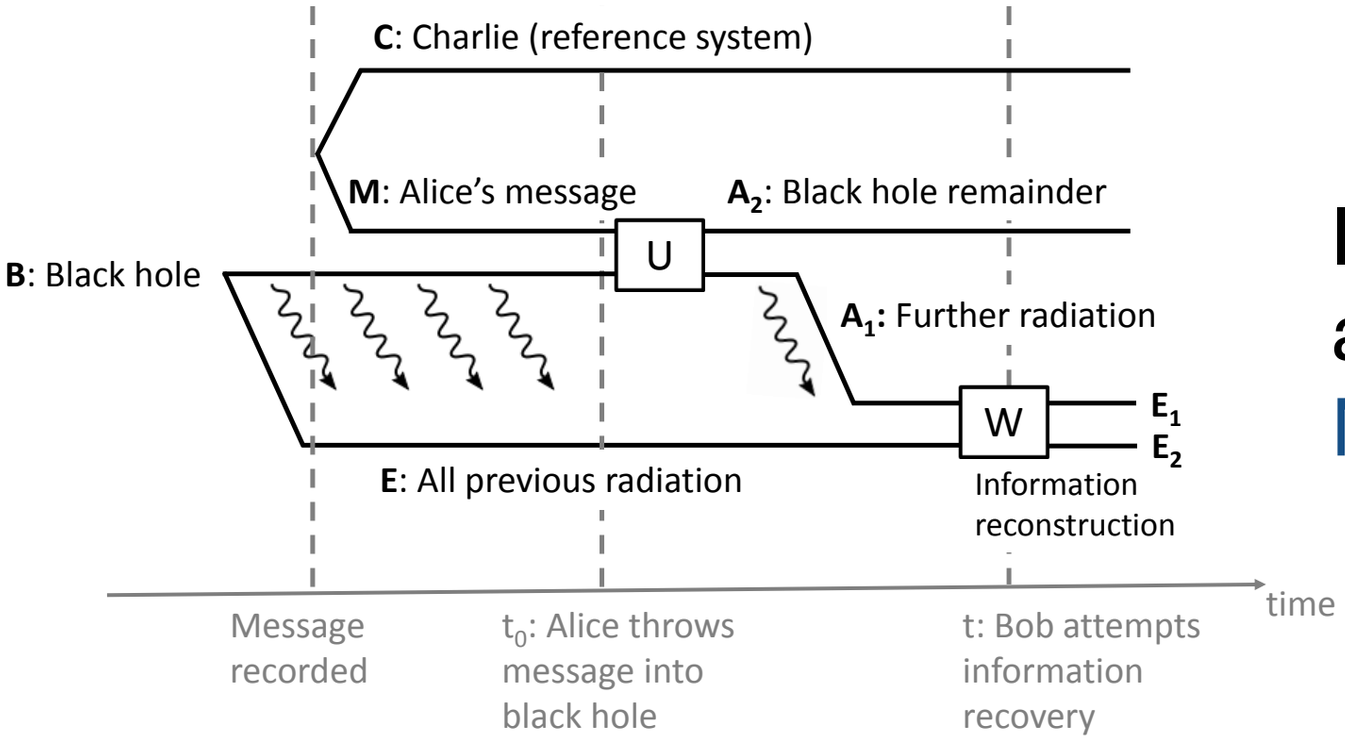
# More general scenario

Generalizes P. Hayden and J. Preskill, *Black holes as mirrors*, JHEP **0709**:120 (2007)



# More general scenario

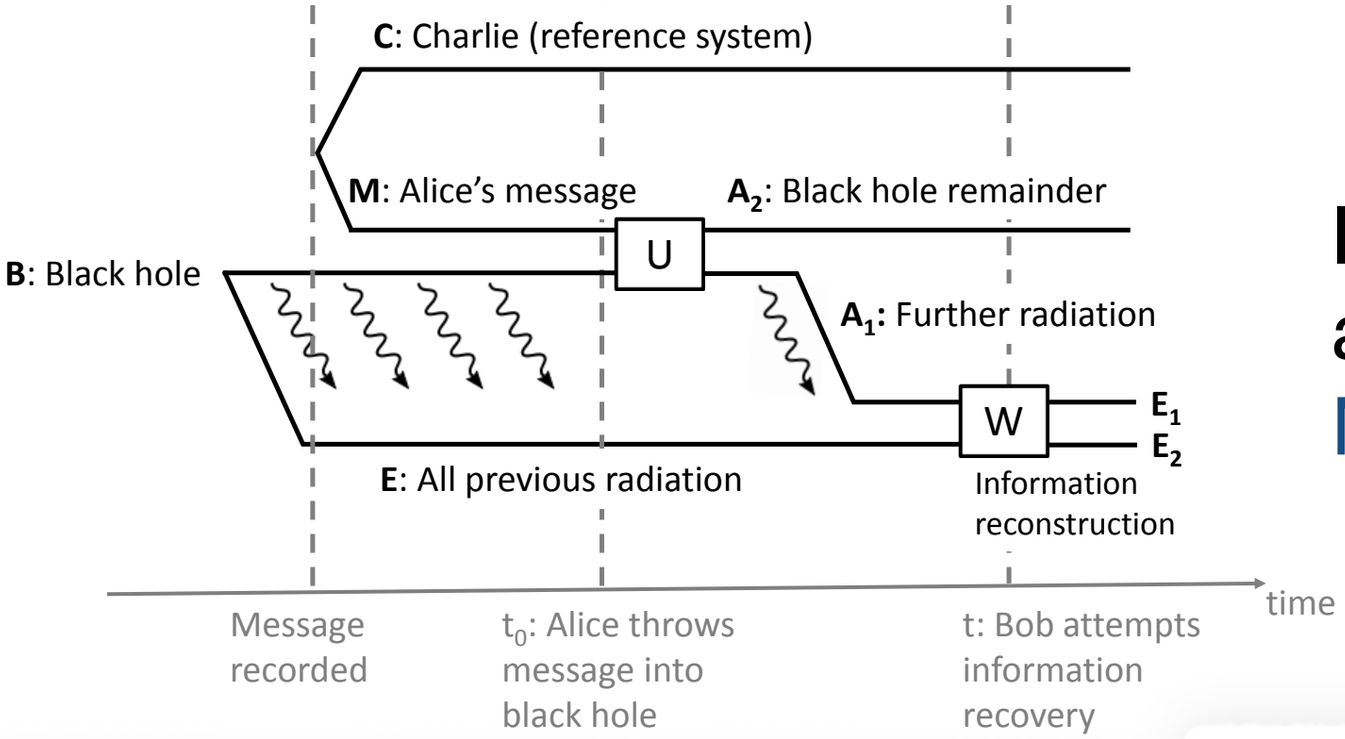
Generalizes P. Hayden and J. Preskill, *Black holes as mirrors*, JHEP **0709**:120 (2007)



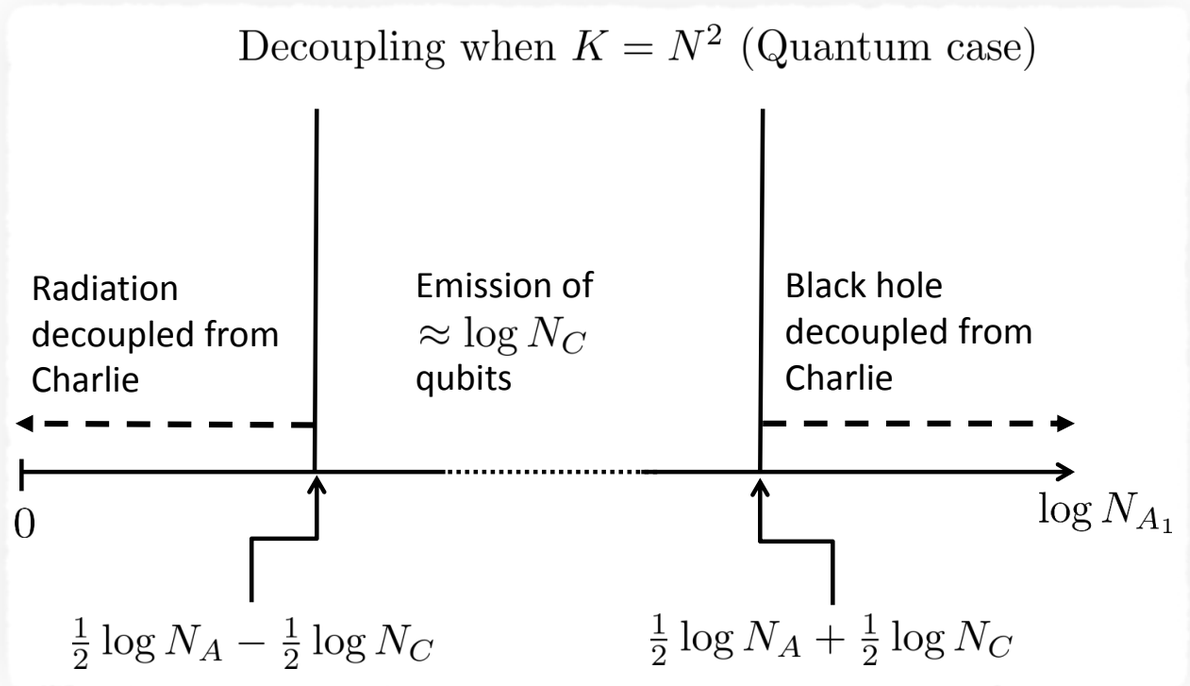

If Alice throws her diary into a very young BH, then QT's No-Hiding Theorem is violated:

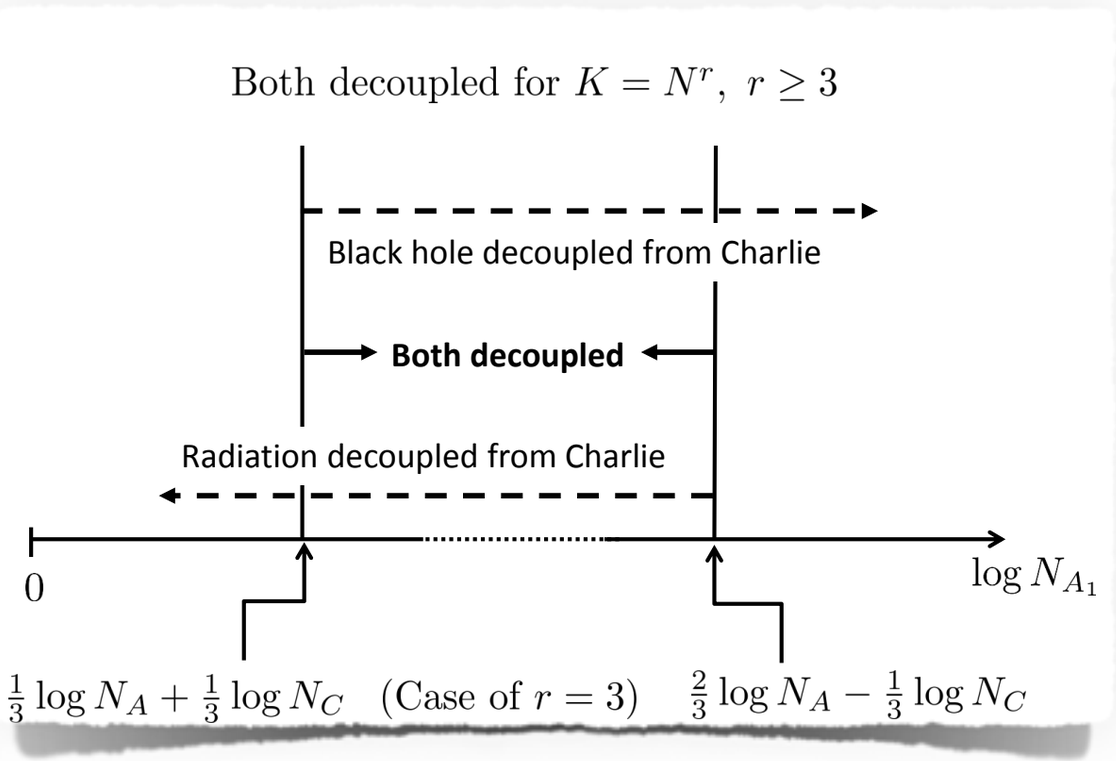
# More general scenario

Generalizes P. Hayden and J. Preskill, *Black holes as mirrors*, JHEP **0709**:120 (2007)




If Alice throws her diary into a very young BH, then QT's No-Hiding Theorem is violated:



## Why we think this is a good idea

- Probably most conservative way to generalize QT:
  just *drop* assumptions of QT, and don't add new ones.

- Satisfies information preservation ("unitarity"), causality,
  preserves subsystem structure, clear operational meaning.

- Mathematically fully rigorous.
  Shows what elbow room there is, within one's favorite
  physical properties / principles.

## Why we think this is a good idea

- Probably most conservative way to generalize QT:
  just *drop* assumptions of QT, and don't add new ones.

- Satisfies information preservation ("unitarity"), causality,
  preserves subsystem structure, clear operational meaning.

- Mathematically fully rigorous.
  Shows what elbow room there is, within one's favorite
  physical properties / principles.

## Drawback

- Not clear how to combine with the rest of physics
  (Hamiltonians etc.)

# Some thoughts as a QG non-expert

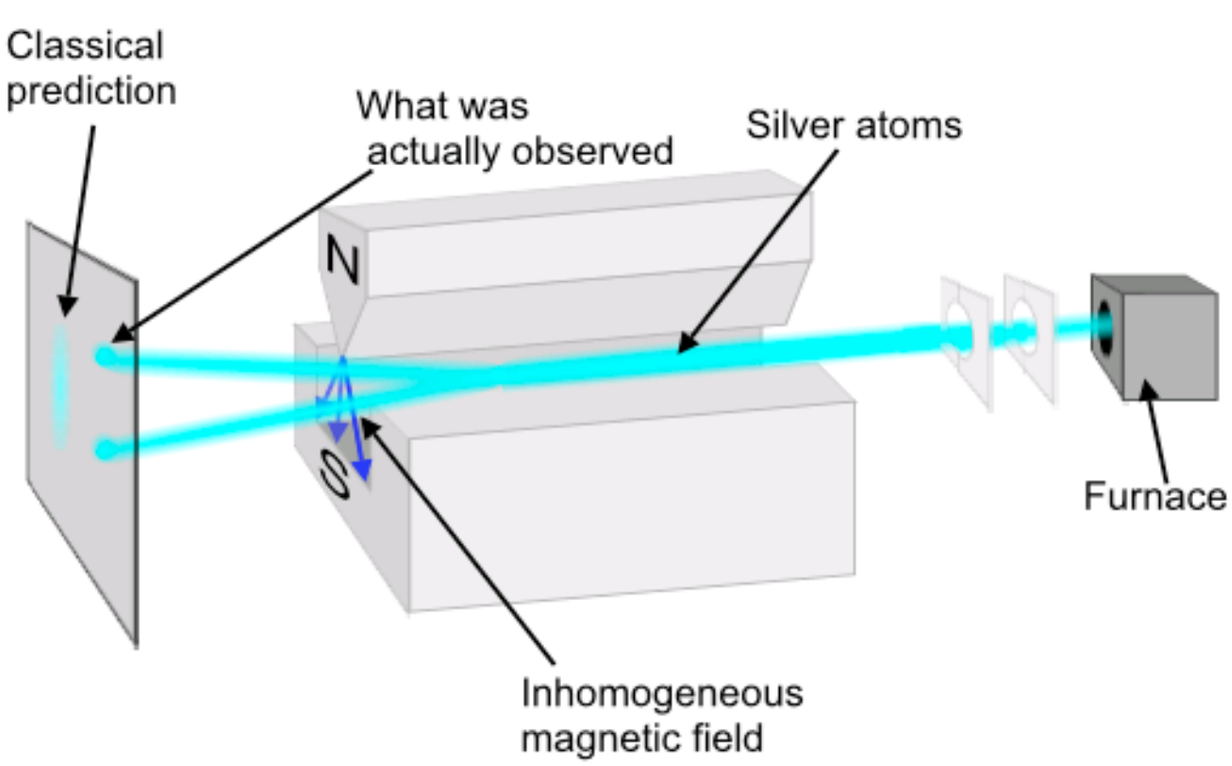
**Q**: Do you *really* think QT is modified in some regime?

**A**:

# Some thoughts as a QG non-expert

**Q**: Do you *really* think QT is modified in some regime?

**A**: I don't know.
But I think we should seriously consider this possibility.
QT seems suspiciously fine-tuned to fit into ordinary spacetime.
So if the latter is only an approximation, then maybe also the former.




quantum 2-level state space

## Some thoughts as a QG non-expert

**Q**: Do you *really* think QT is modified in some regime?

**A**: I don't know.
But I think we should seriously consider this possibility.
QT seems suspiciously fine-tuned to fit into ordinary spacetime.
So if the latter is only an approximation, then maybe also the former.

**Q**: If so, do you really think that these other "probabilistic theories" appear there?

**A**:

## Some thoughts as a QG non-expert

**Q**: Do you *really* think QT is modified in some regime?

**A**: I don't know.
But I think we should seriously consider this possibility.
QT seems suspiciously fine-tuned to fit into ordinary spacetime.
So if the latter is only an approximation, then maybe also the former.

**Q**: If so, do you really think that these other "probabilistic theories" appear there?

**A**: No, probably not.
But they allow us to make an educated guess about what new effects or behaviors we might reasonably expect to see in that regime, if it exists.

## Some thoughts as a QG non-expert

**Q**: Do you *really* think QT is modified in some regime?

**A**: I don't know.
But I think we should seriously consider this possibility.
QT seems suspiciously fine-tuned to fit into ordinary spacetime.
So if the latter is only an approximation, then maybe also the former.

**Q**: If so, do you really think that these other "probabilistic theories" appear there?

**A**: No, probably not.
But they allow us to make an educated guess about what new effects or behaviors we might reasonably expect to see in that regime, if it exists.

**"QT is too weird to be the final theory."**

## Some thoughts as a QG non-expert

**Q**: Do you *really* think QT is modified in some regime?

**A**: I don't know.
But I think we should seriously consider this possibility.
QT seems suspiciously fine-tuned to fit into ordinary spacetime.
So if the latter is only an approximation, then maybe also the former.

**Q**: If so, do you really think that these other "probabilistic theories" appear there?

**A**: No, probably not.
But they allow us to make an educated guess about what new effects or behaviors we might reasonably expect to see in that regime, if it exists.

~~**"QT is too weird to be the final theory."**~~

## Some thoughts as a QG non-expert

**Q**: Do you *really* think QT is modified in some regime?

**A**: I don't know.
But I think we should seriously consider this possibility.
QT seems suspiciously fine-tuned to fit into ordinary spacetime.
So if the latter is only an approximation, then maybe also the former.

**Q**: If so, do you really think that these other "probabilistic theories" appear there?

**A**: No, probably not.
But they allow us to make an educated guess about what new effects or behaviors we might reasonably expect to see in that regime, if it exists.

**Maybe QT is not weird enough to be the final theory.**

## Some thoughts as a QG non-expert

**Q**: Do you *really* think QT is modified in some regime?

**A**: I don't know.
But I think we should seriously consider this possibility.
QT seems suspiciously fine-tuned to fit into ordinary spacetime.
So if the latter is only an approximation, then maybe also the former.

**Q**: If so, do you really think that these other "probabilistic theories" appear there?

**A**: No, probably not.
But they allow us to make an educated guess about what new effects or behaviors we might reasonably expect to see in that regime, if it exists.

**Maybe QT is not weird enough to be the final theory.**

**Thank you!**