Quantum theory as a principle theory:
insights from an information-theoretic reconstruction

Adam Koberinski[1] and Markus P. Müller[1,2,3,4]
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[3]Perimeter Institute for Theoretical Physics, Waterloo, Canada;
[4]Institute for Quantum Optics and Quantum Information, Vienna

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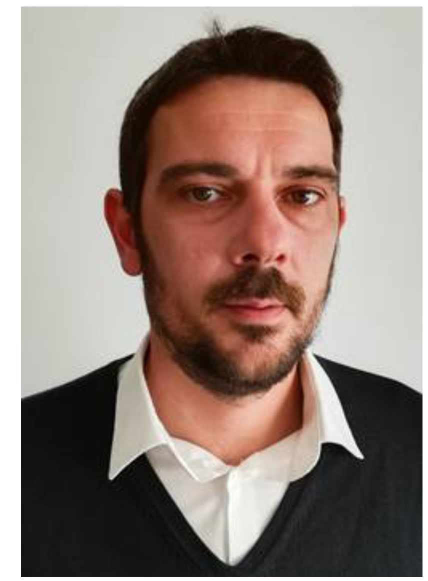
- “Reconstructions” is a topic that we at IQOQI have been interested in. **Illustrates interplay physics⟷philosophy.**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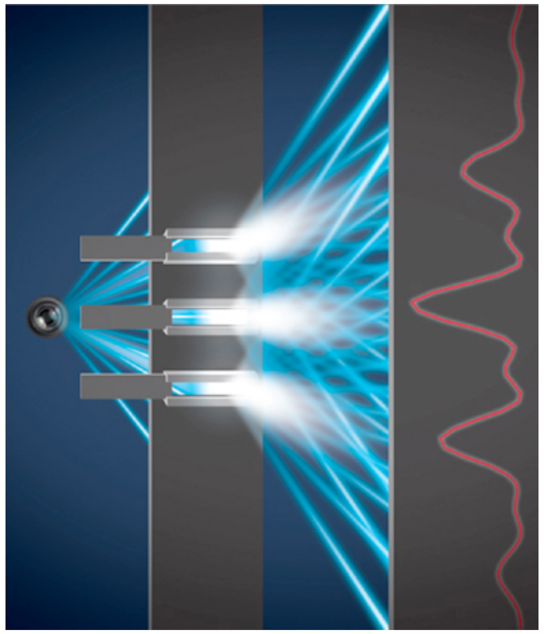
- This talk: Joint project with Philosophy PhD student **Adam Koberinski**.

A. Koberinski and M. P. Müller, *Quantum theory as a principle theory: insights from an information-theoretic reconstruction*, in M.E. Cuffaro and S.C. Fletcher (eds.), *Physical Perspectives on Computation, Computational Perspectives on Physics*, Cambridge University Press, Cambridge, 2018.

Outline

- Quantum theory as a “probabilistic theory”
  Situating QT inside a large landscape of theories



- A reconstruction of quantum theory
  QT from 4 information-theoretic principles

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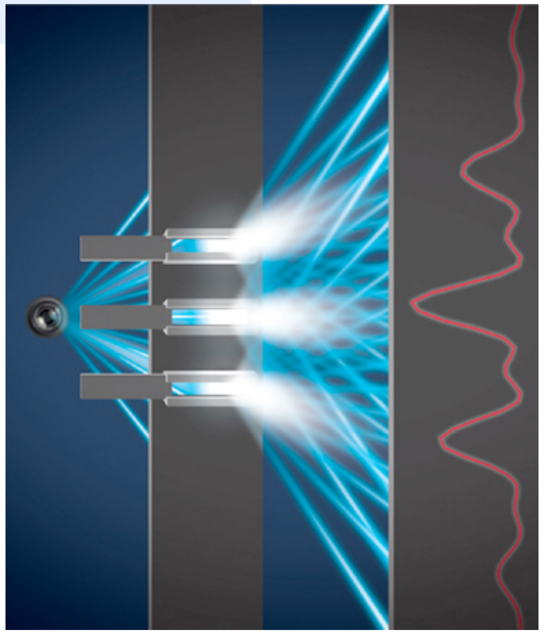

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- What is a quantum state?
  It is the thing that allows us to determine, *for all possible questions that we may decide a physical system to ask*, the probabilities of finding the possible answers.
  All interpretations of QT agree in this point.

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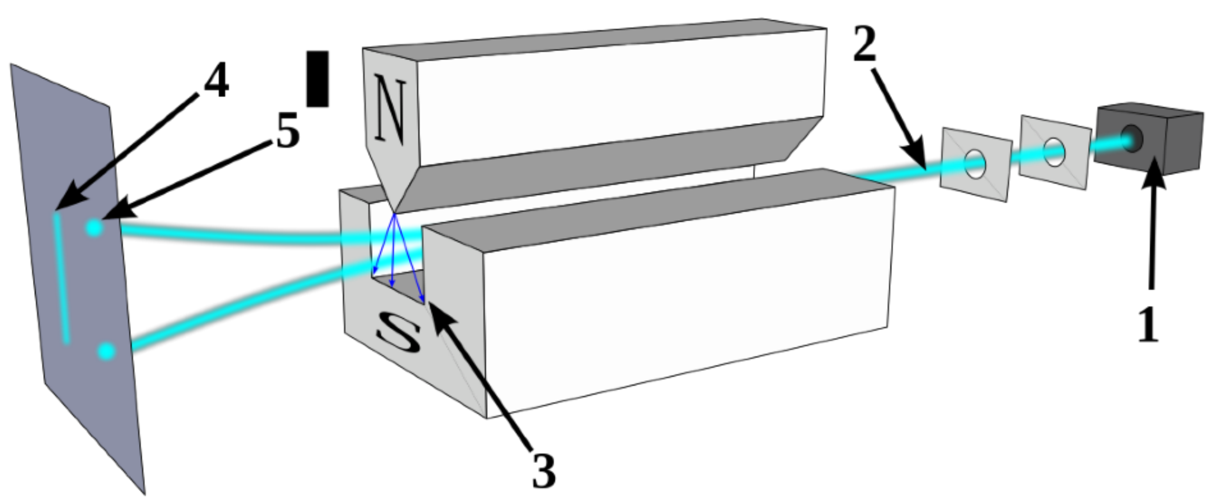
Example: "Is the spin up in z-direction?"



$$\begin{aligned} \mathbf{P}(\text{“yes”}) &= |\langle\psi|\uparrow\rangle|^2 \\ &= \mathrm{tr}(\rho P_\uparrow) \end{aligned}$$

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even: ω
odd: τ

$$\longrightarrow \quad \sigma = \frac{1}{2}\omega + \frac{1}{2}\tau$$

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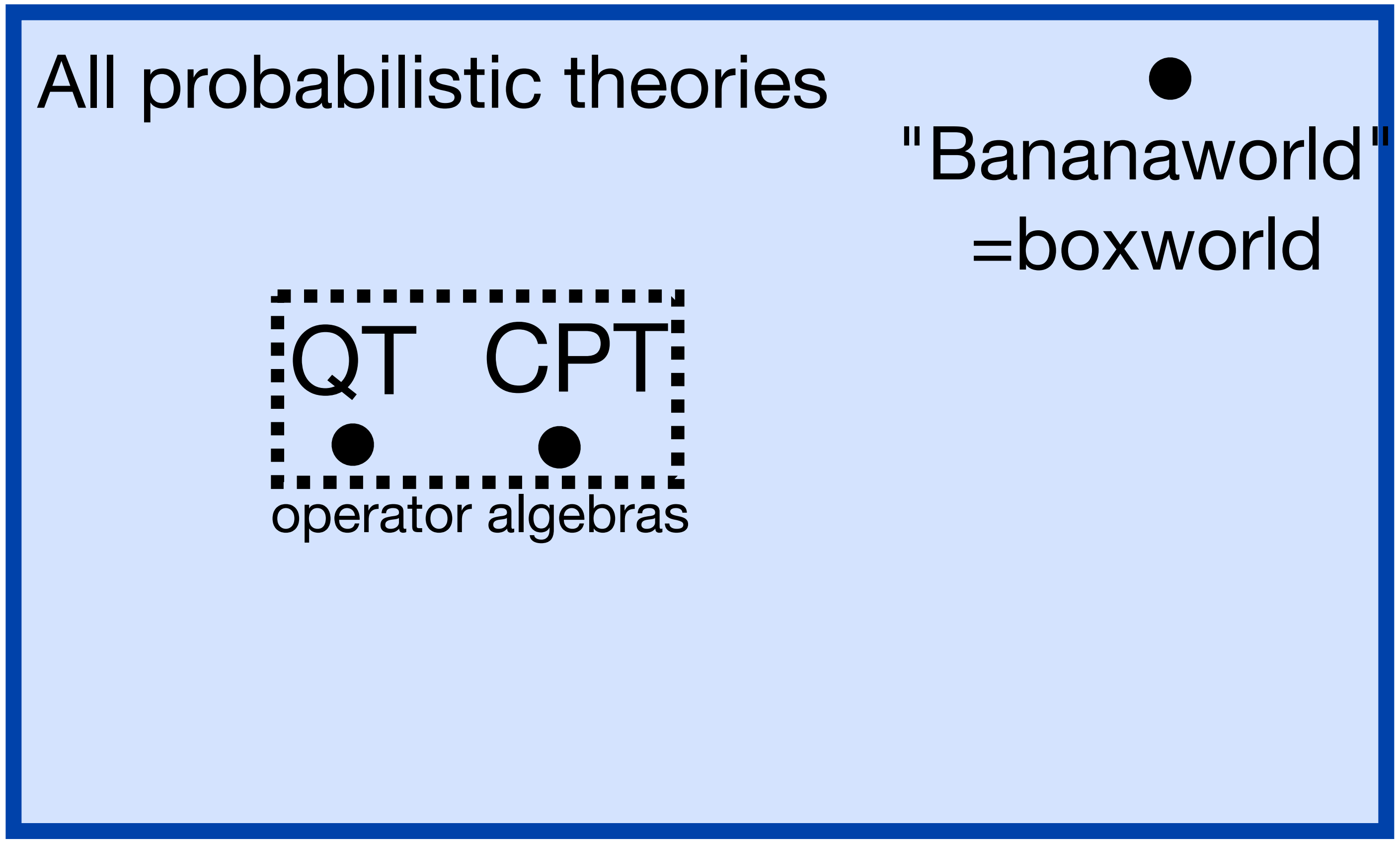
A vast landscape of state spaces, or *theories* (=collection of allowed state spaces) fits this description.



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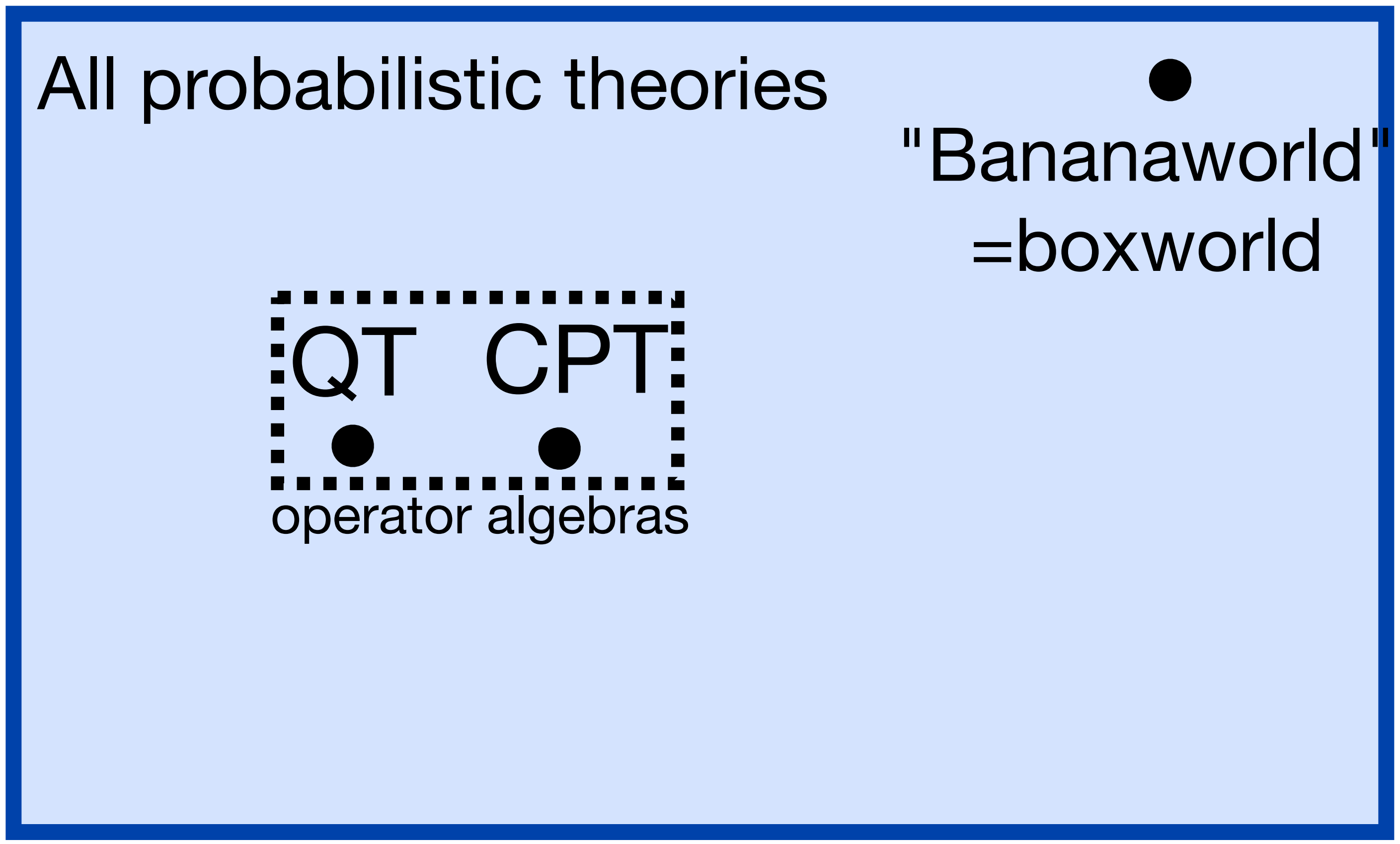

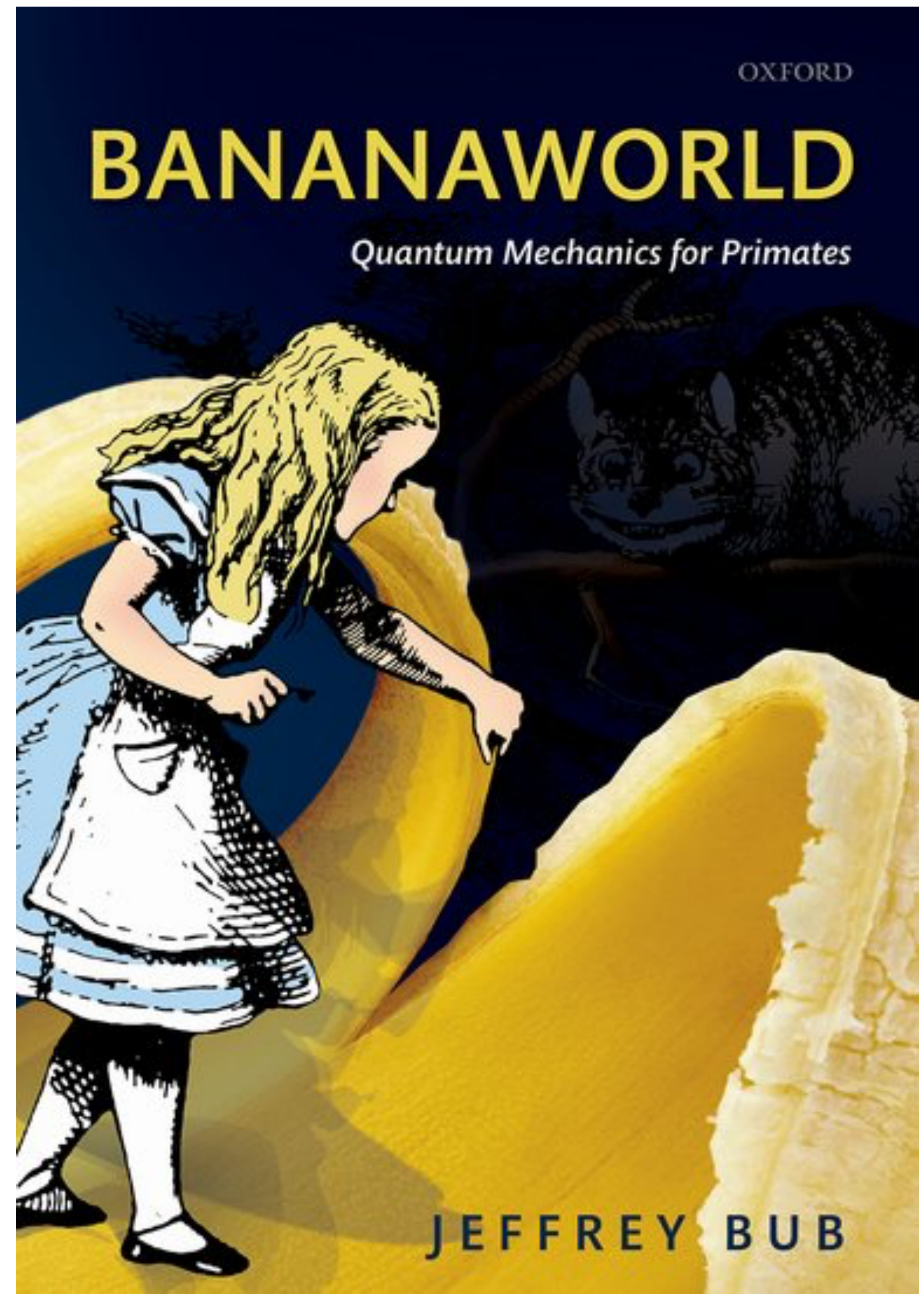

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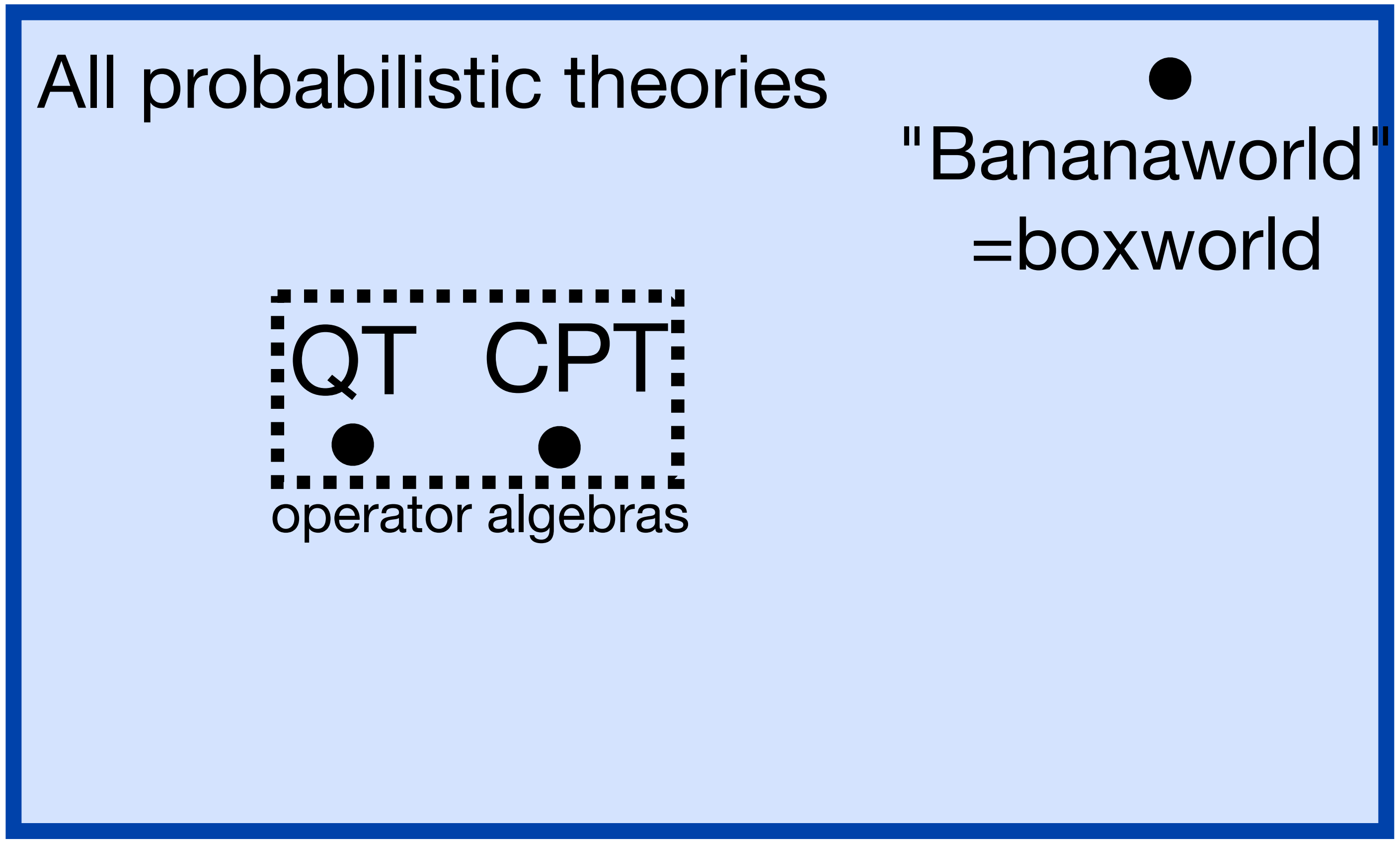

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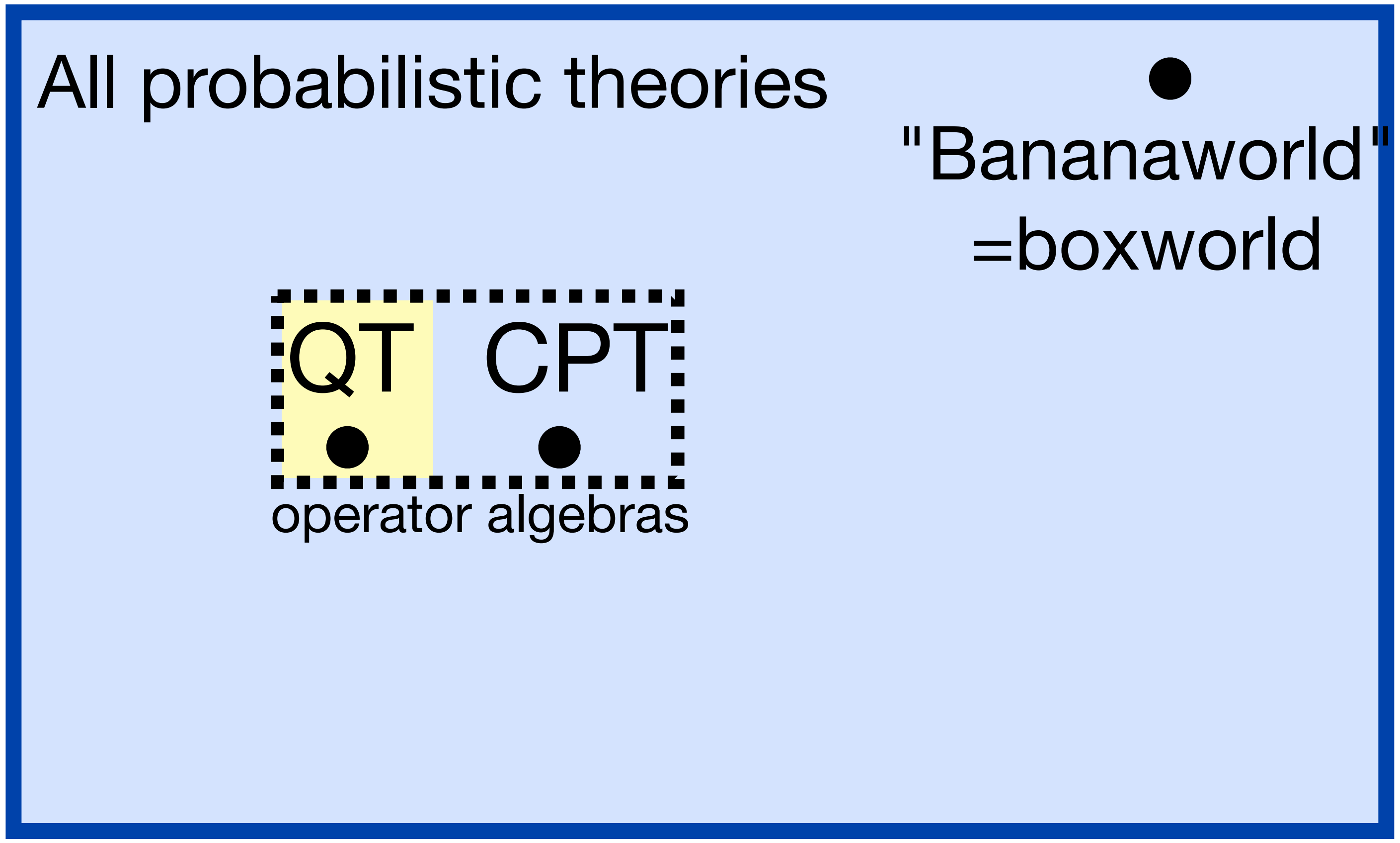

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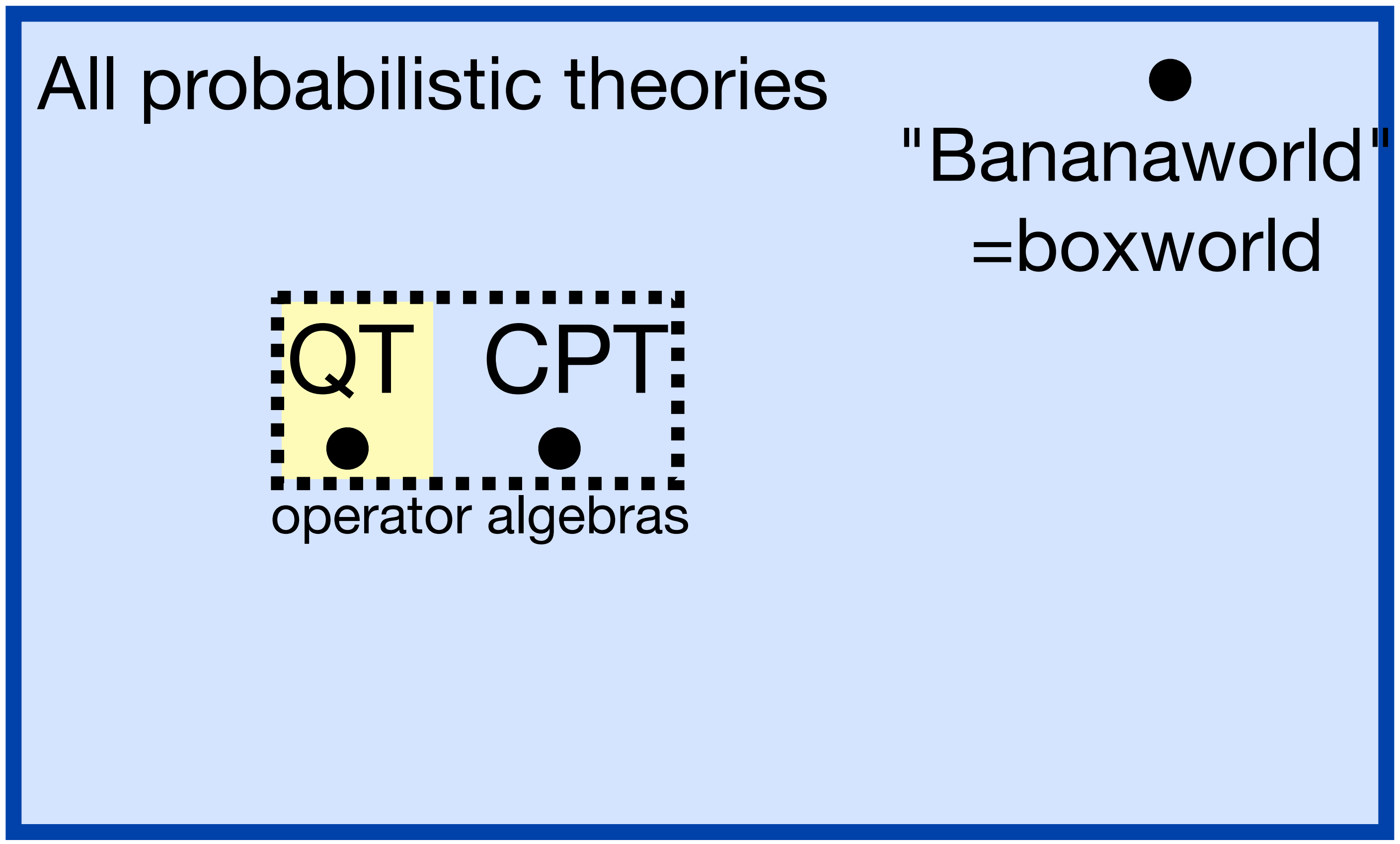

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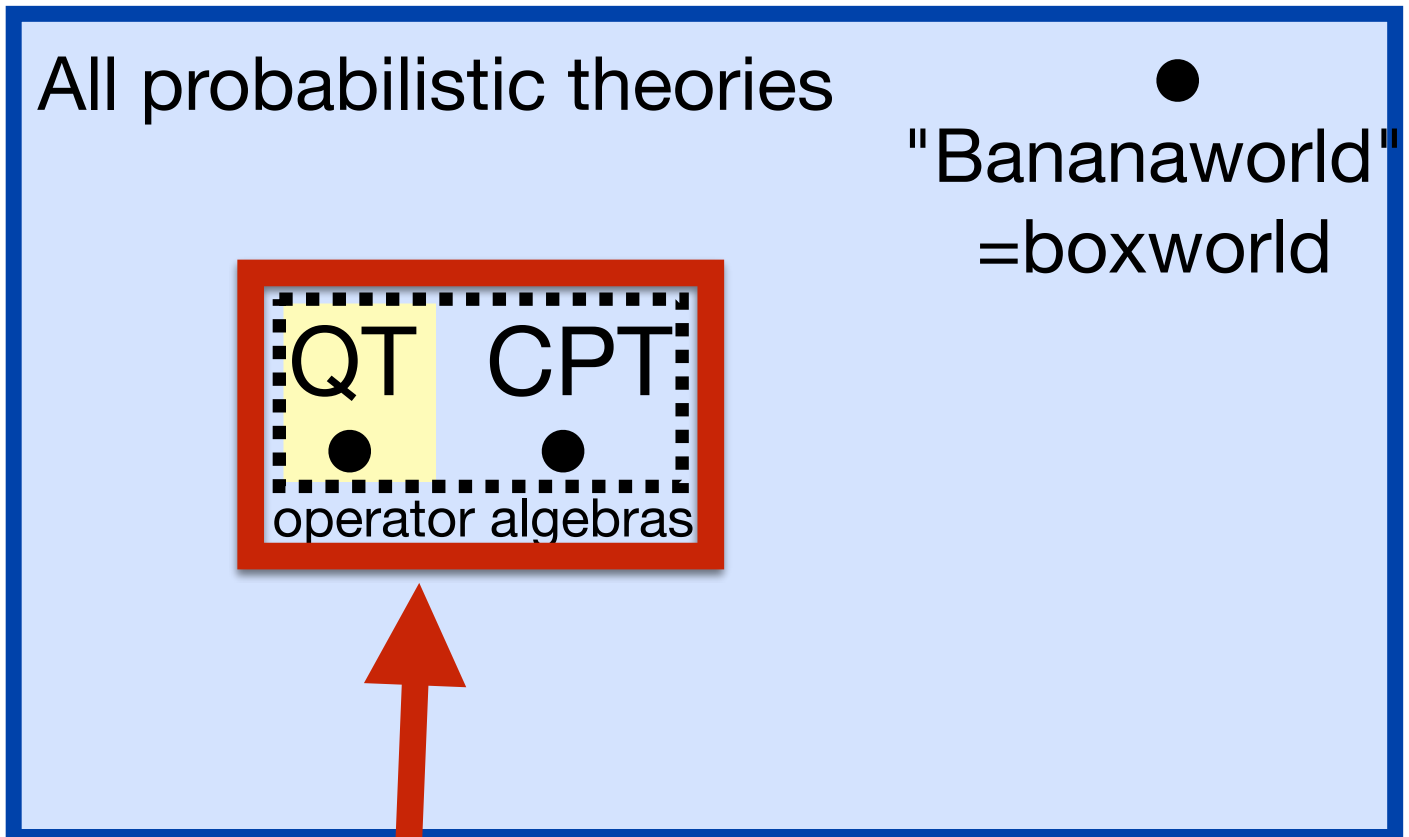

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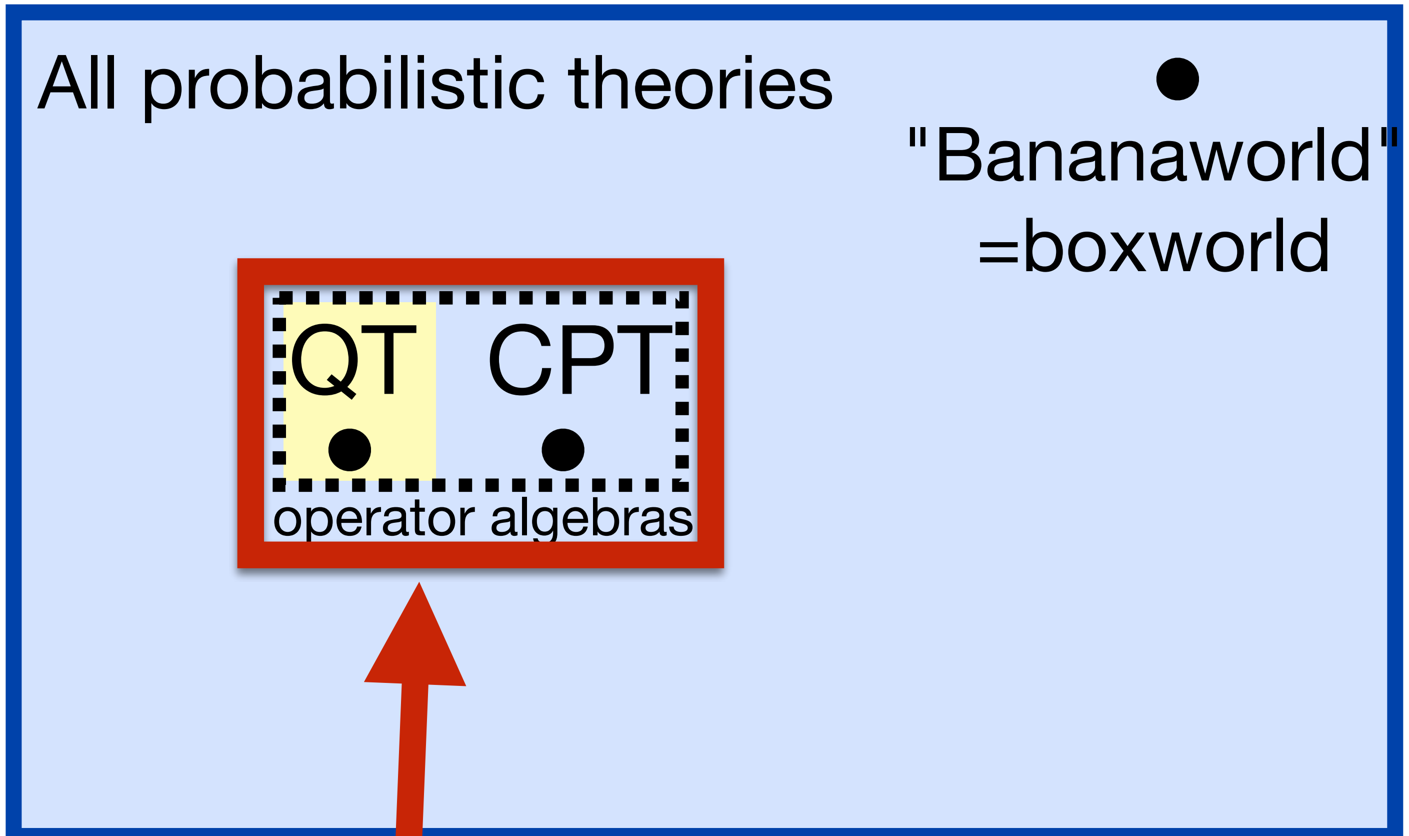

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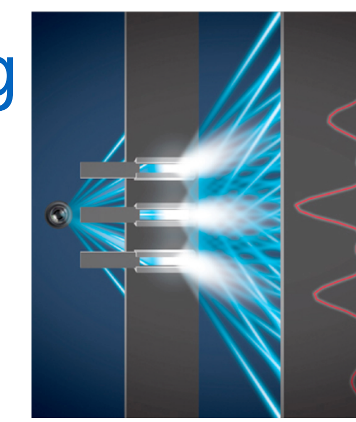
Other theories: differing physical predictions, e.g. different interference patterns.



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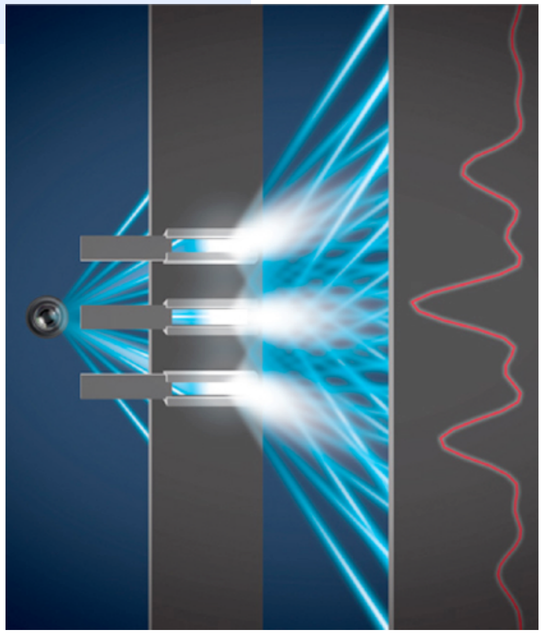

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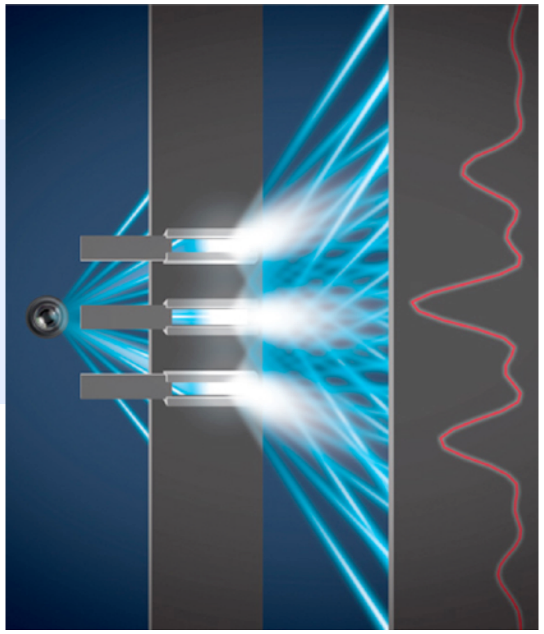

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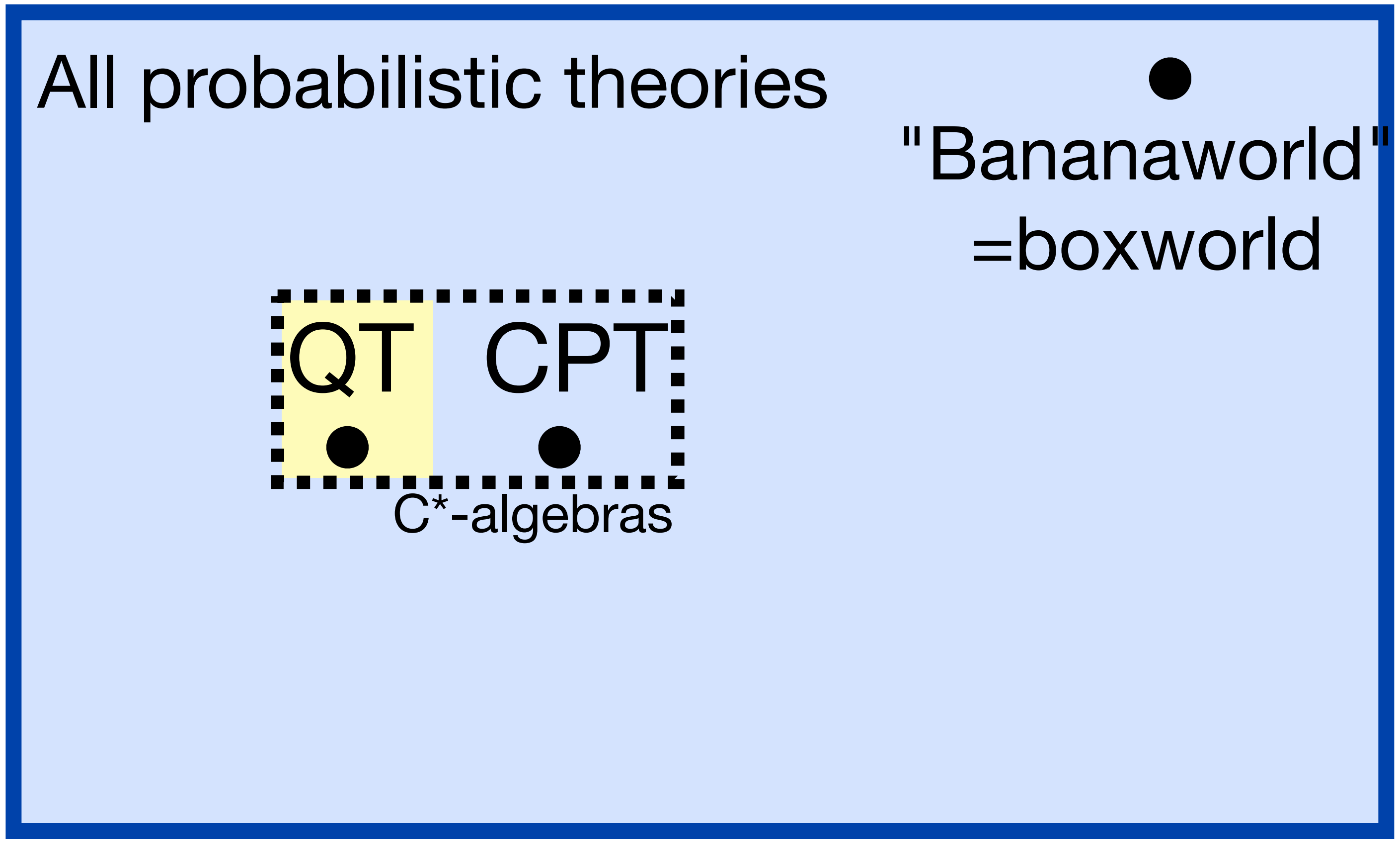

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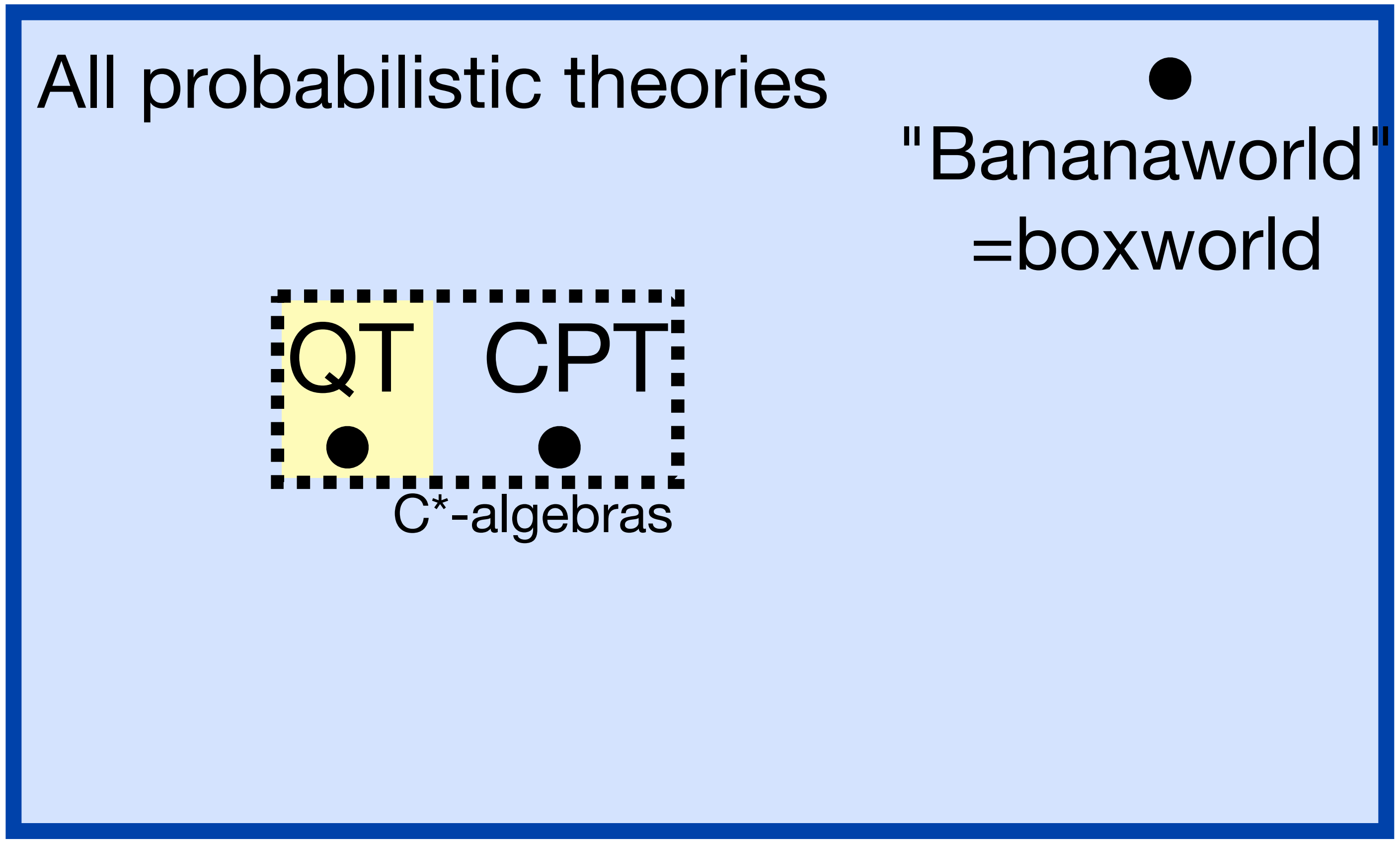

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Will now describe one particular set of principles that accomplish this...

Ll. Masanes, MM, R. Augusiak, and D. Pérez-García, *Existence of an information unit as a postulate of quantum theory*, Proc. Natl. Acad. Sci. **110**(41), 16373 (2013).

... but many others have been found in the last few years.

Reconstructing quantum theory

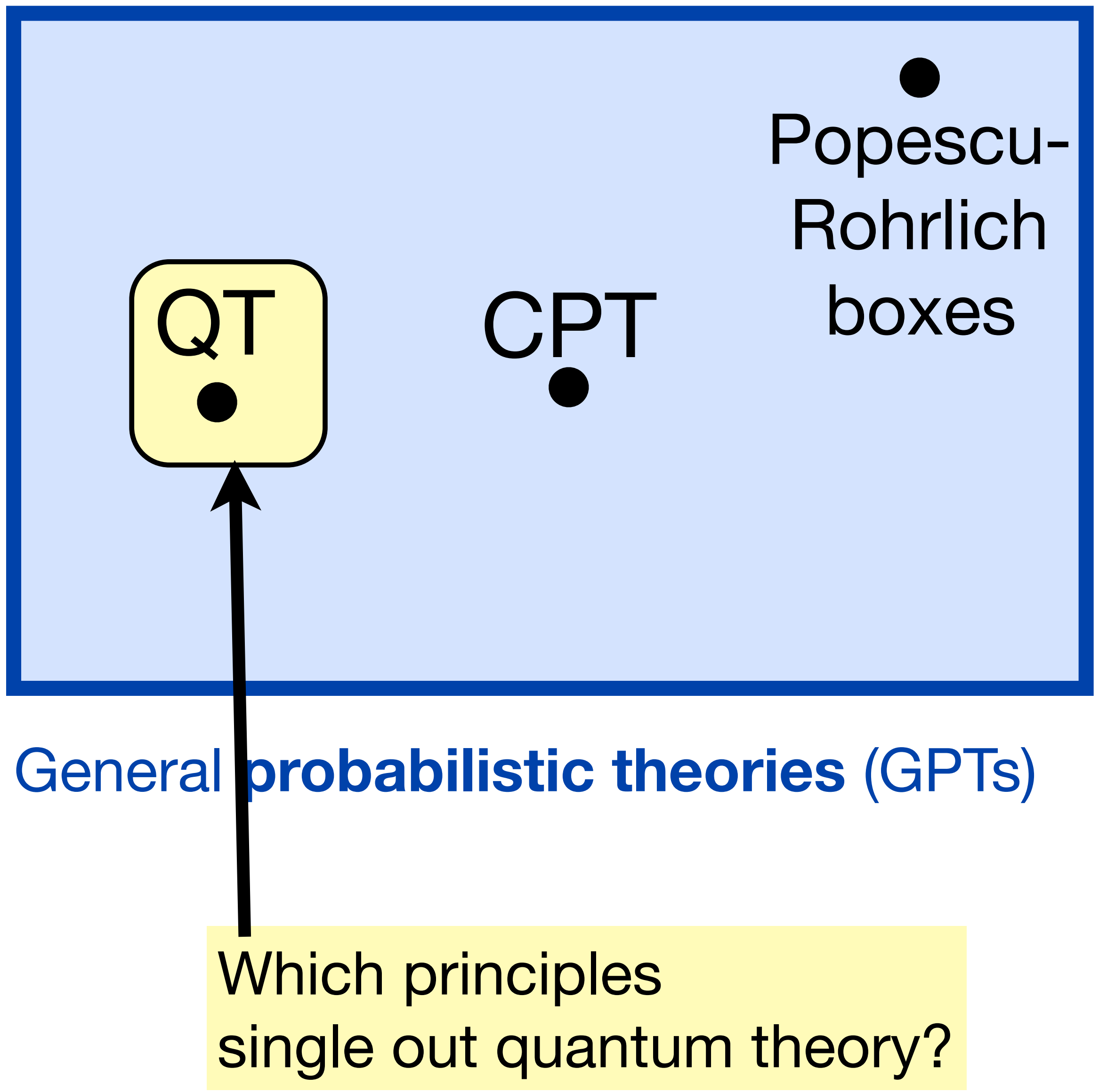
- Prehistory:
  Birkhoff & von Neumann (1936); quantum logic (Piron, ...),
  Ludwig (1954); Alfsen&Shultz (≈1980); .....

- Quantum information revolution:

  Lucien Hardy 2001: *Quantum Theory From Five Reasonable Axioms.* But needs "simplicity axiom"...

Dakic+Brukner 2009; Masanes+MM 2009
Chiribella, d'Ariano, Perinotti 2010; Hardy 2011
the one I'll present now 2013;
Barnum, MM, Ududec 2014; Hoehn 2015;
Wilce 2016 (and earlier results)...

A reconstruction of quantum theory



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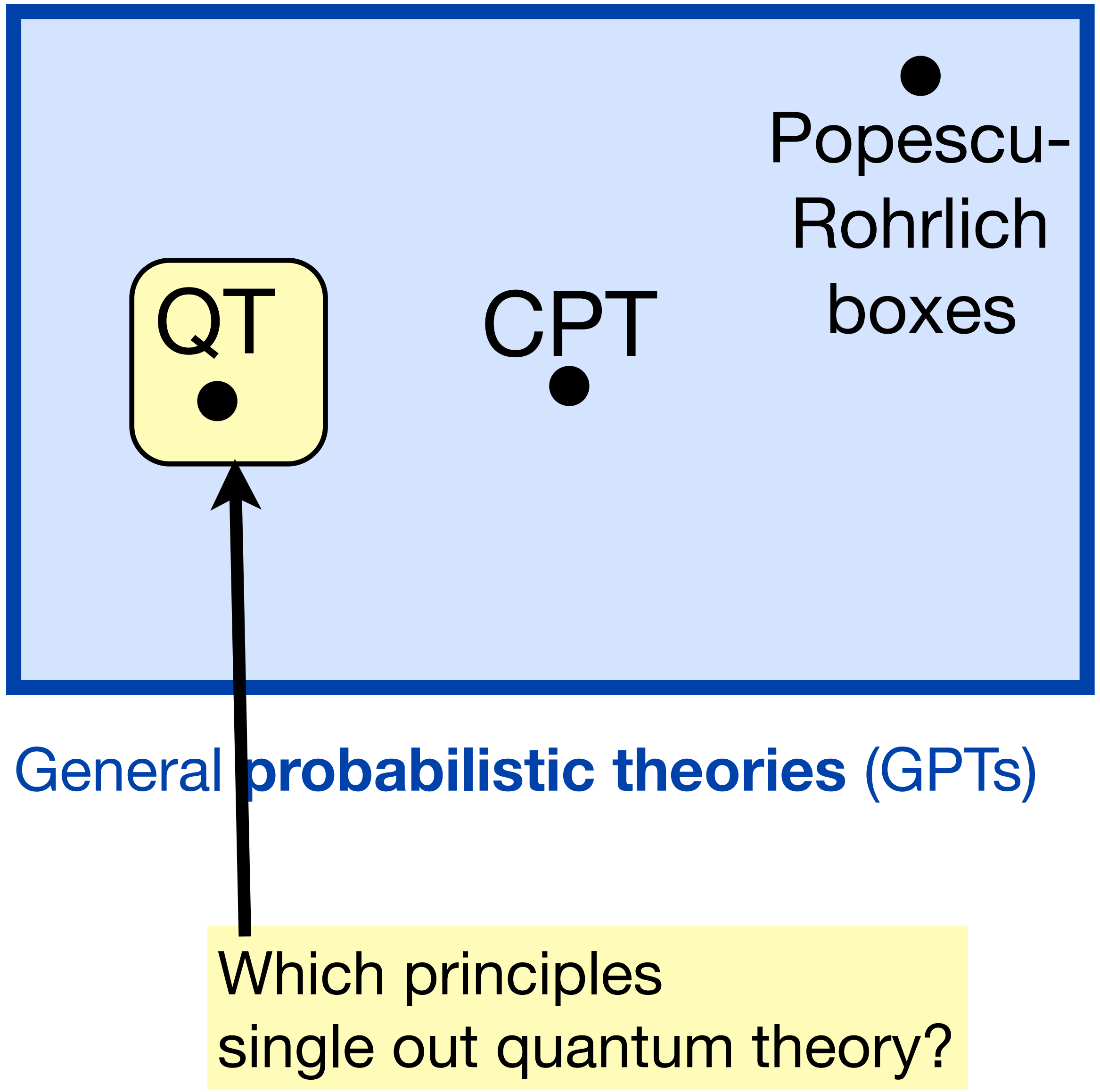

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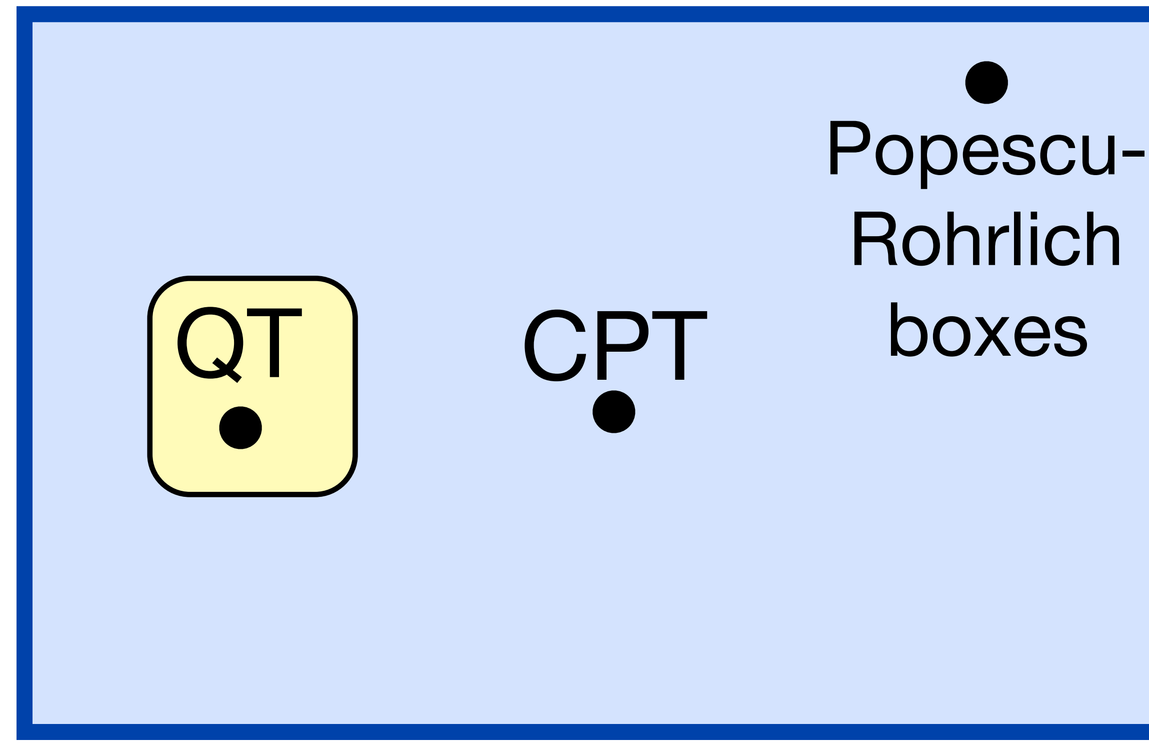
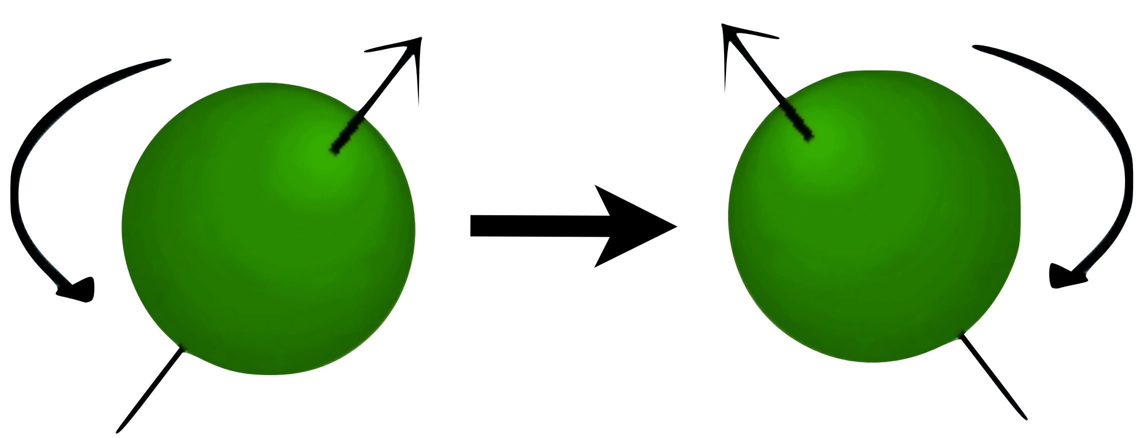
- **Postulate 1**: Continuous reversibility.

Continuous reversible time evolution can (in principle) map every pure state to every other.



General **probabilistic theories** (GPTs)



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- **Postulate 1**: Continuous reversibility.
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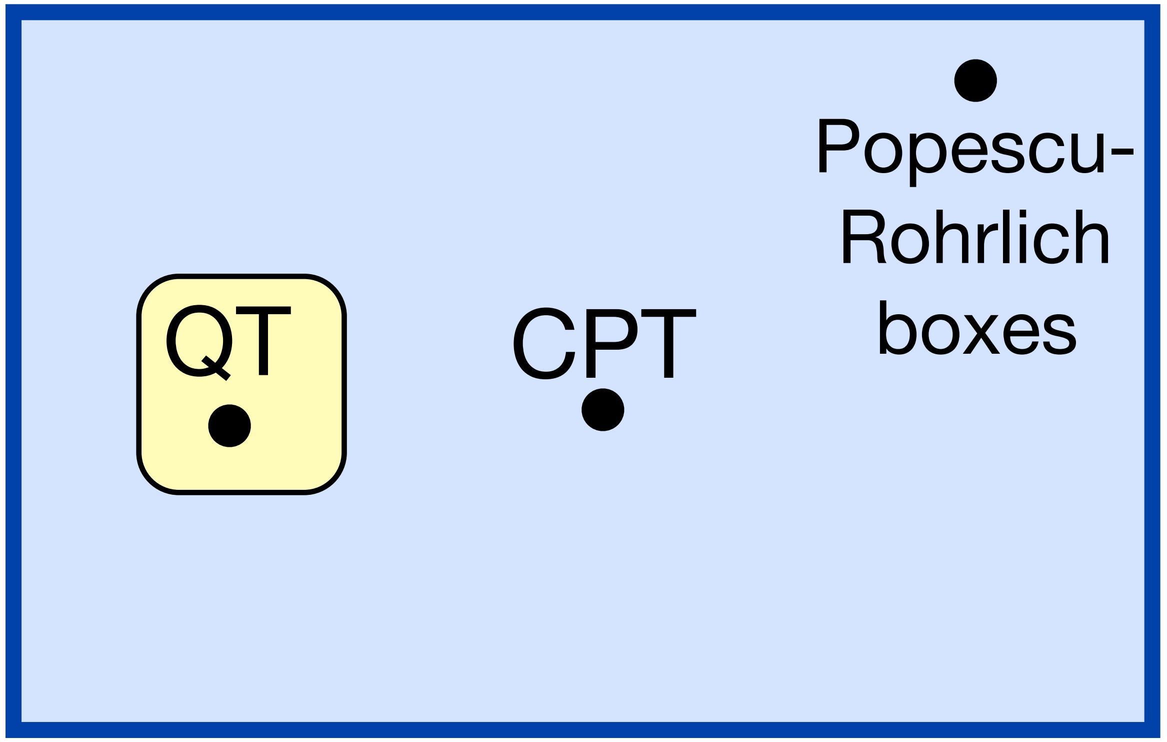
The state of a composite system is completely characterized by the correlations of measurements on the individual components.



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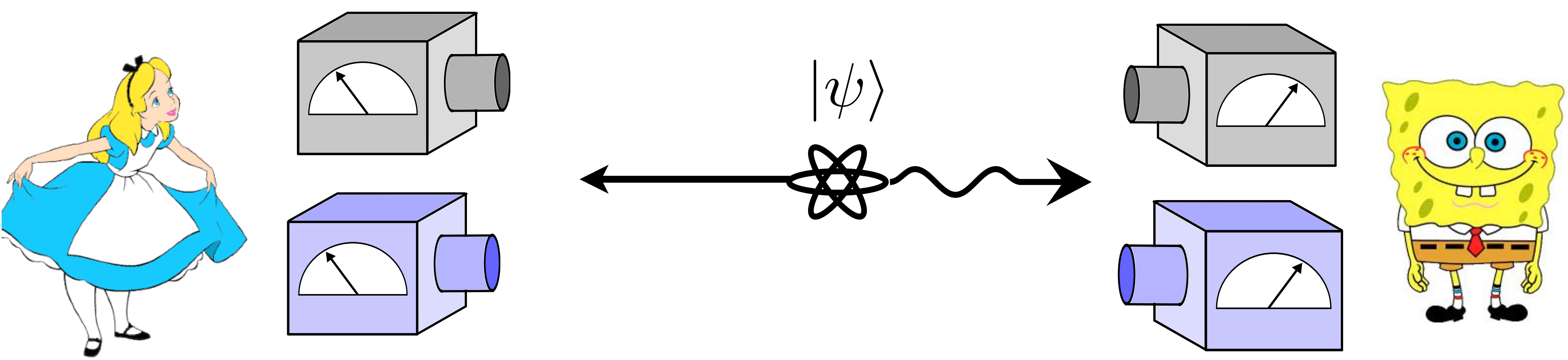

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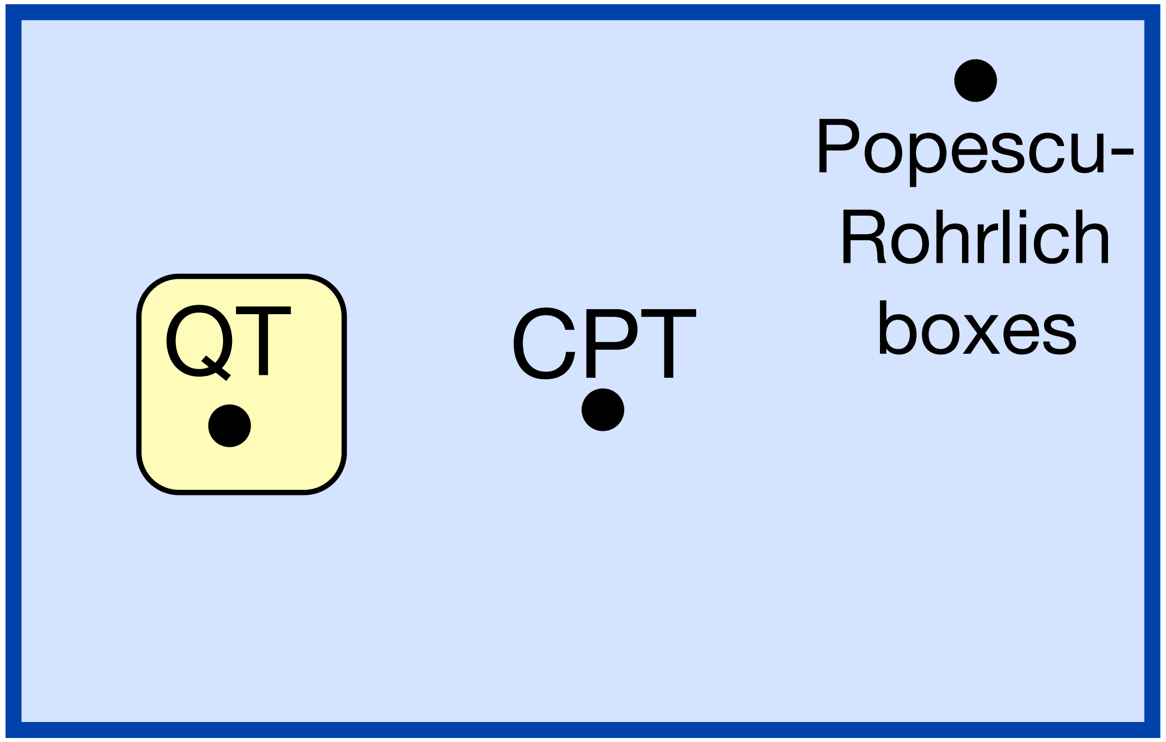

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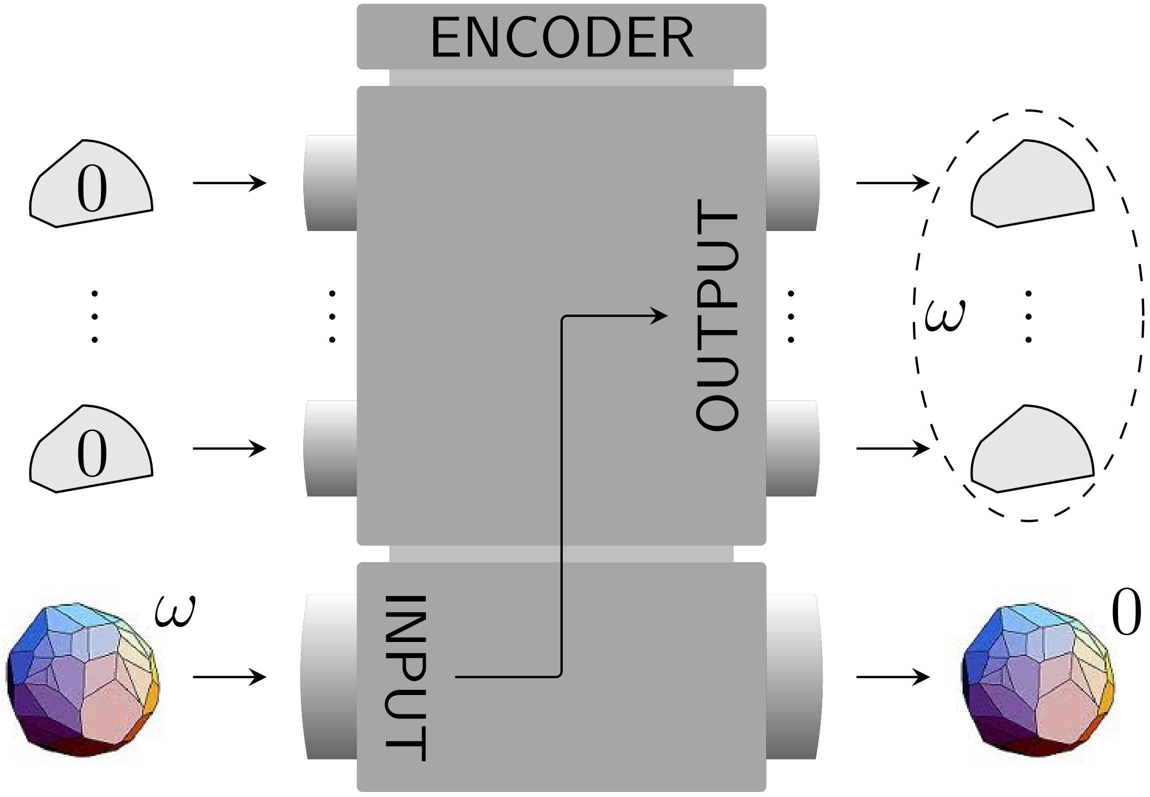

There is a type of system (the "ubit") such that the state of any system can be encoded into a sufficiently large number of ubits.

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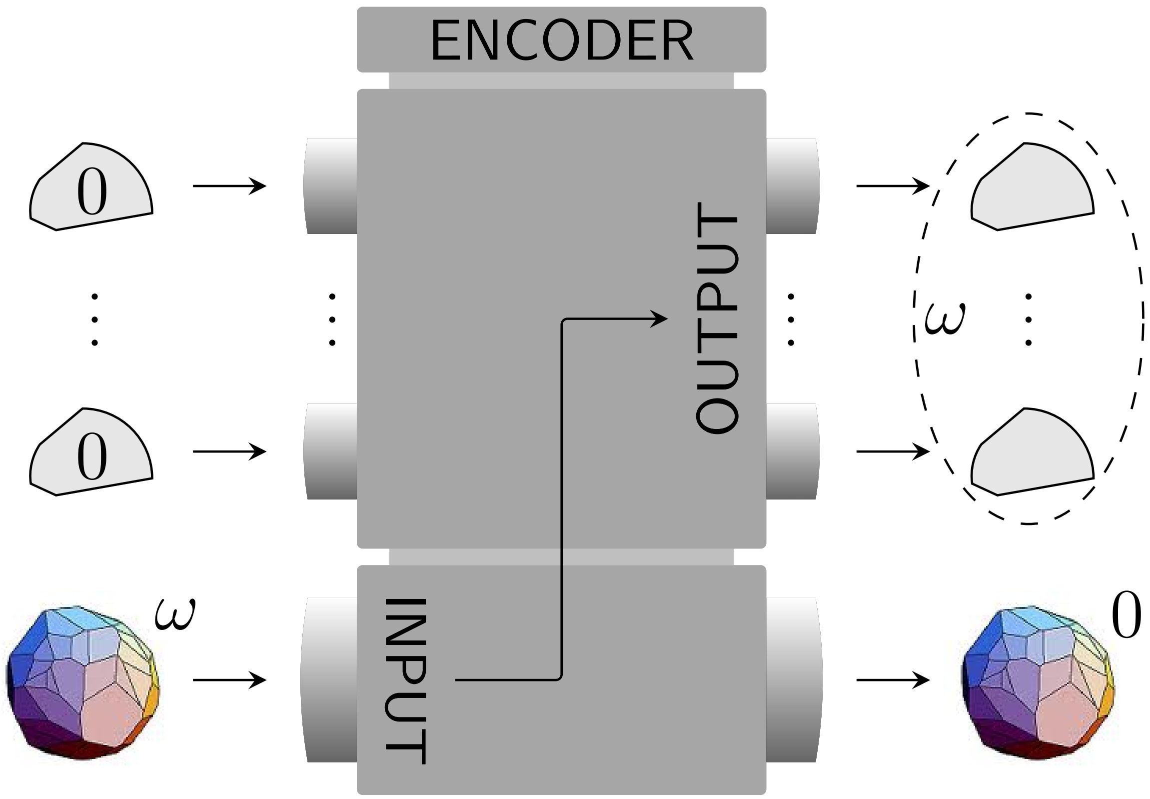

If a ubit is used to perfectly encode one classical bit, it cannot simultaneously encode any further information.

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Theorem: If Postulates 1-4 hold, then the state space of *n* ubits is exactly standard (Hilbert space) quantum theory of 2^n alternatives.

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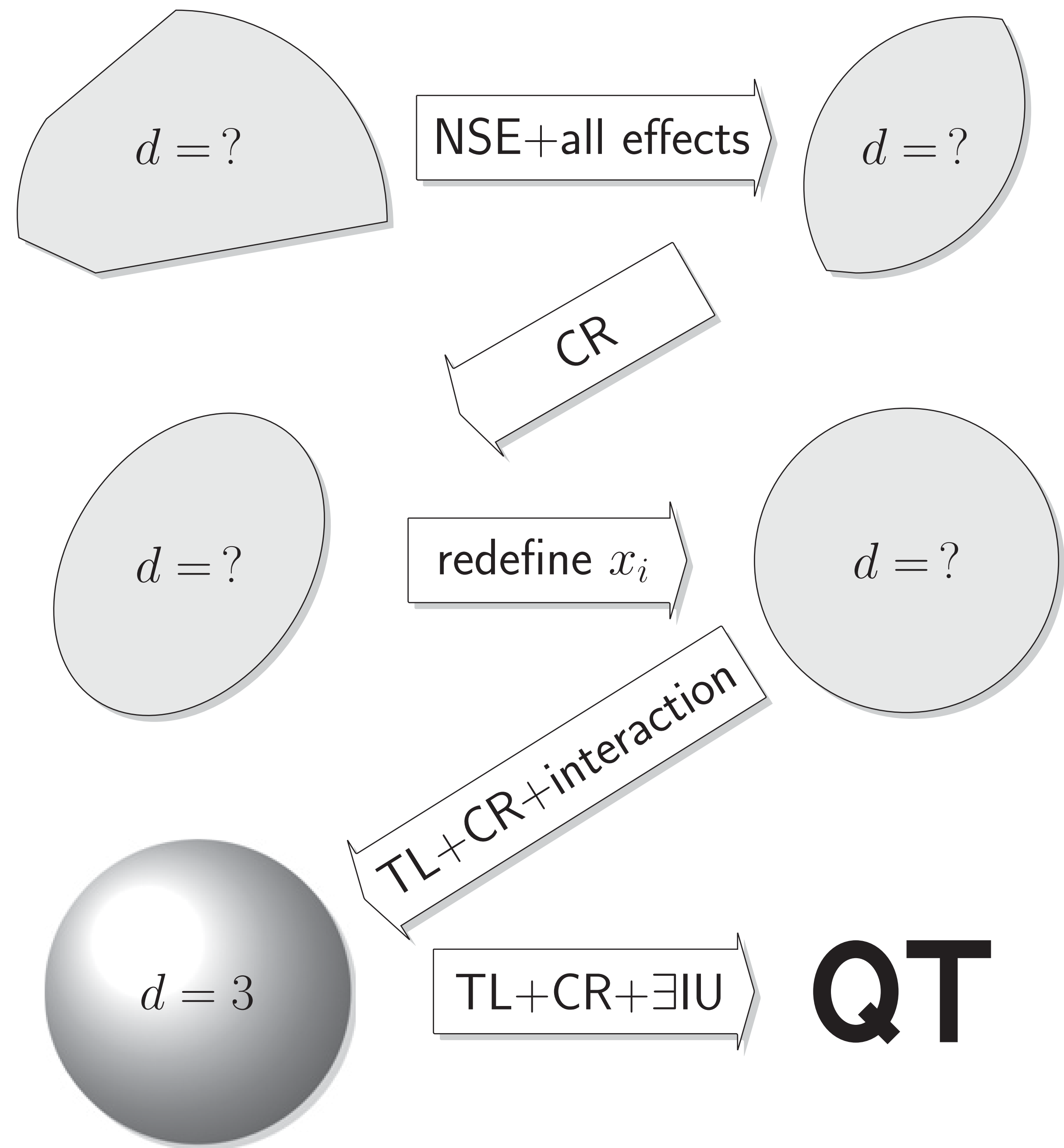

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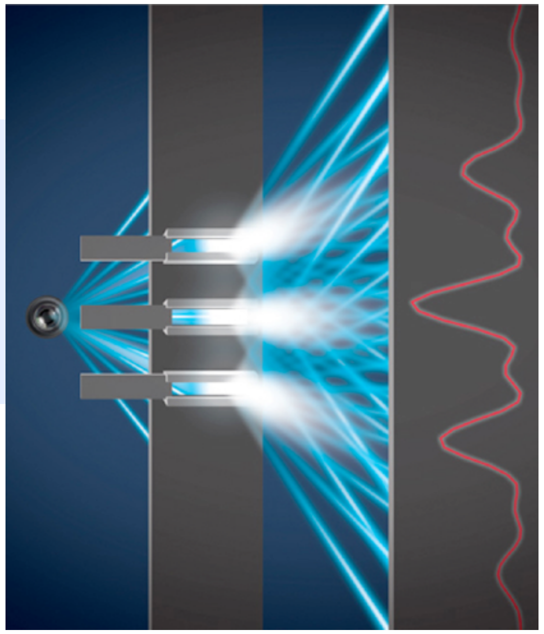

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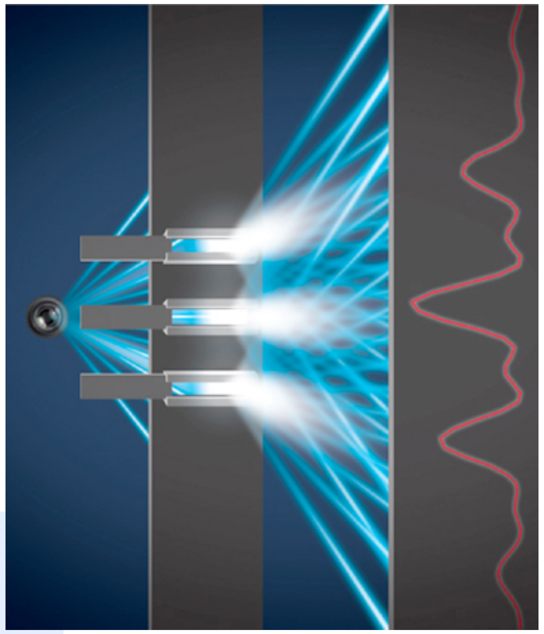

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A. Einstein in "Ideas and Opinions", 1954:

We can distinguish various kinds of theories in physics. Most of them are constructive. They attempt to build up a picture of the more complex phenomena out of the material of a relatively simple formal scheme from which they start out. Thus the kinetic theory of gases seeks to reduce mechanical, thermal, and diffusional processes to movements of molecules—i.e., to build them up out of the hypothesis of molecular motion. When we say that we have succeeded in understanding a group of natural processes, we invariably mean that a constructive theory has been found which covers the processes in question. Along with this most important class of theories there exists a second, which I will call ‘principle theories.’ These employ the analytic, not the synthetic, method. The elements which form their basis and starting-point are not hypothetically constructed but empirically discovered ones, general characteristics of natural processes, principles that give rise to mathematically formulated criteria which the separate processes or the theoretical representations of them have to satisfy. Thus the science of thermodynamics seeks by analytical means to deduce necessary conditions, which separate events have to satisfy, from the universally experienced fact that perpetual motion is impossible [40, p. 228].

- **P1**: Continuous reversibility
- **P2**: Tomographic locality
- **P3**: Existence of an information unit
- **P4**: No simultaneous encoding

This identifies a small set of information-theoretic / computational principles that renders our world a quantum one.

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In what sense is this a "partial interpretation"?

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- Framework very suggestive of the interpretation that "*(quantum) states are the same kind of 'stuff' as probability distributions*". In fact, the following simple modification characterizes classical probability theory:

- **P1'**: Discrete reversibility
- **P2**: Tomographic locality
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What can we learn from this?

A. Koberinski and MM, in "Physical Perspectives on Computation, Computational Perspectives on Physics" (ed. Michael Cuffaro and Samuel Fletcher), CUP, 2018

We argue for the following thesis:

Information-theoretic reconstructions provide a partial interpretation of quantum mechanics as a *principle theory of information*.

This leaves several alternatives for extending to a full-fledged interpretation. The reconstructions present a major challenge for existing "ψ-ontic" interpretations of quantum theory, by highlighting a relative deficiency of those interpretations in terms of their explanatory power.

None of this is completely new; much can be said in more detail...

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Includes (variants of the) Copenhagen interpretation, QBism, Brukner+Zeilinger's view, Wheeler's interpretation...:
Quantum states are not "things in the world", but express our knowledge/information/belief about (things in) the world (or future experiences caused by (things in) the world).

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Option #2: Come up with a constructive successor of QT, something that describes a regime of our world that is currently empirically inaccessible, but which gives rise to the information-theoretic principles (and thus indirectly to QT) after some approximation or coarse-graining.

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Historical example: **kinetic theory of gases**, as a constructive successor of thermodynamics.

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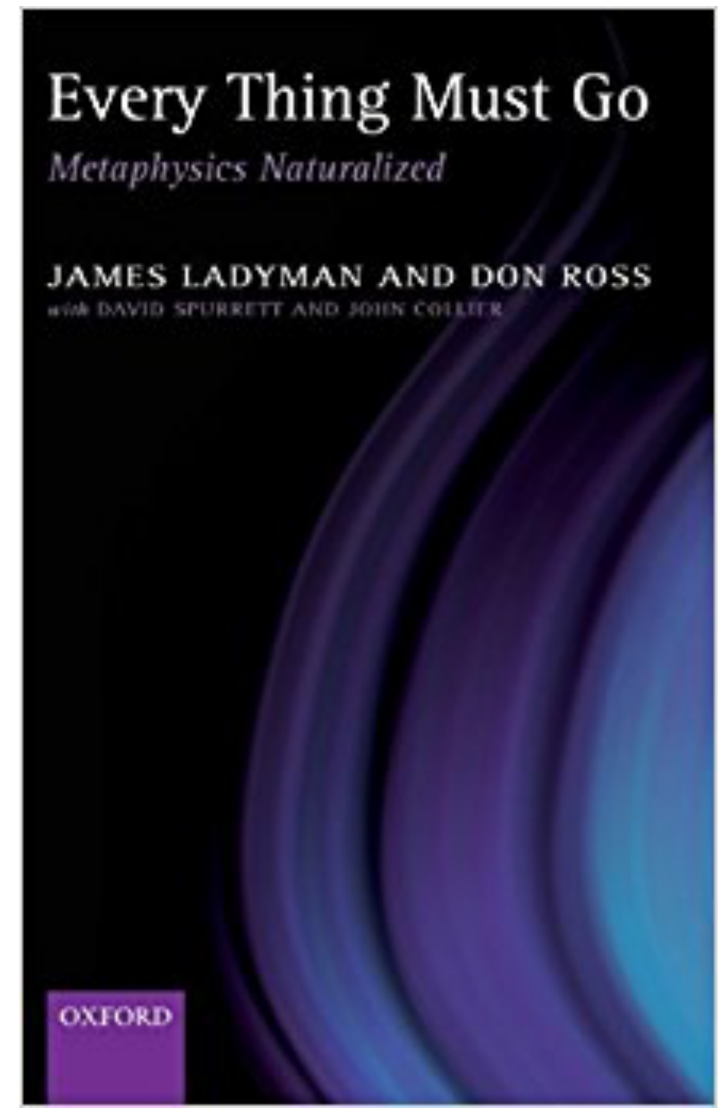
Option #3 (ultimately compatible with Option #2):
Combine QIT with ontic structural realism (OSR).



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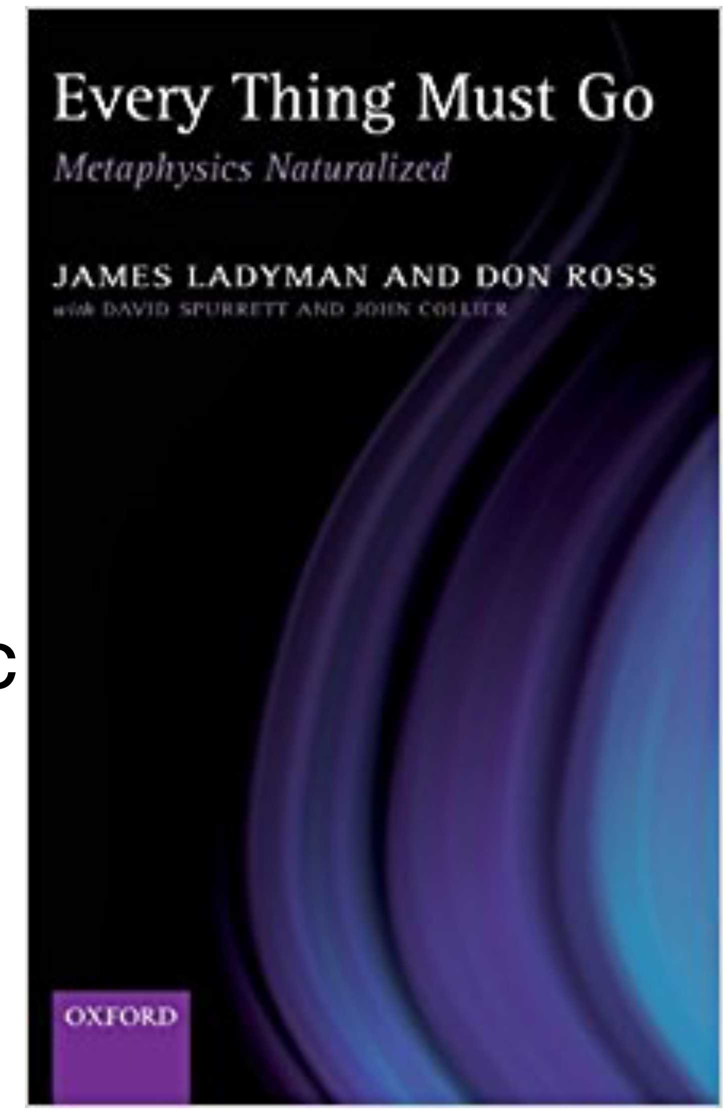
Reject the ultimate need for an entity-based constructive account of fundamental physics. Adopt an ontology of structural relations in some way, expressed by the information-theoretic postulates.



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"ψ-ontic" interpretations: quantum state is viewed as an intrinsic property of the physical system, in a particular strong sense (typically, seen as "stuff out there" like the electromagnetic field).

E.g. Bohmian mechanics, many worlds, collapse theories...

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As long as this challenge is not met, we think that there is a relative deficiency of the (many worlds) interpretation in terms of its explanatory power, as compared to any choice of completion of a partial interpretation as obtained from the information-theoretic reconstructions.

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on to the theory, the idea of quantum states as information has a simple unifying power that goes some way toward explaining why the theory has the very mathematical structure it does.[4] By contrast, who could take the many-worlds idea and derive any of the structure of quantum theory out of it? This would be a bit like trying to regrow a lizard from the tip of its chopped-off tail: The Everettian conception never purported to be more than a reaction to the formalism in the first place.

C. Fuchs, arXiv:1003.5209.

Conclusions

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- Reconstructions of QT as a specific example
- Specific work presented: QT as a “principle theory”
  - The paper with Adam: arXiv.org/abs/1707.05602
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Thank you!