# A general circuit framework for consistent logical reasoning in Wigner's friend scenarios

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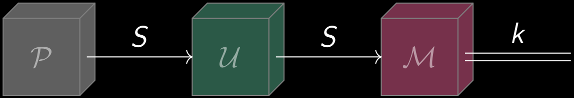
Joint work with Mischa Prebin Woods (Inria, Grenoble)

Based on: Vilasini and Woods 2022, arXiv:2209.09281

# Motivation

# Standard use of quantum theory




$$P(k|\mathcal{P},\mathcal{U},\mathcal{M})$$

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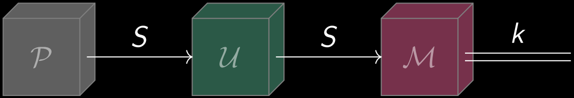


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- All agents outside the purview of theory

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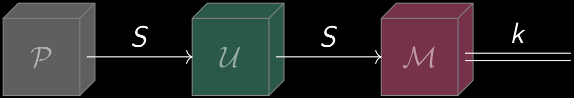


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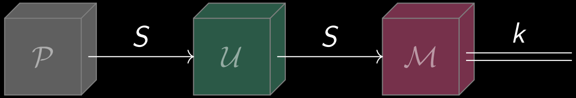


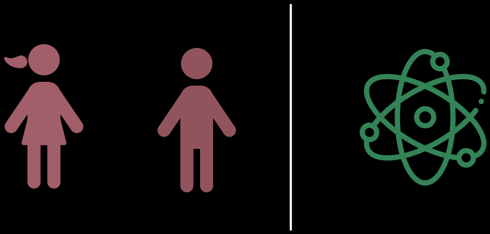

$$P(k|\mathcal{P},\mathcal{U},\mathcal{M})$$

- All agents outside the purview of theory
- Agents not part of the boxes/wires in the circuit
- Objective measurement probabilities (Born rule)

# Standard use of quantum theory (agents outside Heisenberg cut)

effectively classical

fully quantum



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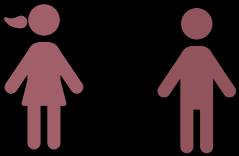

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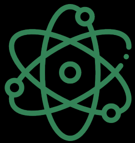
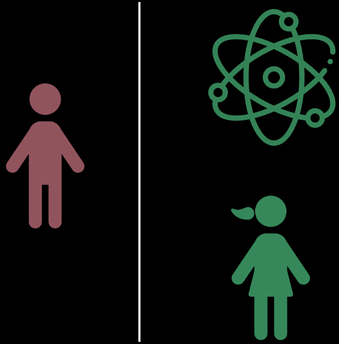


Can QT be consistently extended to include agents as systems of the theory?

# Universal use of quantum theory (agents within Heisenberg cut)

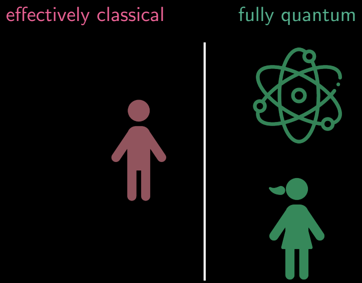
effectively classical | fully quantum



Wigner's Friend Scenarios (WFS): agents as fully quantum systems

Wigner 1967, Frauchiger and Renner 2018, Brukner 2018, Bong. et. al. 2020....

# Universal use of quantum theory (motile Heisenberg cut)

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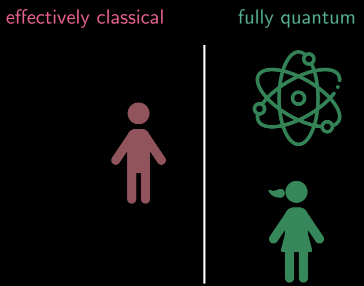


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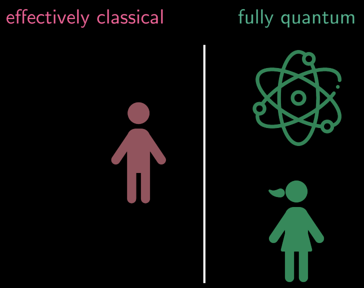


Wigner's Friend Scenarios (WFS): Protocols where agents can

- model other agents' lab as unitarily evolving closed q. systems
- have full quantum control over lab of another agent

⚠ Frauchiger and Renner (FR): Agents modelling each other as quantum systems and reasoning using classical logic in WFS will run into logical paradoxes!

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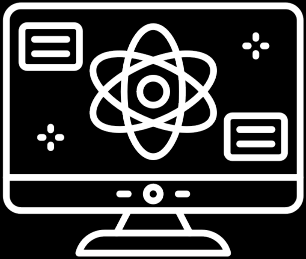
- Consistency w/o giving up quantum theory or classical logic
- Operational formalisation of H-cuts
- Precise neccesary condition for FR-type paradoxes

Agents $\neq$ conscious human beings. Can be quantum computers!



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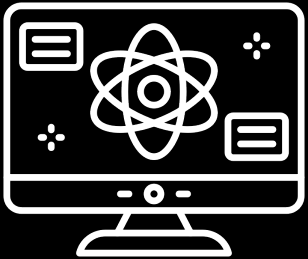

Necessary conditions for agency:

- Can measure another quantum system and store outcome
- Can compute probabilities, perform basic logical deductions

# The FR no-go theorem and apparent paradox

*Q* If Born rule assigns probability 1 to a measurement outcome, an agent can be certain of that outcome.

Frauchiger and Renner 2018. Nurgalieva and del Rio 2019.

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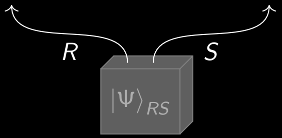
Theorem (FR): $\exists$ a protocol where agents reasoning using $Q$, $U$, $C$ and $S$ will arrive at logically contradictory predictions.

Frauchiger and Renner 2018. Nurgalieva and del Rio 2019.

# The FR protocol (entanglement version)




$$|\Psi\rangle_{RS} = \frac{1}{\sqrt{3}}\big(\,|00\rangle + |10\rangle + |11\rangle\,\big)_{RS}$$

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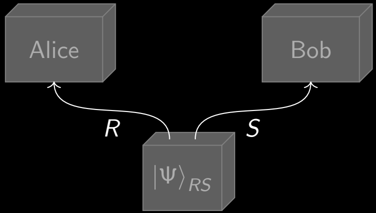
Meas. $R$ in $\{|0\rangle, |1\rangle\}$ basis




Meas. $S$ in $\{|0\rangle, |1\rangle\}$ basis

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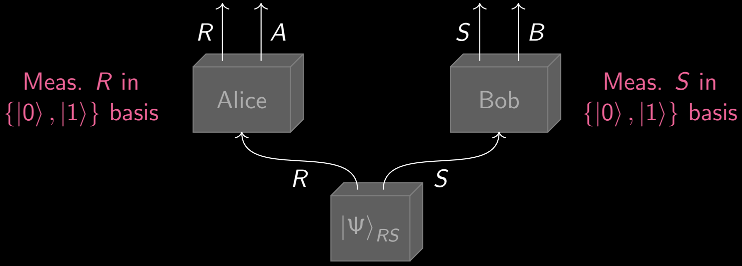


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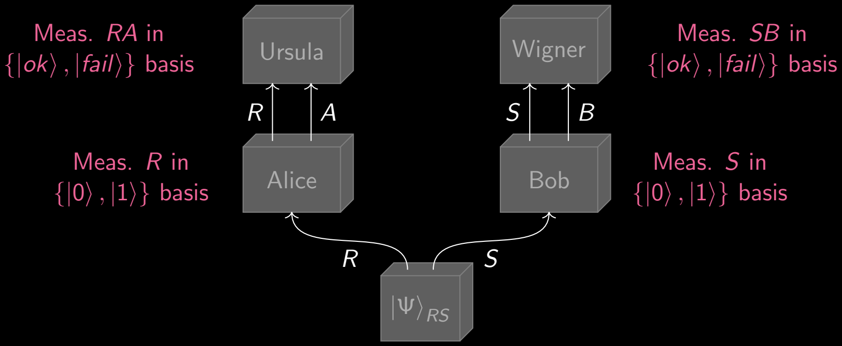


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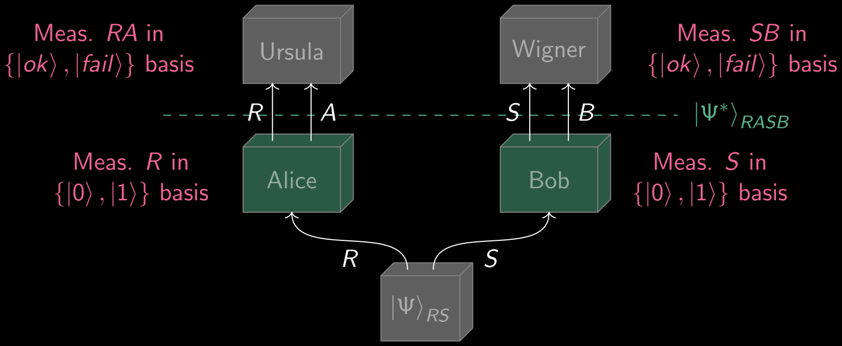
$$|ok\rangle := \frac{1}{\sqrt{2}}\big( |00\rangle - |11\rangle \big),\ |fail\rangle := \frac{1}{\sqrt{2}}\big( |00\rangle + |11\rangle \big)$$

# Applying $U$ to Alice and Bob's labs

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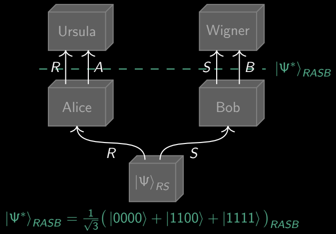
$$|\Psi^*\rangle_{RASB} = \frac{1}{\sqrt{3}}\big( |0000\rangle + |1100\rangle + |1111\rangle \big)_{RASB}$$

# FR's steps in proof of theorem (reasoning using $Q$, $U$ and $C$)




(1) Ursula reasons about Bob: $\langle ok|_{RA} \otimes \langle 00|_{SB} \cdot |\Psi^*\rangle_{RASB} = 0$ she concludes $P(b = 1|u = ok) = 1$, or $K_U(u = ok \Rightarrow b = 1)$.

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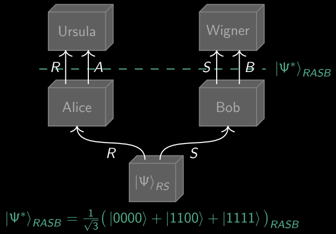


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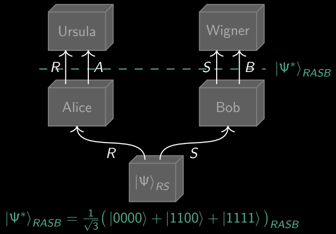


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$$K_U K_B(b = 1 \Rightarrow a = 1)$$

(3) Ursula reasons about Bob's reasoning about Alice's reasoning about Wigner

$$K_U K_B K_A(a = 1 \Rightarrow w = fail)$$

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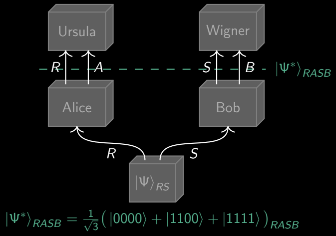


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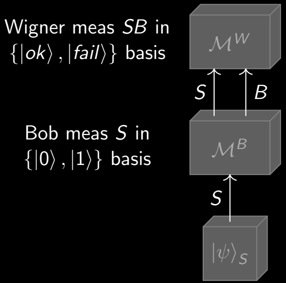
Violation of $S$ in any round where $u = w = ok$ (non-zero prob)

$K_U(w = fail)$ and $K_U(w = ok)$

PARADOX!

# A simple resolution to FR paradoxes

# Wigner's original expt: unitarity vs projection postulate

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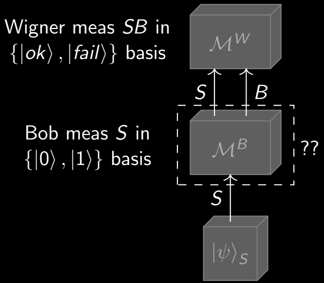


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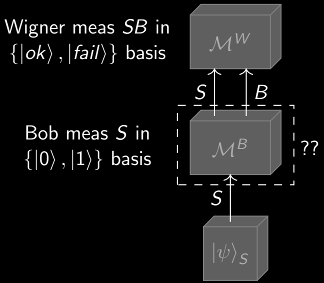


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Unitary $\mathcal{M}^B_{unitary}$

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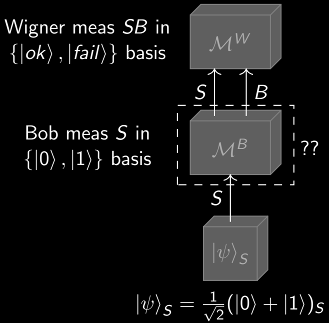


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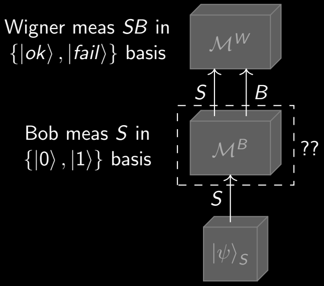


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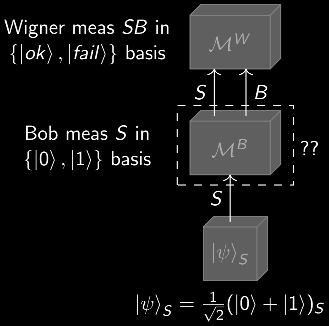


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$$\Rightarrow P(w = ok | x_B = 0) = 0$$

Projection $\mathcal{M}^B_{projection}$ : $x_B = 1$

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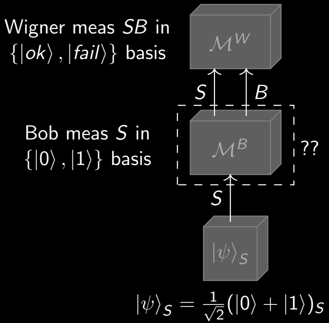


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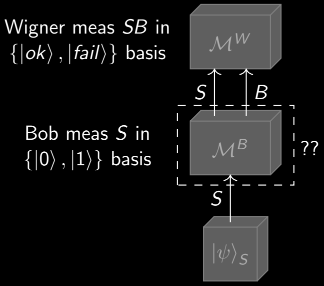


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- Predictions do depend on how mmt is modelled ($x_B \in \{0, 1\}$)!
- Formalises the H-cut: agents' "memory' as q. system vs storing effectively classical values

# FR paradox disappears once "settings"/H-cuts are accounted for

## FR's statements

- $u = ok \Rightarrow b = 1$ "$P(b = 1 | u = ok) = 1$"
- $b = 1 \Rightarrow a = 1$ "$P(a = 1 | b = 1) = 1$"
- $a = 1 \Rightarrow w = fail$ "$P(w = fail | a = 1) = 1$"
- $P(u = w = ok) = \frac{1}{12} > 0$

## Explicit statements in our framework

- $u = ok \wedge (x_A = 0, x_B = 1) \Rightarrow b = 1$
- $b = 1 \wedge (x_A = 1, x_B = 1) \Rightarrow a = 1$
- $a = 1 \wedge (x_A = 1, x_B = 0) \Rightarrow w = fail$
- $P(u = w = ok | (x_A = 0, x_B = 0)) = \frac{1}{12} > 0$

Cannot be chained together by any axiom of classical logic

## Necessary condition for FR-type apparent paradoxes

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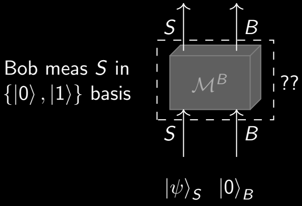
Universality of QT does not threaten logic! ☺

# Quantum circuit framework for WFS

# What is the channel $\mathcal{M}_B$?

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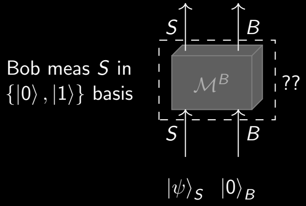


$$|\psi\rangle_S = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)_S$$

Unitary: $\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)_{SB}$

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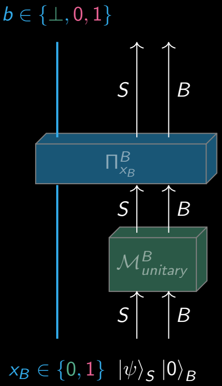
## Explicit description of $\mathcal{M}_B$



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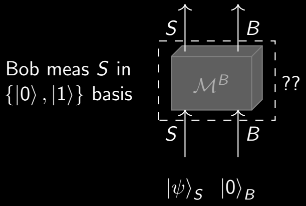


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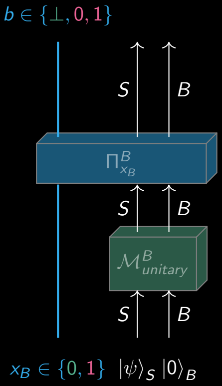
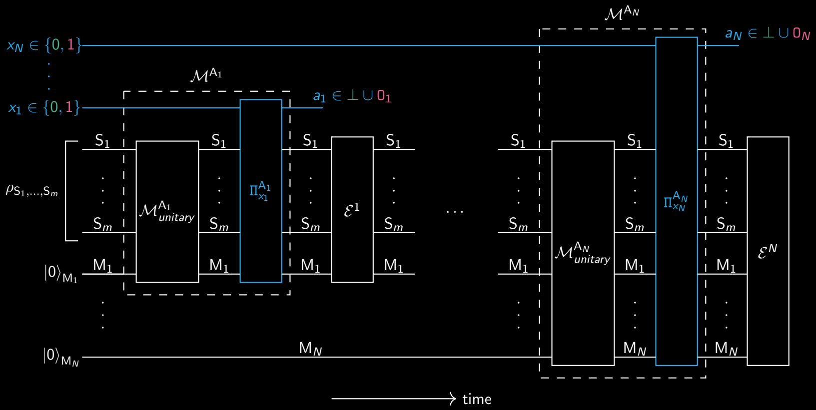



### Setting-dependent projectors

$$\Pi^B_{x_B=0} = \mathcal{I}_{SB} \text{ (trivial outcome } b = \perp)$$

$$\Pi^B_{x_B=1} = \{|00\rangle\langle 00|_{SB}, |11\rangle\langle 11|_{SB}\} \text{ (non-trivial } b \in \{0, 1\})$$

Generalises to arbitrary WFS over $N$ agents $A_1, \ldots, A_N$, performing arbitrary quantum operations on each other's labs/memories




An augmented circuit for a general WFS

# Completeness, logical and causal consistency

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Theorem (informal): An augmented circuit for a WFS

(1) Encodes all predictions that can made in that WFS
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Further...

- Unifying framework for previous responses
- Reasoning rules for quantum agents
- Allows subjective H-cuts, non-absolute measurement events

# Emergence of objective measurement events

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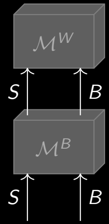
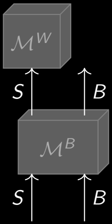
(Causal) structural distinction

WFS (quantum control of full lab)




Standard quantum expt



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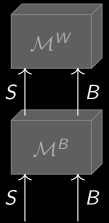


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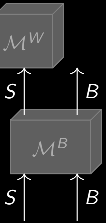


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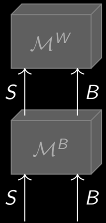


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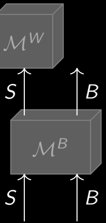


- <u>Theorem:</u> Predictions in standard q. expts are setting-indep
- Objective probabilities, independent of H-cuts emerge

# Summary and conclusions

FR: Logical paradox in a particular WF scenario with q. agents

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Take home: Quantum agents in WFS can always reason consistently without giving up quantum theory or classical logic, as long as they don't ignore non-trivial dependences on H-cuts.

# Outlook

- WFS and measurement problem beyond quantum theory
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THANK YOU!