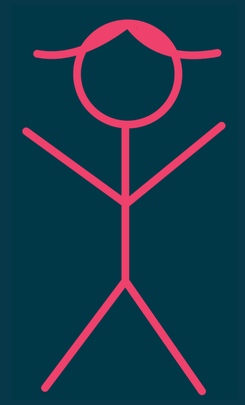
What quantum foundations teach us about black holes

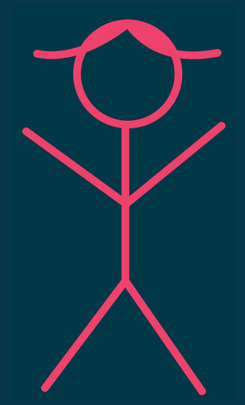
Ladina Hausmann
ETH Zürich

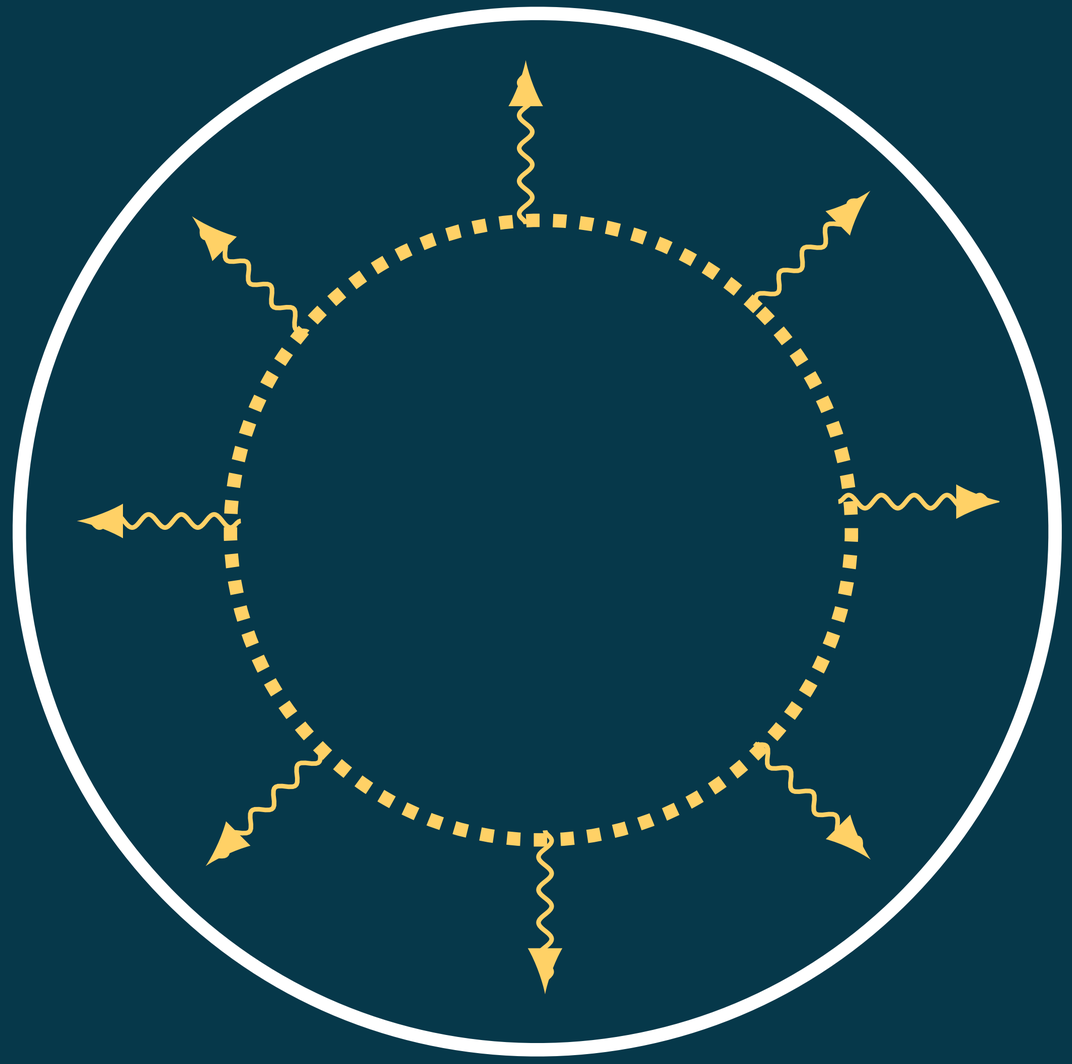
Based on joint work with Renato Renner, arXiv:2504.03835

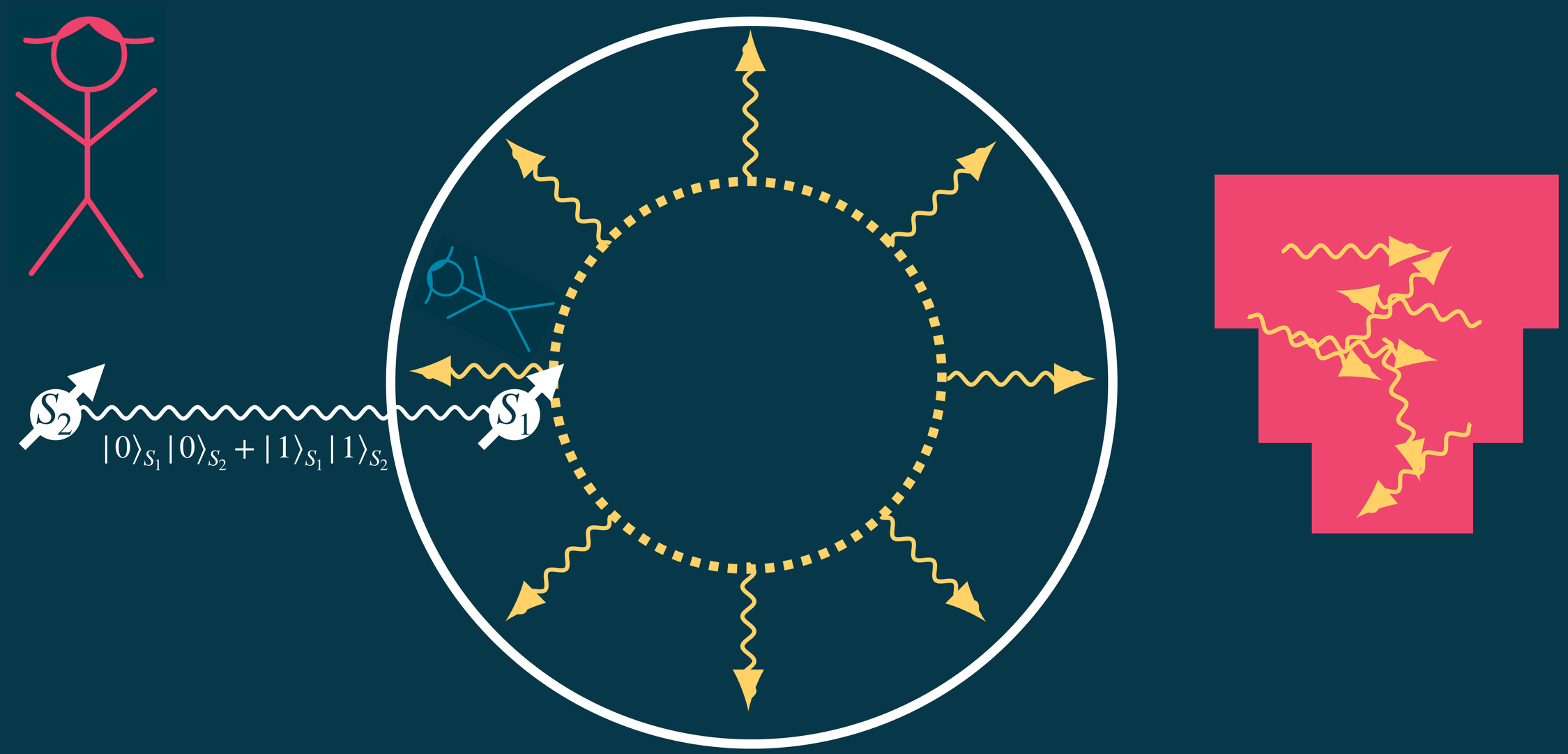
A black hole puzzle

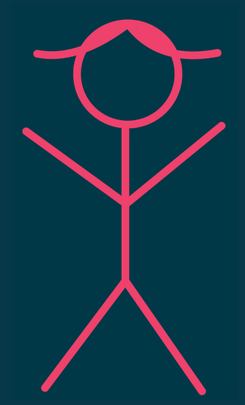
Hayden, Preskill, 2007



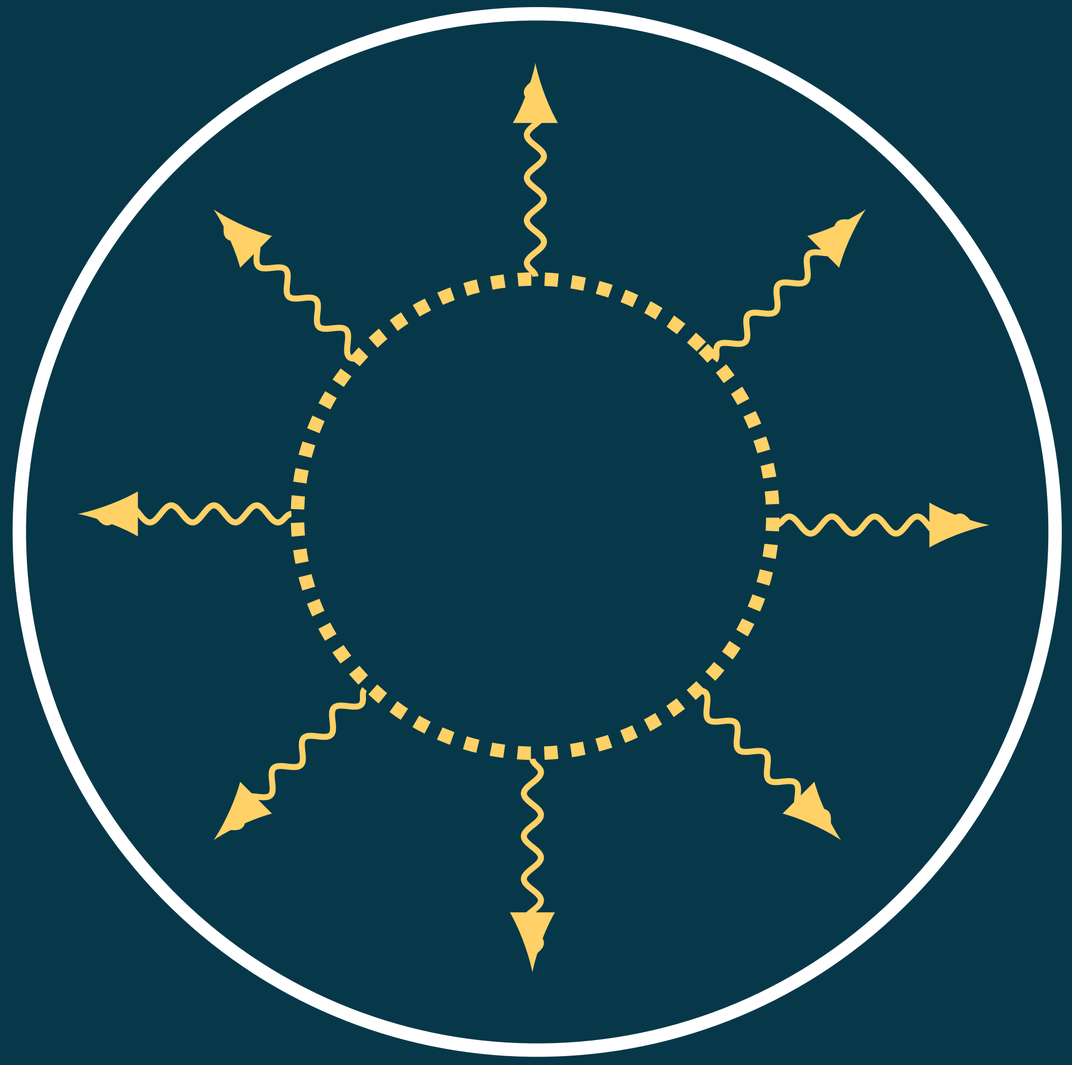


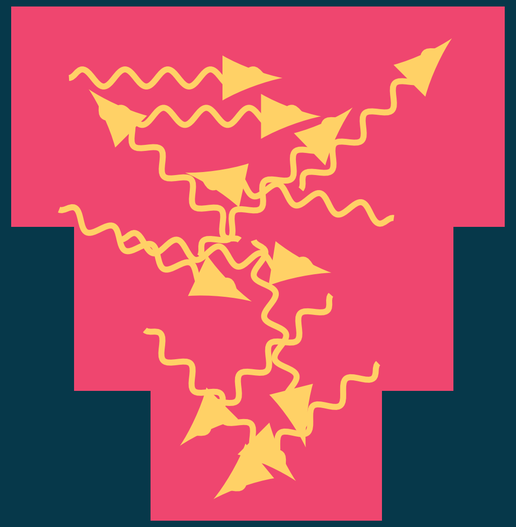


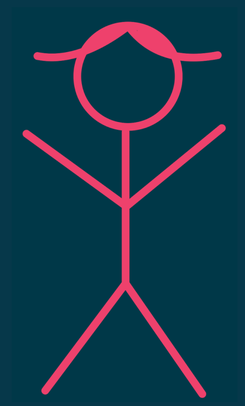

S_2
S_1
$|0\rangle_{S_1}|0\rangle_{S_2} + |1\rangle_{S_1}|1\rangle_{S_2}$

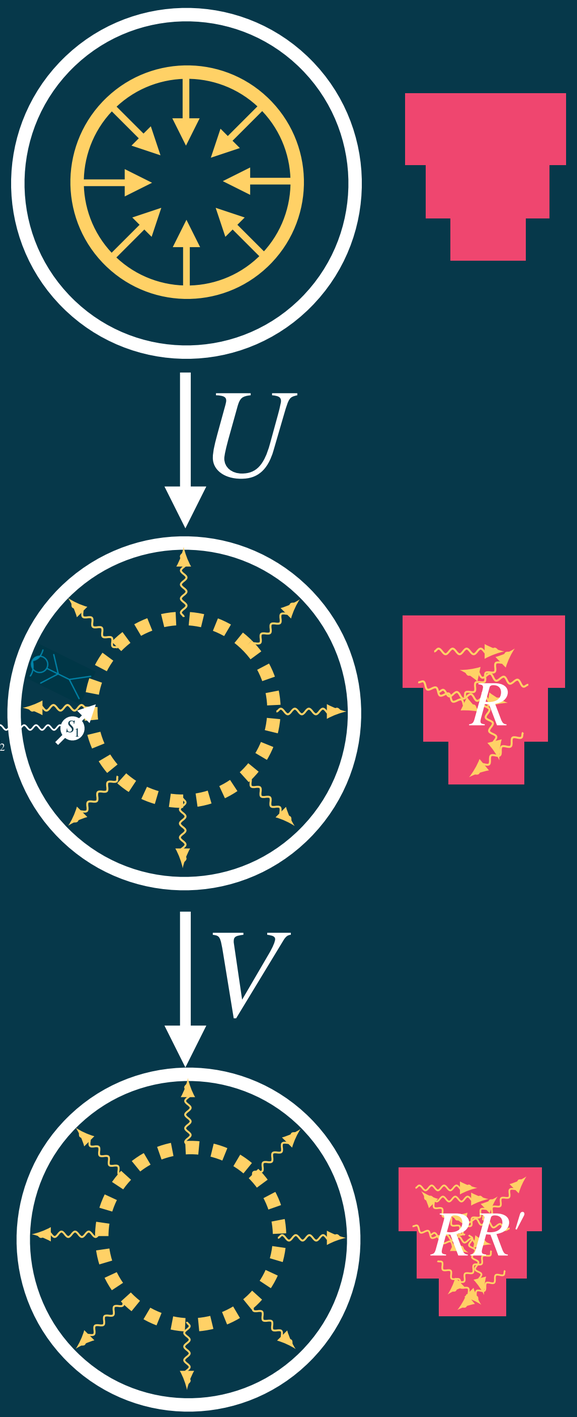


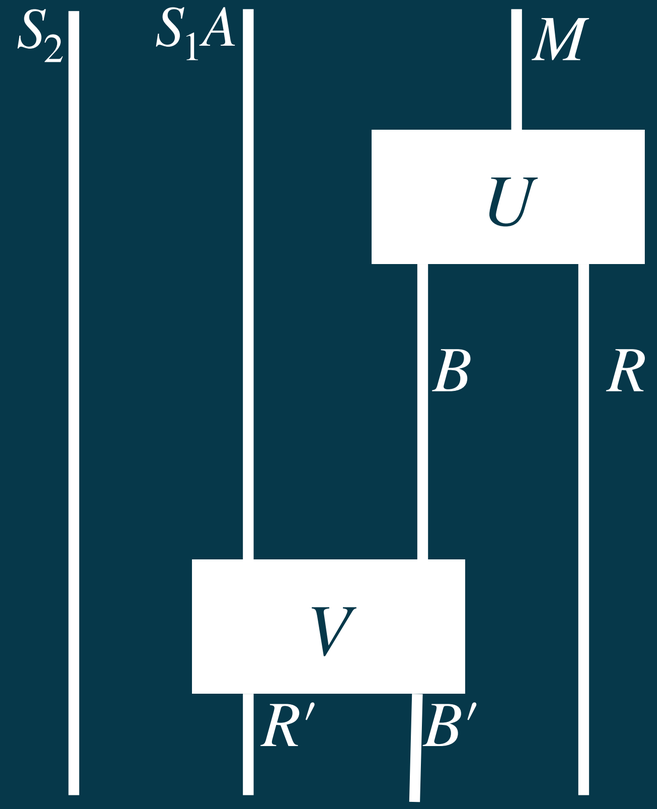

S_2



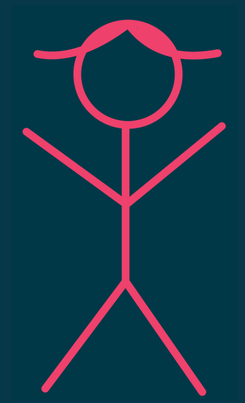




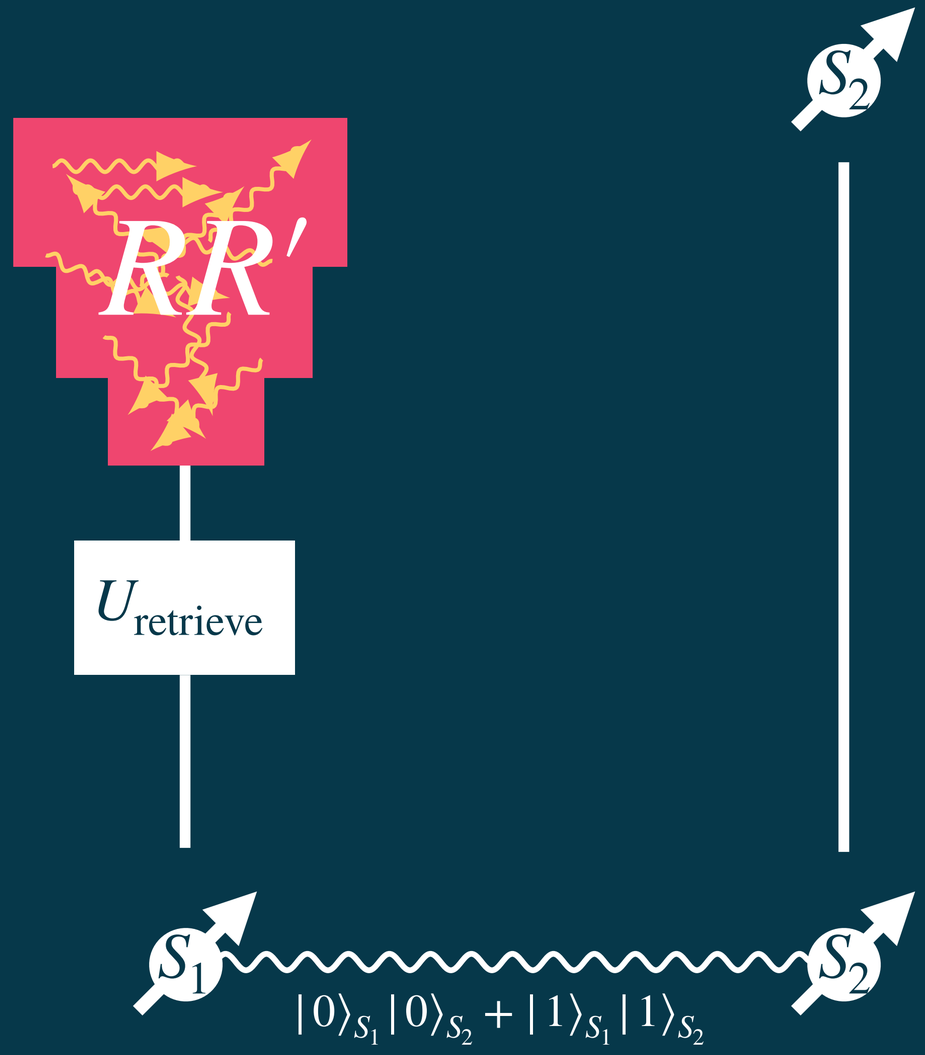


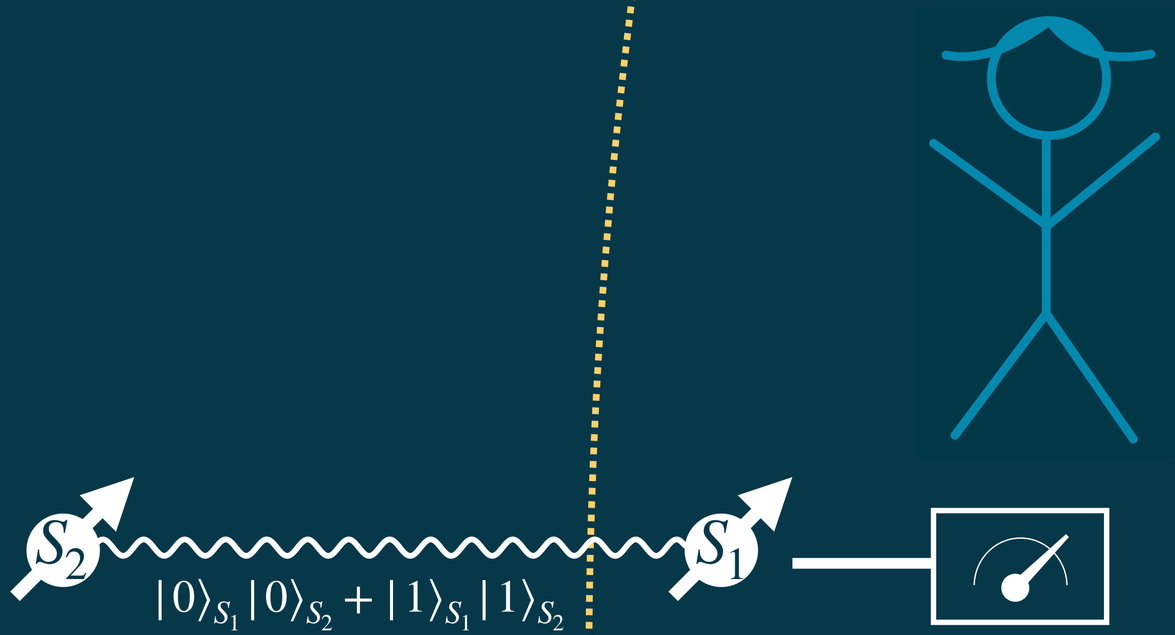


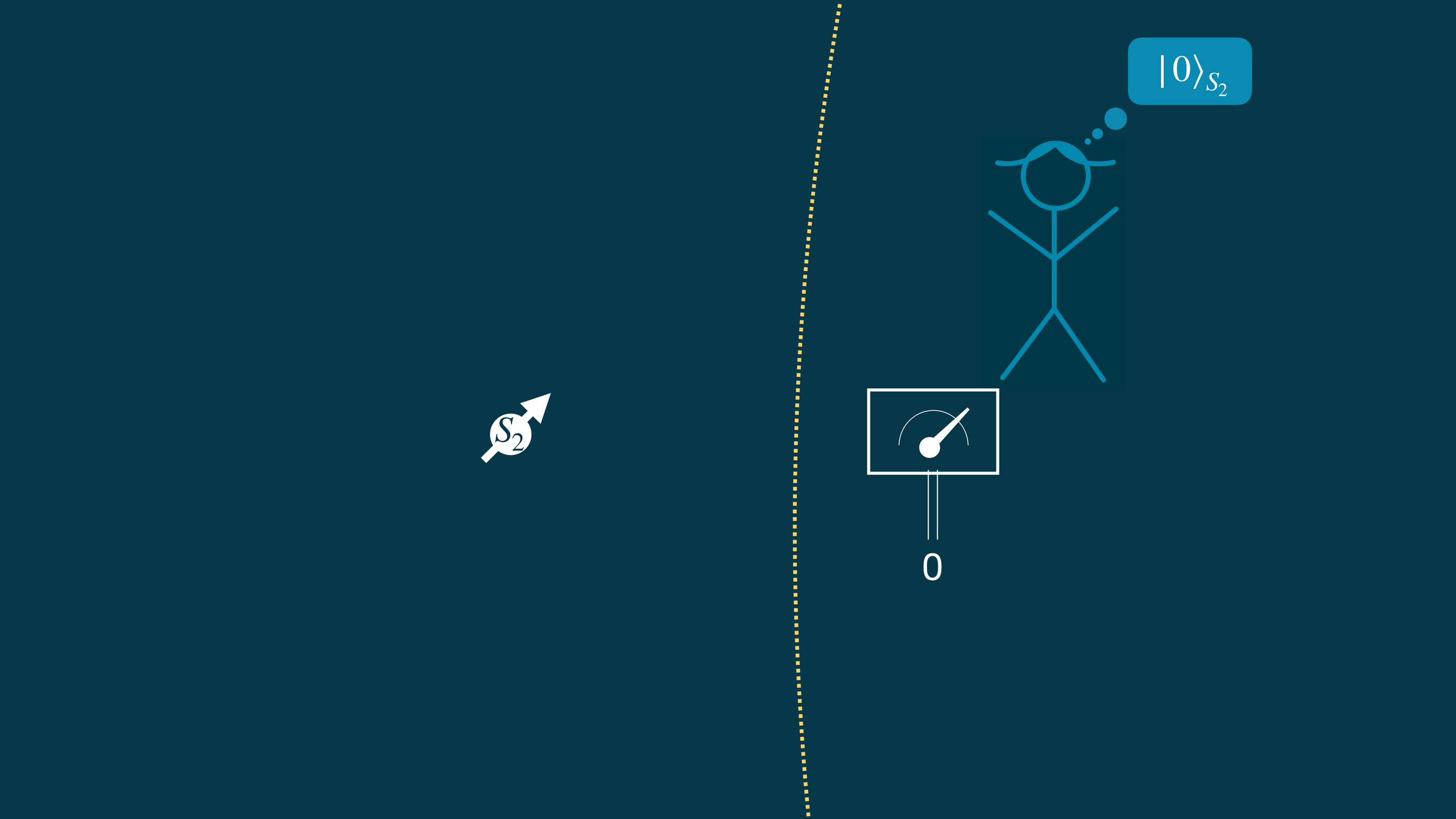
U and V are typical unitaries



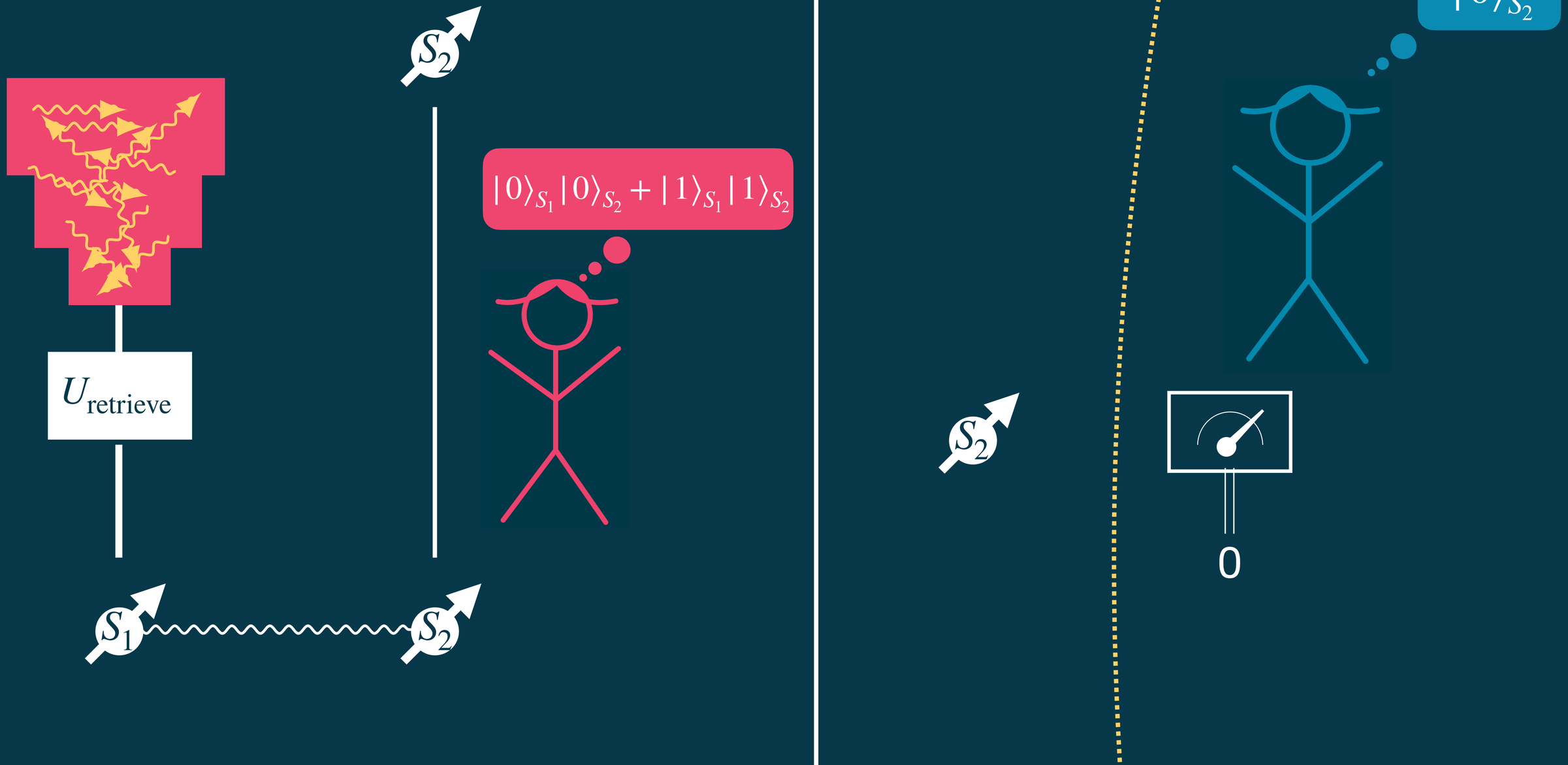
Typical unitarity $\Longrightarrow$




S_2
S_1
$|0\rangle_{S_1}|0\rangle_{S_2} + |1\rangle_{S_1}|1\rangle_{S_2}$


$|0\rangle_{S_2}$
S_2
0

Combining the perspectives



Combining the perspectives

No-go theorem

The following premises lead to a contradiction:

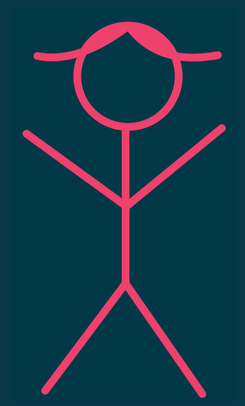
(Q) Universality of quantum theory

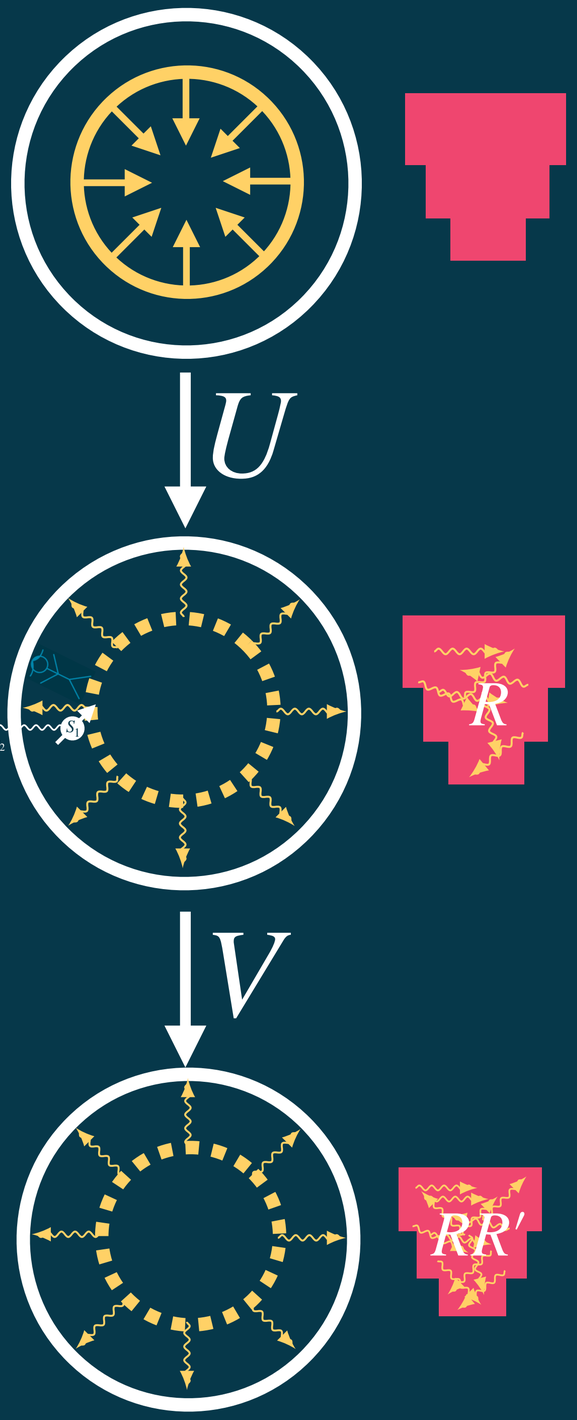
(C) State compatibility

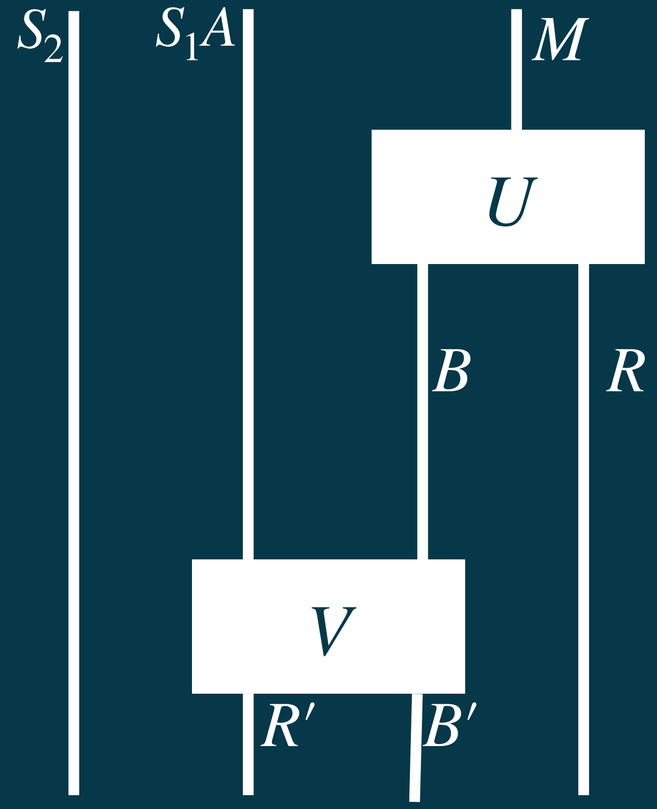
(G) Gravity assumptions:

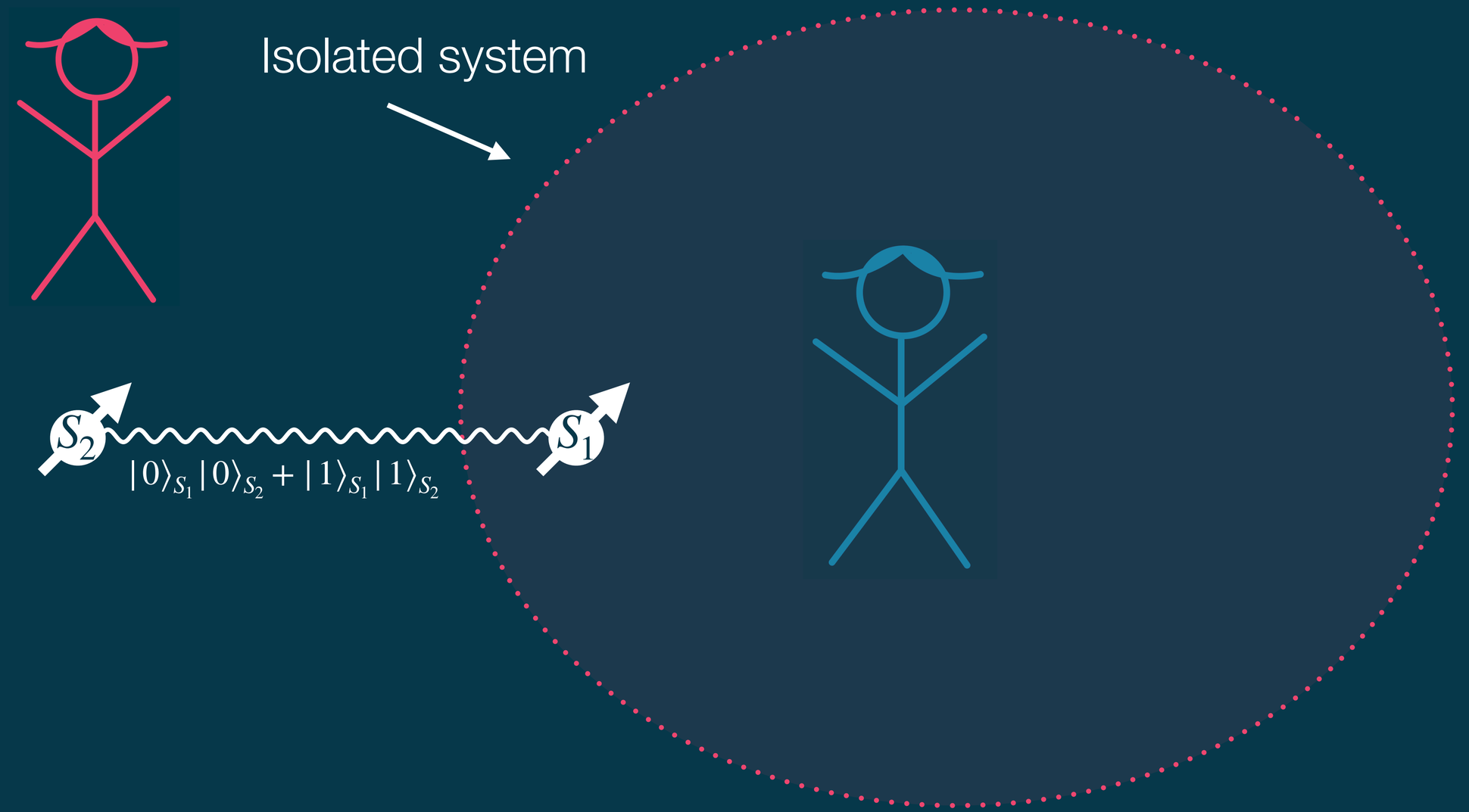
1. Smooth horizon
2. A black hole is a quantum system with a finite dimensional Hilbert space
3. A black hole evolves according to a typical unitary
4. …

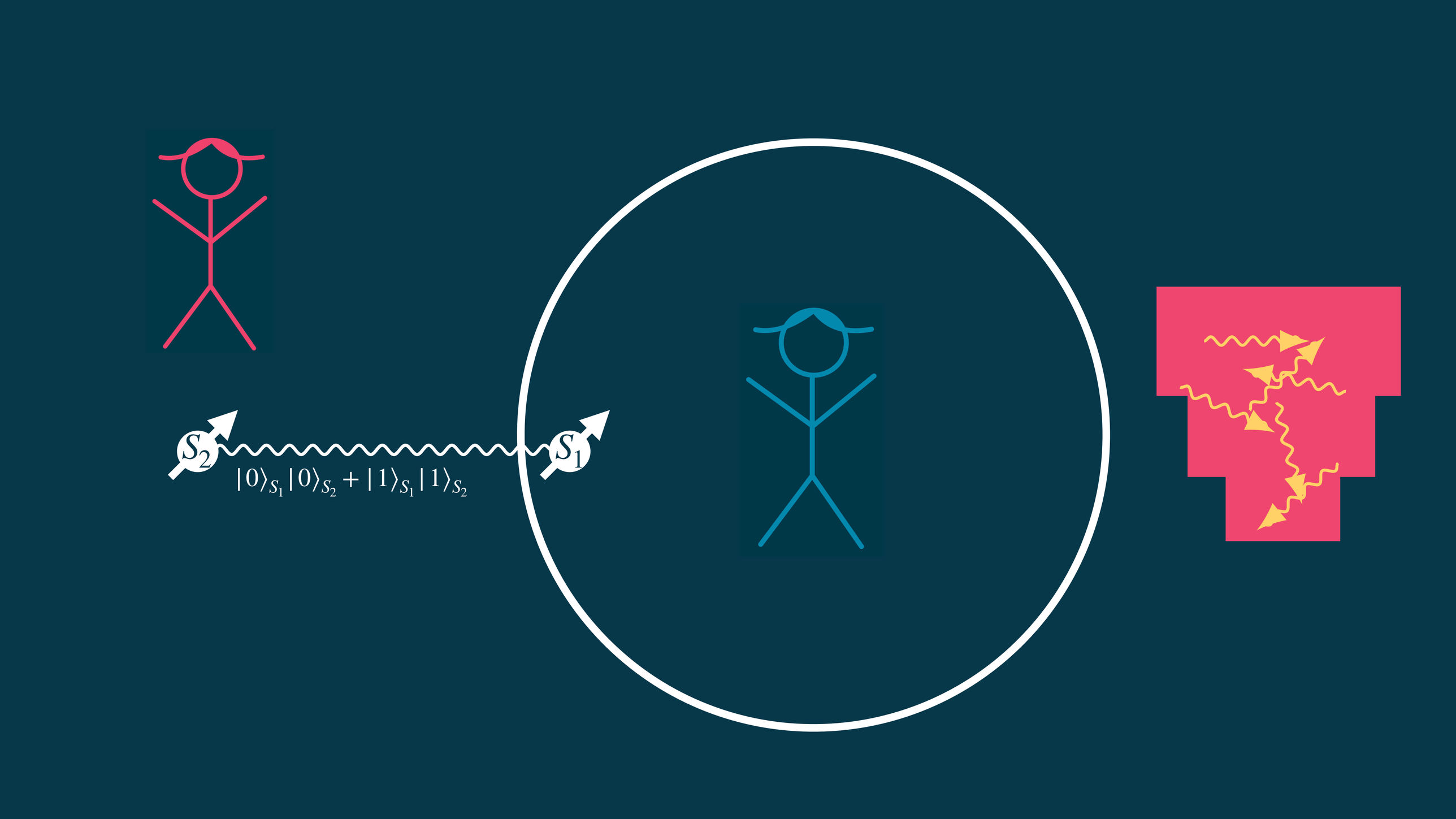
Abstracting the puzzle

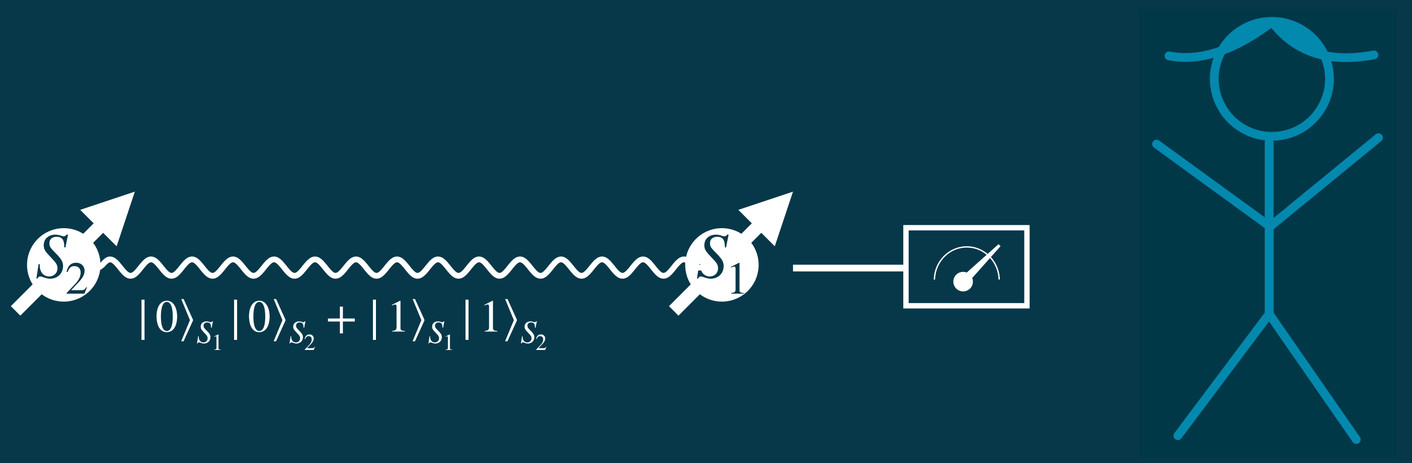



U
R
S_2
S_1
$|0\rangle_{S_1}|0\rangle_{S_2} + |1\rangle_{S_1}|1\rangle_{S_2}$
V
S_2
RR′


S_2
S_1A
M
U
B
R
V
R′
B′

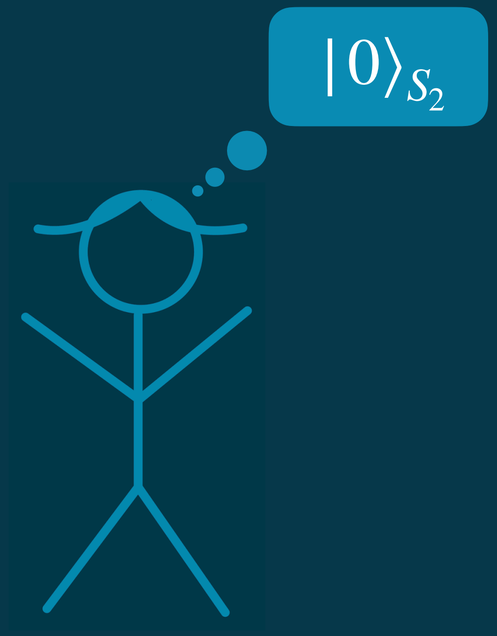

Isolated system
S_2
S_1
$|0\rangle_{S_1}|0\rangle_{S_2} + |1\rangle_{S_1}|1\rangle_{S_2}$


S_2
S_1
$|0\rangle_{S_1}|0\rangle_{S_2} + |1\rangle_{S_1}|1\rangle_{S_2}$

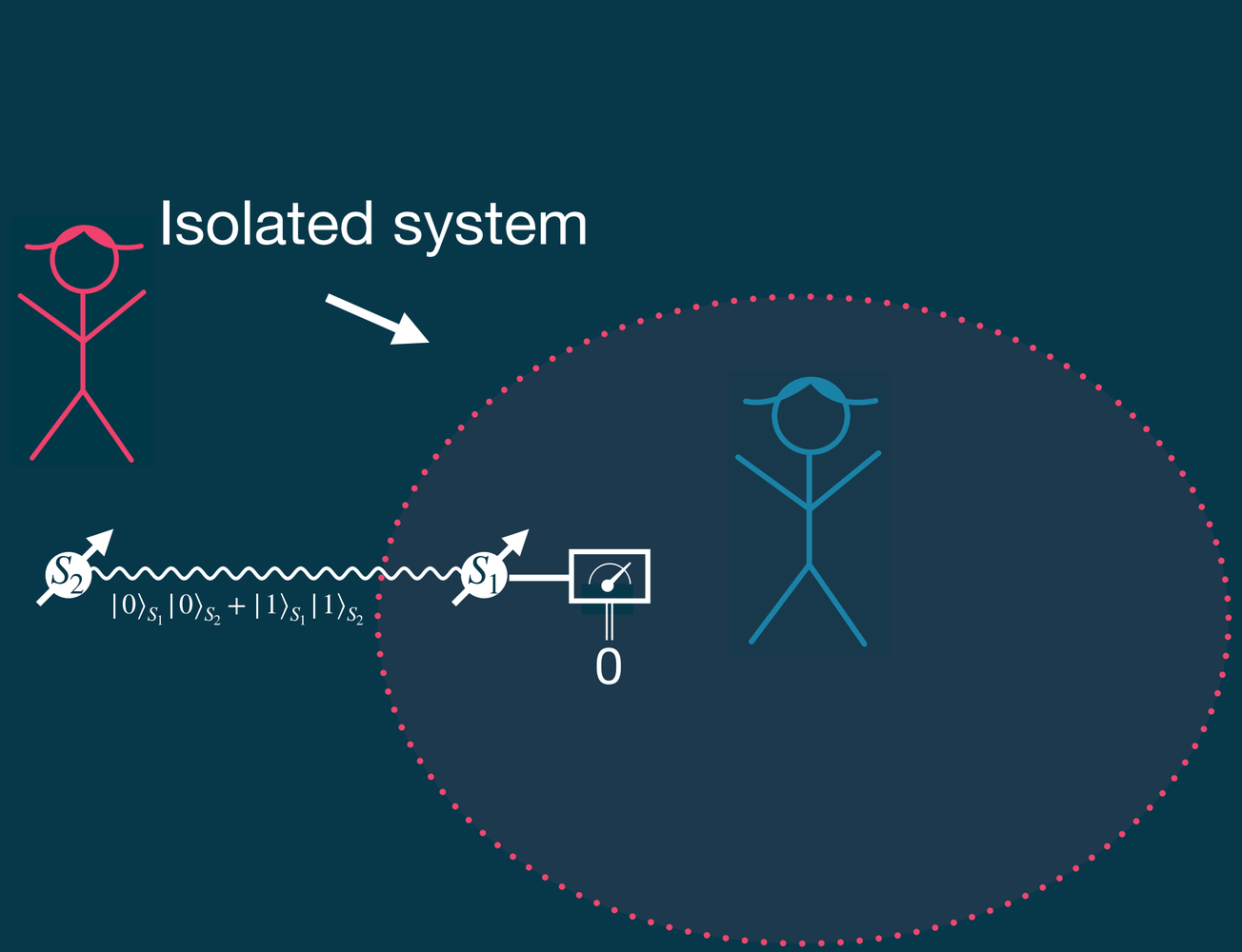

S_2
S_1
$|0\rangle_{S_1}|0\rangle_{S_2} + |1\rangle_{S_1}|1\rangle_{S_2}$

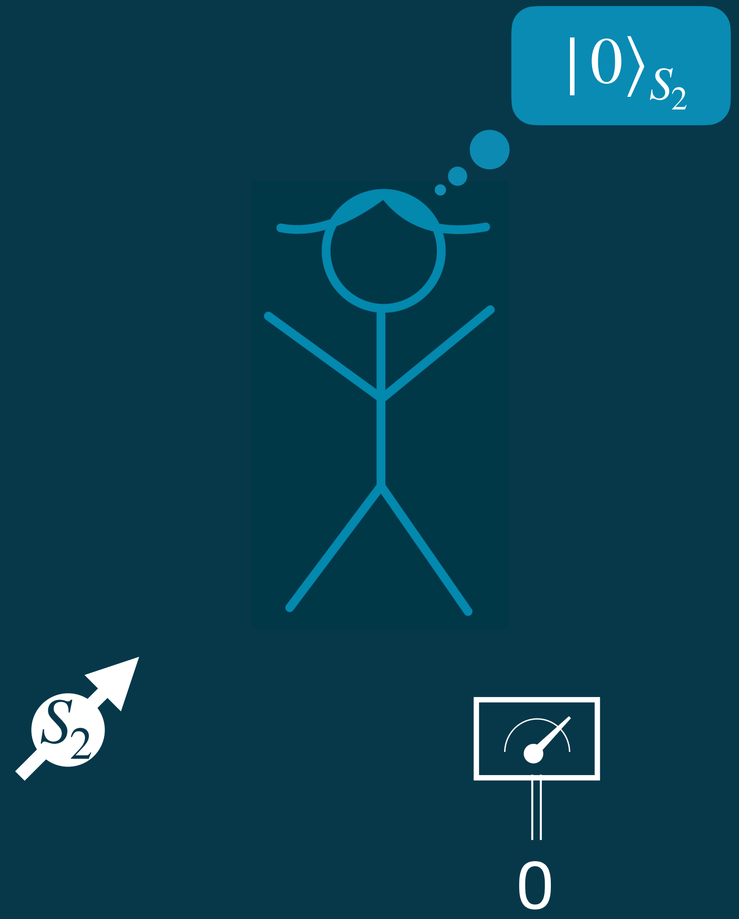

S_2


0

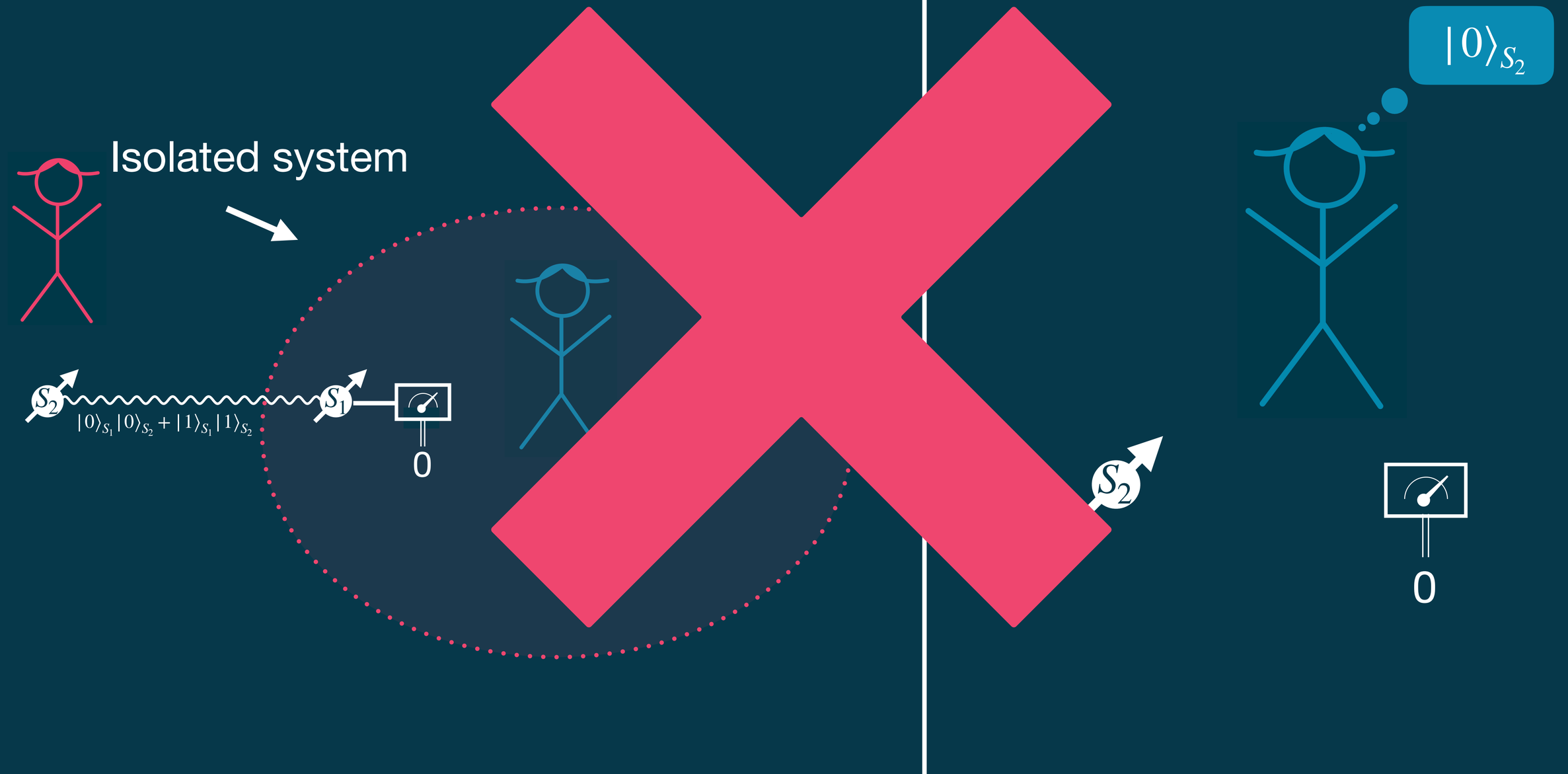

$|0\rangle_{S_2}$

Combining the perspectives

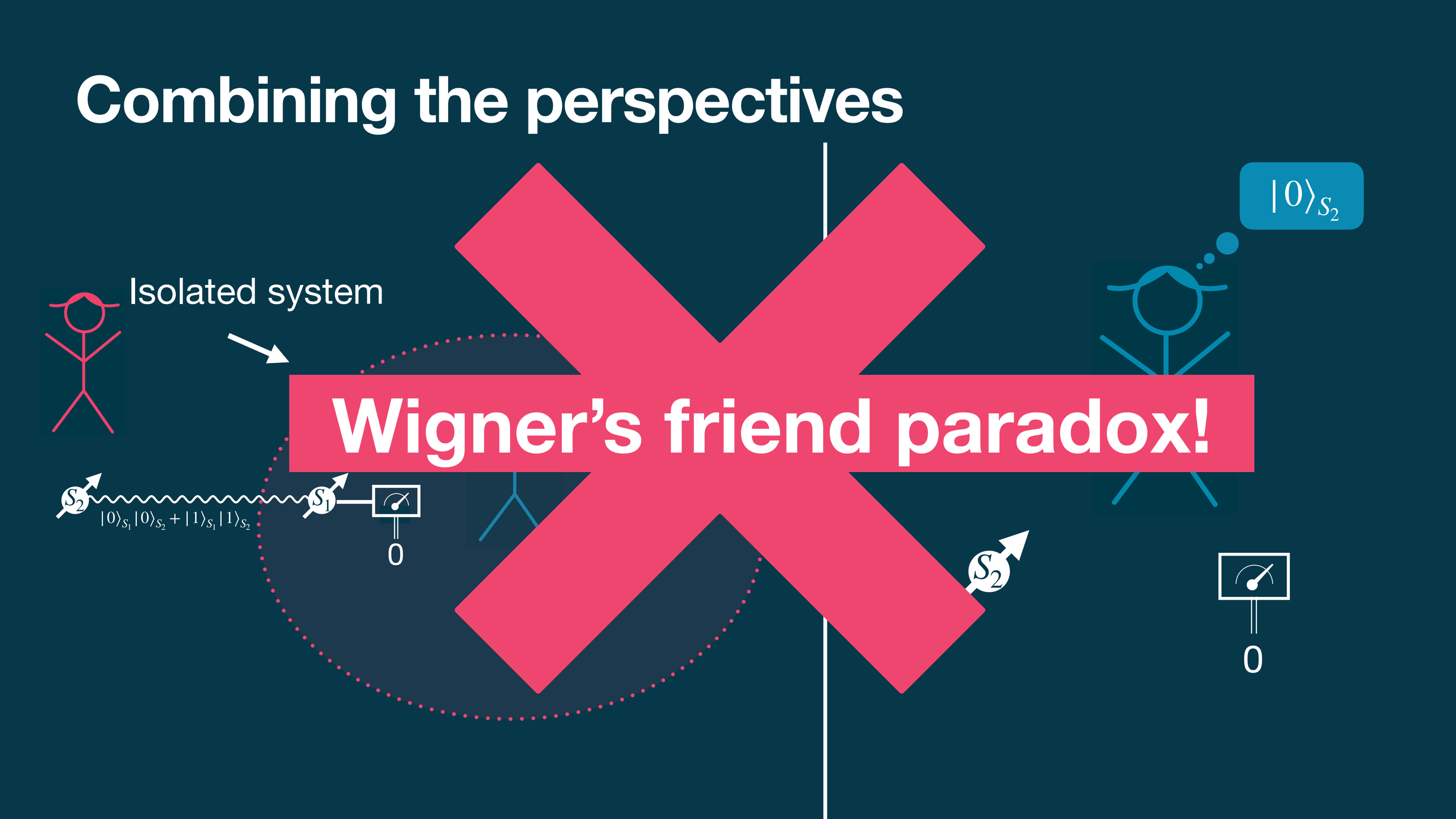




Combining the perspectives



Combining the perspectives



Wigner's friend paradox!

No-go theorem

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(C) State compatibility

(G) Gravity assumptions:

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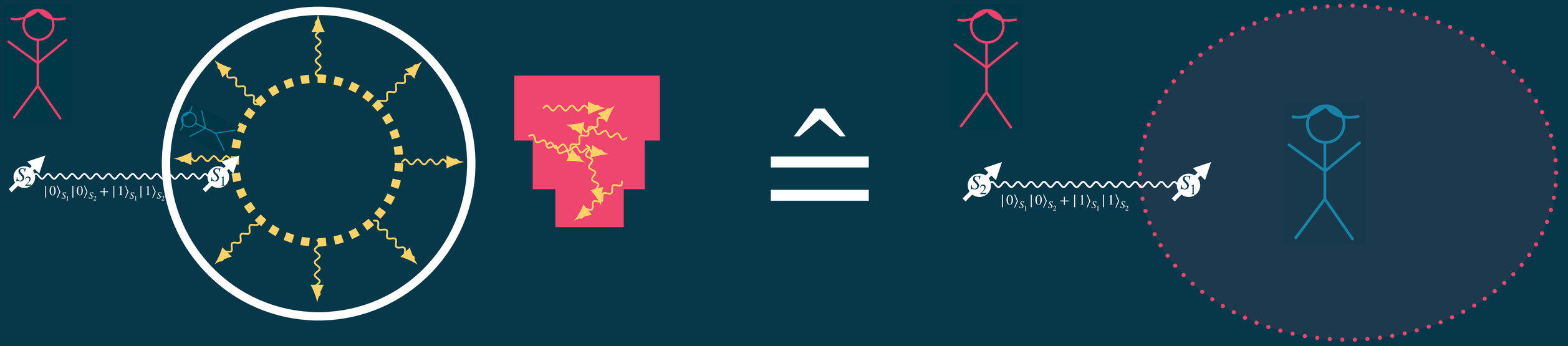
What can we learn from this?

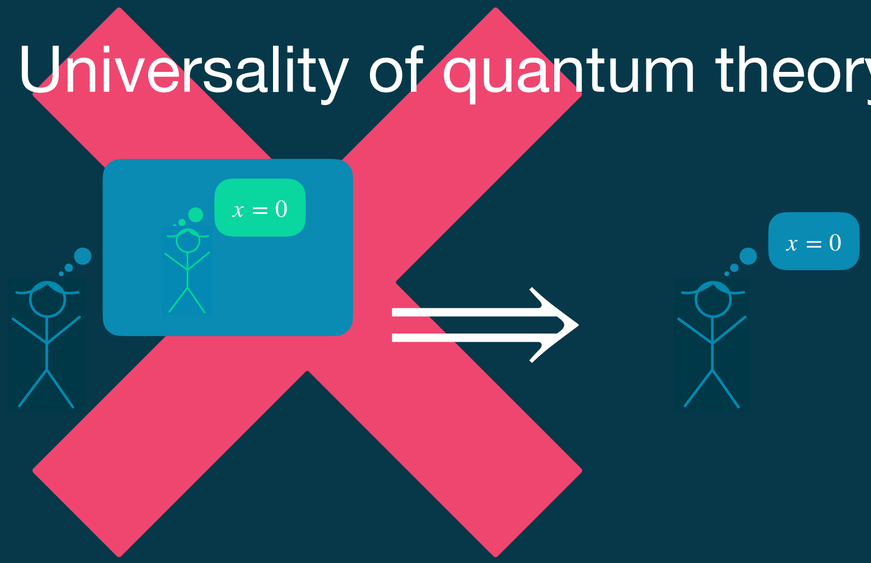

S_2
S_1
$|0\rangle_{S_1}|0\rangle_{S_2} + |1\rangle_{S_1}|1\rangle_{S_2}$
$\hat{=}$
S_2
S_1
$|0\rangle_{S_1}|0\rangle_{S_2} + |1\rangle_{S_1}|1\rangle_{S_2}$

Application to other paradoxes

Quantum collaboration paradox:

(Q) Universality of quantum theory

(C)



Frauchiger, Renner, 2018

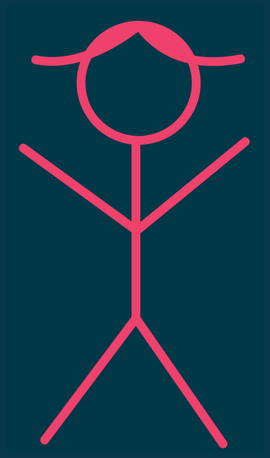
Firewall Paradox:

(Q) Universality of quantum theory

(C)

(G) Gravity assumptions

Almheiri, Marolf, Polchinski, Sully, 2012



Thank you!