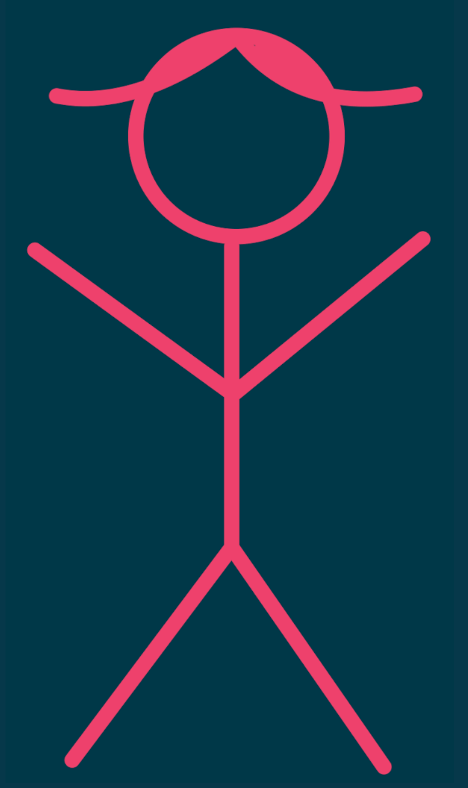
What quantum foundations teach us about black holes

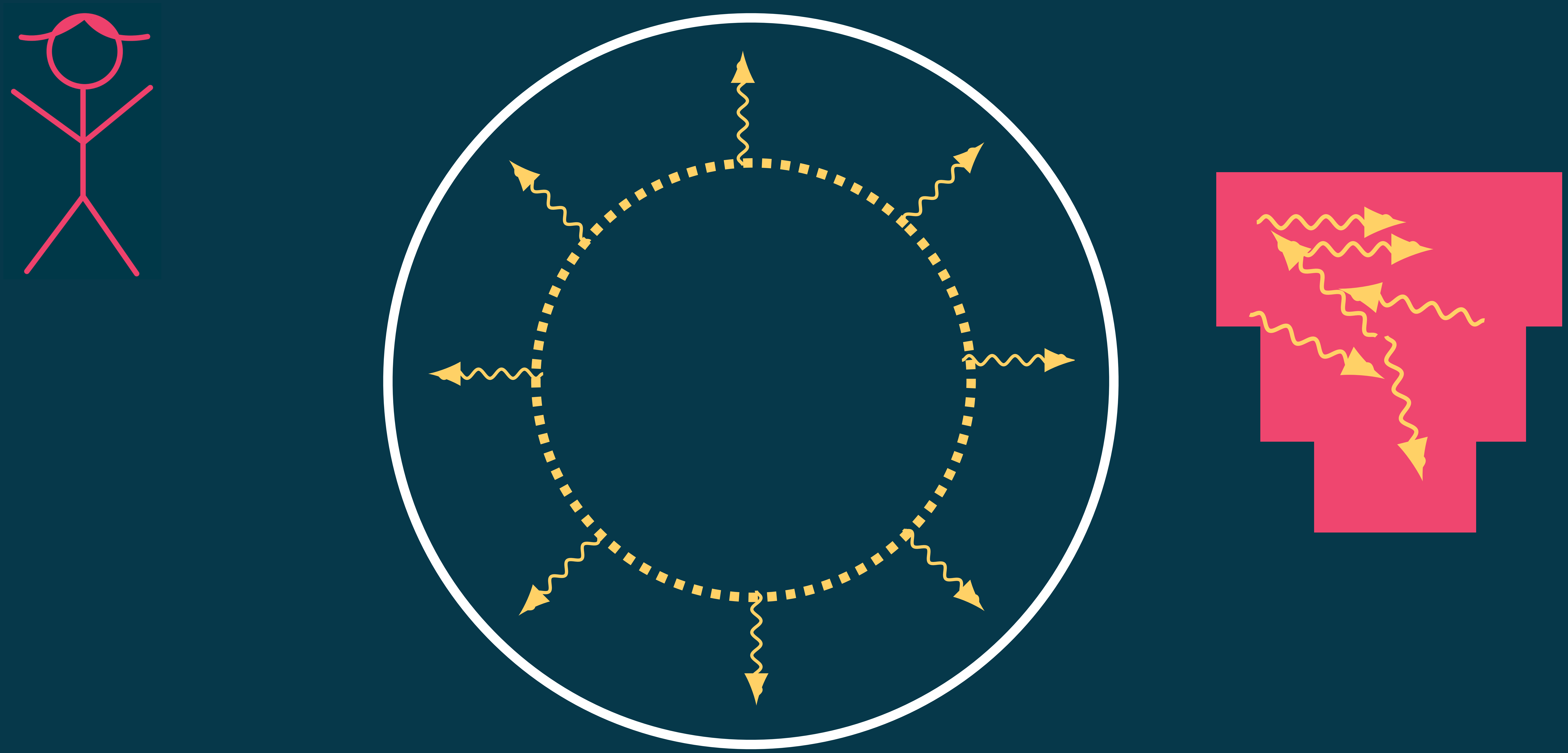
Ladina Hausmann
ETH Zürich

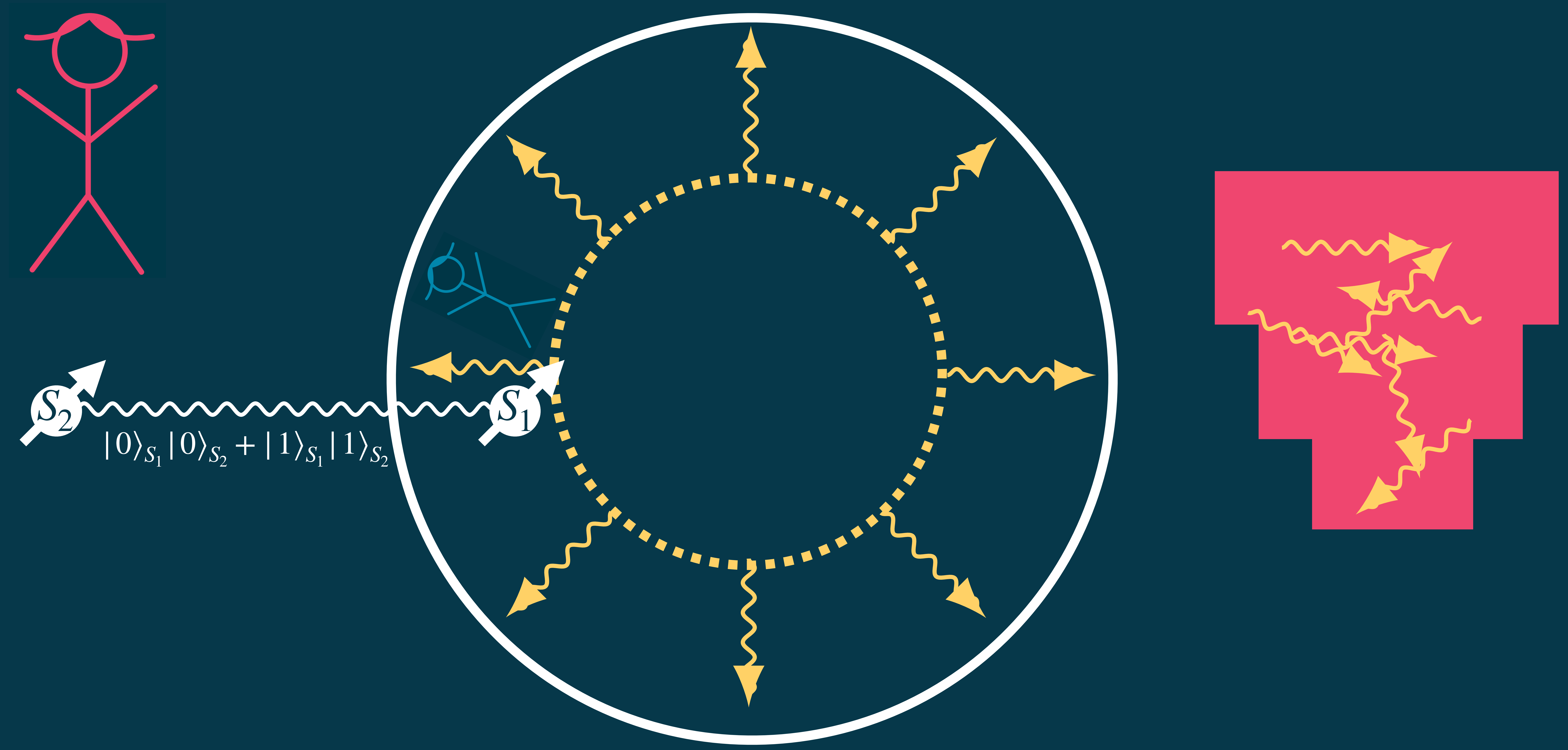
Based on joint work with Renato Renner, arXiv:2504.03835

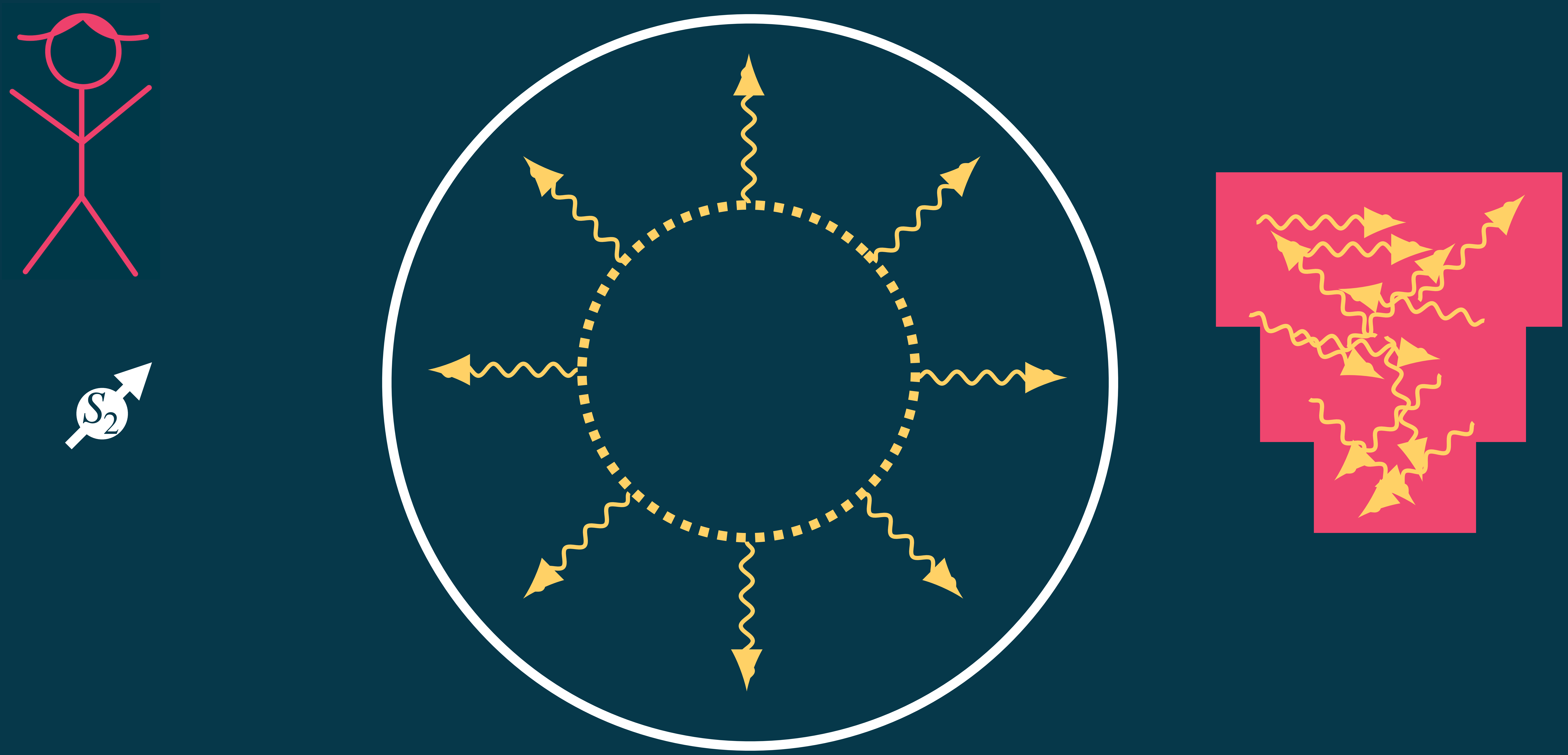
A black hole puzzle

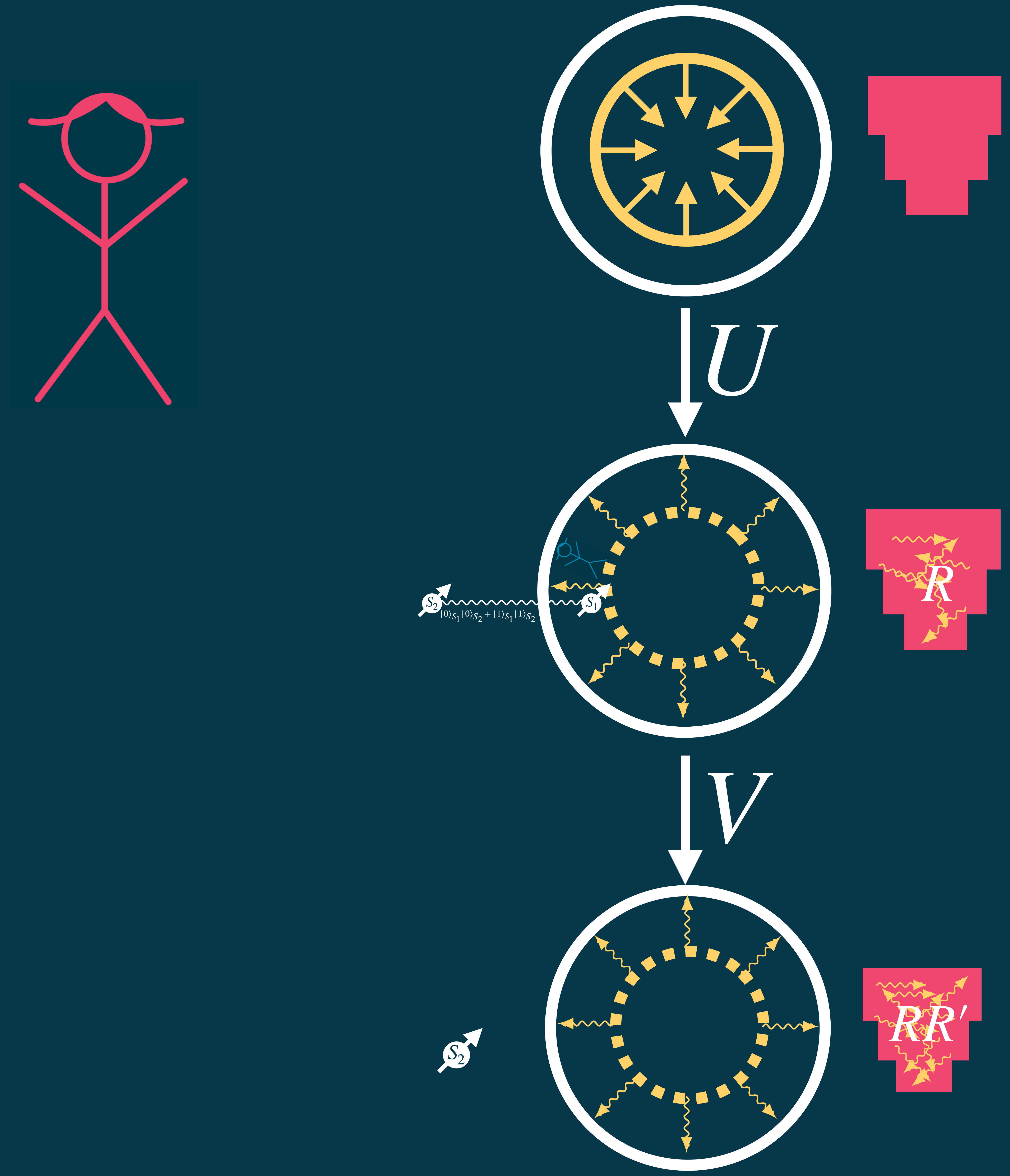
Hayden, Preskill, 2007

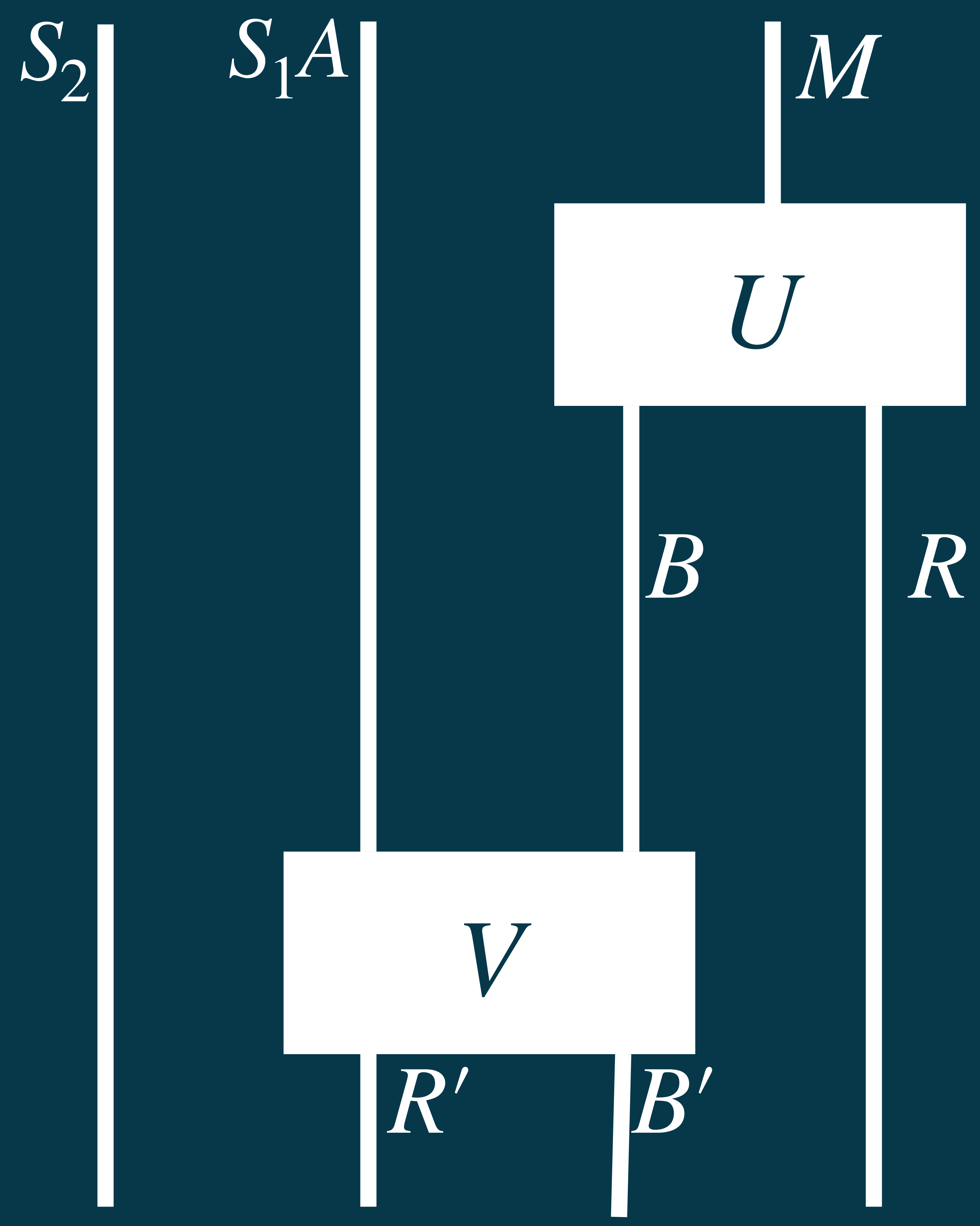




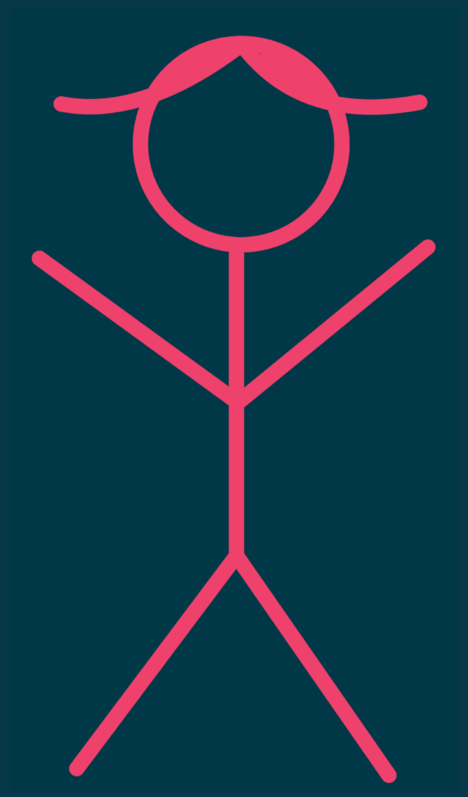

S_2
S_1
$|0\rangle_{S_1}|0\rangle_{S_2} + |1\rangle_{S_1}|1\rangle_{S_2}$


S_2

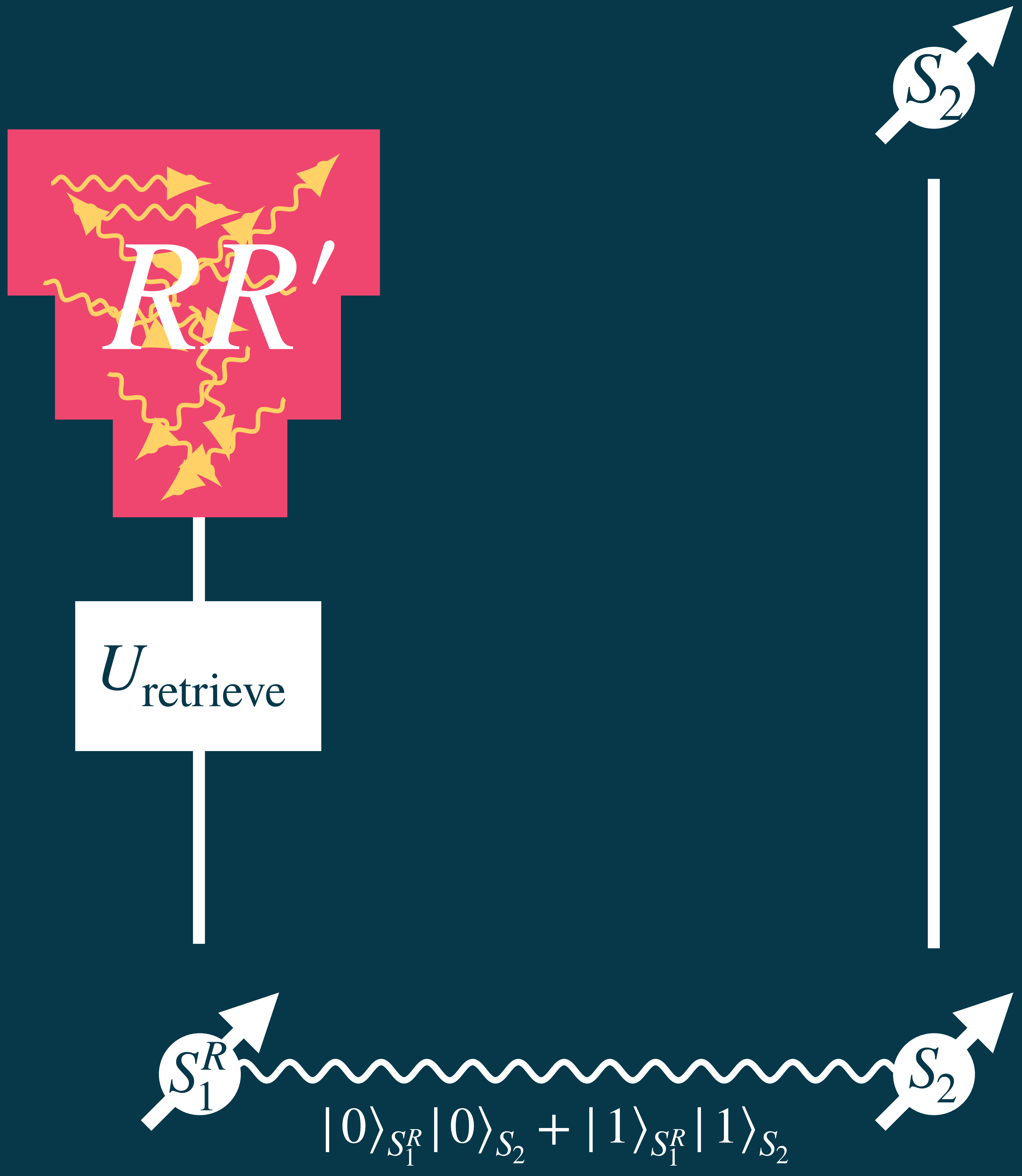


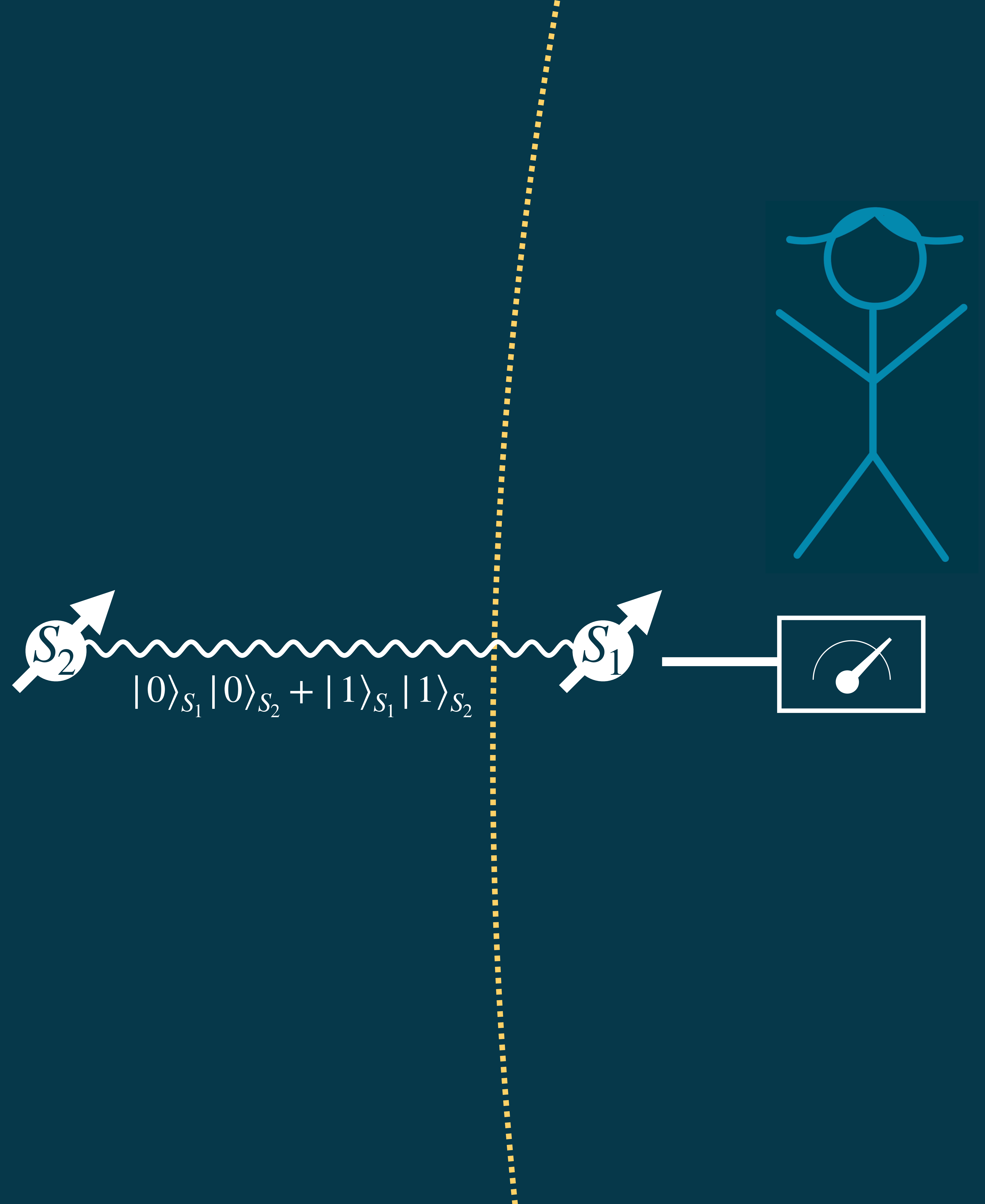


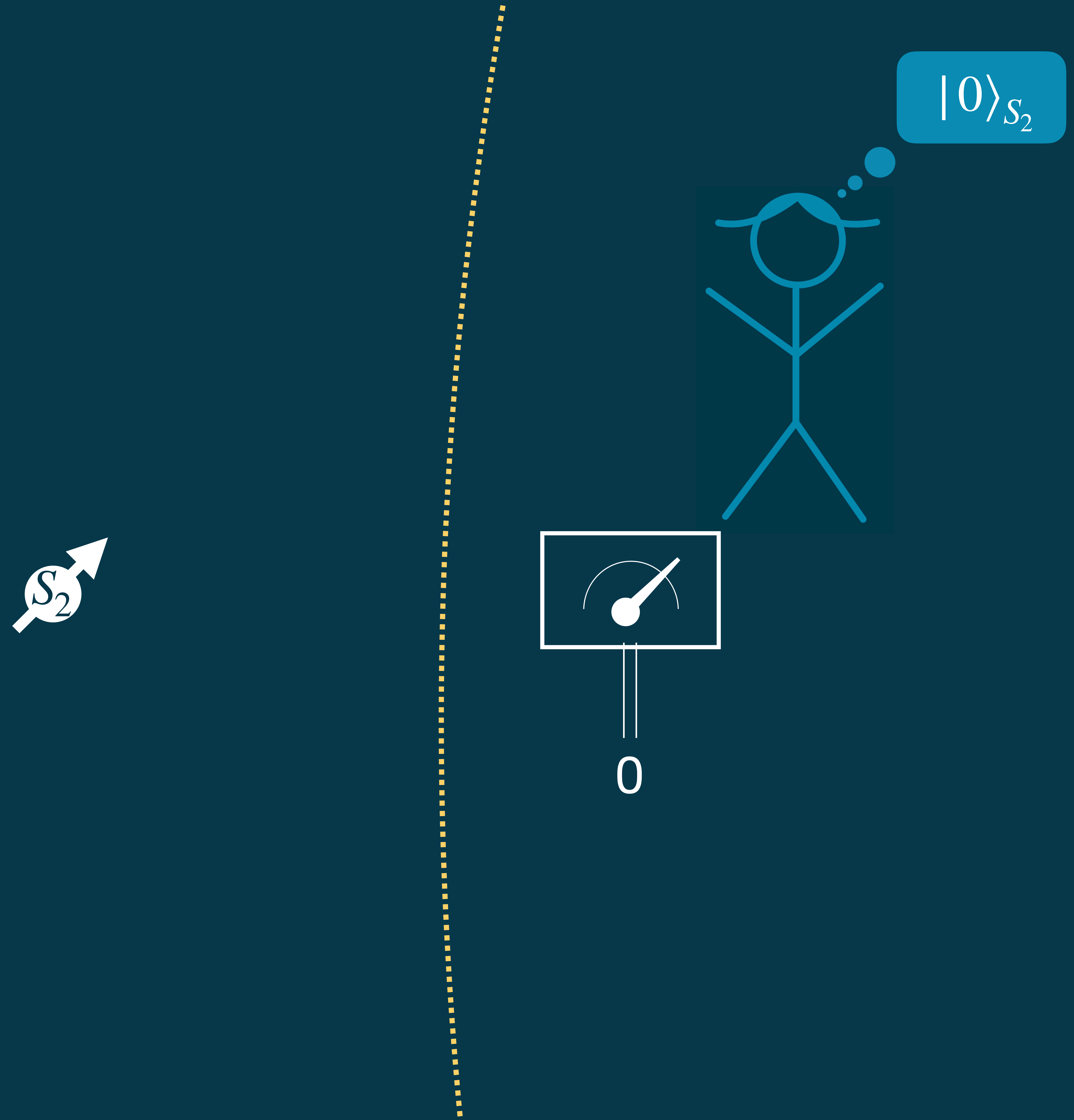
U and V are typical unitaries



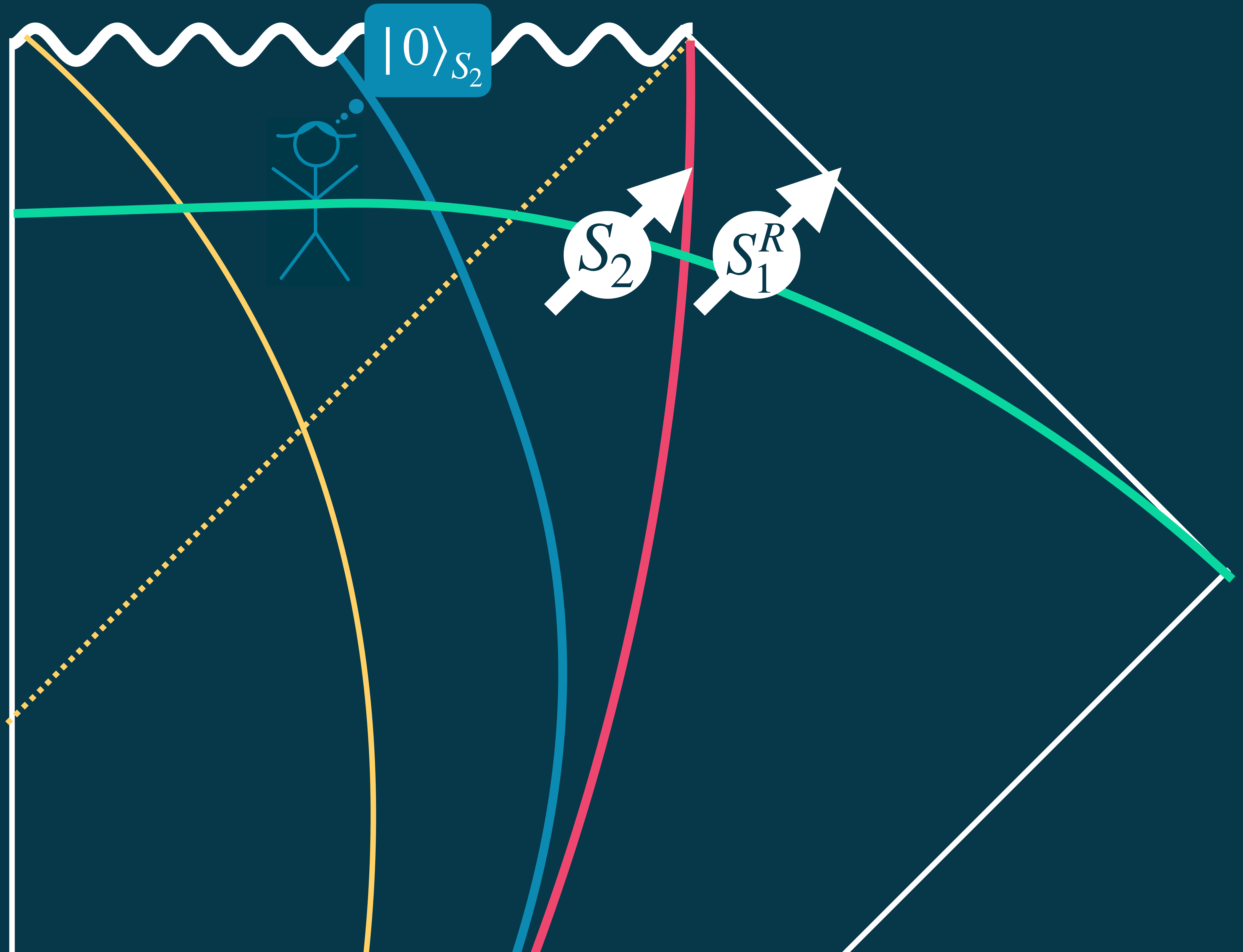
Typical unitarity $\Longrightarrow$



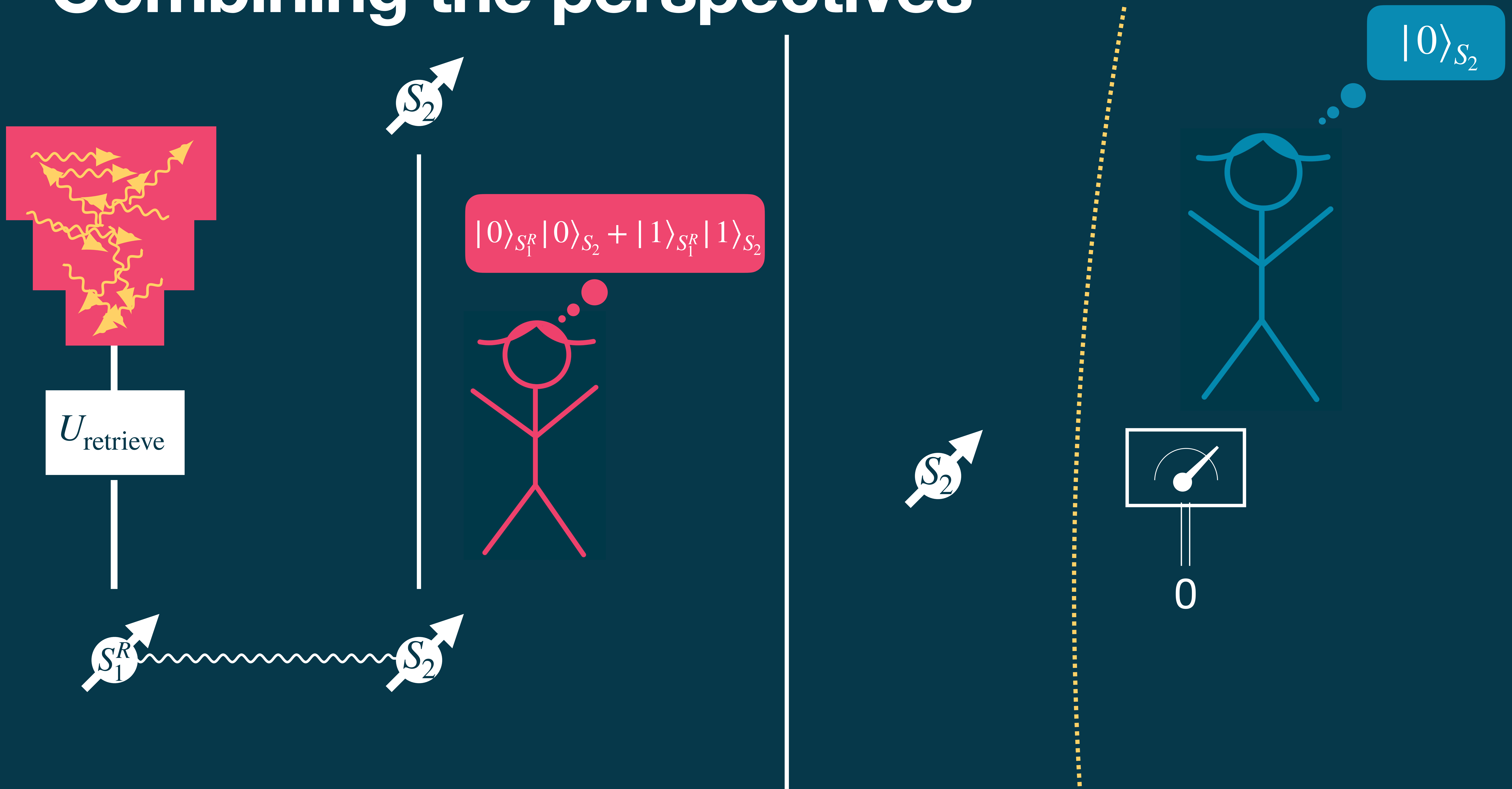

S_2
S_1
$|0\rangle_{S_1}|0\rangle_{S_2} + |1\rangle_{S_1}|1\rangle_{S_2}$


S_2
$|0\rangle_{S_2}$
0

Summary

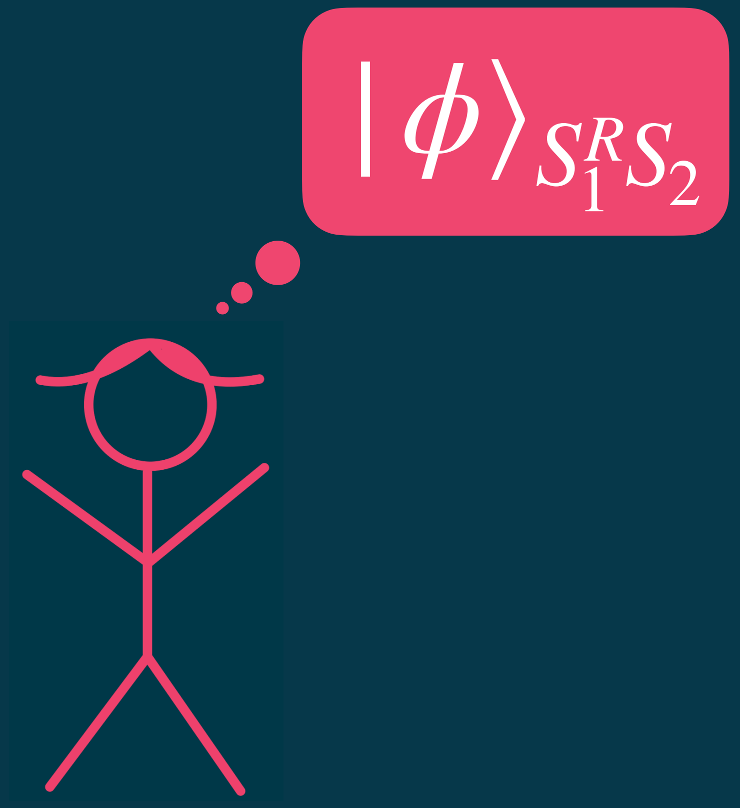


Combining the perspectives

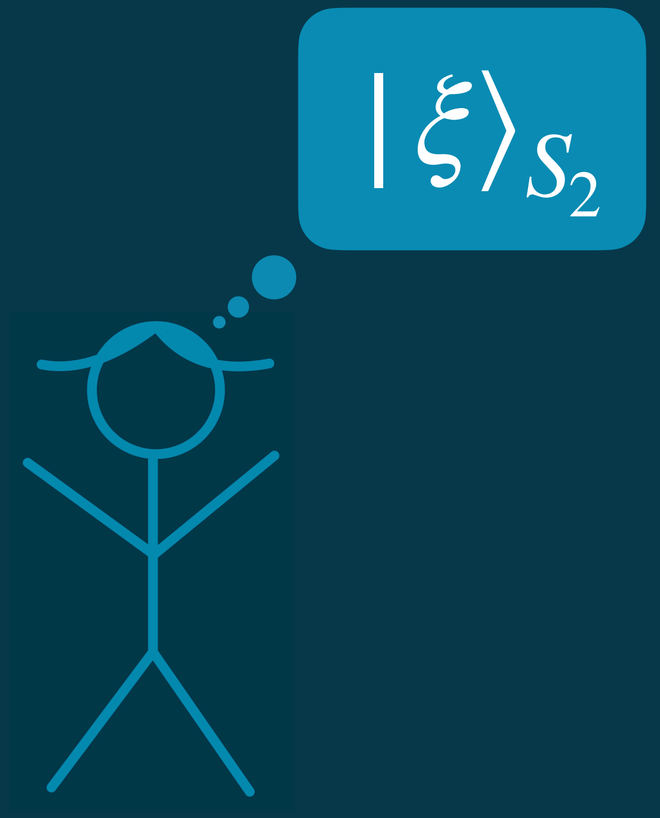


State compatibility

$$\exists\, |\Psi\rangle :$$

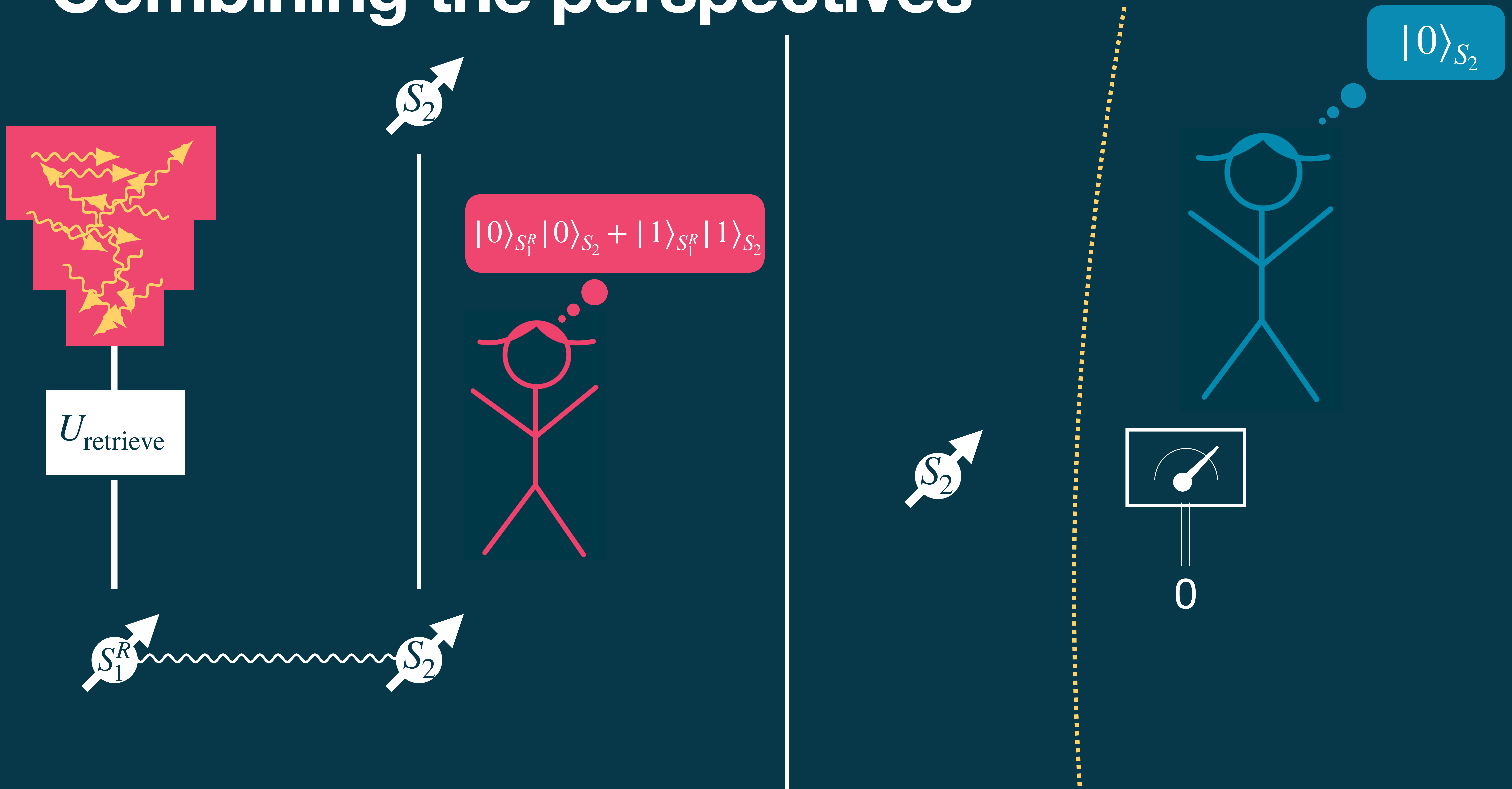


$$\mathrm{tr}_{\overline{S_1^R S_2}}(|\Psi\rangle\langle\Psi|) = |\phi\rangle\langle\phi|_{S_1^R S_2}$$



$$\mathrm{tr}_{\overline{S_2}}(|\Psi\rangle\langle\Psi|) = |\xi\rangle\langle\xi|_{S_2}$$

Combining the perspectives



Combining the perspectives

No-go theorem

The following premises lead to a contradiction:

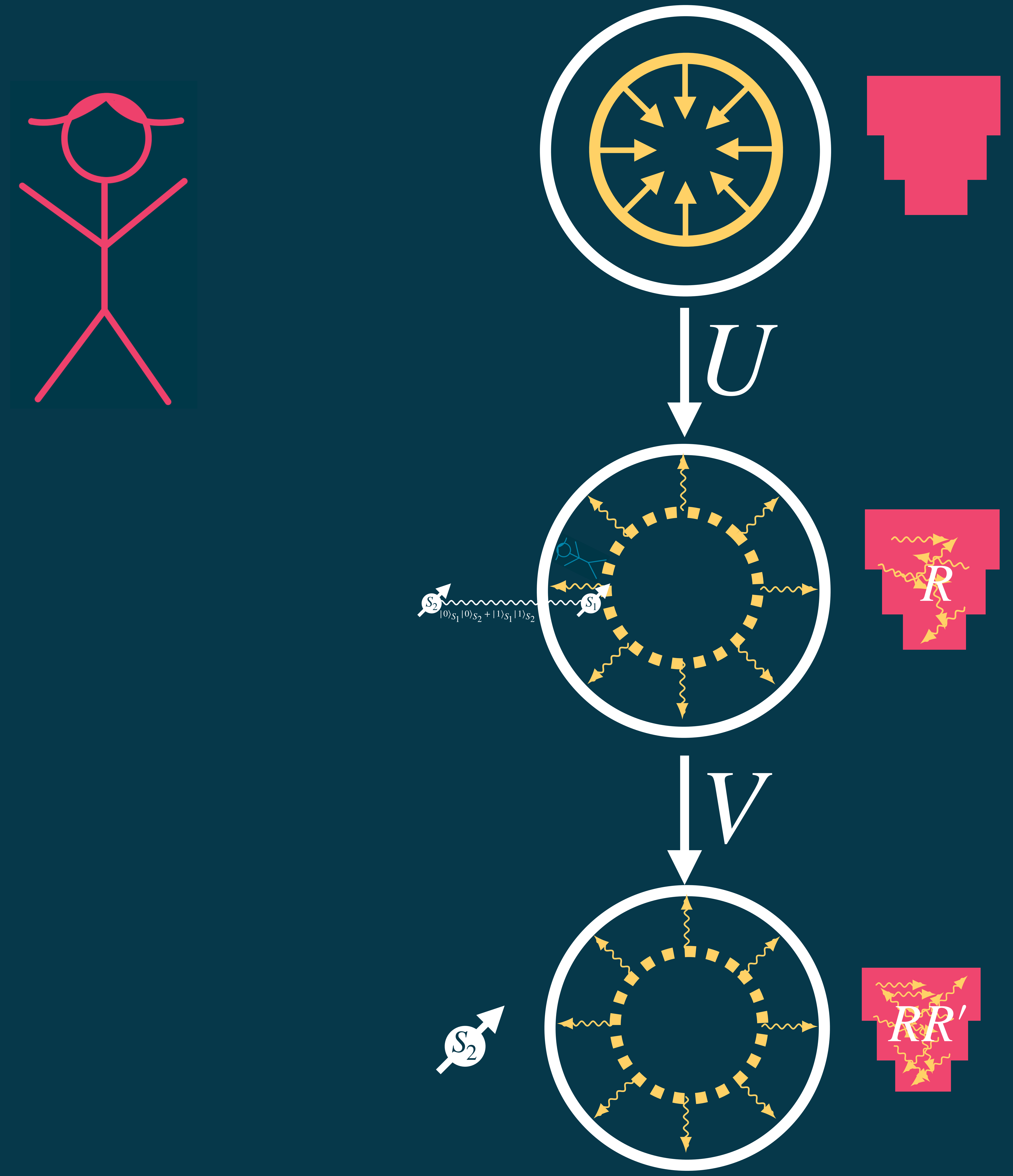
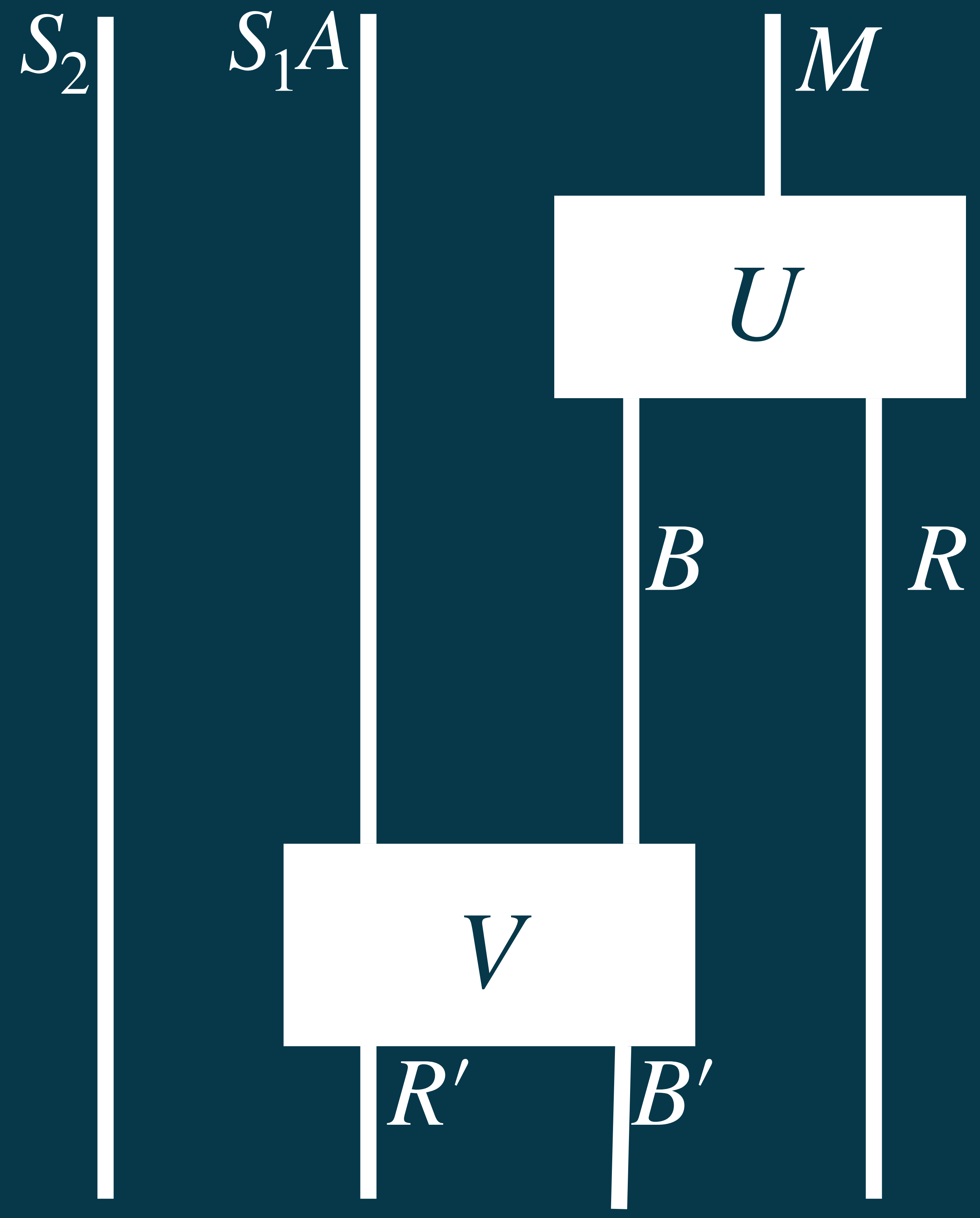
(Q) Universality of quantum theory

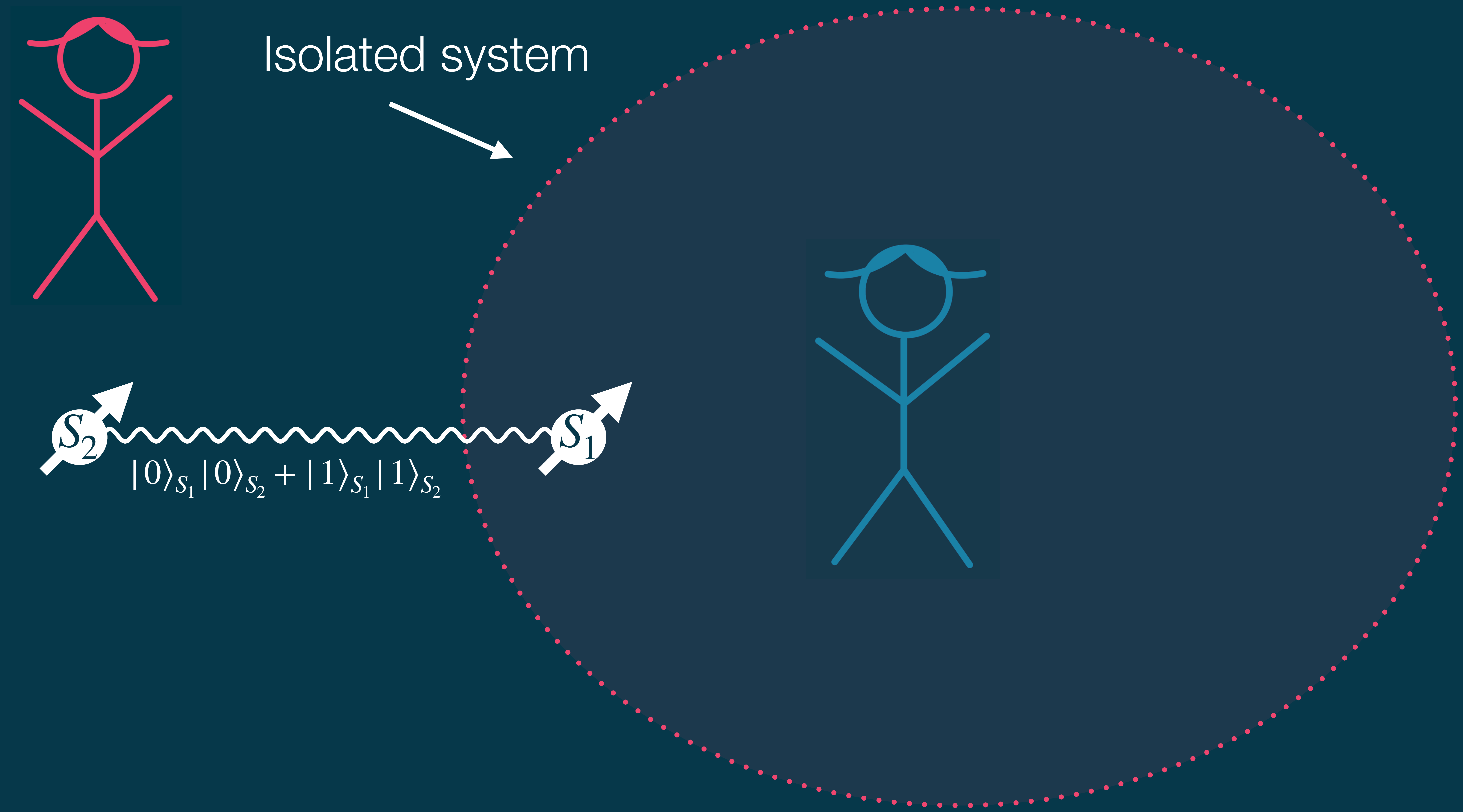
(C) State compatibility

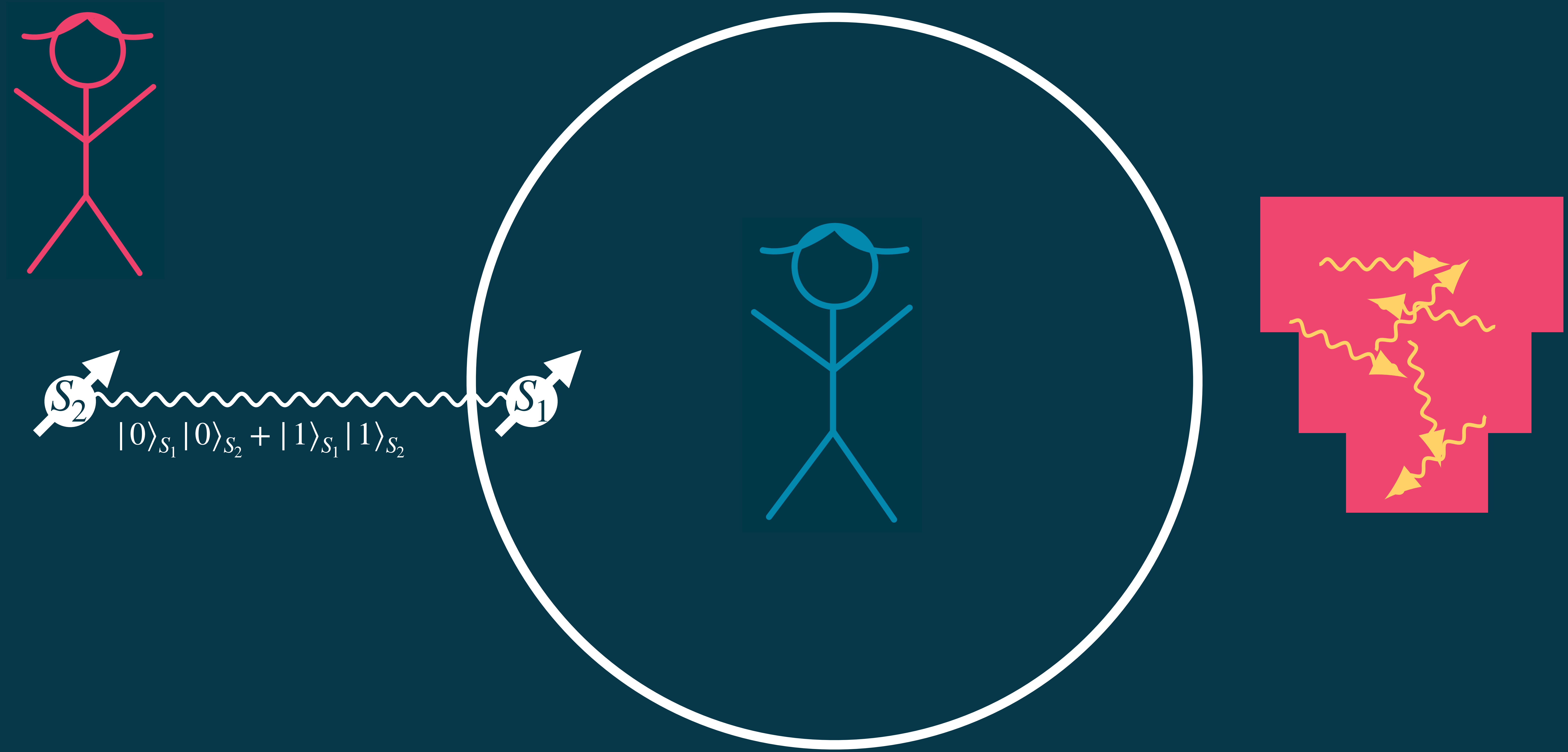
(G) Gravity assumptions:

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
V
R
RR′
S₂

S₂
S₁A
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
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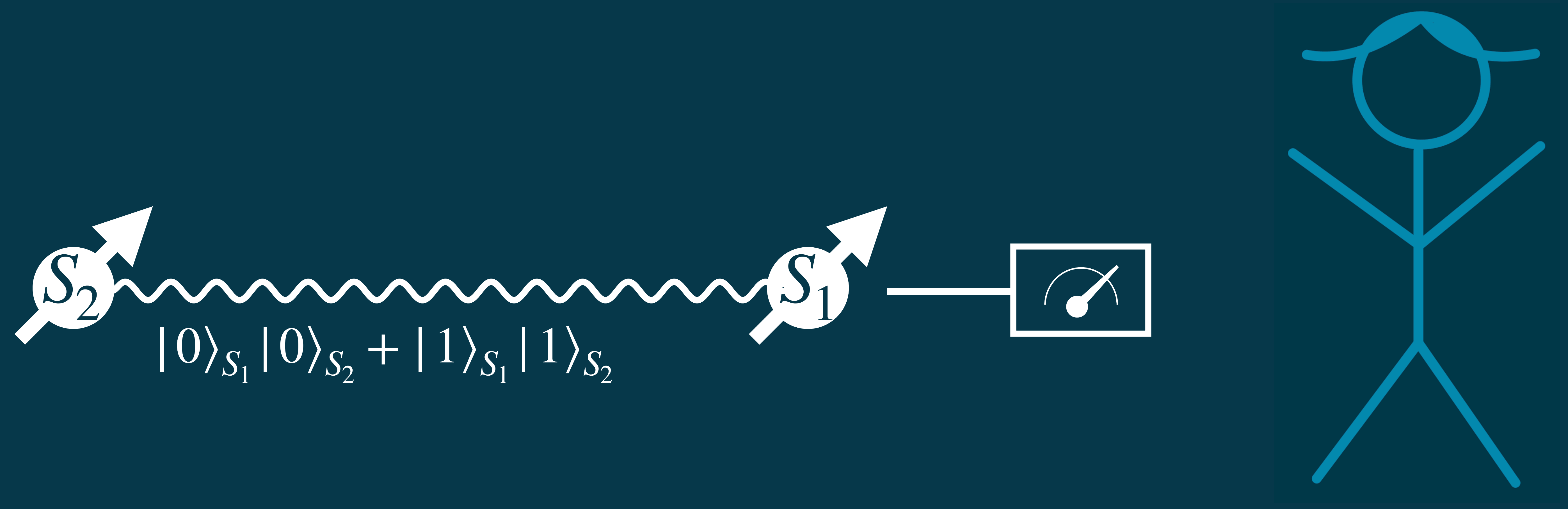
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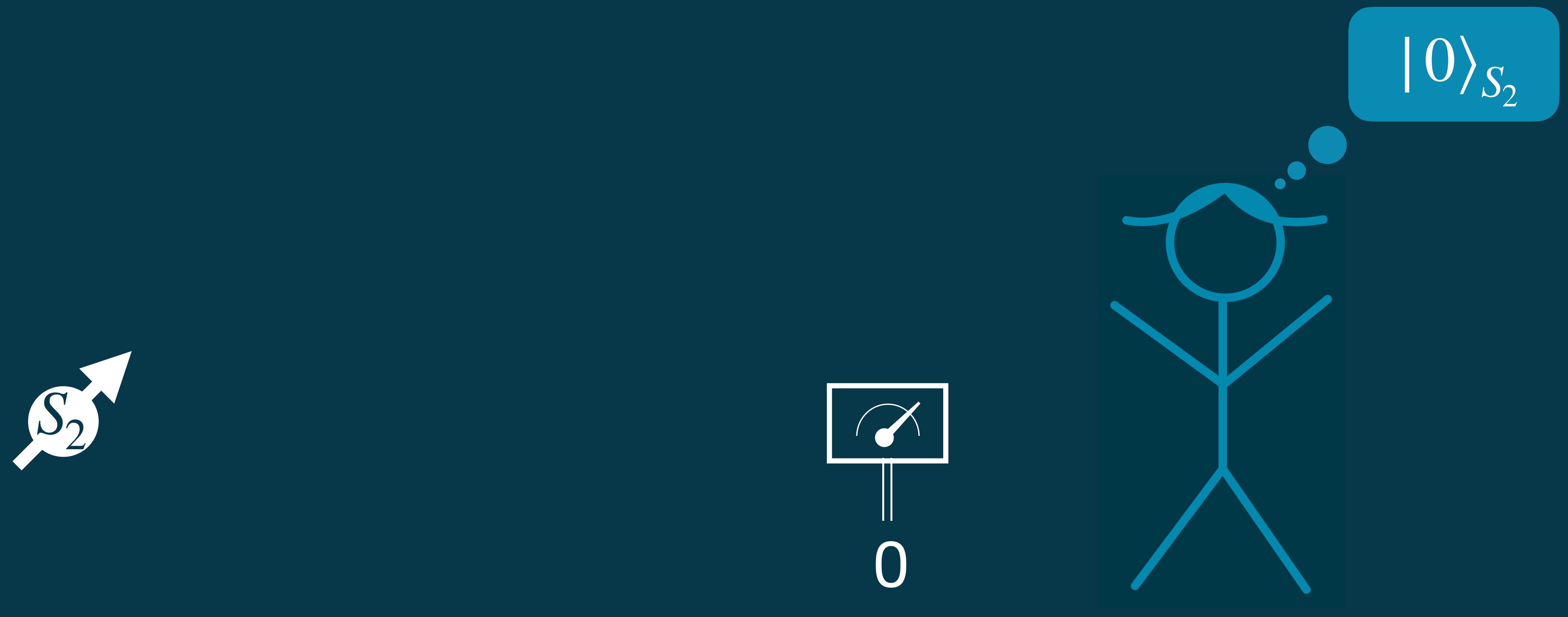
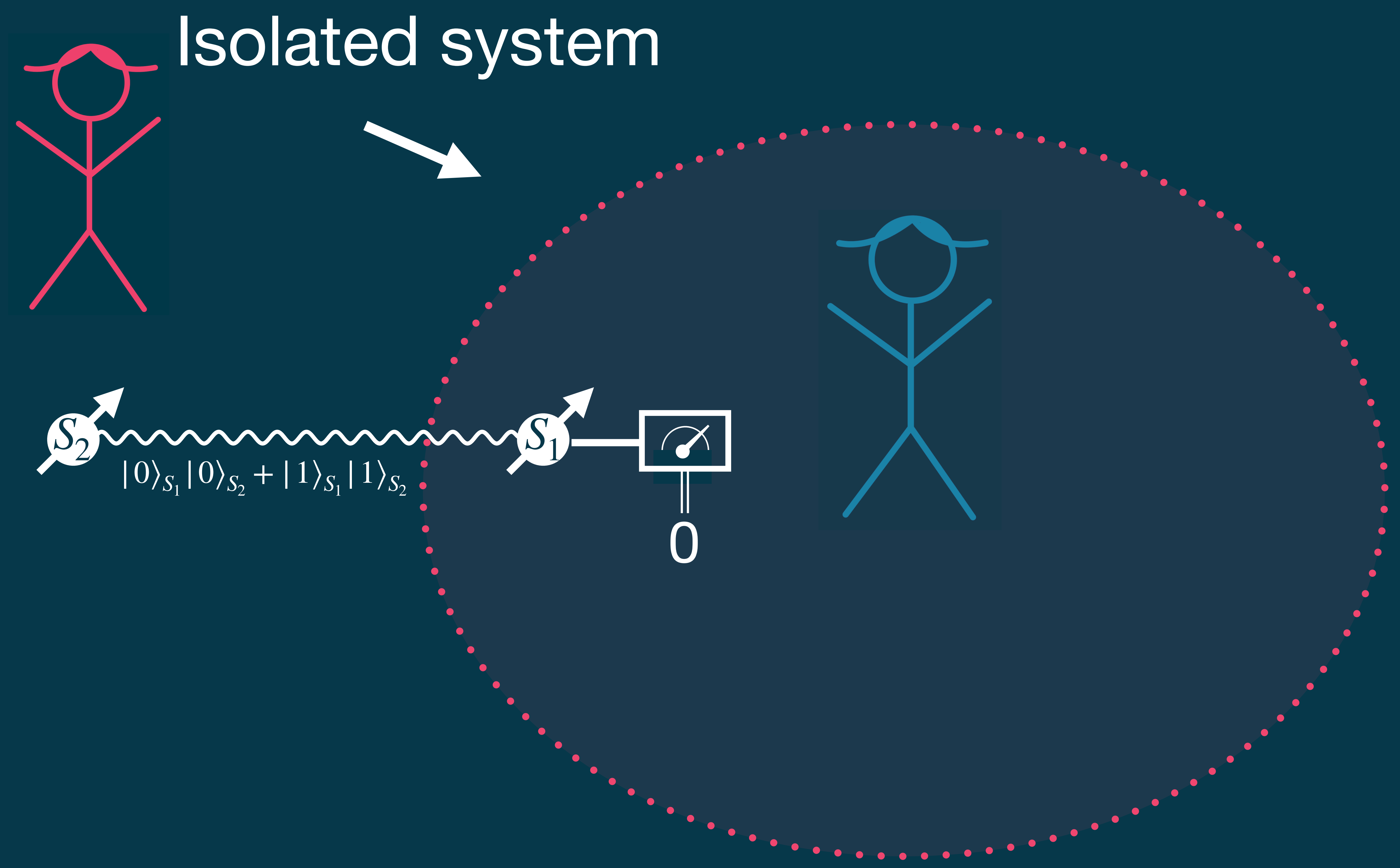
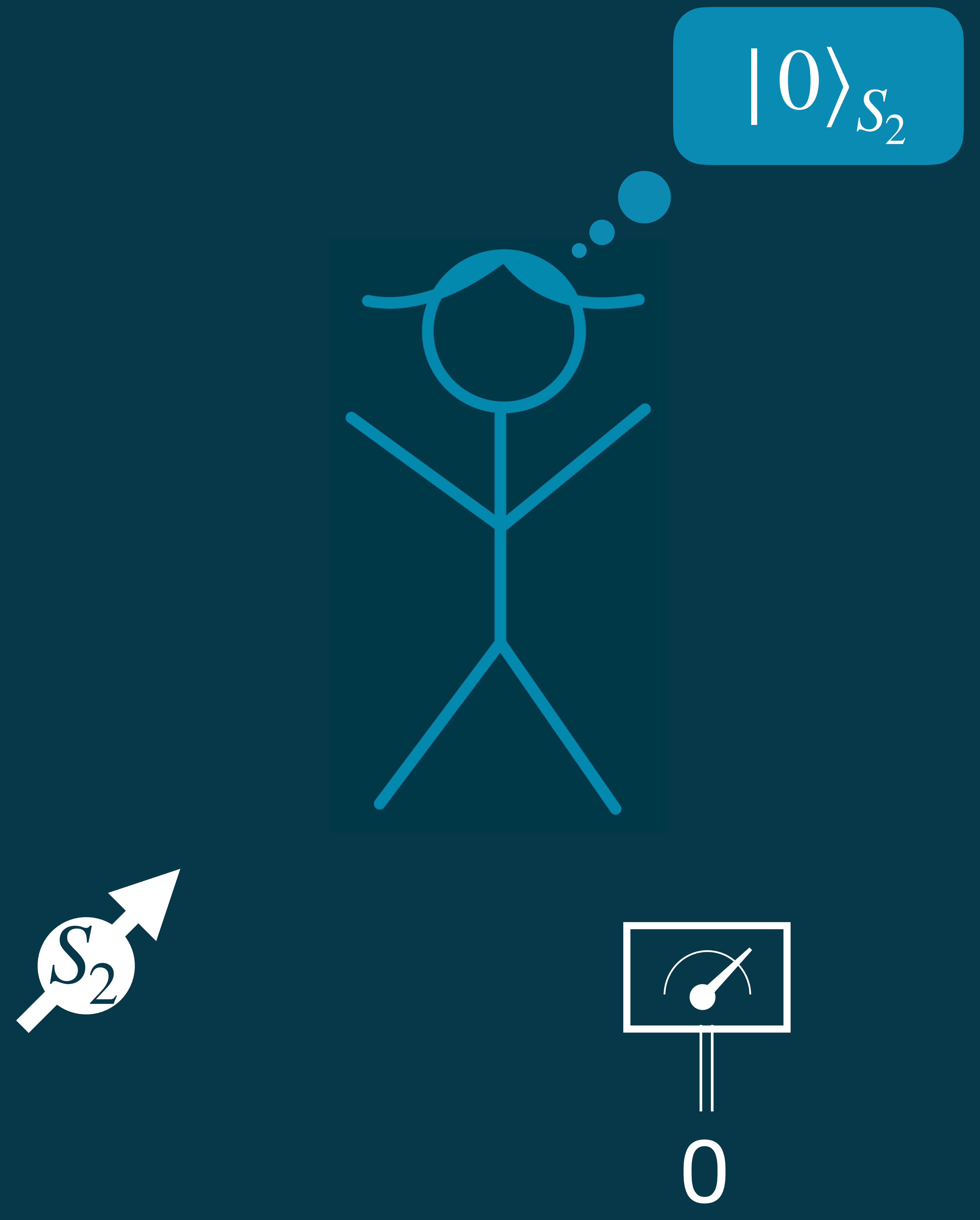

S_2
0
$|0\rangle_{S_2}$

Combining the perspectives





Combining the perspectives

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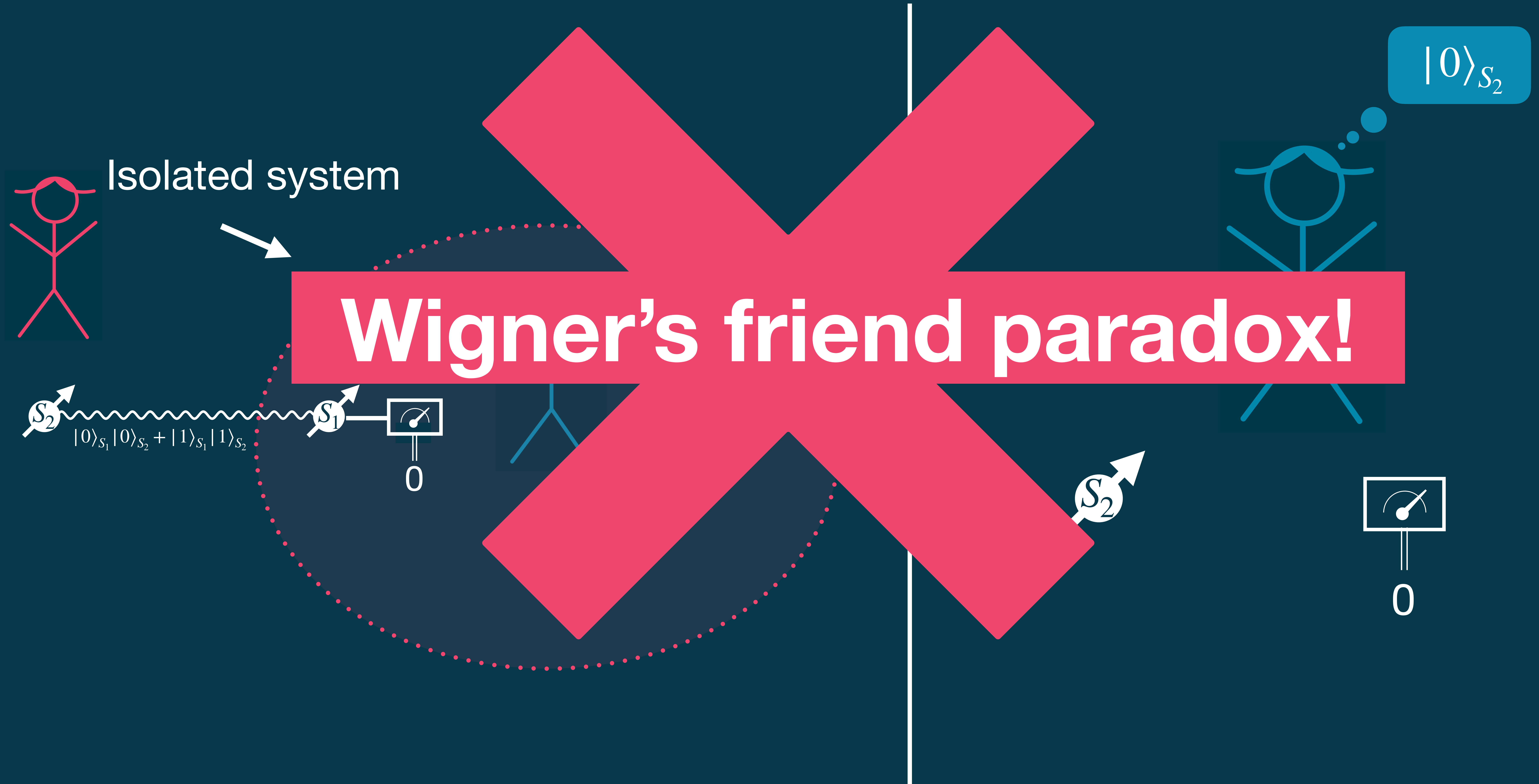

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(G) Gra[illegible] assumpt[illegible]:

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No-go theorem

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(C) State compatibility

What can we learn from this?

BridgeQG - Theoretical questions

- Is gravity quantised, and what constitutes a quantum signature of gravity? [Entanglement, …]
- What are the symmetries at the Planck scale?
- Is there a separation of scales in gravitational interactions, or shall we expect ultraviolet effects to percolate to low energies?
- How are observers & reference frames defined in QG?
- How does gravity (both classical and quantum) affect the dynamics of quantum systems? [Decoherence, modified Schoroedinger equation,…]

BridgeQG

S2
S1
|0⟩S1 |0⟩S2 + |1⟩S1 |1⟩S2
≙
S2
S1
|0⟩S1 |0⟩S2 + |1⟩S1 |1⟩S2

Instance of $\hat{=}$ ~~State compatibility~~

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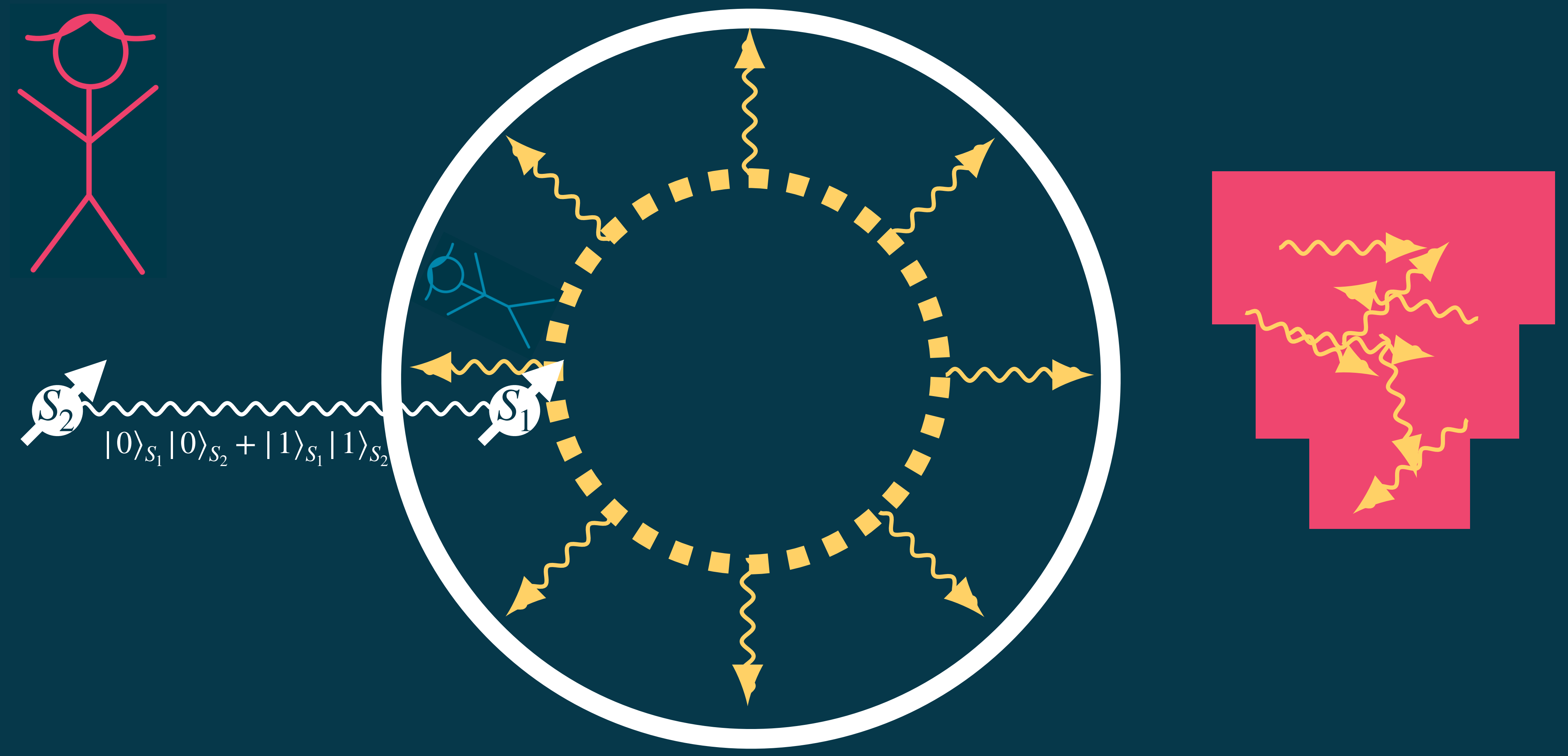
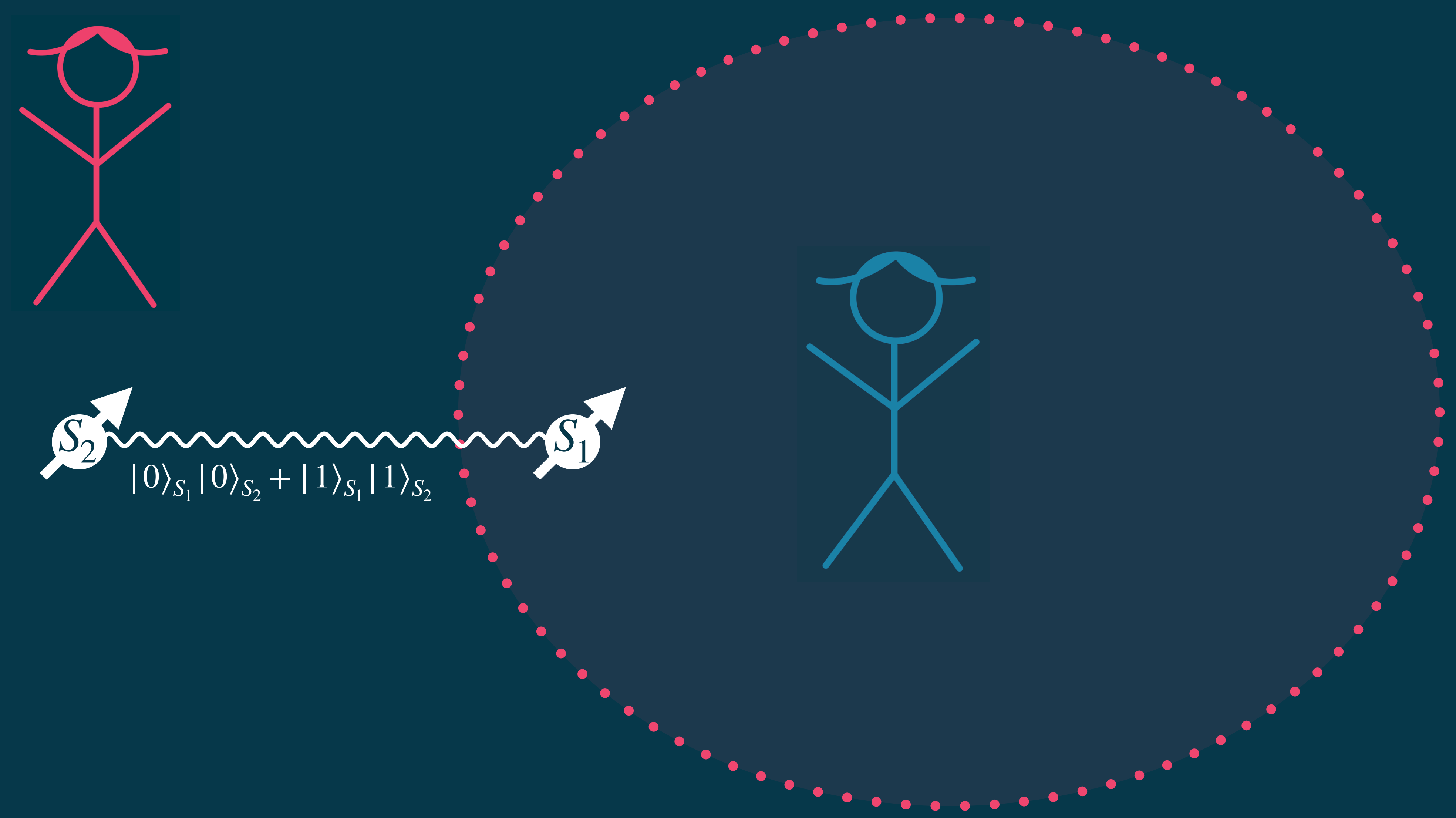
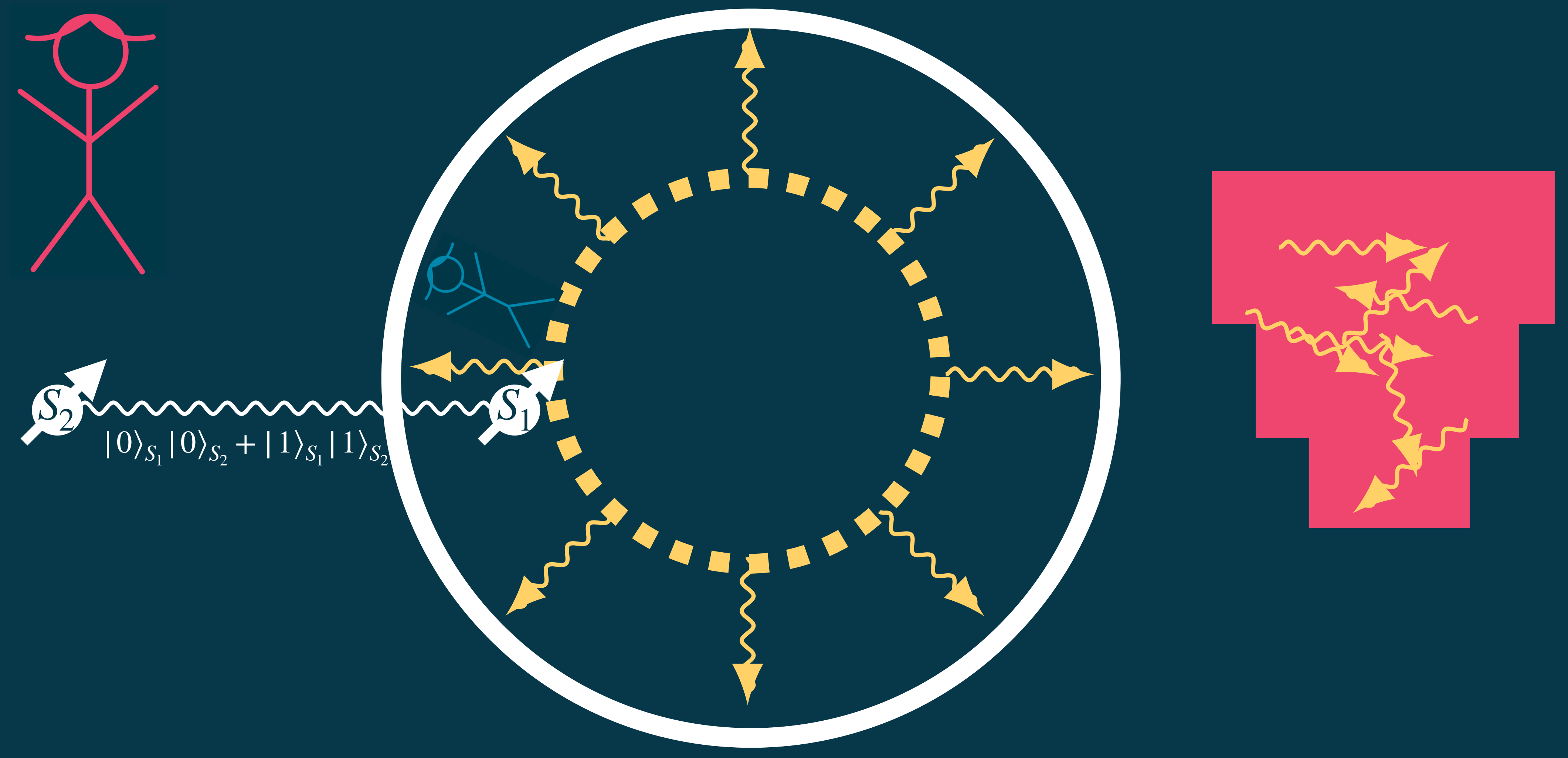


$\hat{=}$

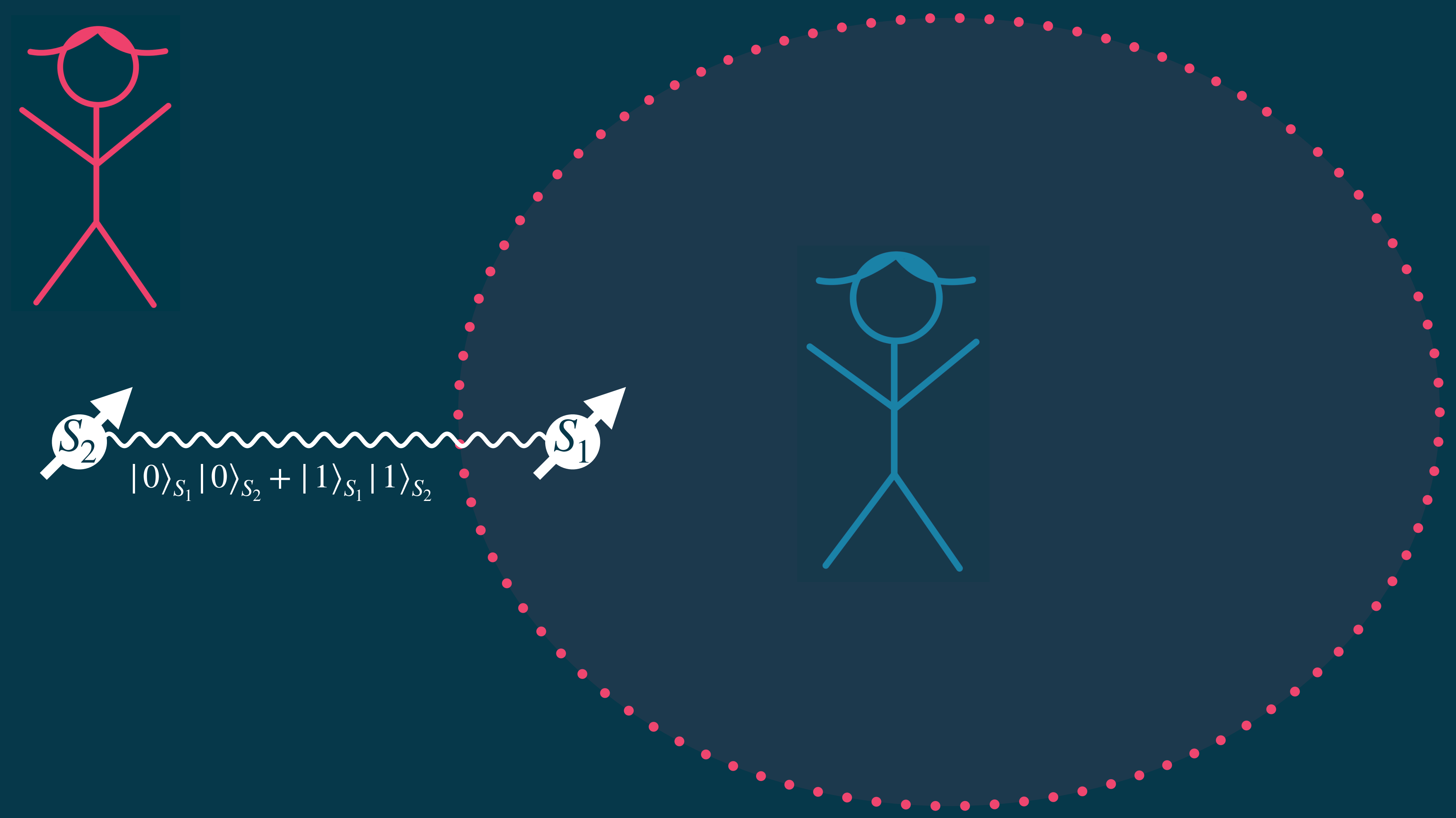


Black hole complementarity

Instance of $\hat{=}$ ~~State compatibility~~



$\hat{=}$



Black hole complementarity

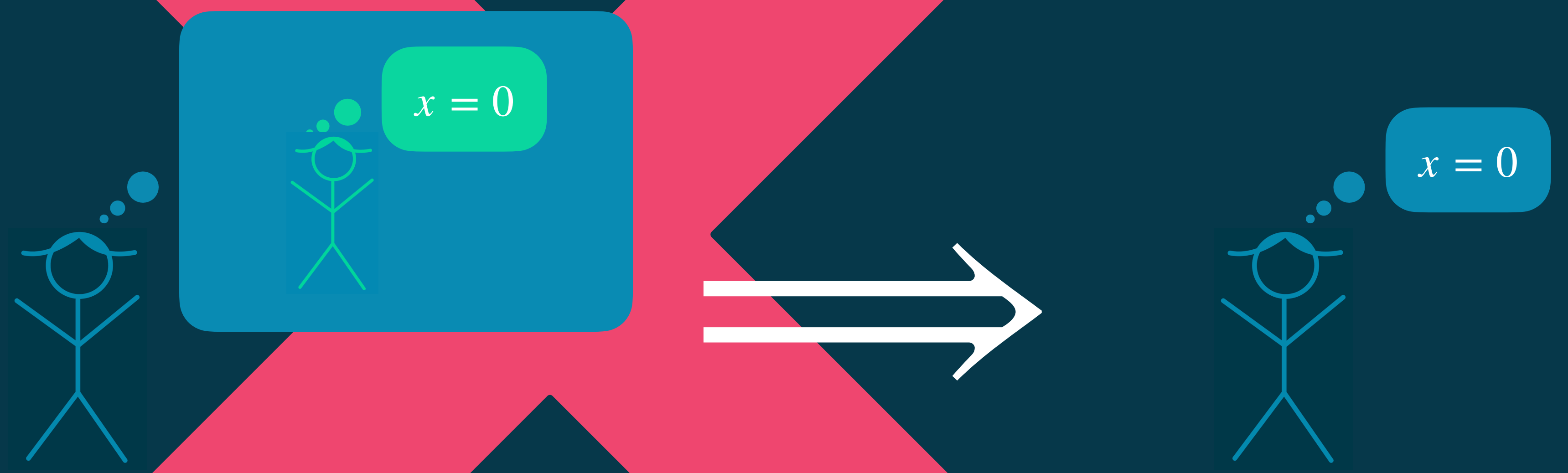
State is epistemic

Application to other paradoxes

Quantum collaboration paradox:

(Q) Universality of quantum theory

(C)

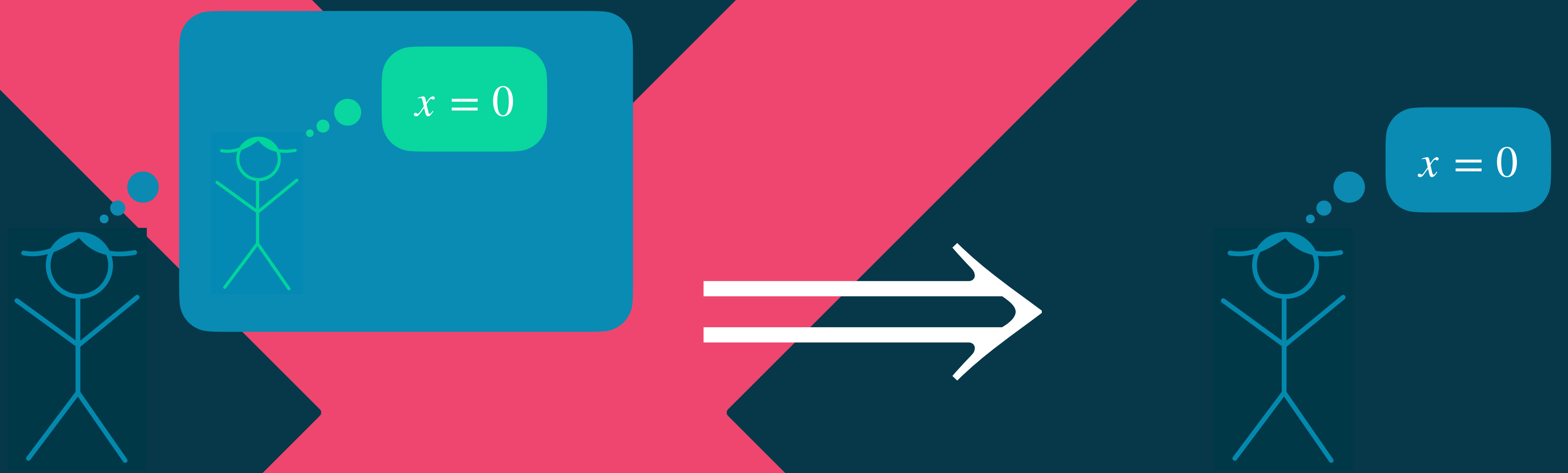


Frauchiger, Renner, 2018

Firewall Paradox:

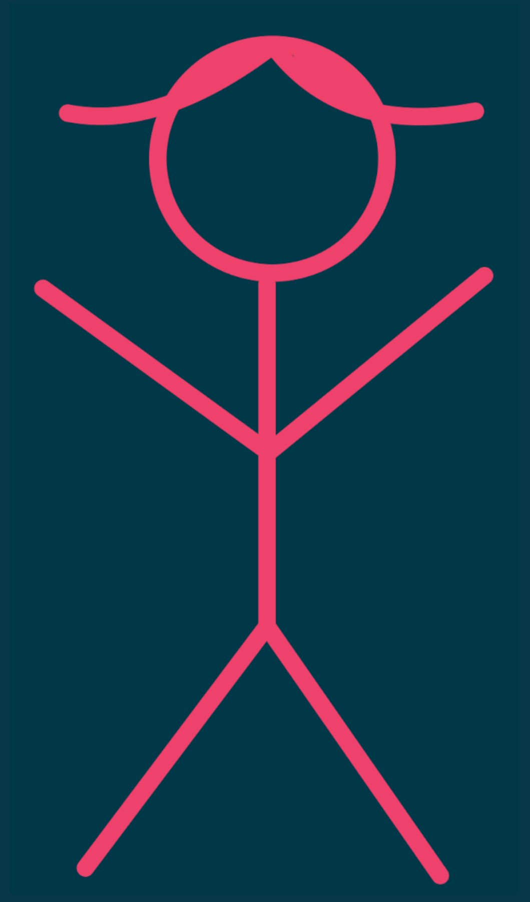
(Q) Universality of quantum theory

(C)



(G) Gravity assumptions

Almheiri, Marolf, Polchinski, Sully, 2012



Thank you!