

Communication through quantum-controlled noise

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Phys. Rev. A **99**, 062317 (2019). [arXiv:1812.06848](https://arxiv.org/abs/1812.06848)

Causality in the quantum world
Anacapri, September 19th, 2019



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Motivation

- Advantages of the quantum switch for information processing: query complexity, communication complexity.

Chiribella Phys. Rev. A **86**, 040301 (2012), Araújo et al *Phys. Rev. Lett.* **113**, 250402 (2014), Guérin et al *Phys. Rev. Lett.* **117**, 100502 (2016),

Switch is better at these tasks than all causally separable processes

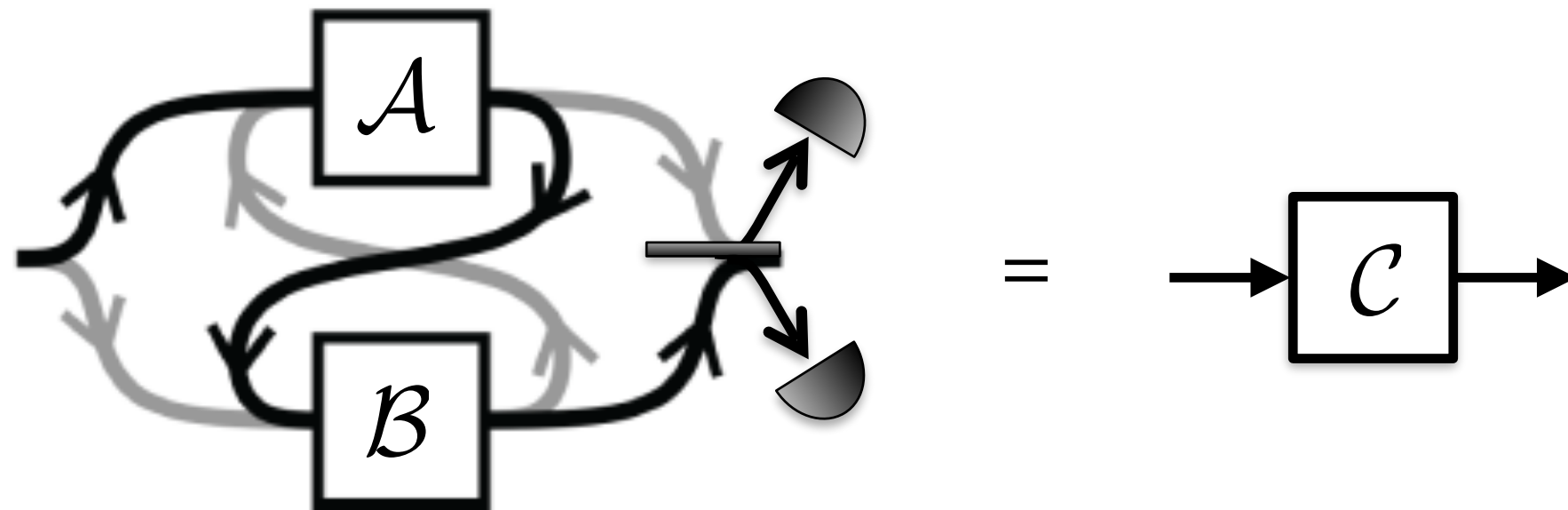
- Recent works on Shannon theory with the switch

Ebler et al. Phys. Rev. Lett. **120**, 120502 (2018), Salek et al. arXiv:1809.06655, Chiribella et al. arXiv:1810.10457

Where do these advantages come from? Causal non-separability?

Shannon theory with the switch: reminder

Choose two noisy channels \rightarrow A \rightarrow B \rightarrow

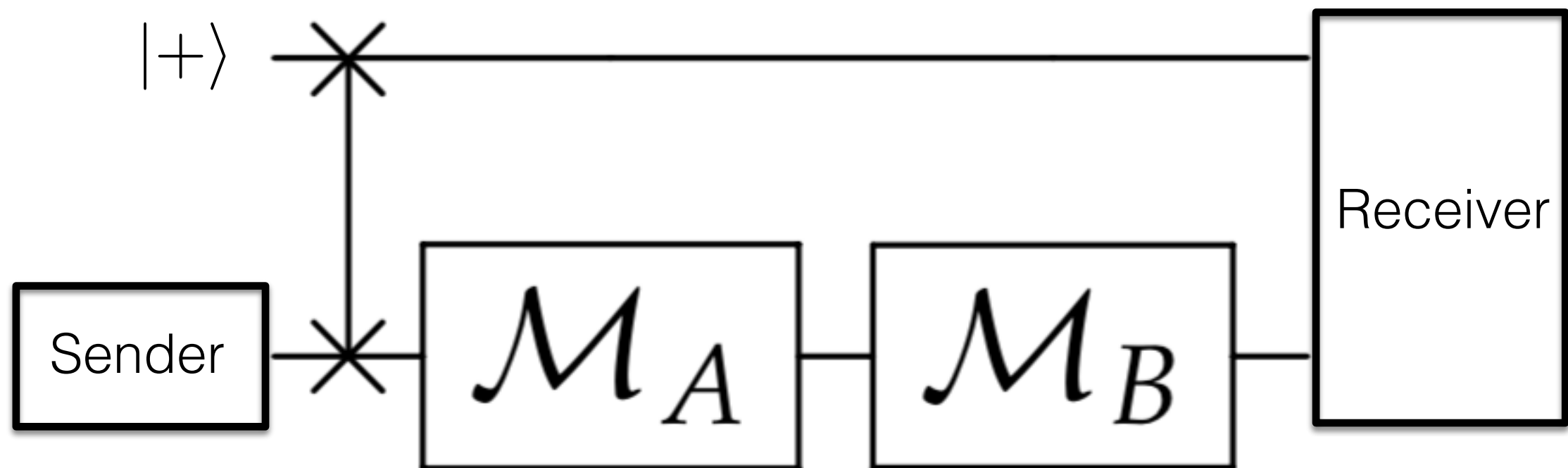


Channel capacity is better than what you would get by sequentially composing A and B

The sender does not have access to the control qubit, but the receiver does

What is the source this
advantage?

Side channels?



This causally ordered process is clearly using the noiseless wire as a side channel.

These processes have to be excluded

What is a process without side-channel?

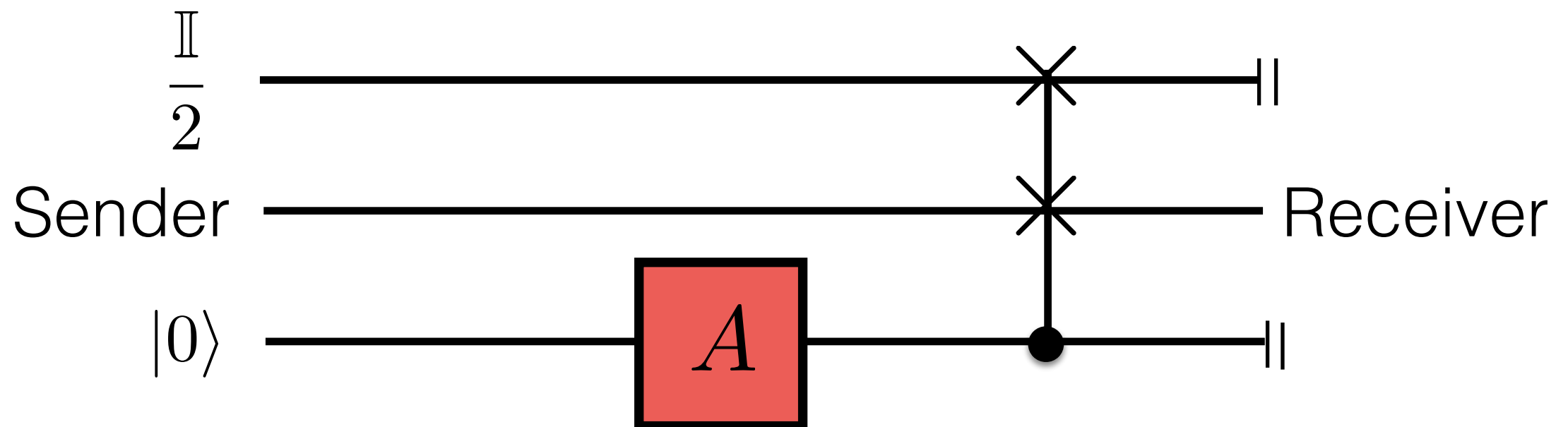
- Naive attempt: trace over the parties in the process matrix. Then the resulting channel from sender to receiver should have zero capacity

$$\frac{1}{4} \text{tr}_{A_I A_O B_I B_O} |w\rangle\langle w|_{\text{switch}} = \frac{1}{4} \mathbb{I}^{PCF} + \frac{1}{8} (|0\rangle\langle 1| + |1\rangle\langle 0|)^C \otimes |\mathbb{I}\rangle\rangle\langle\langle \mathbb{I}|^{PF}$$

- Has non-zero classical capacity! Ebler et al. *Phys. Rev. Lett.* **120**, 120502 (2018)
- Tracing over a party is equivalent to the party performing the completely depolarising channel...

Other definitions of side-channel?

- *A process does not contain a side-channel if it is possible, by choosing some zero-capacity channels, to prevent any communication from sender to receiver.* (Chiribella - my understanding)



Satisfies this definition but looks like a side-channel that can be messed with.

- It might be possible to get a good definition that identifies the switch as having no side-channel
- Instead here we take the point of view that the free operations in a resource theory should be motivated by what is experimentally „equally hard“
- If we allow ourselves to take a superposition of processes with different causal order, why not superpositions of processes with the same causal order?

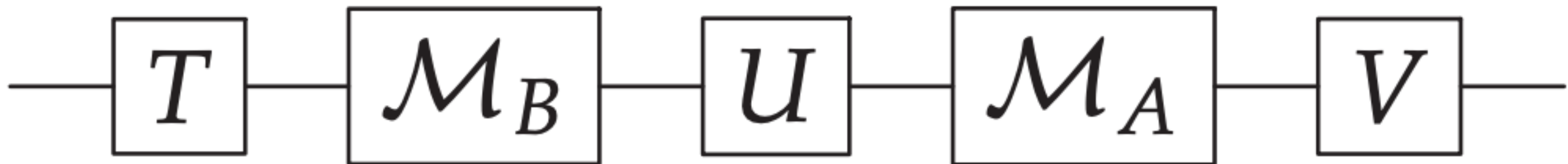
Superpositions of
direct pure processes

Direct pure processes

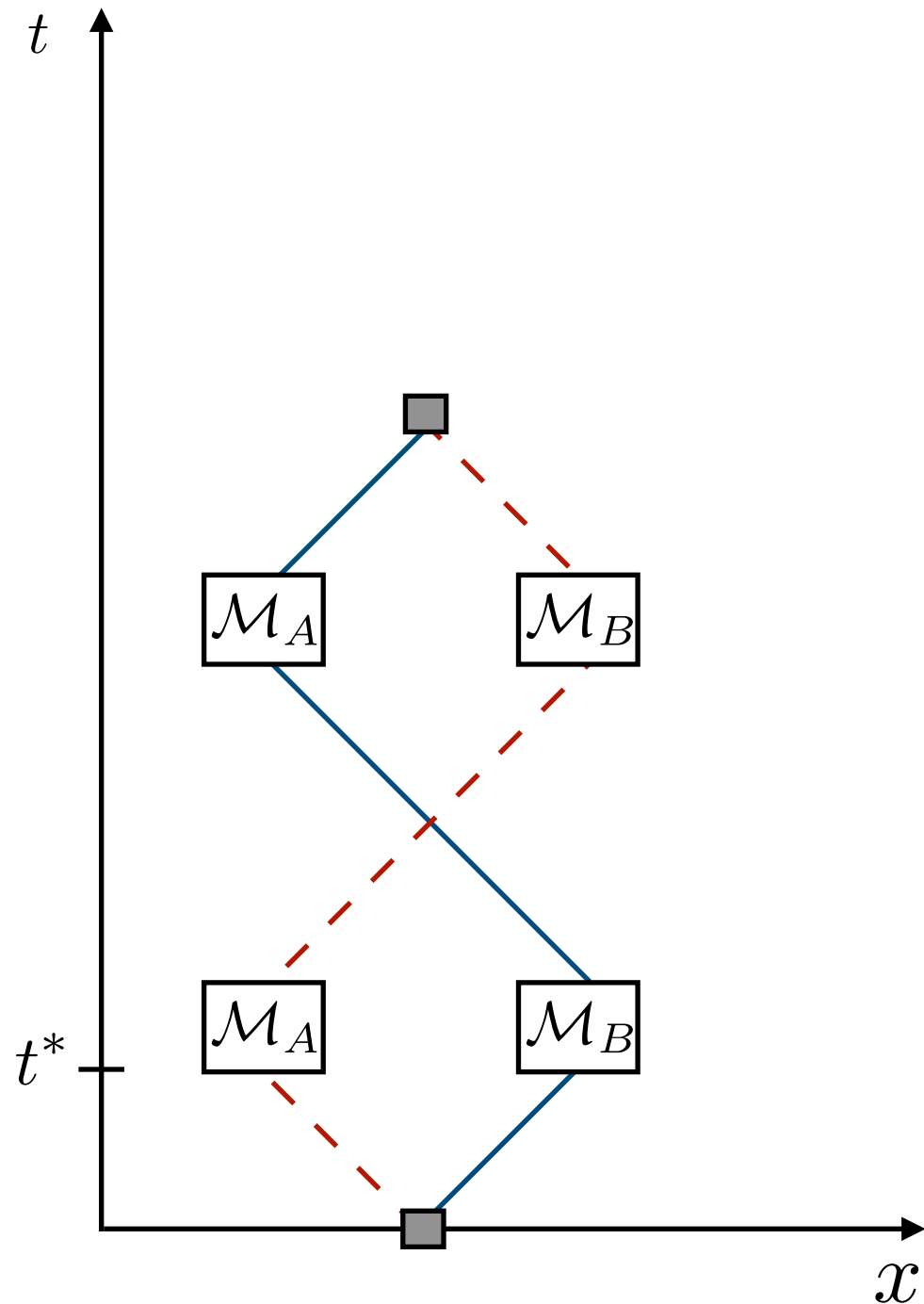
A class of processes with no side-channel



or



The quantum switch



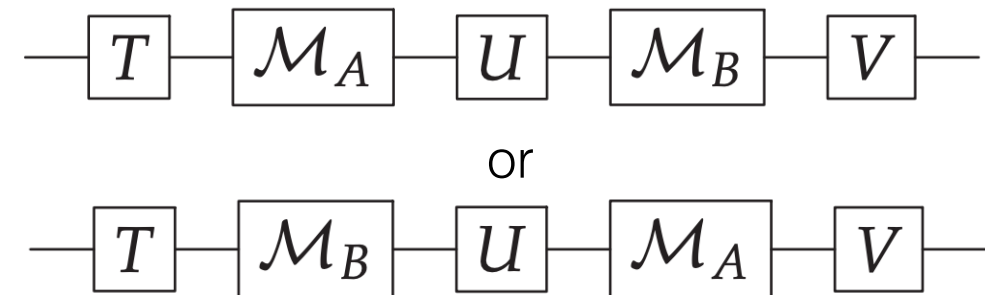
Important features

- We can delocalise a carrier of information over different spatial modes
- We can delocalise the noisy channels in space-time
- In each spatial mode, the carrier of information goes through a direct pure process
- We can re-interfere the different modes after the noisy channels are applied

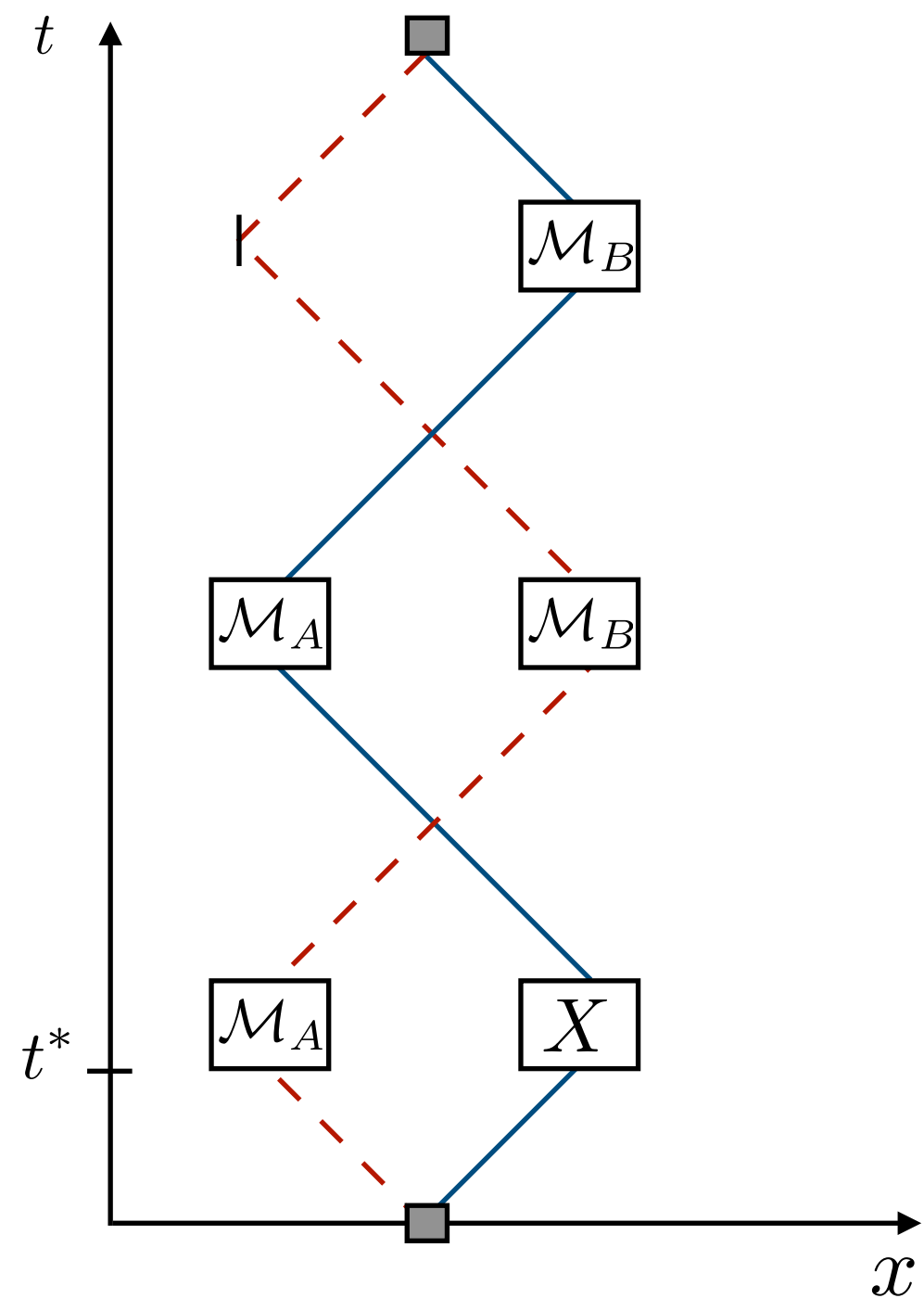
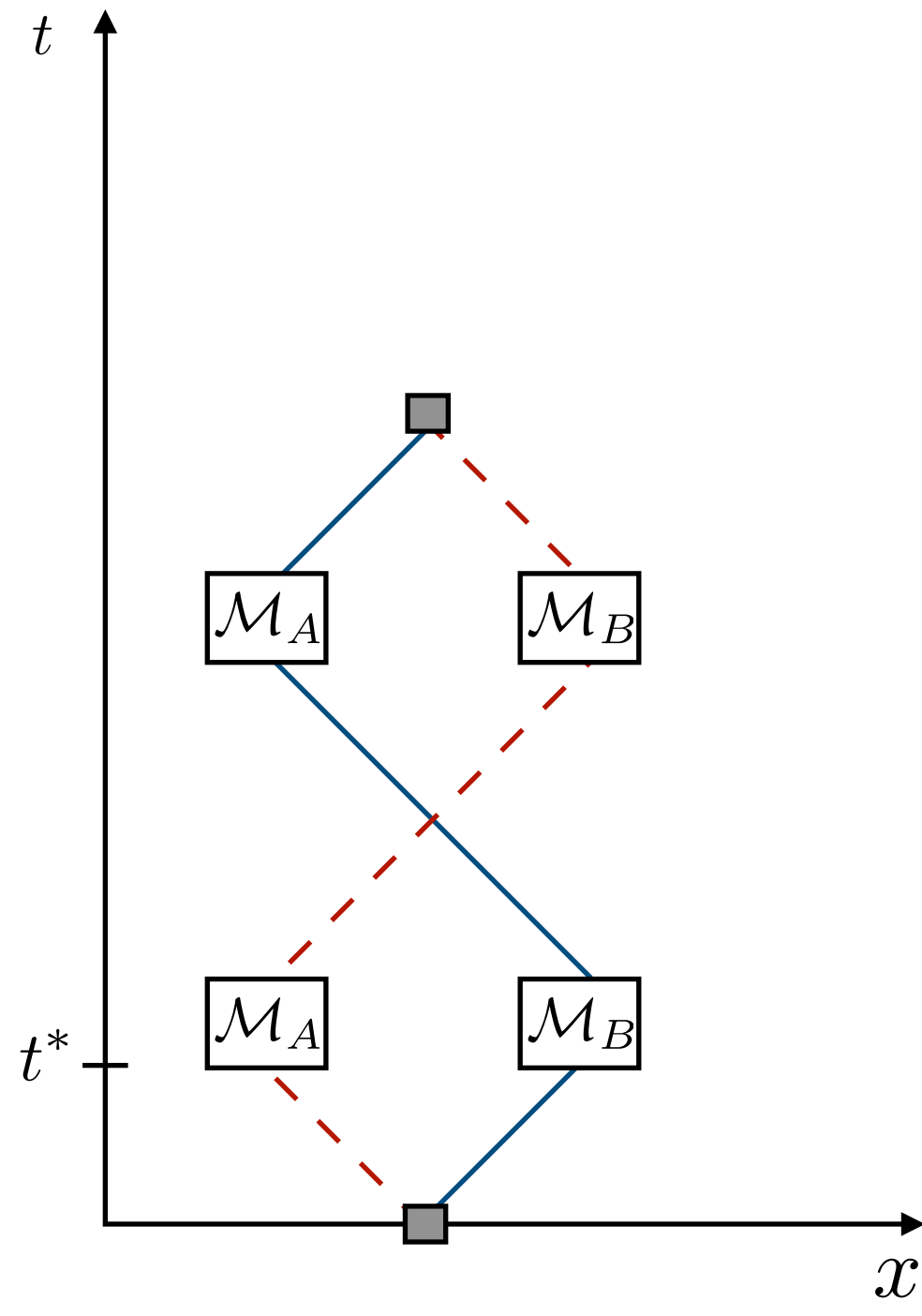
Superpositions of direct pure processes (SDPP)

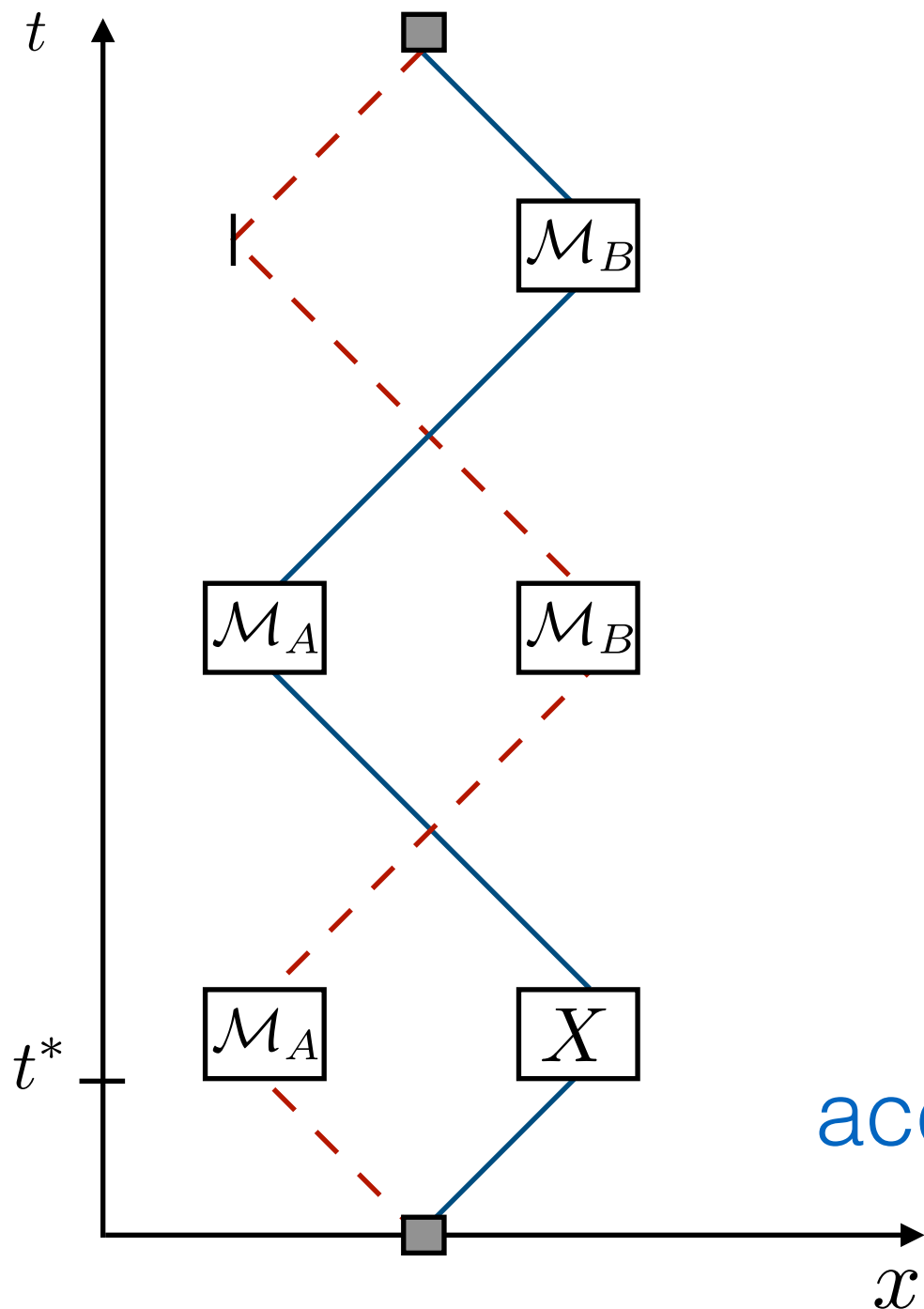
$$|w\rangle = \sum_i \alpha_i |i\rangle^C |w_i\rangle^{PA_I A_O B_I B_O F}$$

Direct process



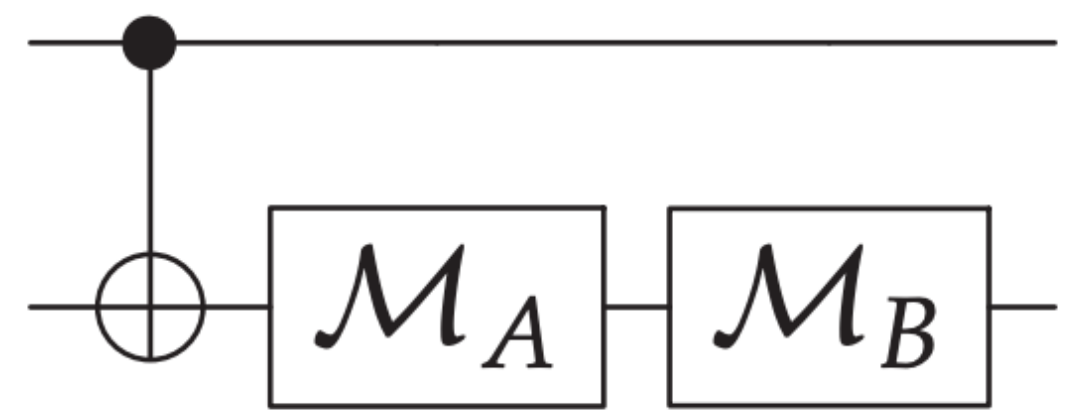
If we find a task where the switch outperforms all causally separable SDPPs, then it's natural to say that the advantage is due to indefinite causality





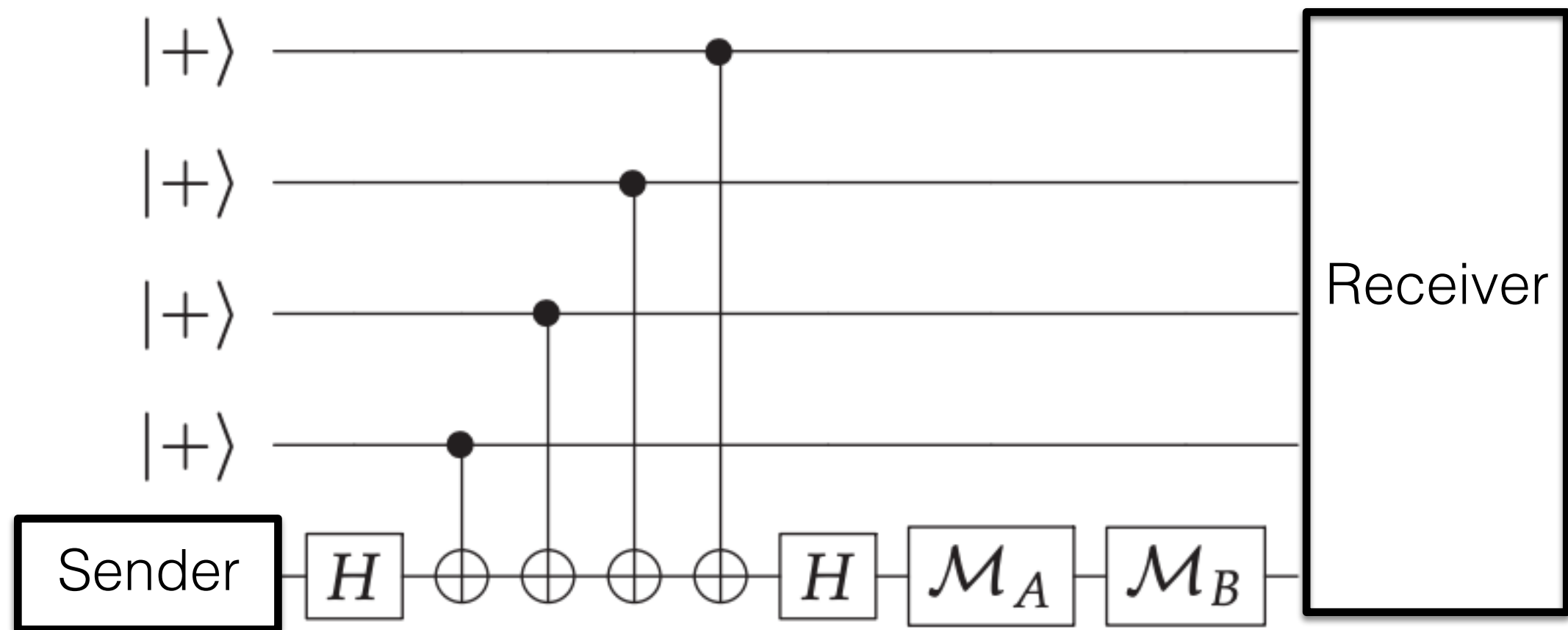
Outperforms the switch for the Shannon theory tasks

$|+\rangle$



Clearly contains side-channel according to any reasonable definition

Shor code



This SDPP can correct for arbitrary errors

Concluding comments

- The Shannon theory advantages seem attributable to the ability to delocalise noisy channels in space-time, and not necessarily indefinite causality.
- It is mathematically possible to define a resource theory containing some definite-order process and the switch, but not general SDPPs. This might not capture all experimentally relevant „easy operations“.
- SDPPs can be implemented by superpositions of spacetime similar to the gravitational switch.
- What does this imply for the assumptions of Bell's theorem for causal order?

Thank you!