A time-symmetric relativistic model violating Bell's inequality

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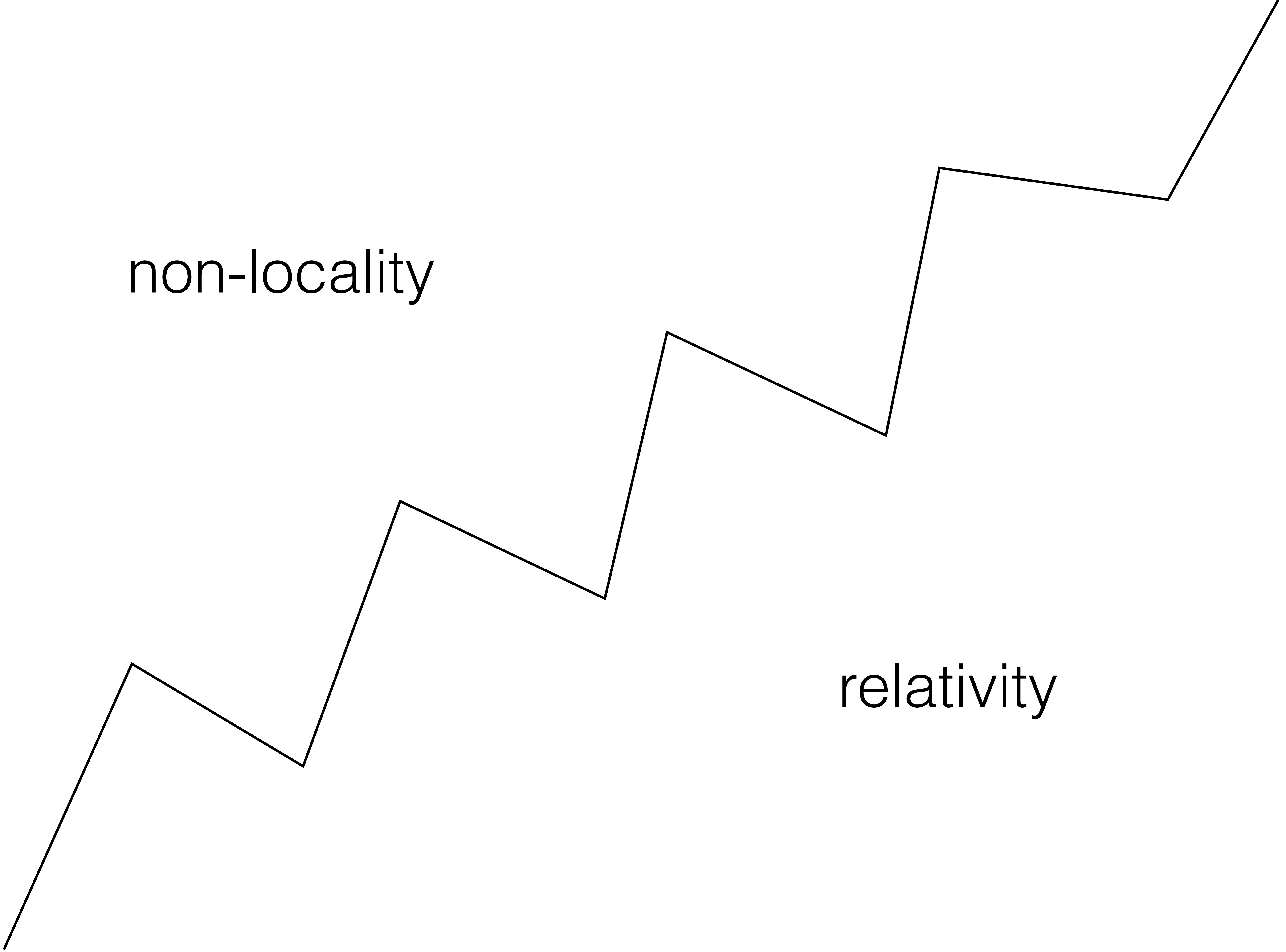
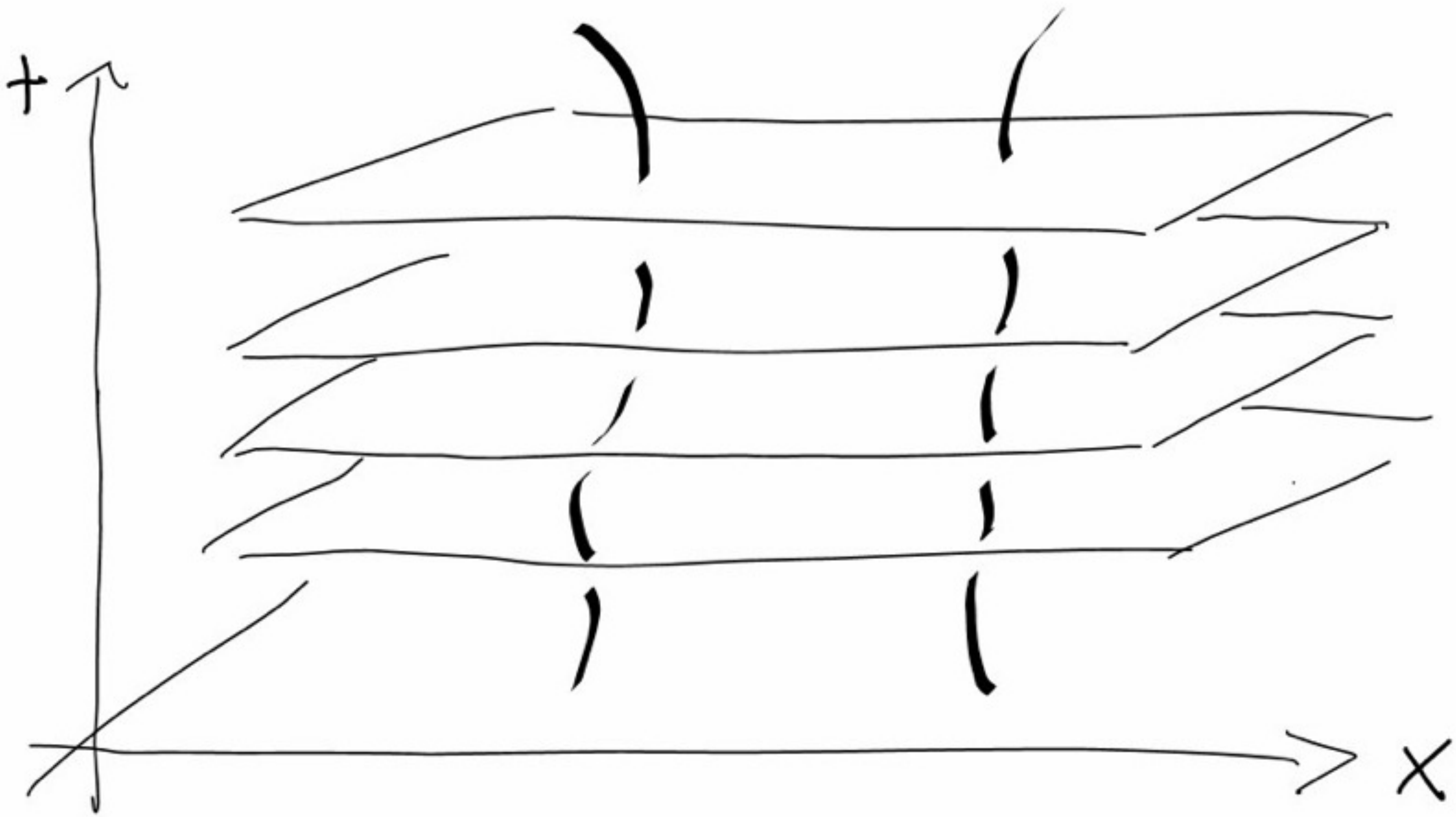
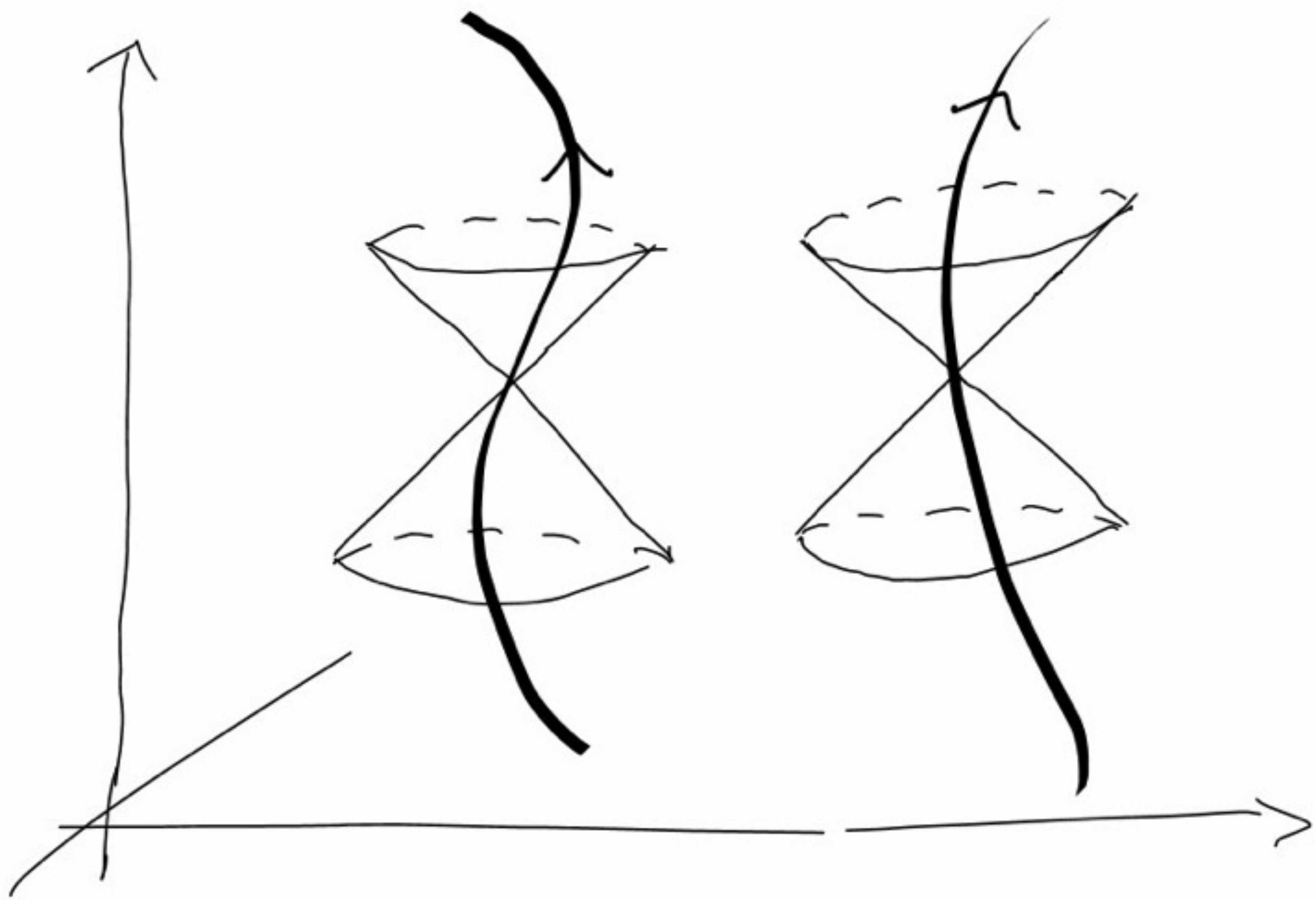
What is the greatest challenge posed by QM?


non-locality
relativity


t
x



A neglected route:

time-symmetric relativistic interactions

advanced + retarded

A toy model

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1) Particles with an internal degree of freedom („Spin“)

$$\mathbf{S} \in S^2$$

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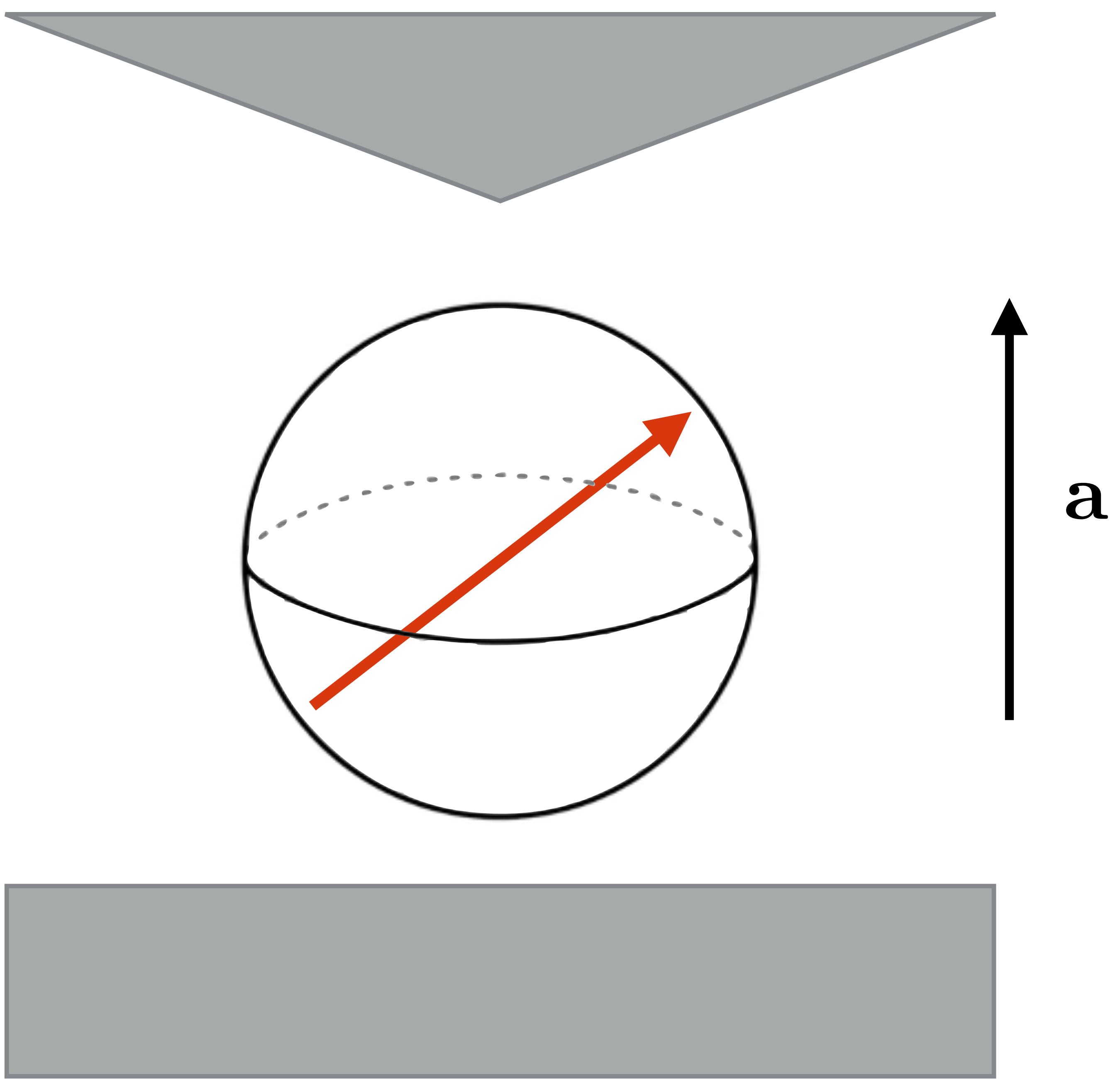
4) Measurement projects **S** into the measured direction

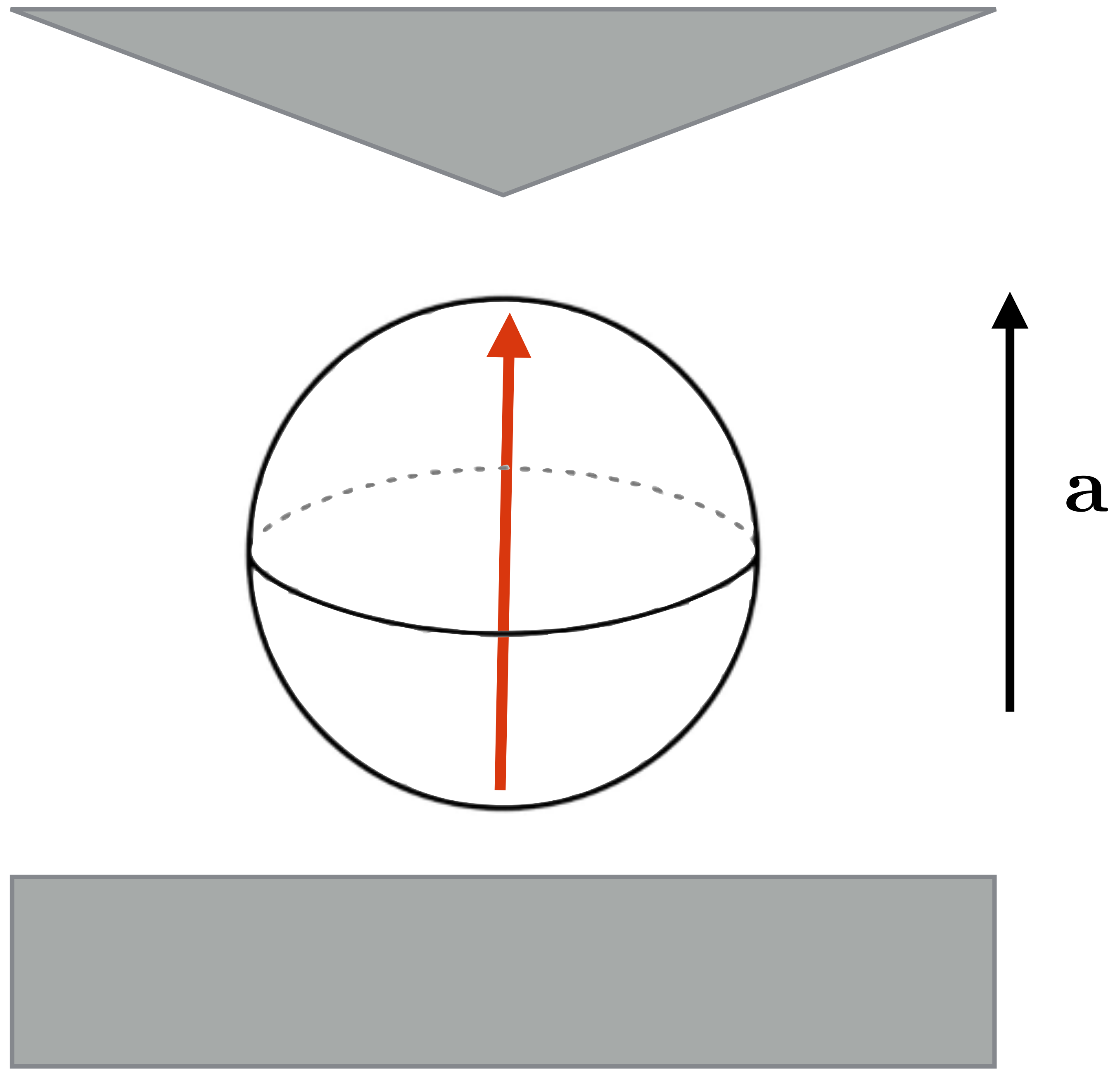
$$\mathbf{S} \longrightarrow \operatorname{sgn}\langle \mathbf{a}, \mathbf{S} \rangle\, \mathbf{a} = \frac{\langle \mathbf{a}, \mathbf{S} \rangle}{|\langle \mathbf{a}, \mathbf{S} \rangle|}\, \mathbf{a}$$

Measurement

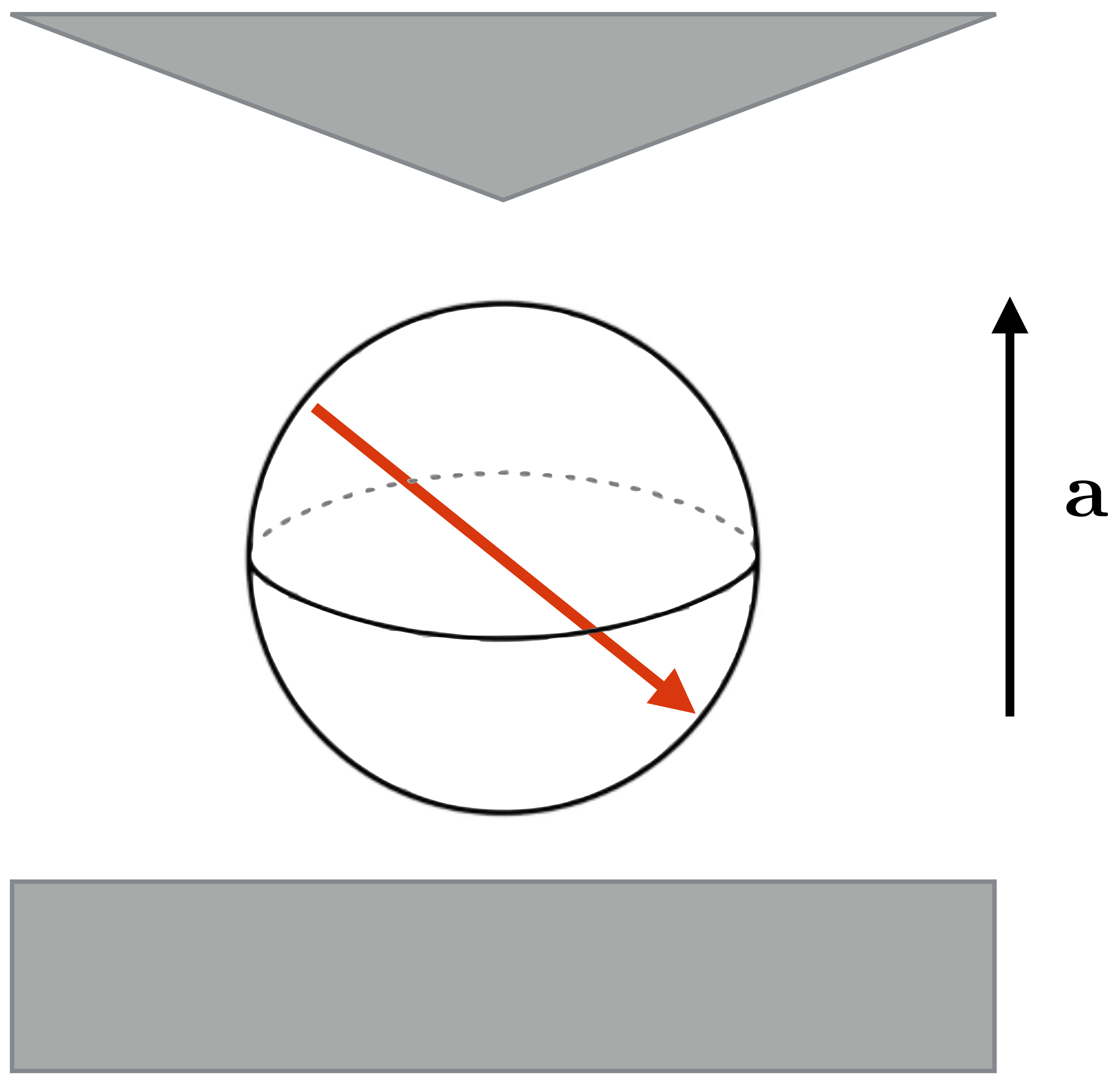


Measurement

„a-spin up“

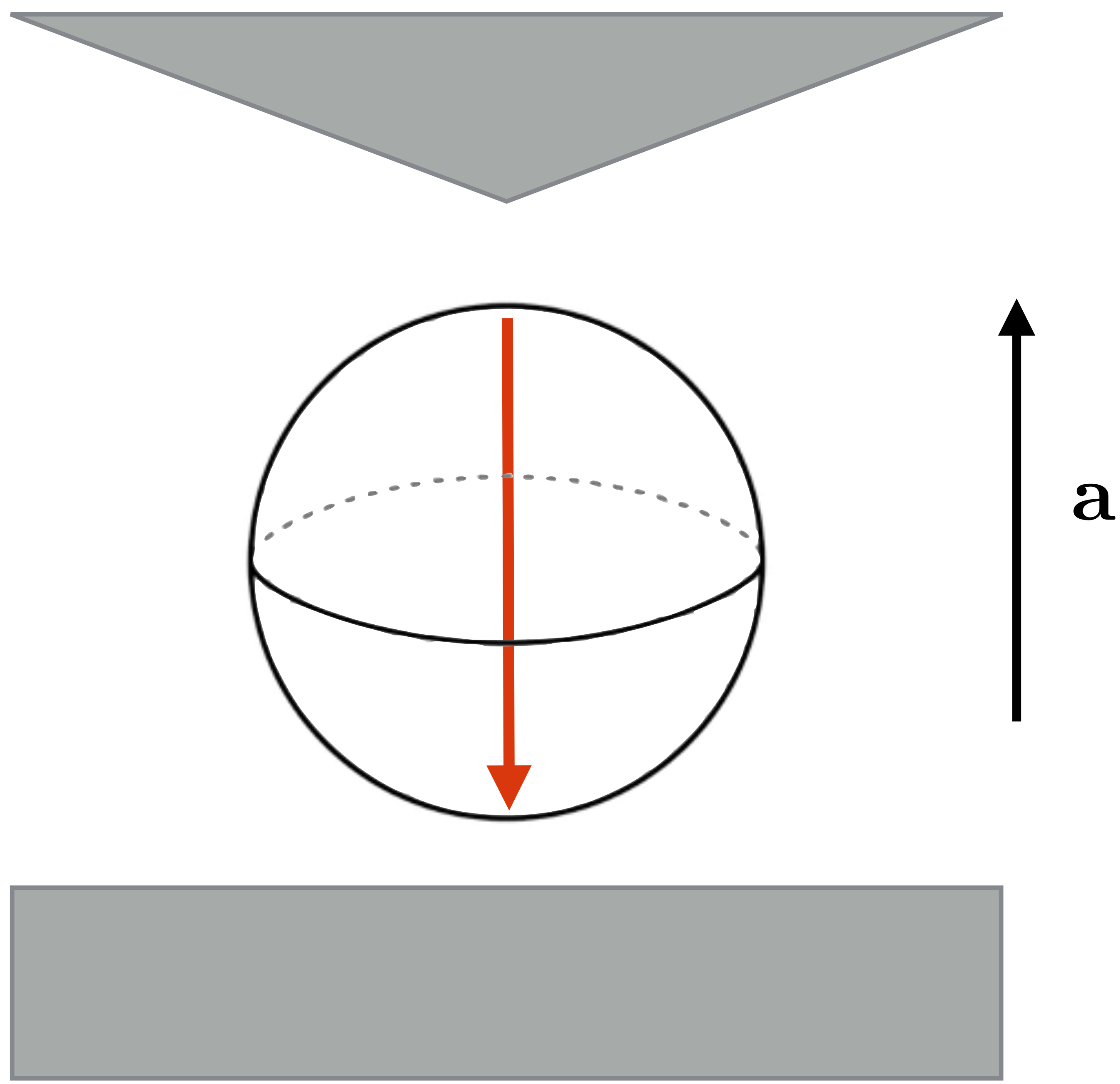


Measurement

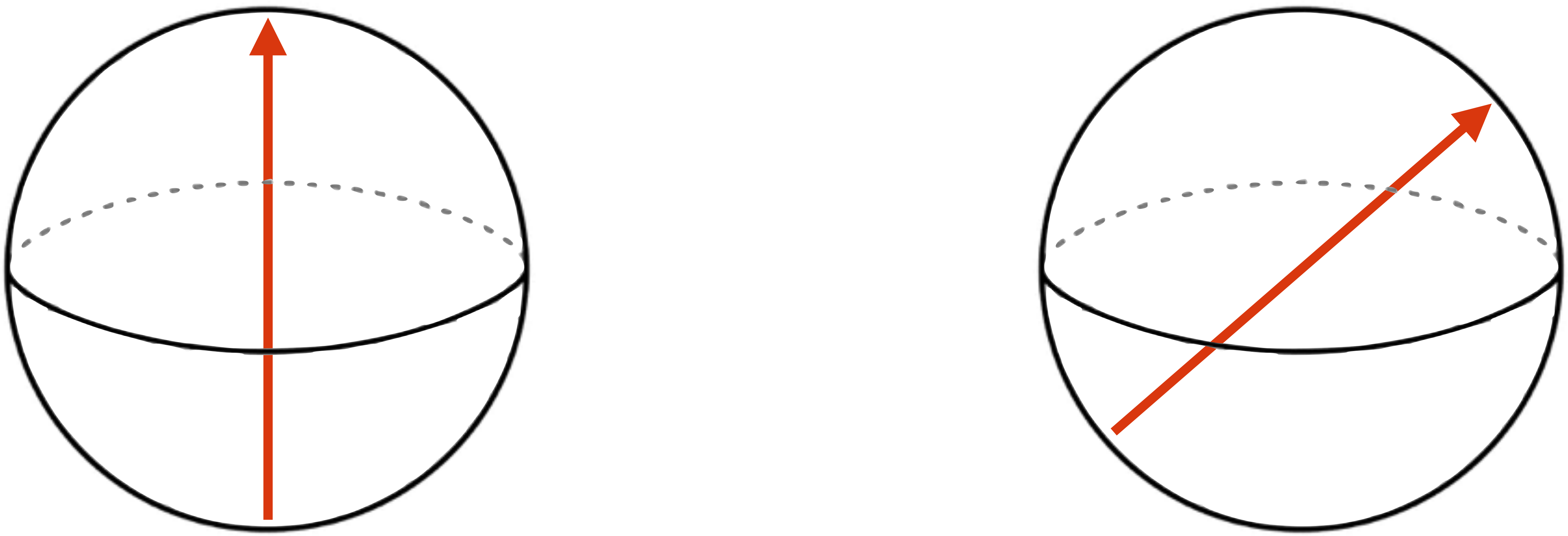


Measurement

„a-spin down“



4) Particle Interaction



The spin state S is subject to a pair interaction whose effect is such that a particle continuously rotates the spin of its partner towards the orientation antipodal to its own. This effect is manifested by an advanced and retarded action of one particle on the other which is unattenuated by spatial distance.

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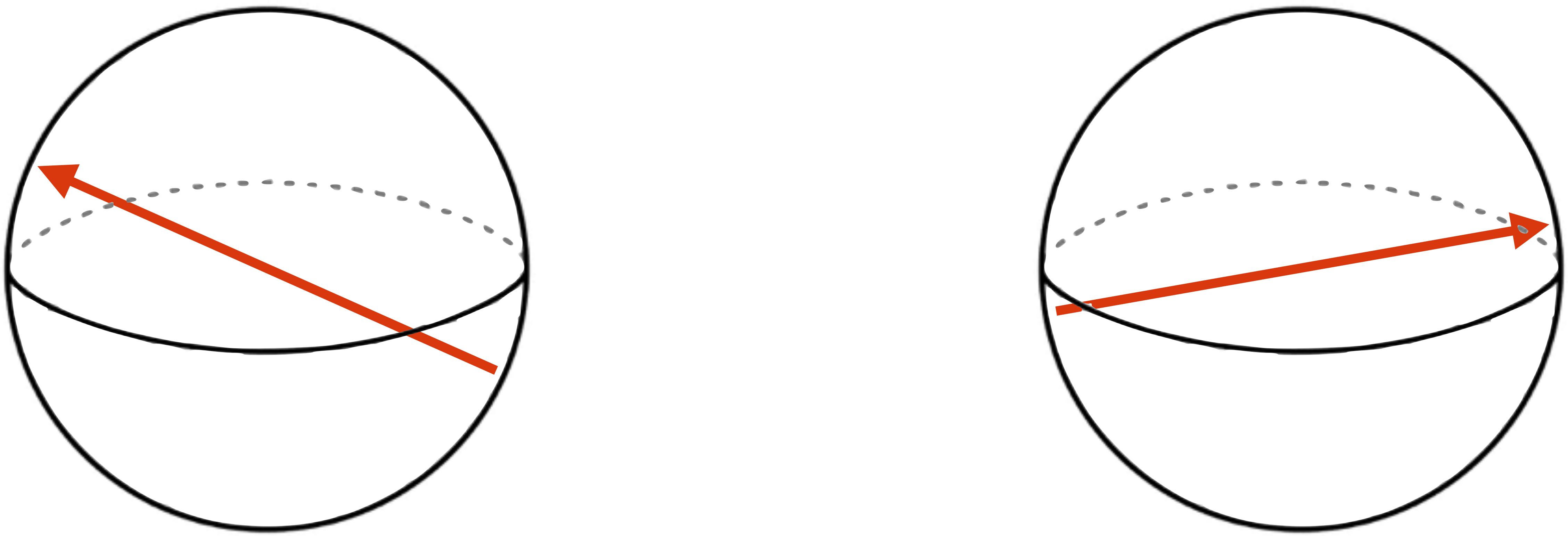

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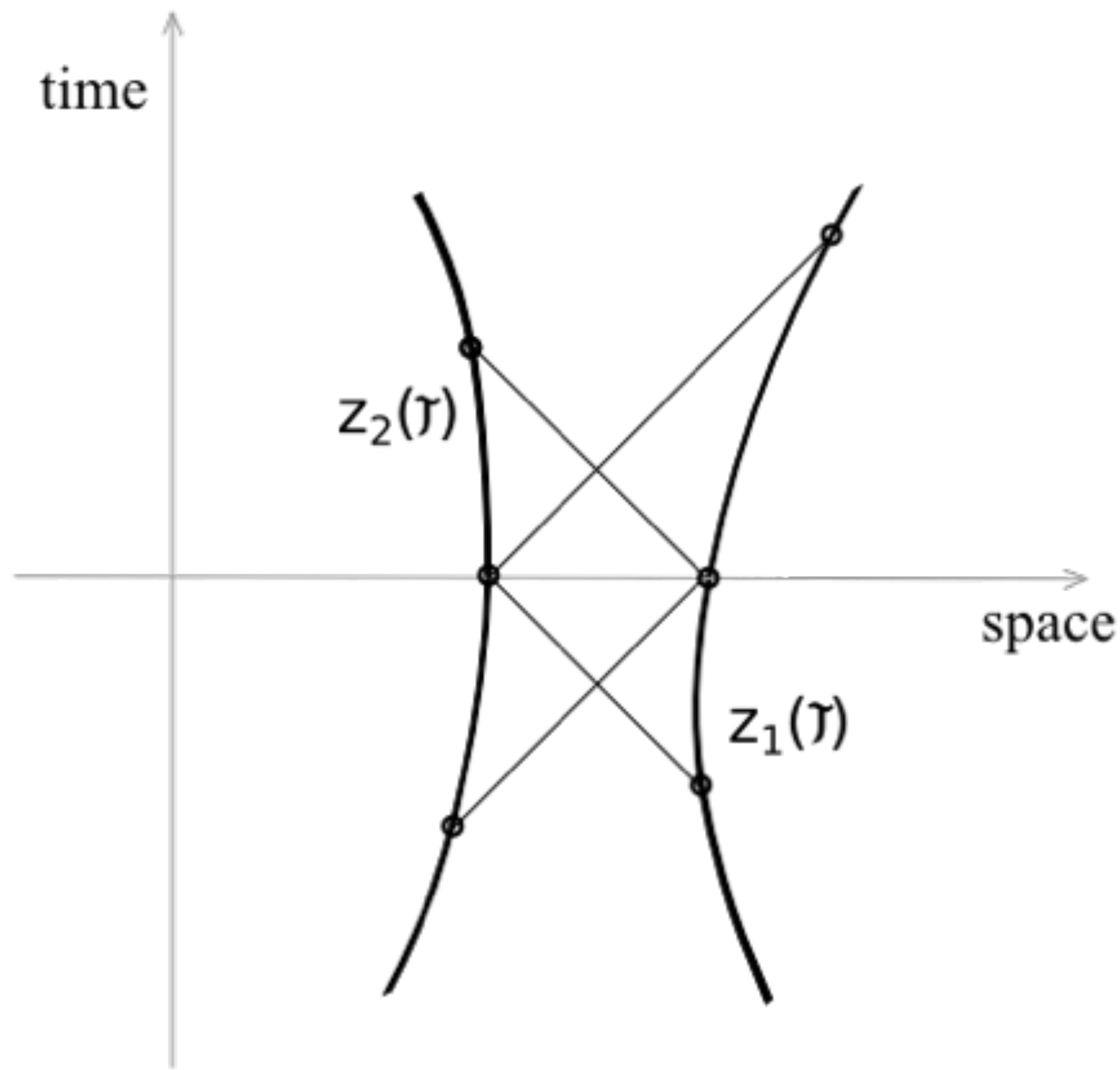
advanced + retarded



Without advanced interactions $\Rightarrow$ local theory

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e.g. for $a = 0^\circ, b = 120^\circ, c = 240^\circ$:

$$\mathbb{P}(A \neq B|a,b) + \mathbb{P}(A \neq B|b,c) + \mathbb{P}(A \neq B|a,c) = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1.$$

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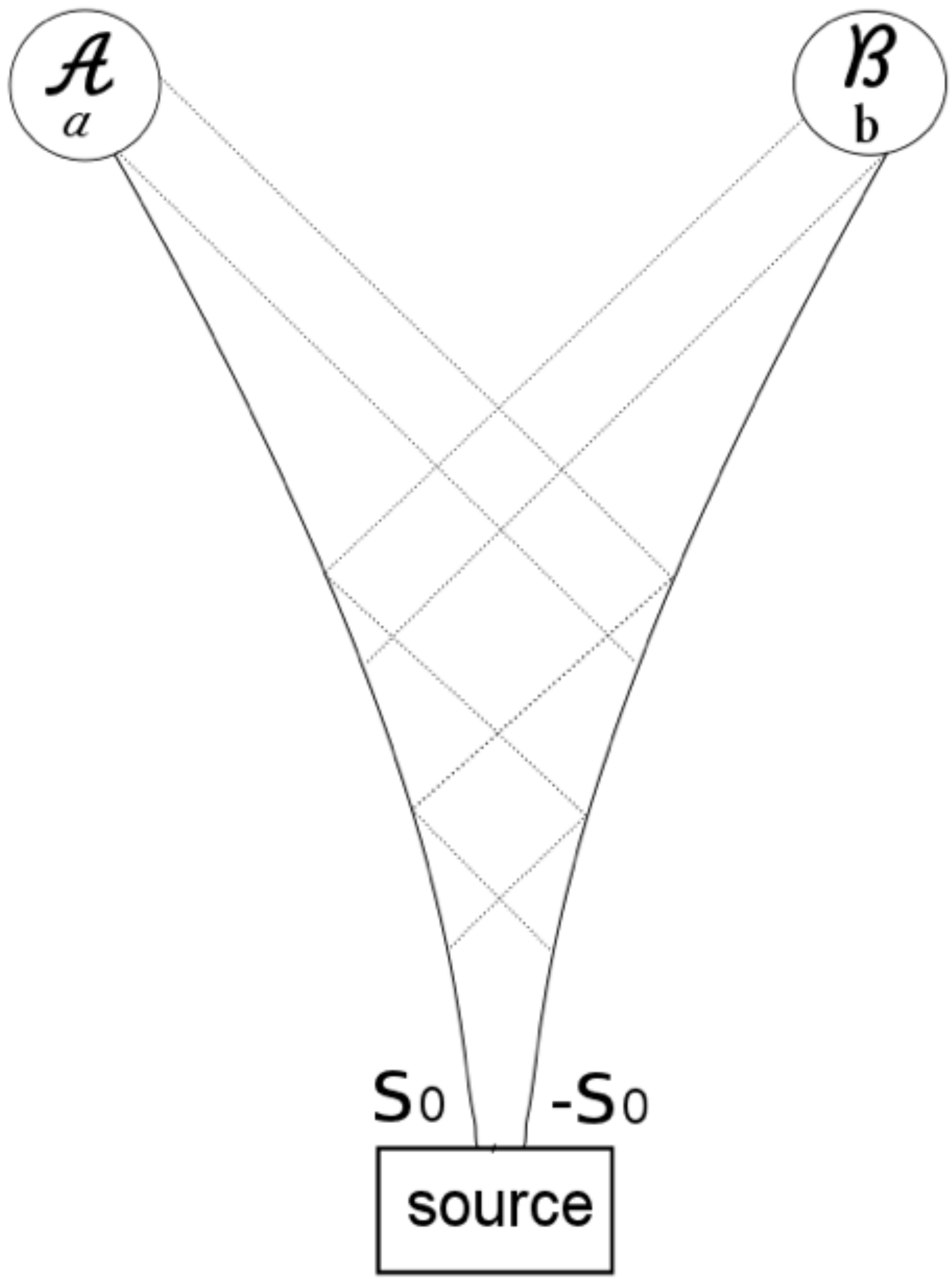
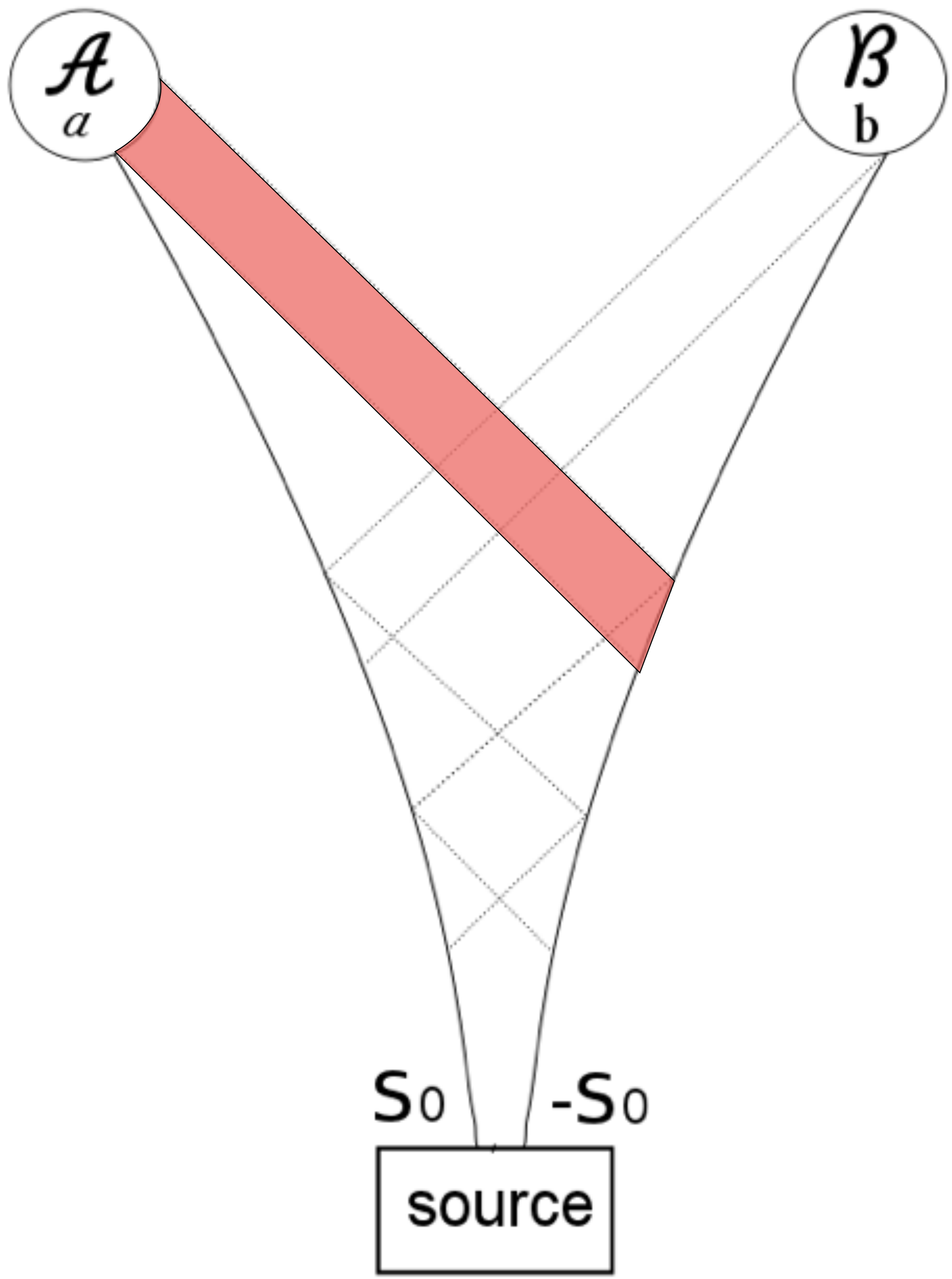
Bell's inequality:

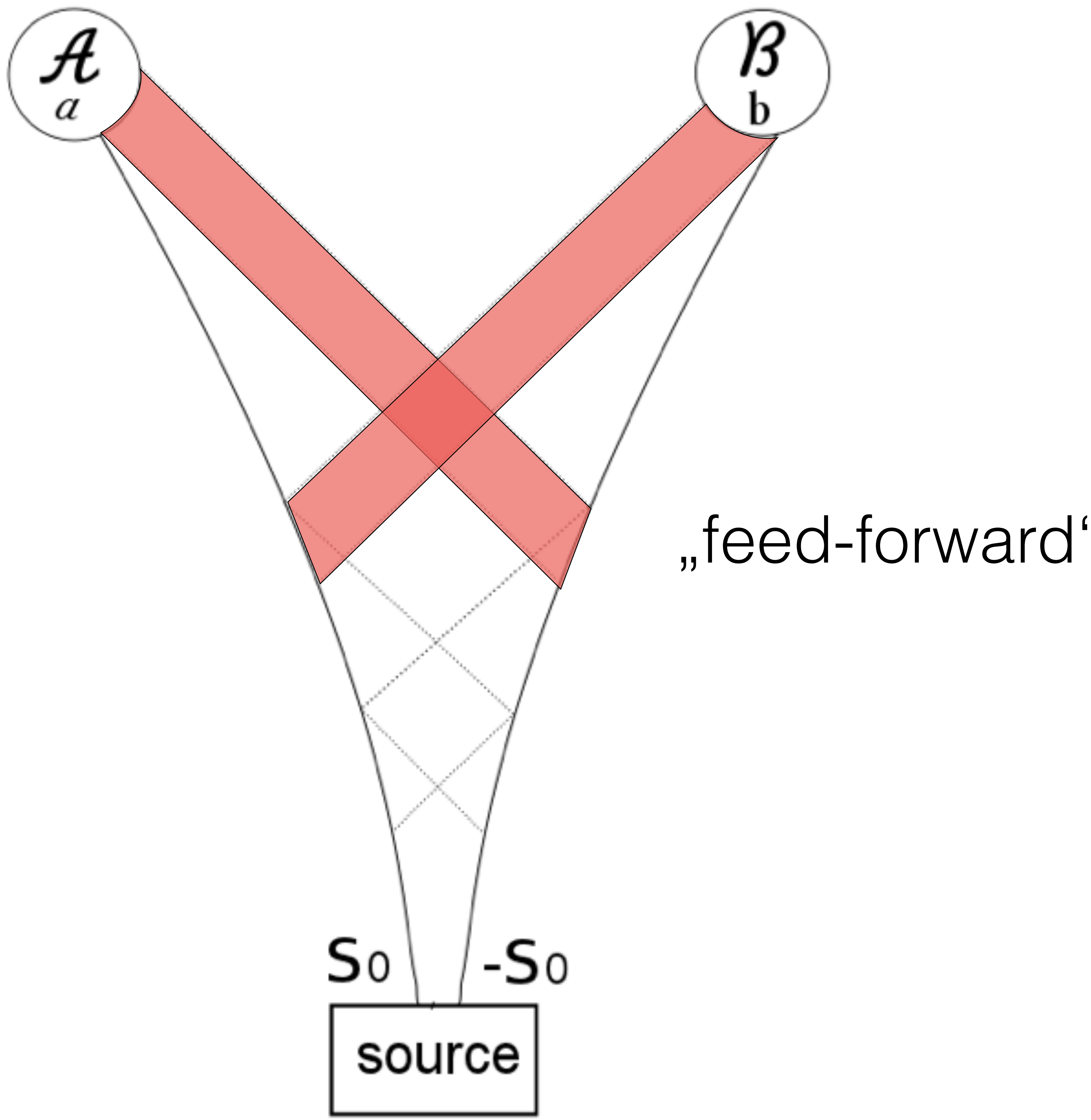
$$P(A \neq B|a,b) + P(A \neq B|b,c) + P(A \neq B|a,c) \geq 1$$



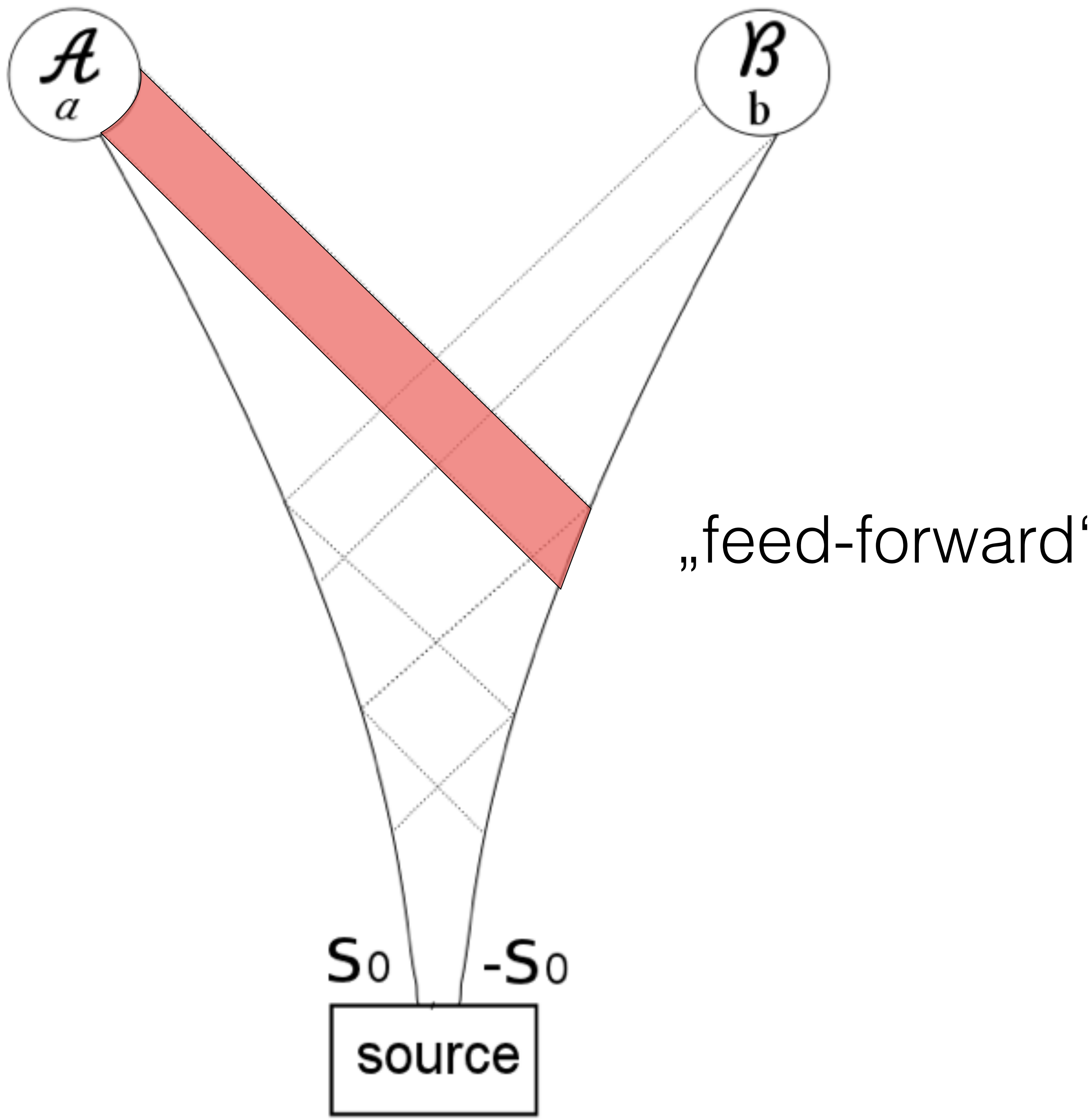
$\mathcal{A}$
a
$\mathcal{B}$
b
S0
-S0
source



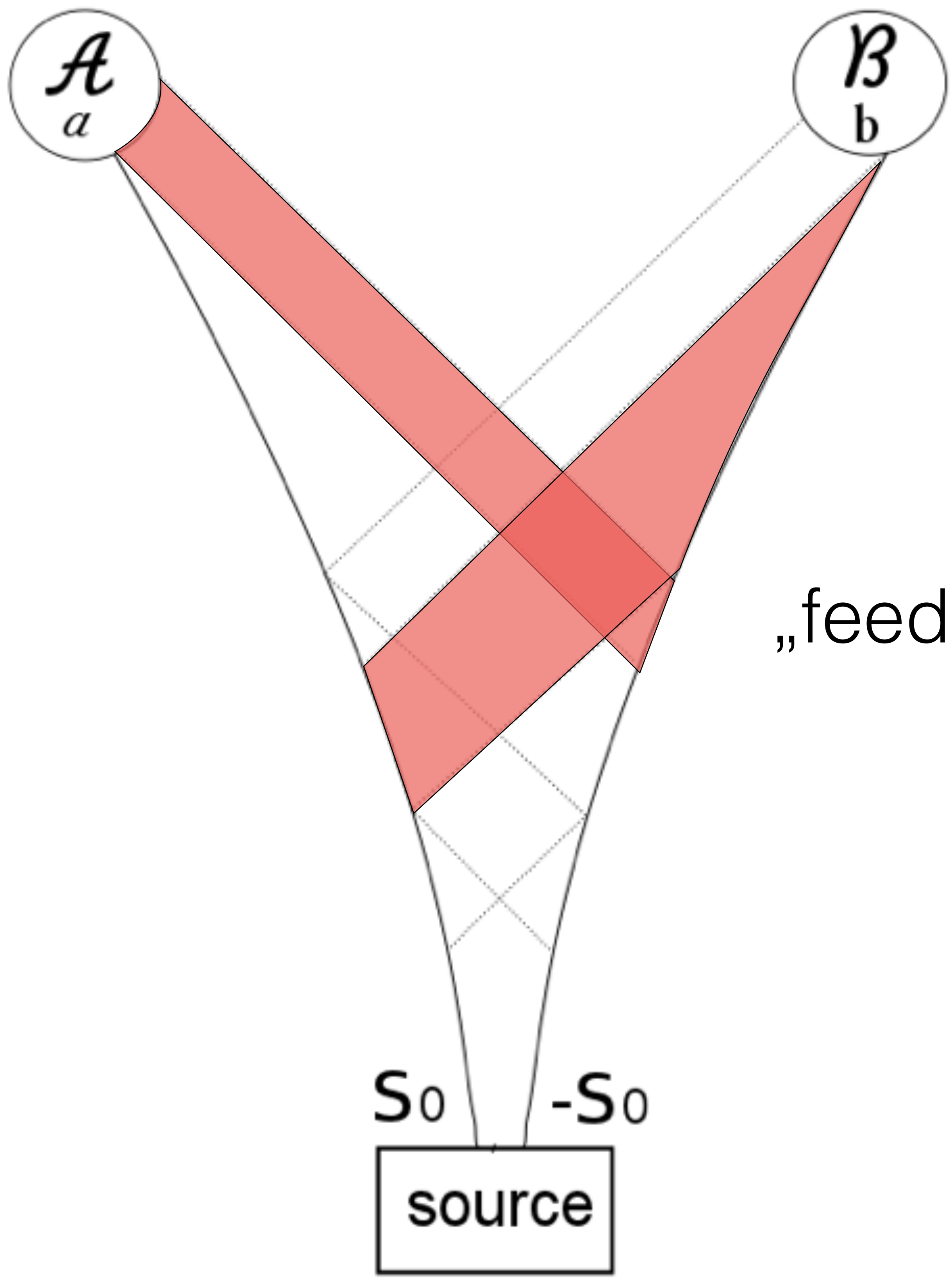
$\mathcal{A}$
a
$\mathcal{B}$
b
s_0
$-s_0$
source



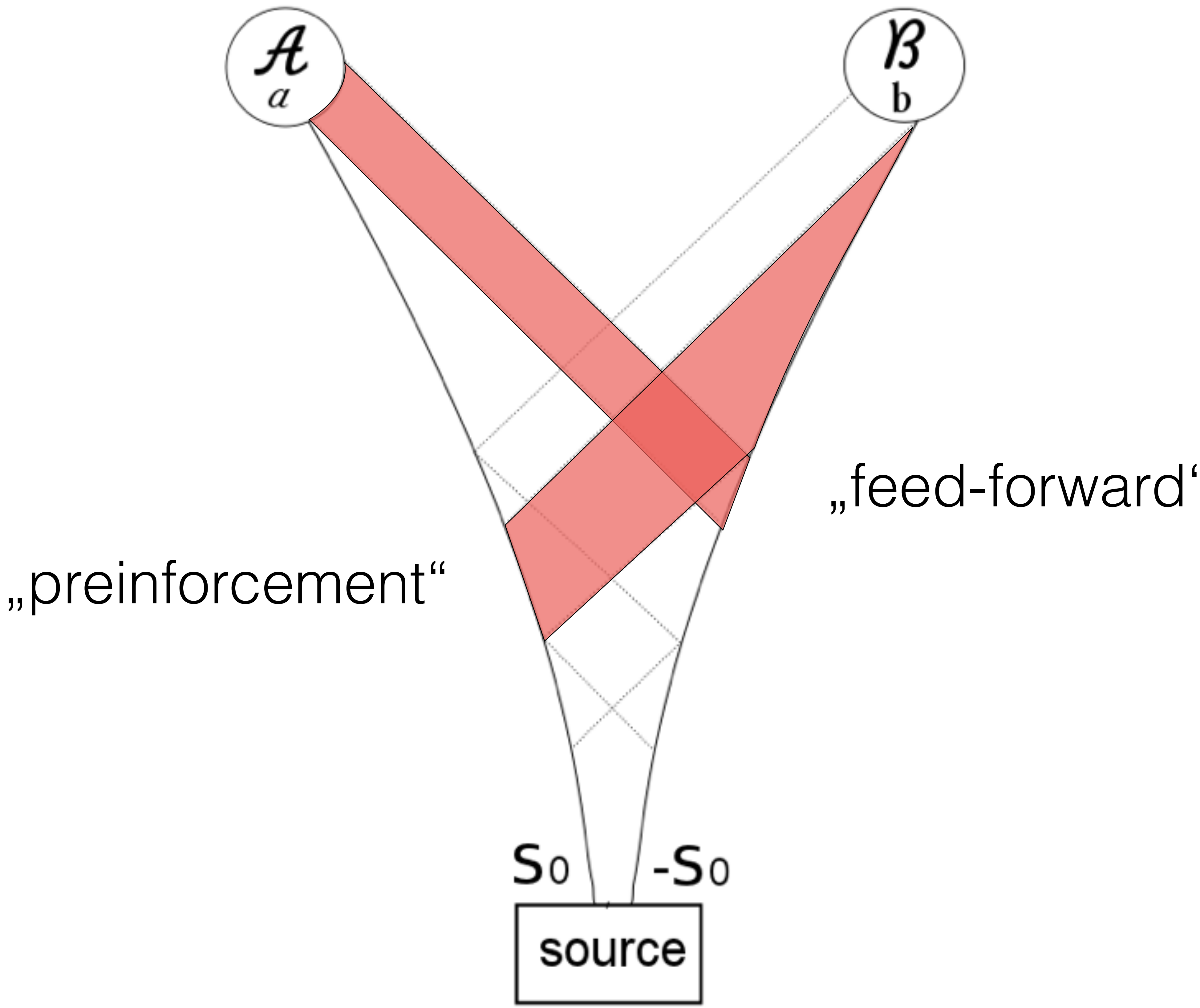
𝒜
a
ℬ
b
„feed-forward“
S0
-S0
source



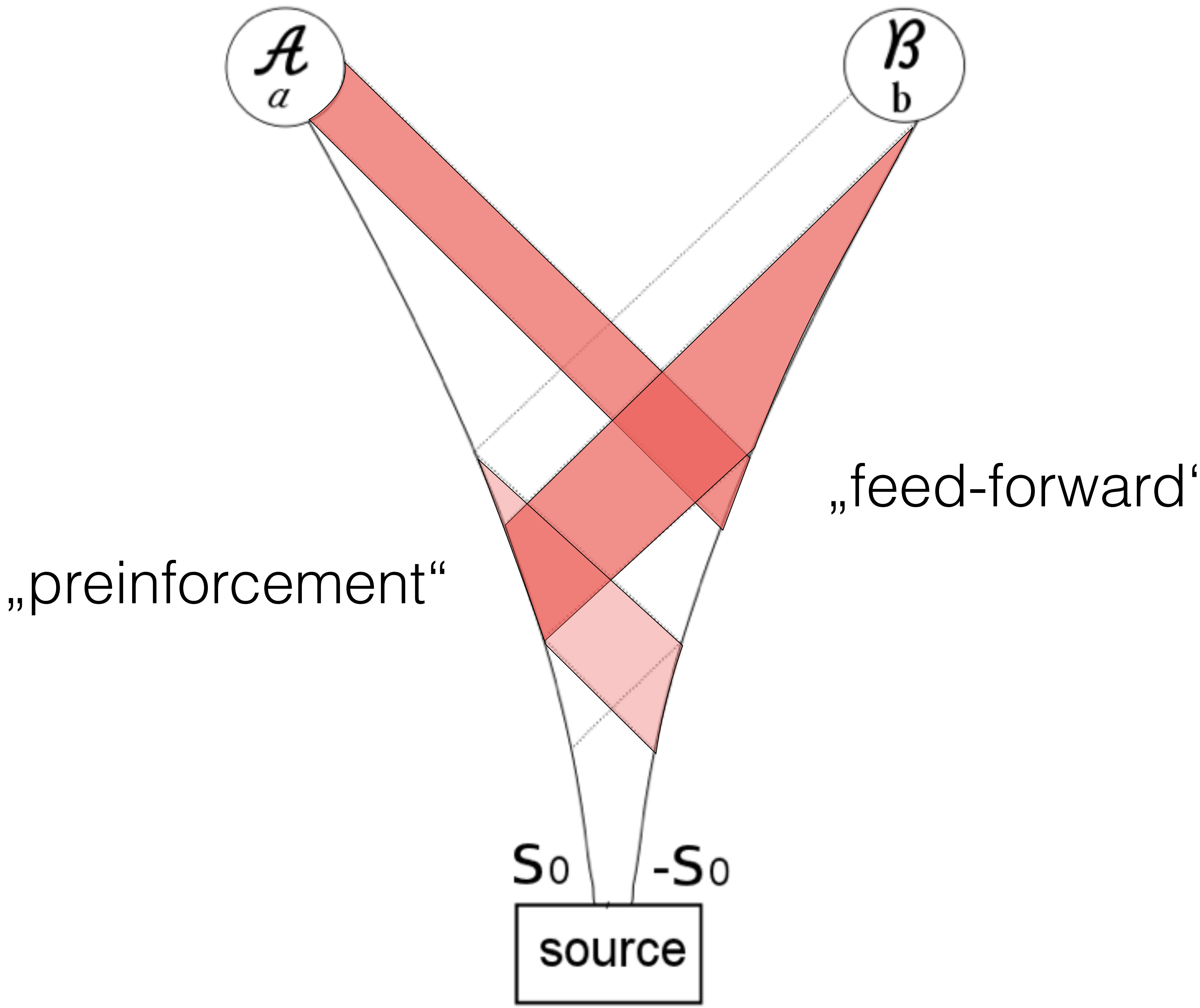
A
a
B
b
„feed-forward“
S0
-S0
source



„feed-forward“



𝒜
a
ℬ
b
„feed-forward“
„preinforcement“
S0
-S0
source



𝒜
a
ℬ
b
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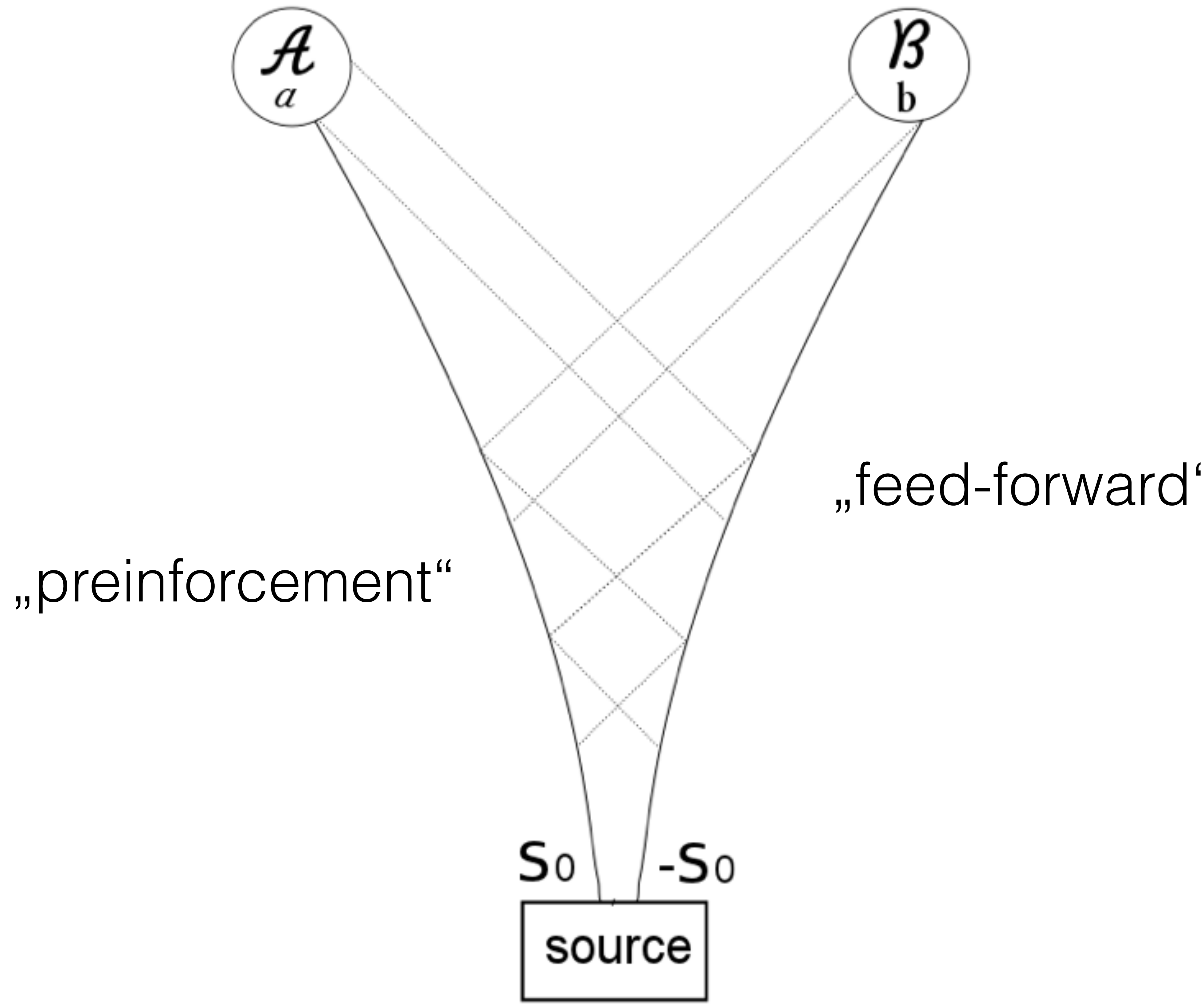
S0
-S0
source



A
a
B
b
„feed-forward“
„preinforcement“
s_0
$-s_0$
source

Final state

$$\mathbf{S}_A = \frac{\alpha\,\mathbf{S}_0 - \beta B\,\mathbf{b} + \gamma A\mathbf{a}}{\|\alpha\,\mathbf{S}_0 - \beta B\,\mathbf{b} + \gamma\,A\mathbf{a}\|}$$

Final state

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$$\mathbf{S}_B = \frac{-\alpha\,\mathbf{S}_0 - \beta A\,\mathbf{a} + \gamma B\mathbf{b}}{\|-\alpha\,\mathbf{S}_0 - \beta A\,\mathbf{a} + \gamma B\mathbf{b}\|}$$

Final state

$$\mathbf{S}_A = \frac{\alpha\,\mathbf{S}_0 - \beta B\,\mathbf{b} + \gamma A\mathbf{a}}{\|\alpha\,\mathbf{S}_0 - \beta B\,\mathbf{b} + \gamma\,A\mathbf{a}\|}$$

$$\mathbf{S}_B = \frac{-\alpha\,\mathbf{S}_0 - \beta A\,\mathbf{a} + \gamma B\mathbf{b}}{\|-\alpha\,\mathbf{S}_0 - \beta A\,\mathbf{a} + \gamma B\mathbf{b}\|}$$

Measurement outcomes

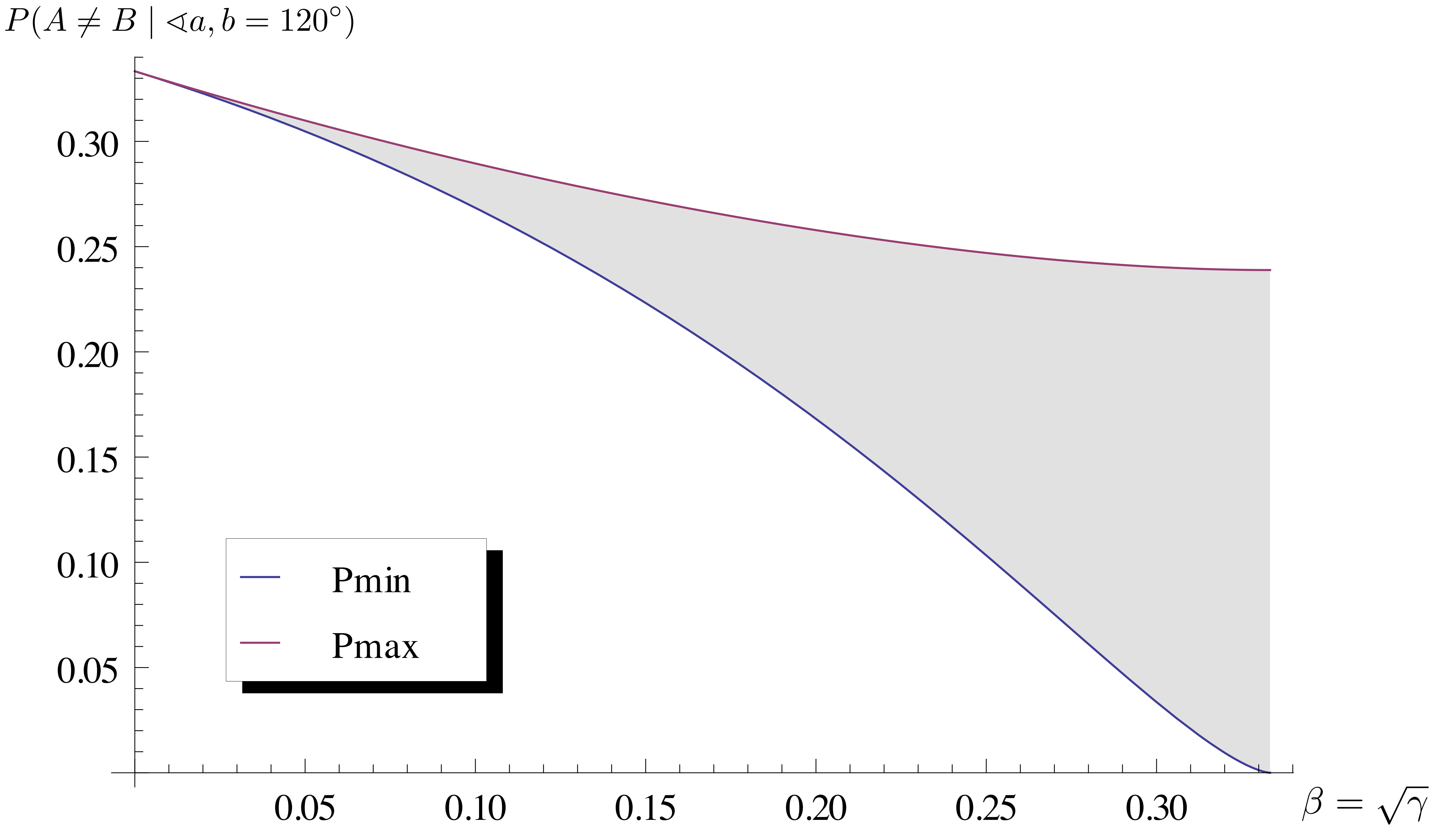
$$\begin{aligned} A &= \operatorname{sgn}\langle\mathbf{a},\mathbf{S}_A\rangle = \operatorname{sgn}\big\{\quad\alpha\,\langle\mathbf{a},\mathbf{S}_0\rangle - B\,\beta\,\langle\mathbf{a},\mathbf{b}\rangle + A\,\gamma\,\big\} \\ B &= \operatorname{sgn}\langle\mathbf{b},\mathbf{S}_B\rangle = \operatorname{sgn}\big\{-\alpha\,\langle\mathbf{b},\mathbf{S}_0\rangle - A\,\beta\,\langle\mathbf{a},\mathbf{b}\rangle + B\gamma\,\big\}. \end{aligned}$$

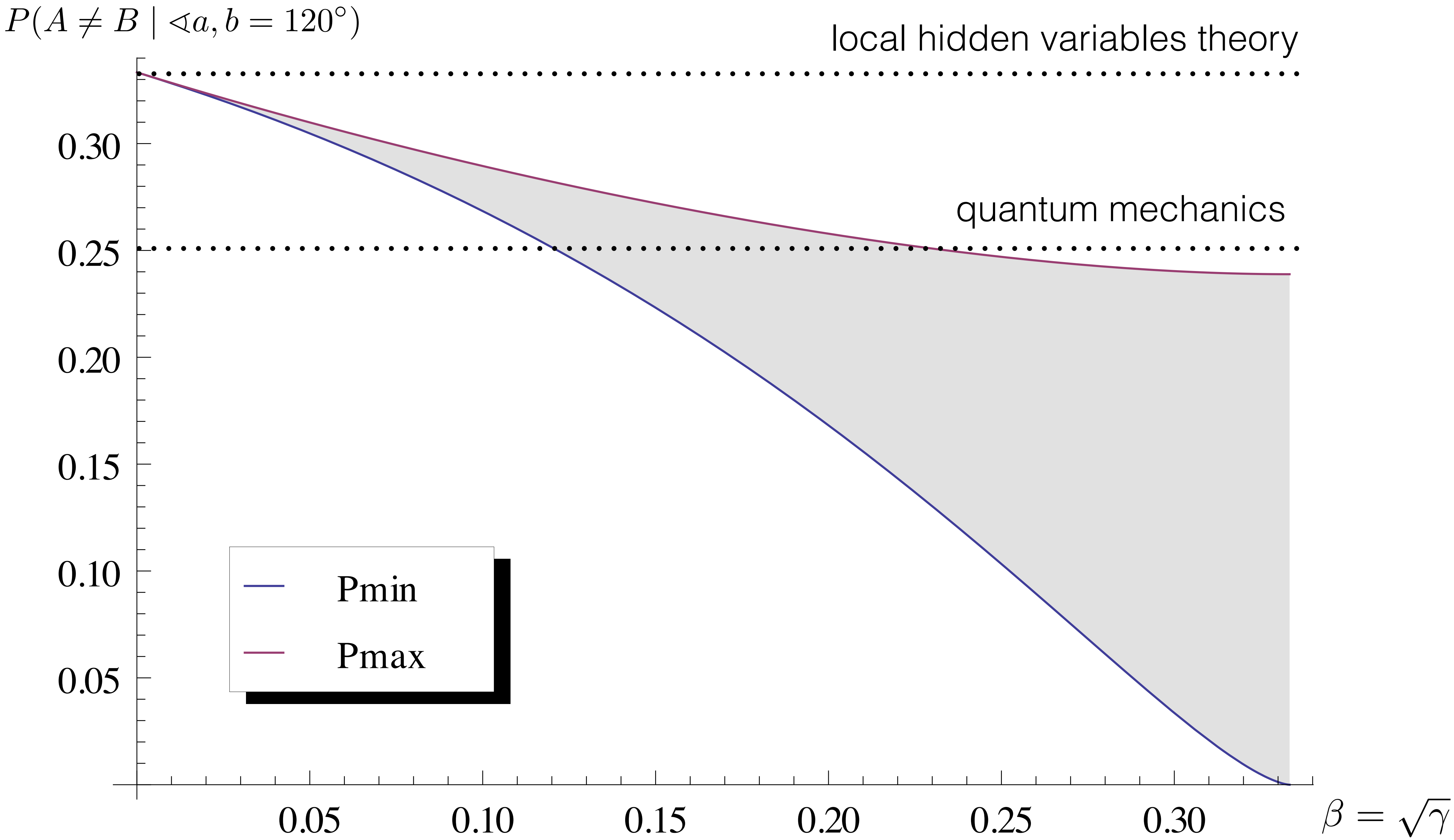
Problem: No Cauchy data!

„Self Fulfilling Prophecies“

Idea: Determine upper and lower bounds

for the probability of $A \neq B$

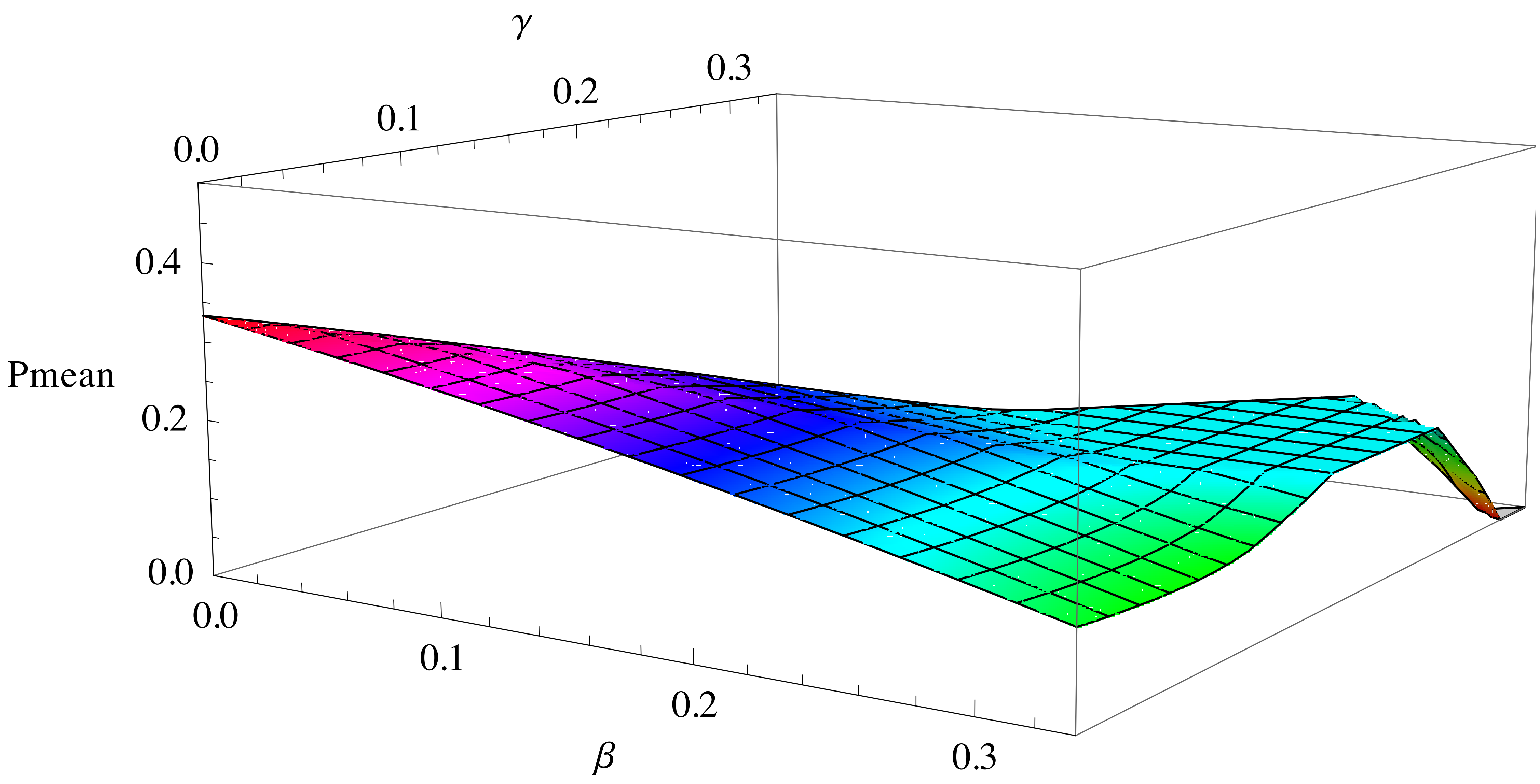

$P(A \neq B \mid \sphericalangle a, b = 120^\circ)$
0.30
0.25
0.20
0.15
0.10
0.05
Pmin
Pmax
0.05
0.10
0.15
0.20
0.25
0.30
$\beta = \sqrt{\gamma}$



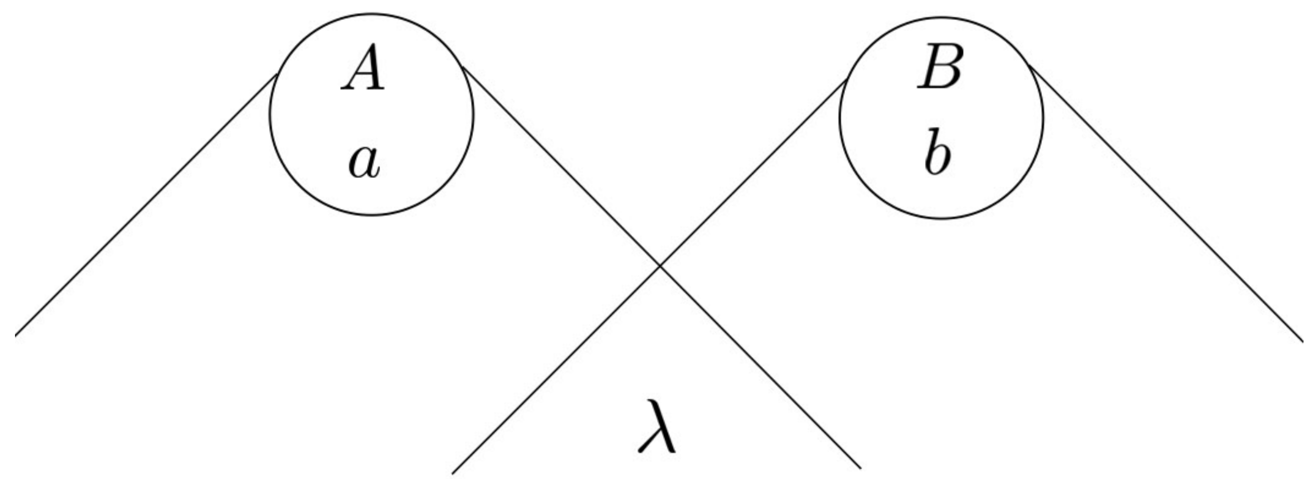
$P(A \neq B \mid \sphericalangle a, b = 120°)$
local hidden variables theory
quantum mechanics
0.30
0.25
0.20
0.15
0.10
0.05
Pmin
Pmax
0.05
0.10
0.15
0.20
0.25
0.30
$\beta = \sqrt{\gamma}$

$$\mathbb{P}(A \neq B|a,b) + \mathbb{P}(A \neq B|b,c) + \mathbb{P}(A \neq B|a,c) < 1$$

$\Rightarrow$ Bell’s inequality violated!


γ
0.0
0.1
0.2
0.3
0.4
0.2
0.0
Pmean
0.0
0.1
0.2
0.3
β

Derivation of the Bell / CHSH inequality



Locality:

$$\mathbb{P}(A|B,a,b,\lambda) = \mathbb{P}(A|a,\lambda),$$
$$\mathbb{P}(B|A,a,b,\lambda) = \mathbb{P}(B|b,\lambda).$$

No Conspiracy

$$\mathbb{P}(\lambda|a,b) = \mathbb{P}(\lambda).$$

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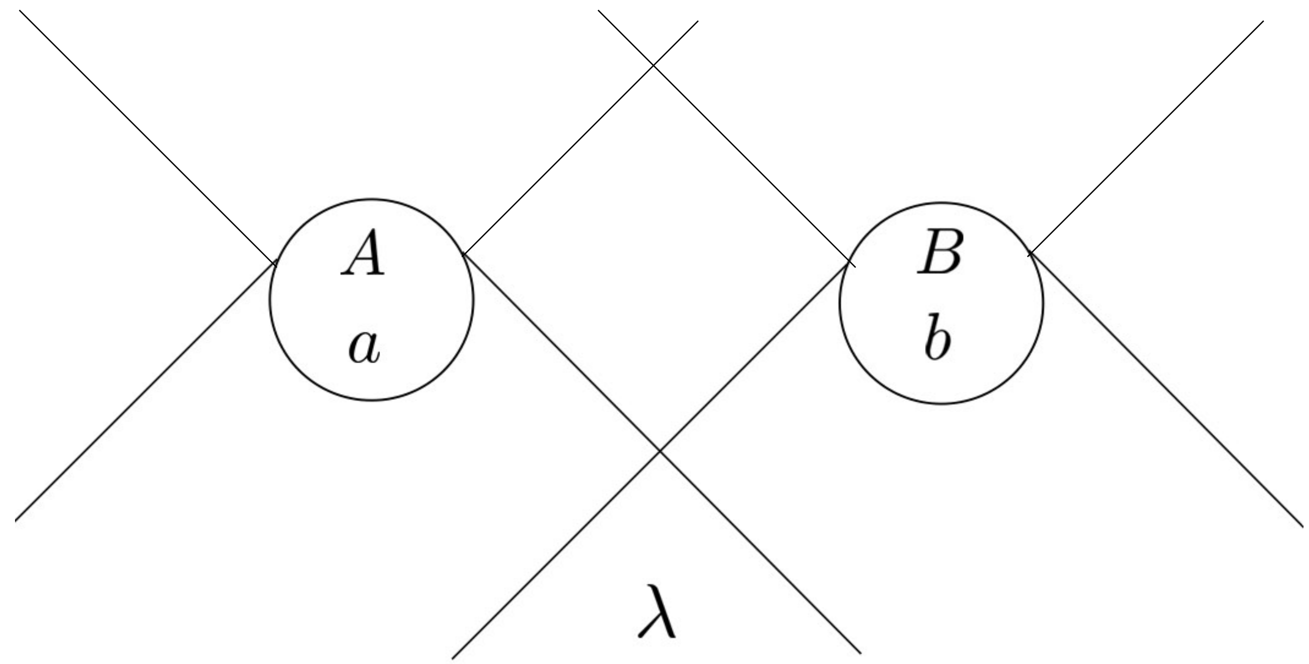

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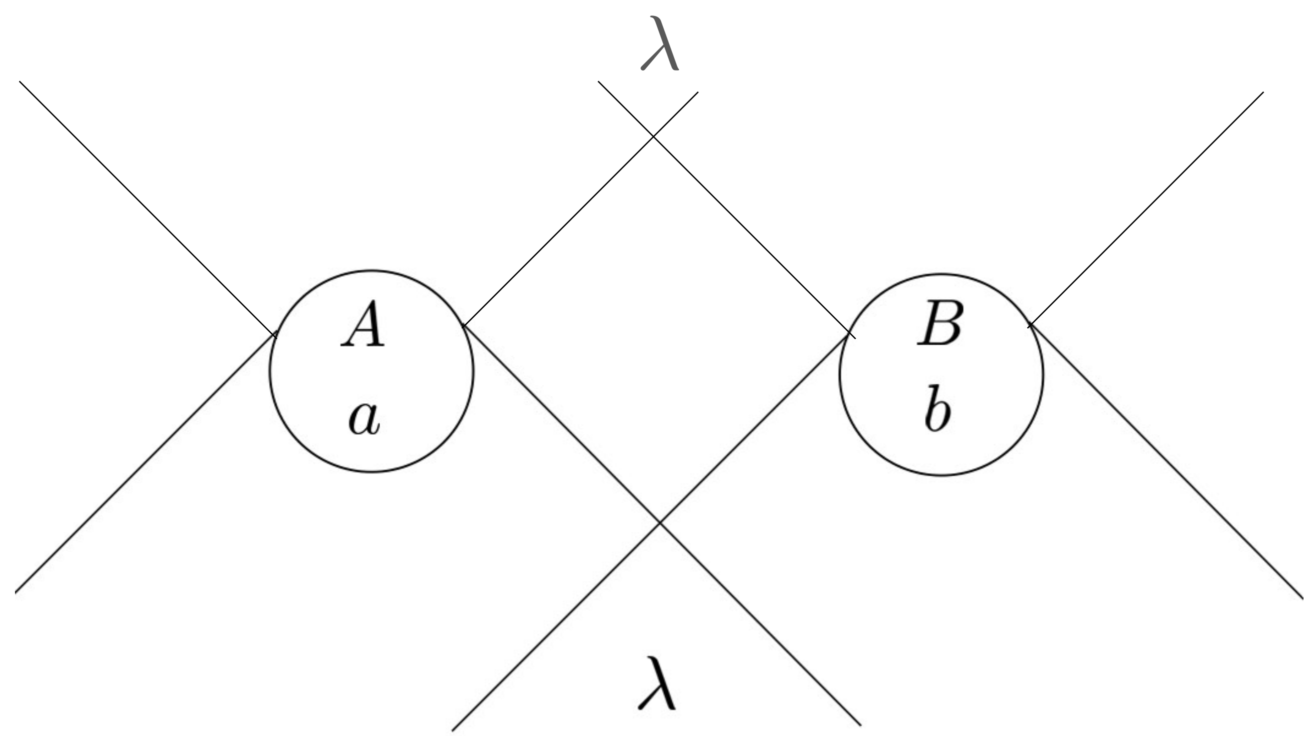

Locality:

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Bell non-local

No direct space-like influences

No conspiracy

Violations of the Bell inequalities could be understood as the signature of advanced effects rather than instantaneous influences.

This understanding of quantum non-locality could be more compatible with our current understanding of relativistic space-time.

References (not complete)

Non-locality vs Relativity

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Cramer 1980 Reznik and Aharonov 1995 Sutherland 2008

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