IQOQI – INSTITUTE FOR QUANTUM OPTICS AND QUANTUM INFORMATION VIENNA

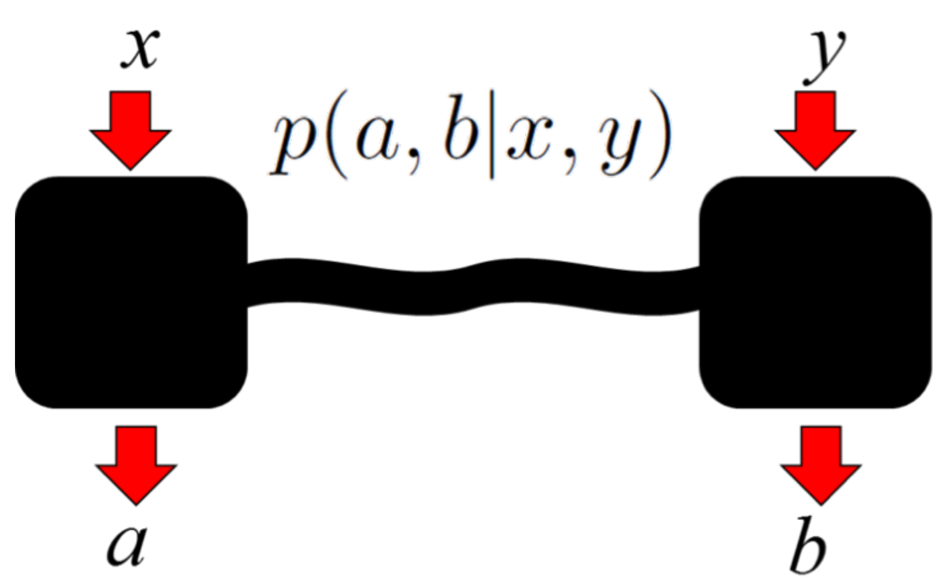
Black boxes in space and time:

semi-device-independent information processing via representation theory

Markus P. Müller

Institute for Quantum Optics and Quantum Information (IQOQI), Vienna

Perimeter Institute for Theoretical Physics (PI), Waterloo, Canada



AUSTRIAN ACADEMY OF SCIENCES

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Work in progress!

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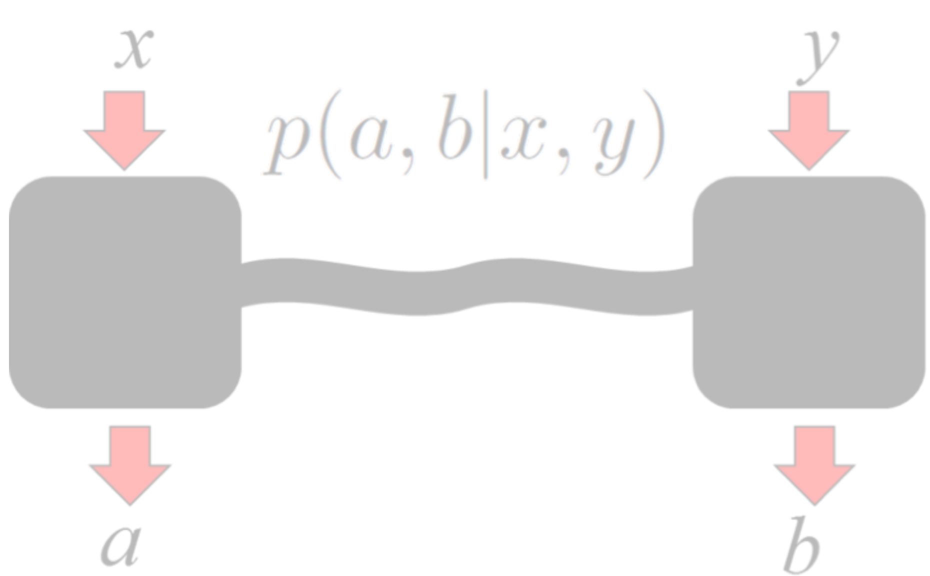
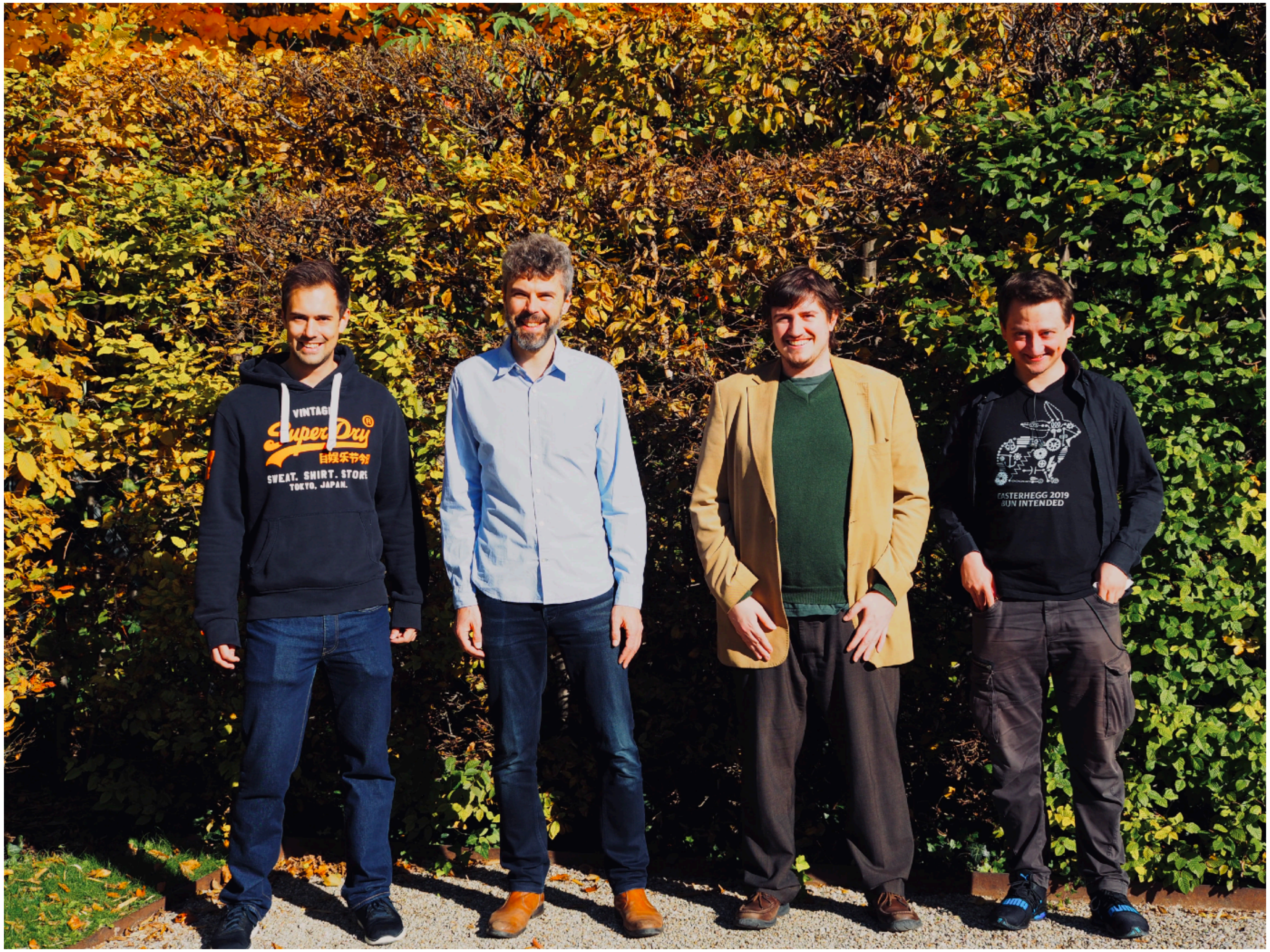


PERIMETER INSTITUTE

Our group at IQOQI



left to right:

Stefan Ludescher (PhD student), **Markus Müller** (group leader), **Andy Garner** (postdoc), **Marius Krumm** (PhD student).

coming soon:

Caroline Jones
(PhD student)

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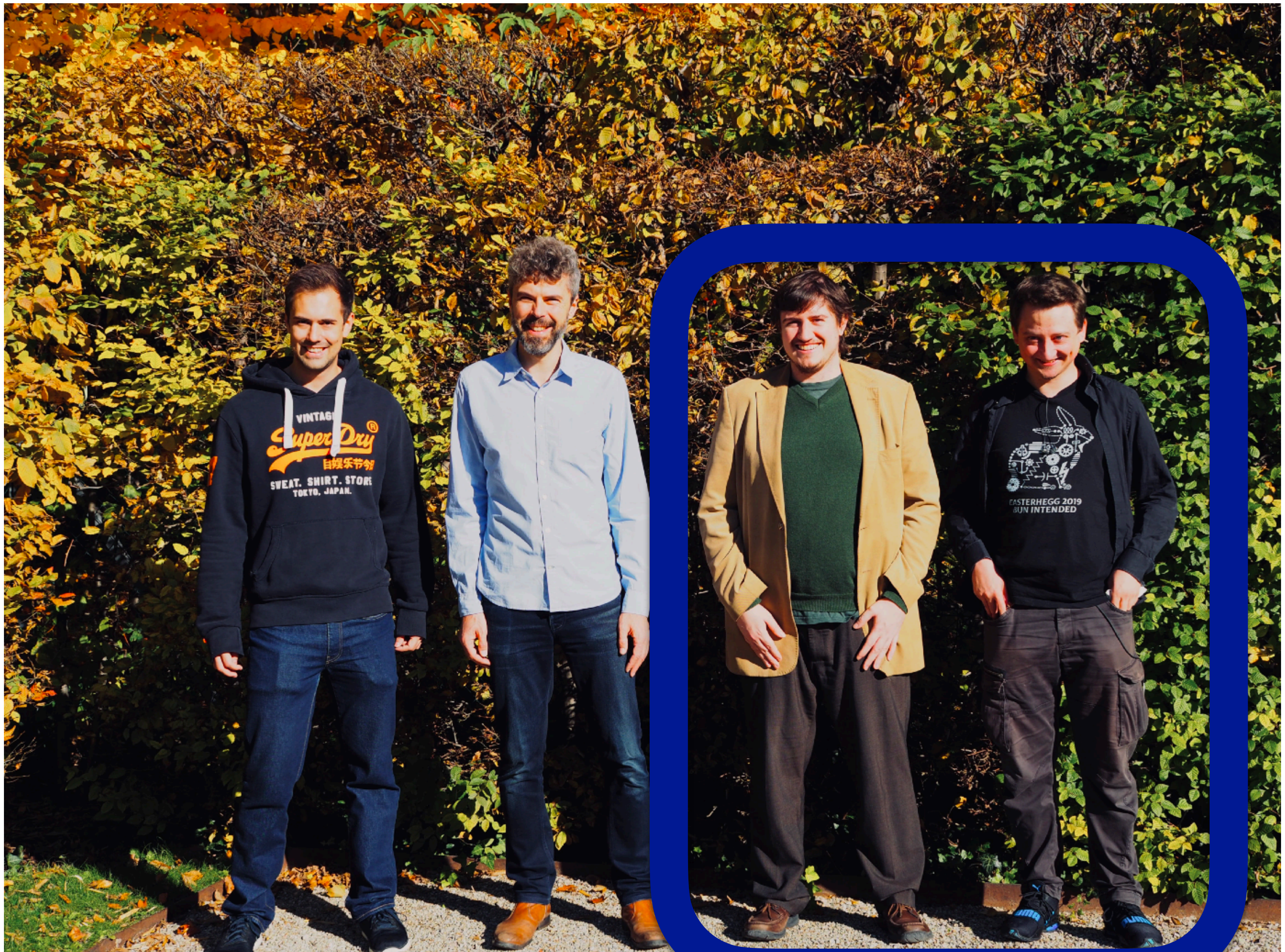

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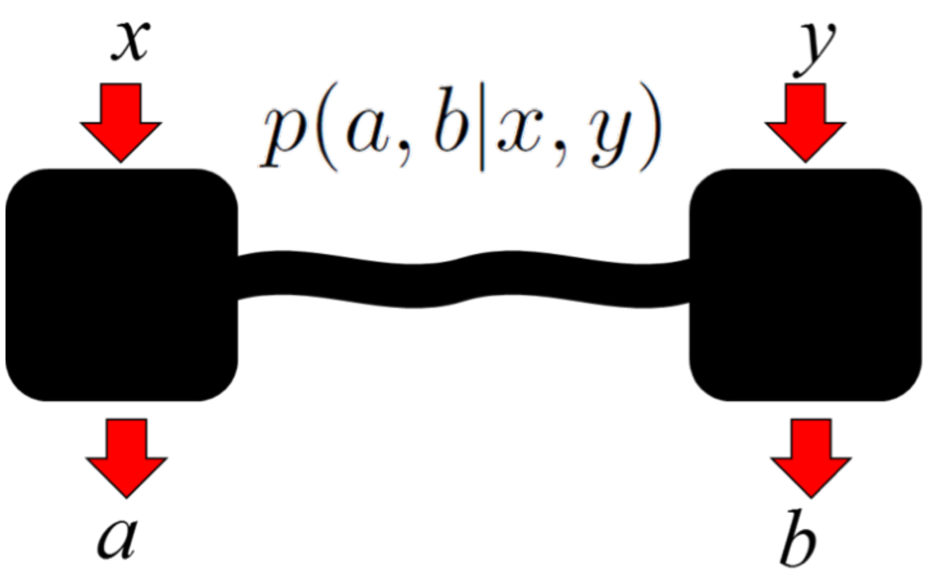
Overview

1. General framework of “spacetime boxes”

2. Foundational insights



3. Towards novel protocols…

4. … and experimental tests of QT

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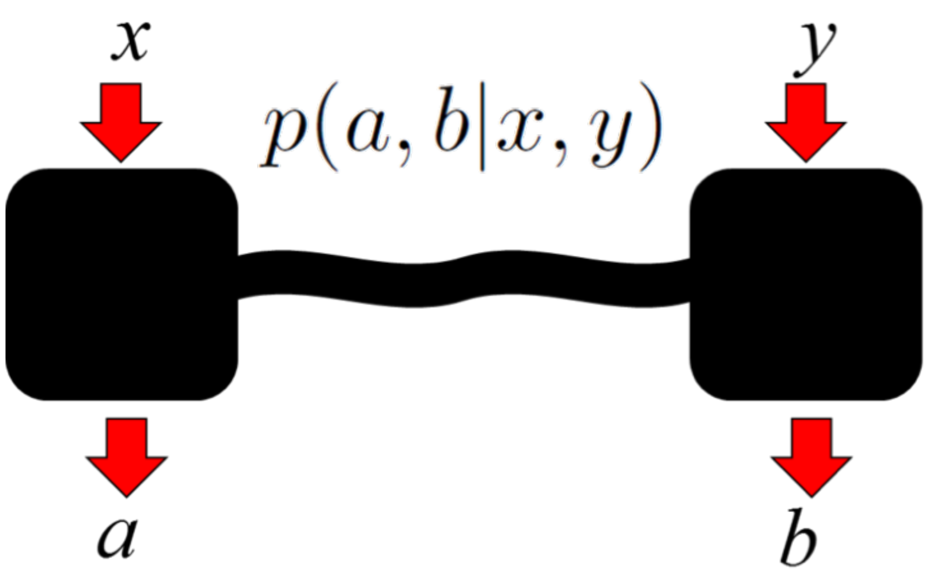

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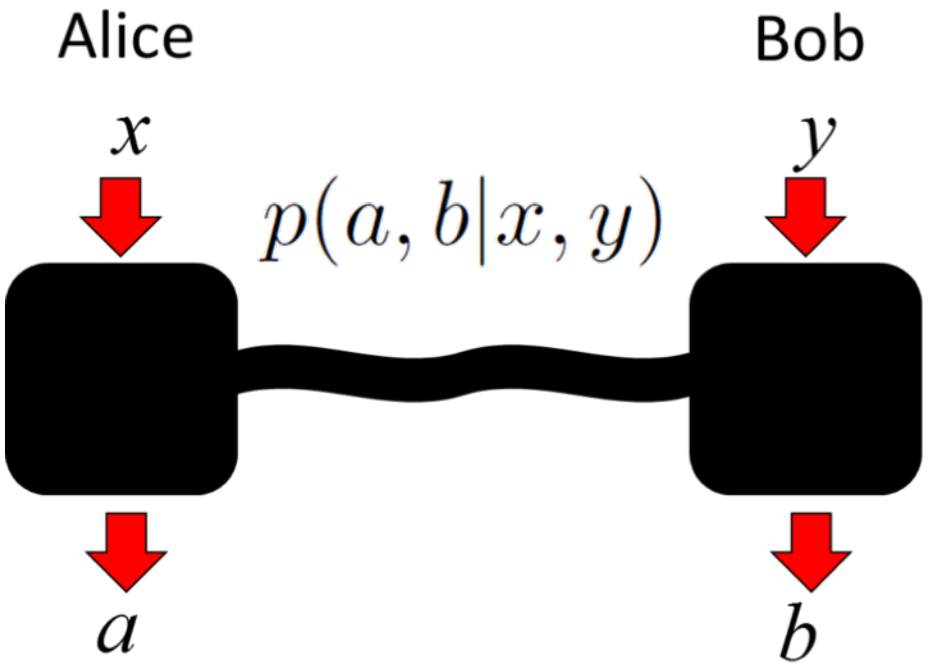
Black boxes and correlations

Black boxes and correlations



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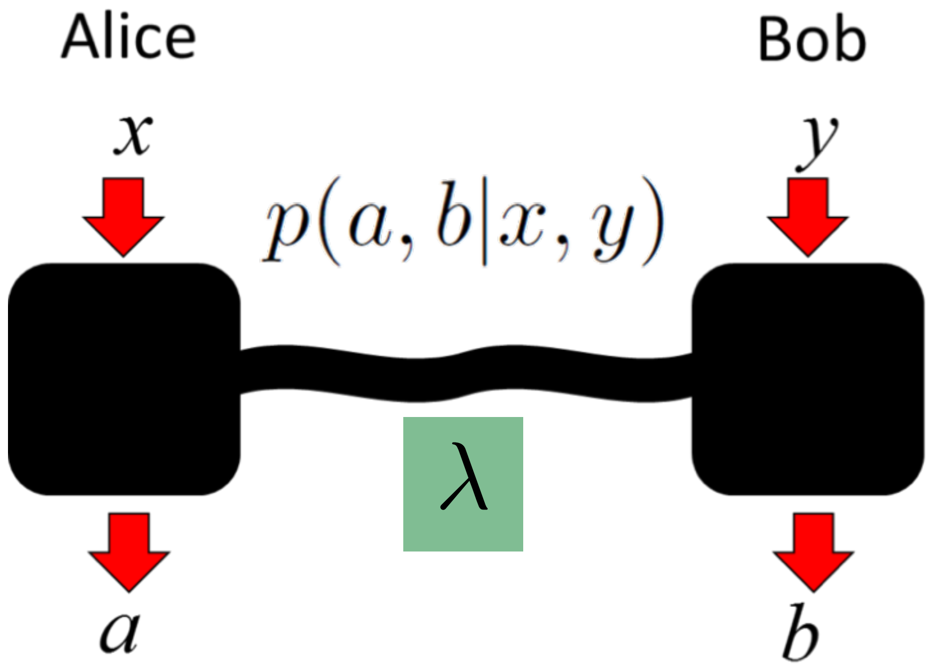

- In **classical** physics / prob. theory:

$$P(a, b|x, y) = \sum_{\lambda \in \Lambda} P_A(a|x, \lambda) P_B(b|y, \lambda) P_\Lambda(\lambda)$$

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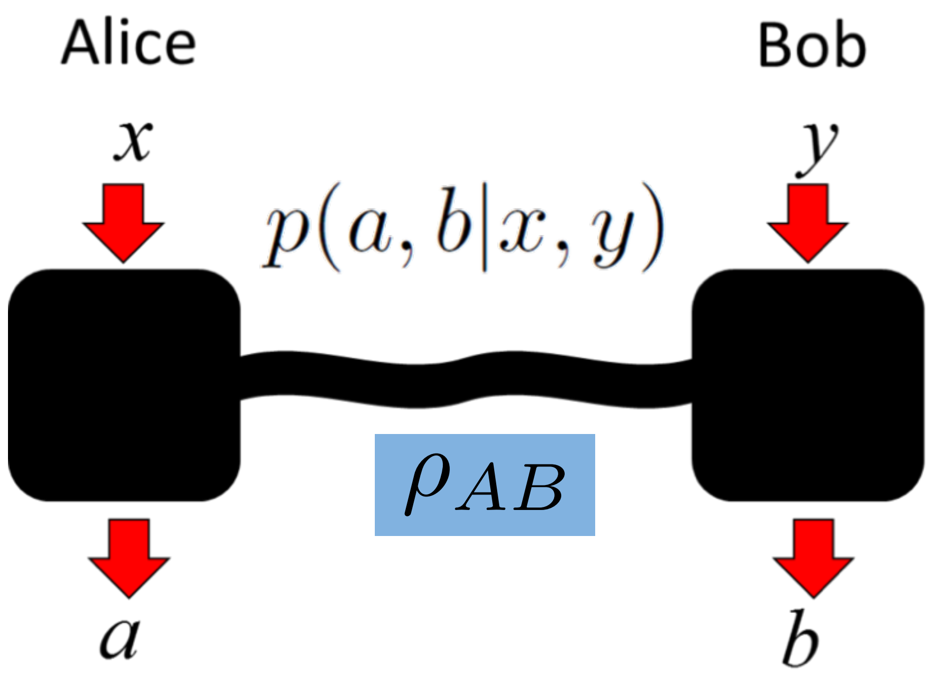

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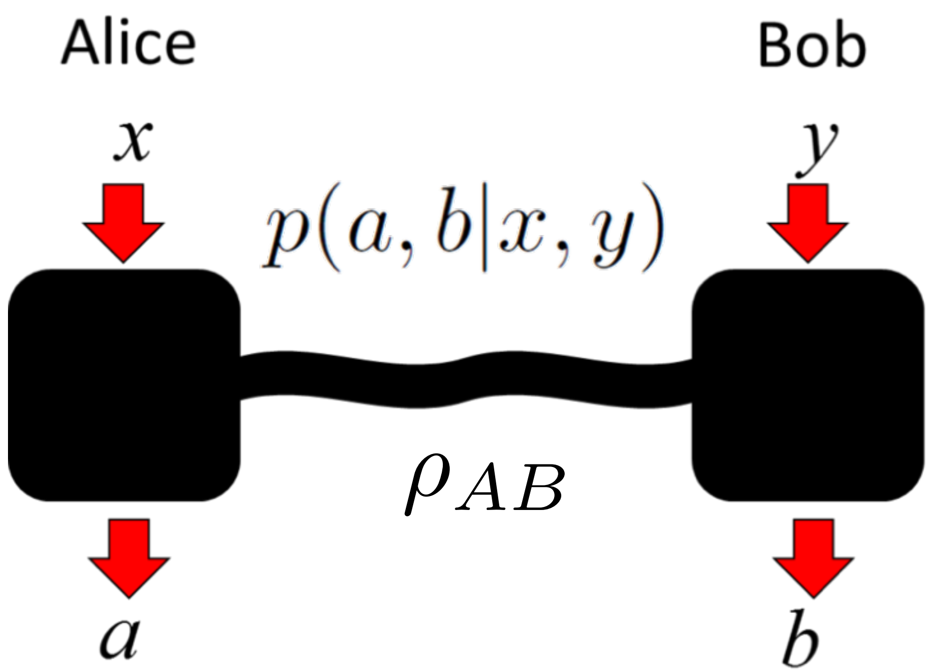

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$P(a|x,y)$ is independent of y,

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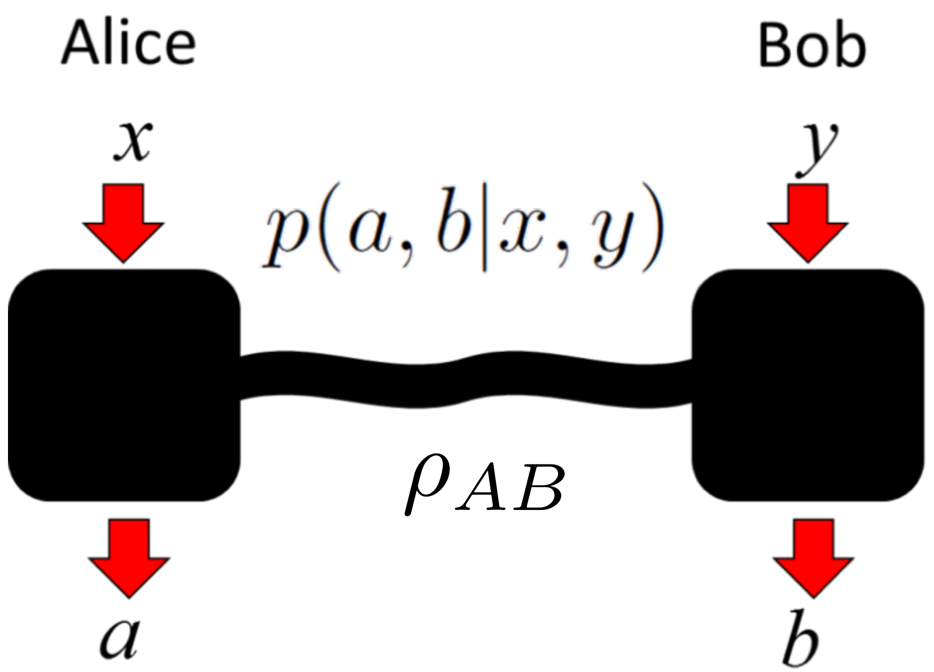

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Quantum admits more general *P*'s due to the **violation of Bell inequalities**.

The Bell-CHSH inequality

Classical probability distributions satisfy Bell inequality:

$$\mathrm{CHSH} := |C_{00} + C_{01} + C_{10} - C_{11}| \leq 2 \quad \text{where} \quad C_{ab} := \mathbb{E}\left(x \cdot y | a, b\right).$$

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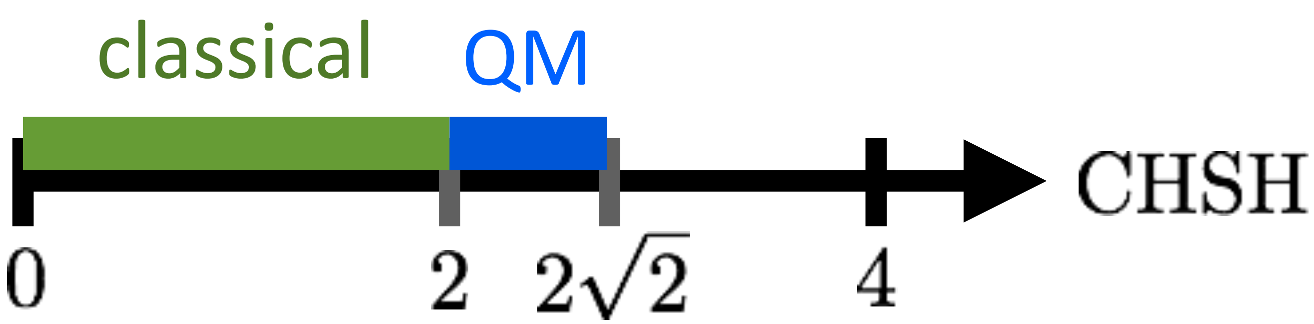

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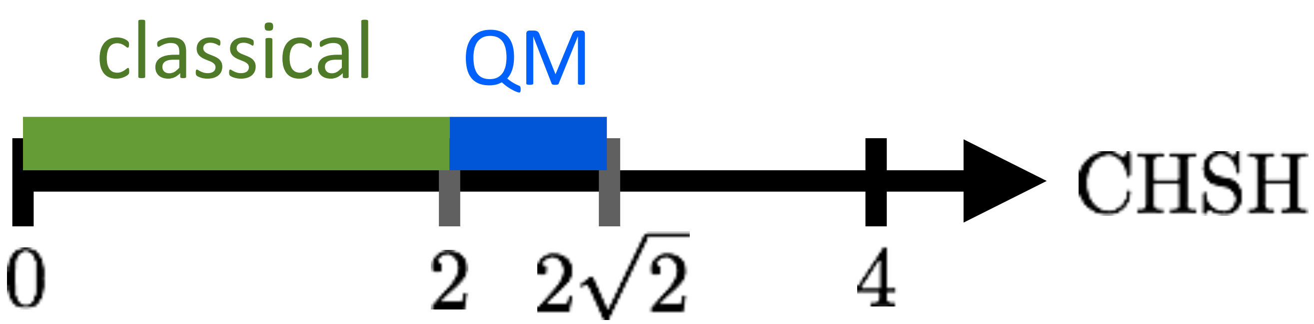

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Are **quantum** correlations the **most general** $P(a, b|x, y)$ that satisfy the no-signalling principle?

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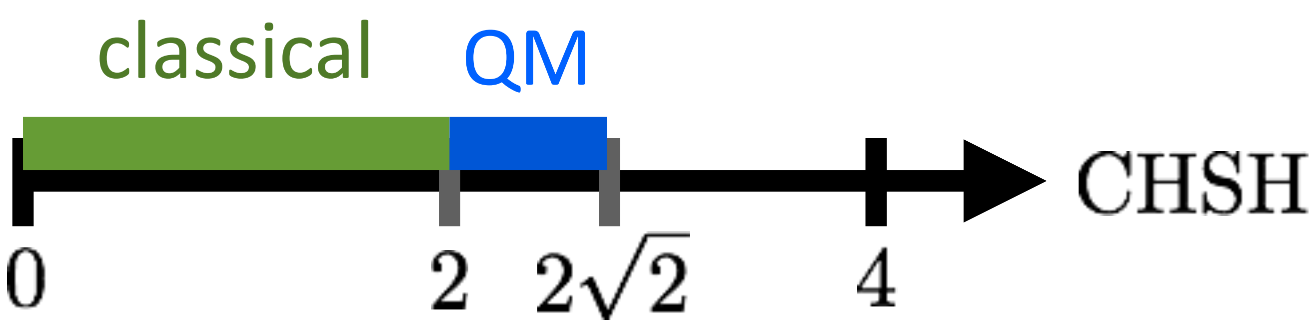

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No! Counterexample: the PR-box correlations

$$\begin{aligned} p(+1,+1|a,b) &= p(-1,-1|a,b) = \frac{1}{2} \\ &\quad \text{if } (a,b) \in \{(0,0),(0,1),(1,0)\} \\ p(+1,-1|1,1) &= p(-1,+1|1,1) = \frac{1}{2} \end{aligned}$$

CHSH=4

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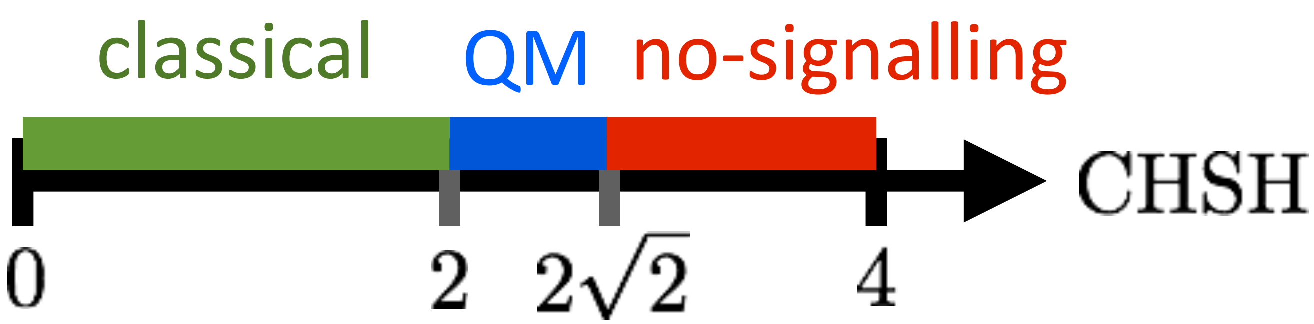

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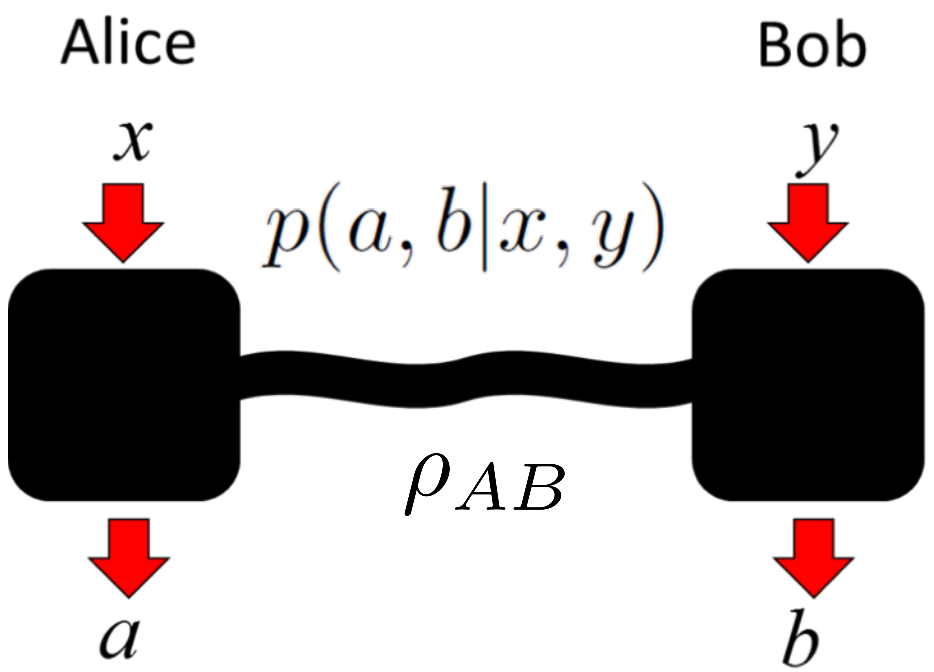
Black boxes and correlations



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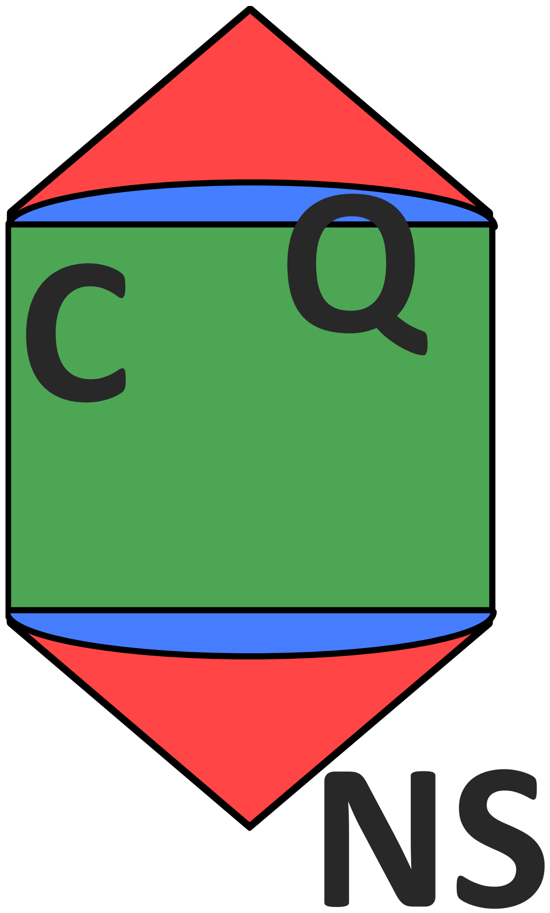

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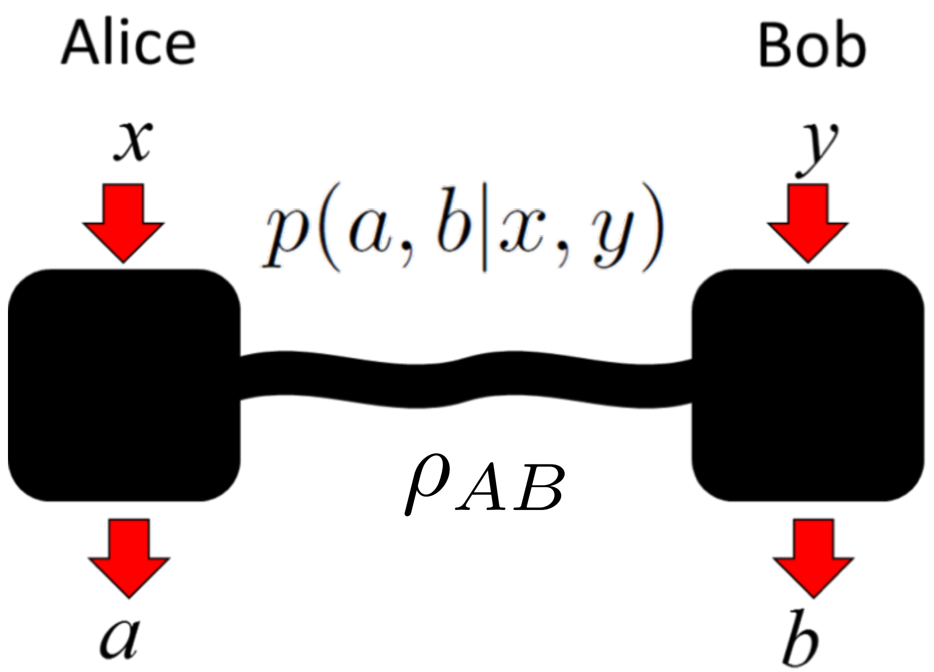

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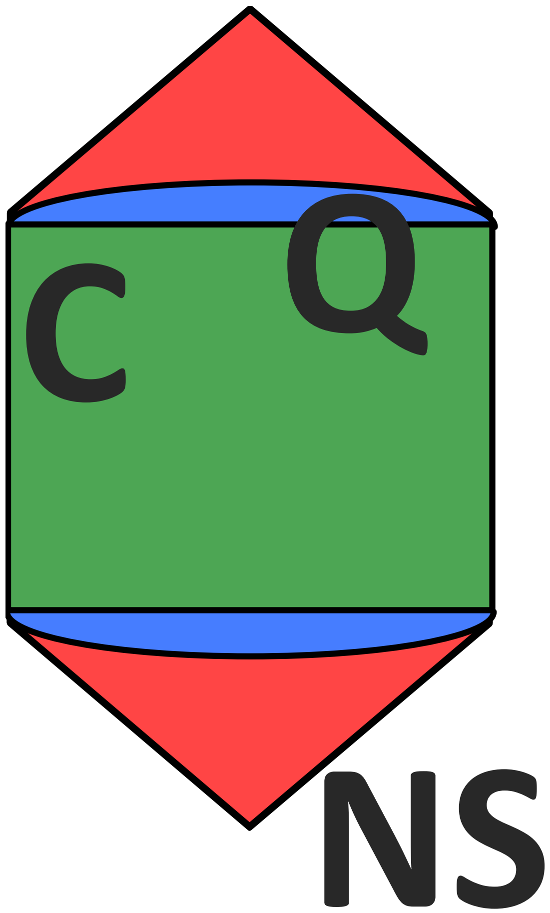
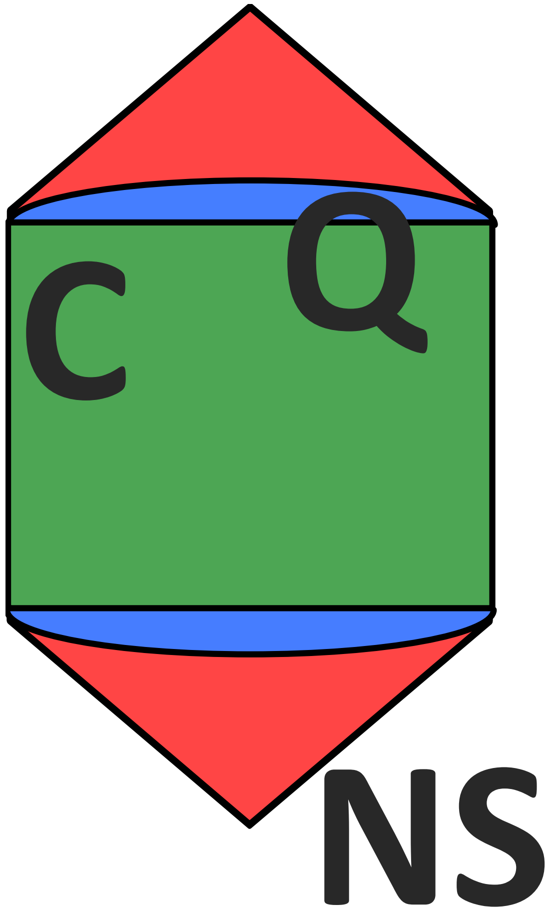


Correlations in **C** come from **classical prob. theory**, correlations in **Q** from **quantum theory**, correlations in **NS** describe **alternative physics.**

Black boxes and correlations

Why study such correlations?



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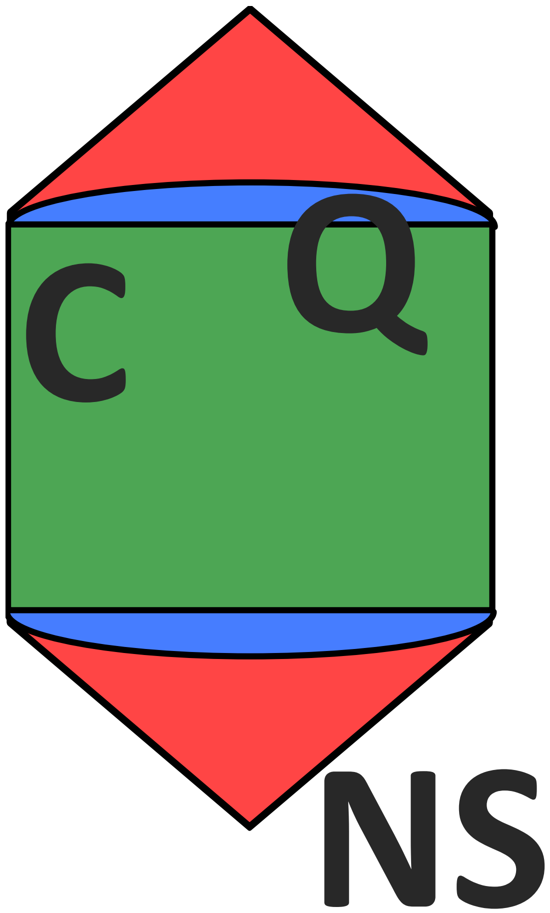

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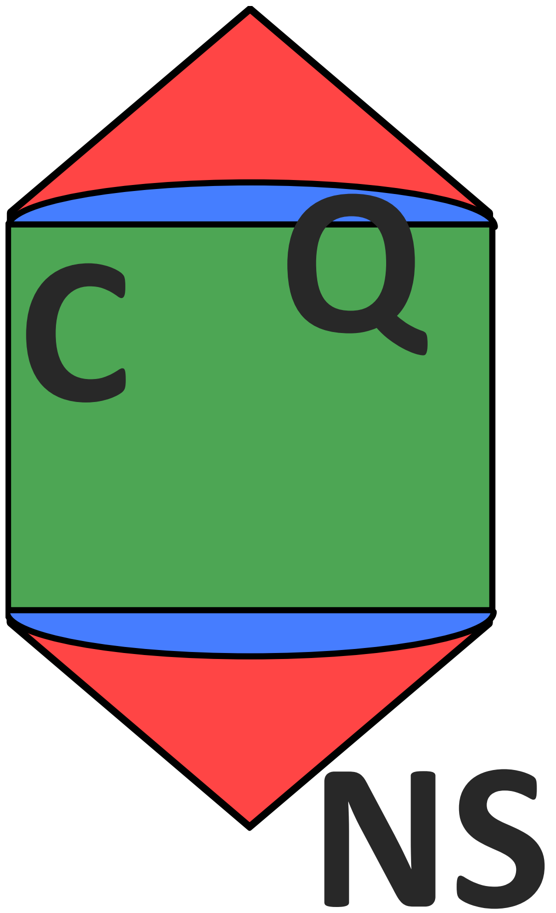

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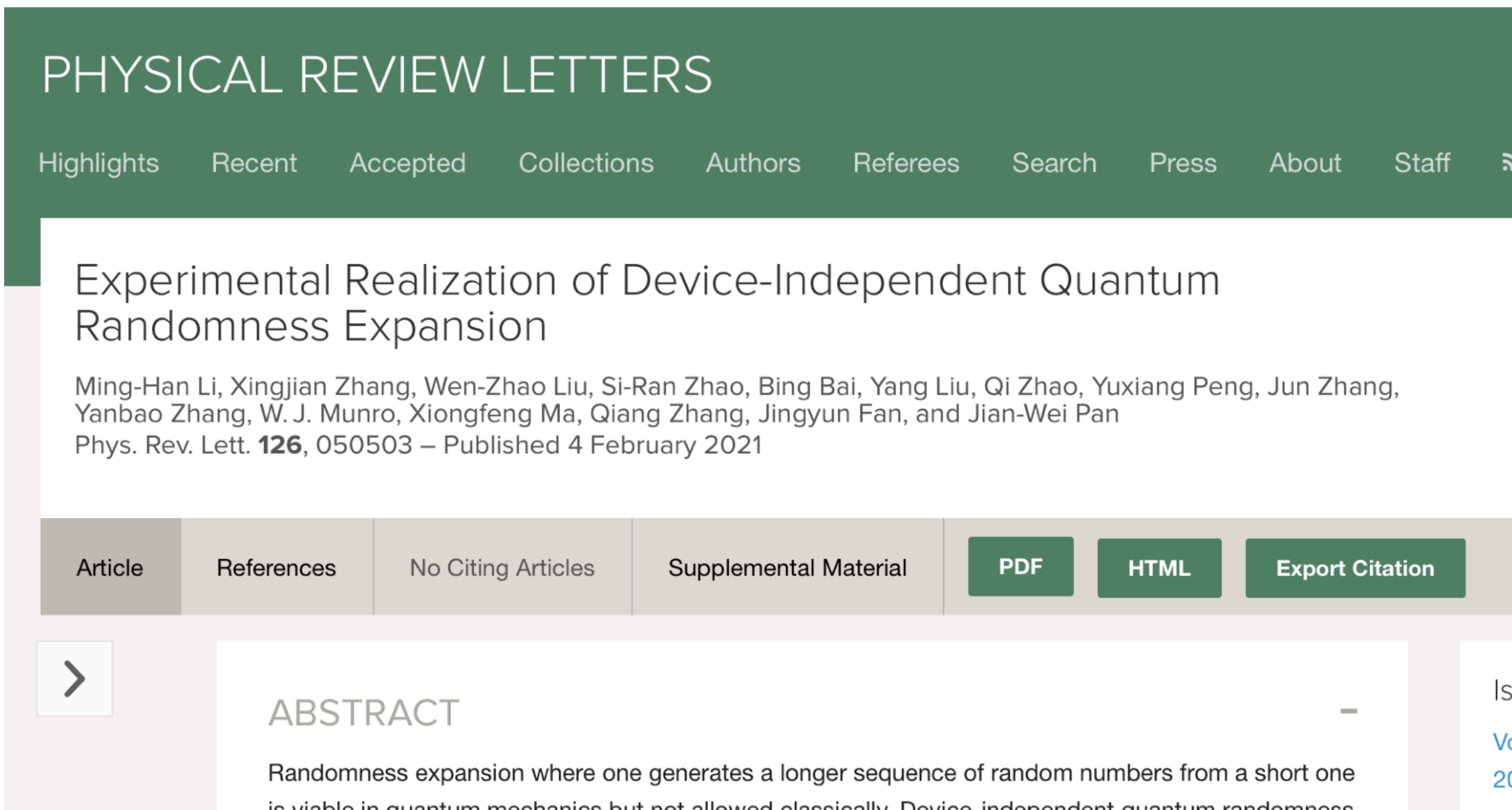
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Experimental Realization of Device-Independent Quantum Randomness Expansion

Ming-Han Li, Xingjian Zhang, Wen-Zhao Liu, Si-Ran Zhao, Bing Bai, Yang Liu, Qi Zhao, Yuxiang Peng, Jun Zhang, Yanbao Zhang, W. J. Munro, Xiongfeng Ma, Qiang Zhang, Jingyun Fan, and Jian-Wei Pan

Phys. Rev. Lett. **126**, 050503 – Published 4 February 2021

Article | References | No Citing Articles | Supplemental Material | PDF | HTML | Export Citation

ABSTRACT

Randomness expansion where one generates a longer sequence of random numbers from a short one

Black boxes and correlations

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- **Foundational:** "Why" does nature admit **Q** but not more? **Principles?**
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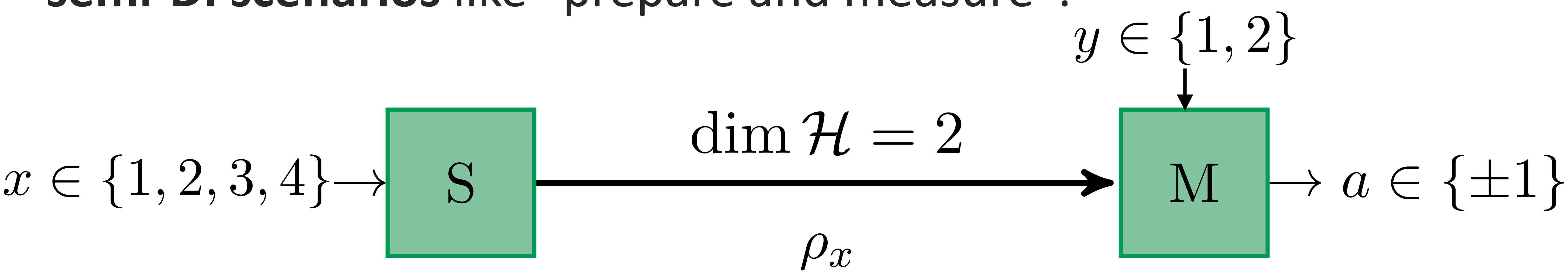
Other scenarios:

not just Bell scenarios, but for example
semi-DI scenarios like "prepare and measure":



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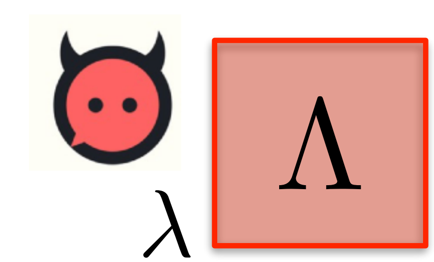

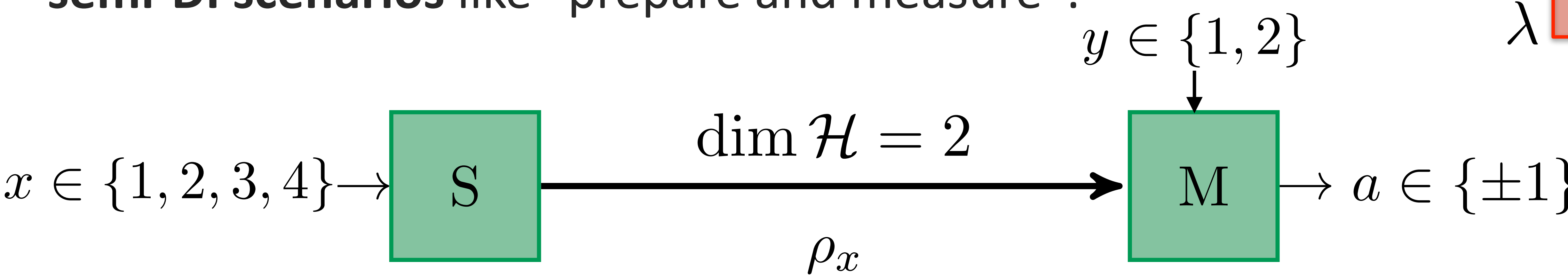

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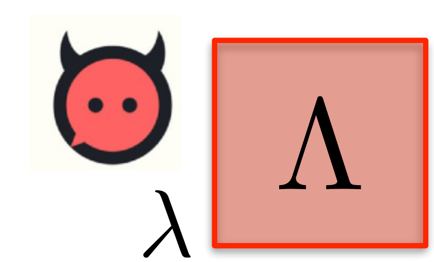
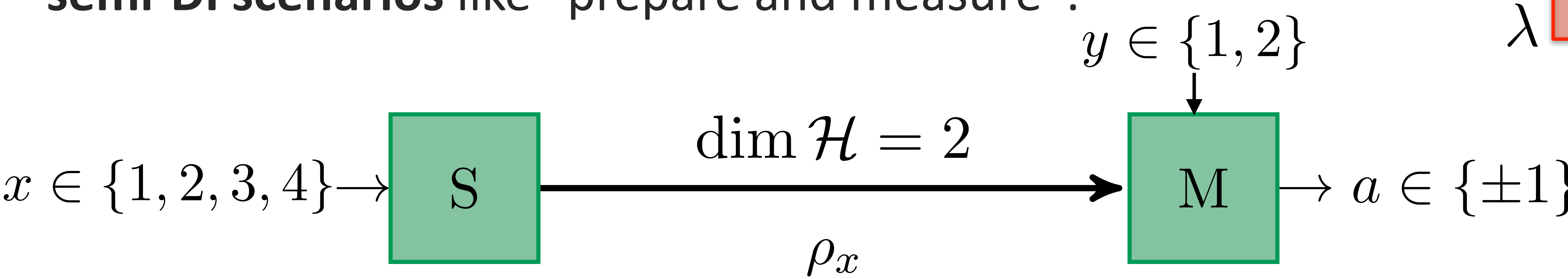
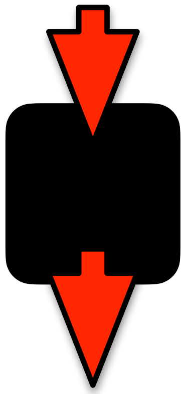




From the data table $p(a|x,y)$ and the assumption $\dim \mathcal{H} = 2$ **alone**, one can infer that $H(A|X,Y,\Lambda) \geq \ldots > 0$.

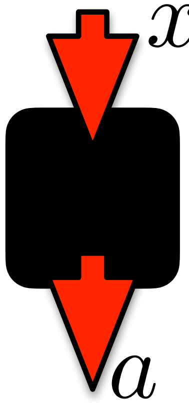
Single black boxes



$$P(a|x)$$

Single black boxes

$x \in \{0,1\}$



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Inputs and outputs are typically taken as **abstract labels** (bits etc.)

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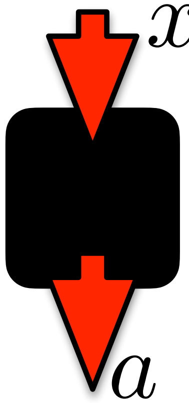

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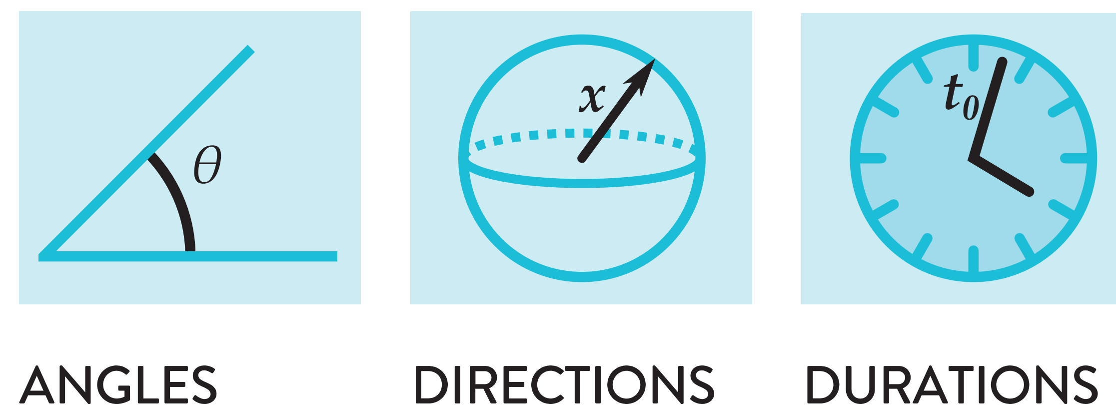

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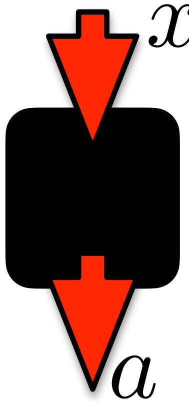

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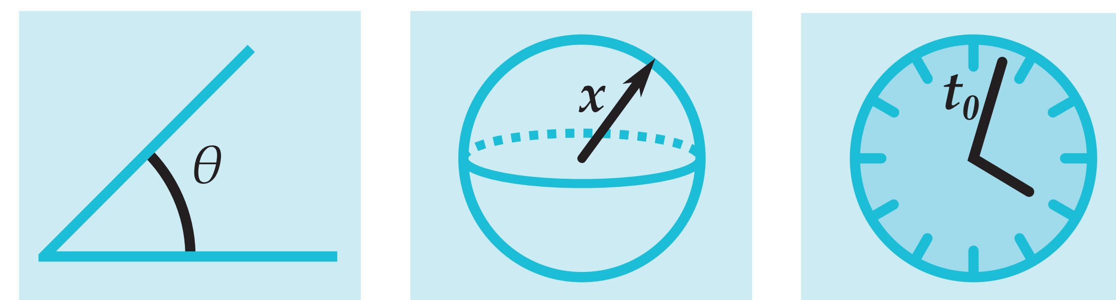

ANGLES DIRECTIONS DURATIONS

- This is the case in many **actual experimental settings**.

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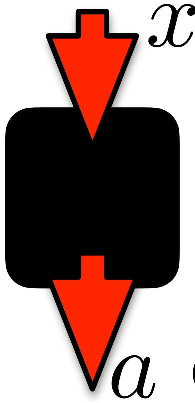

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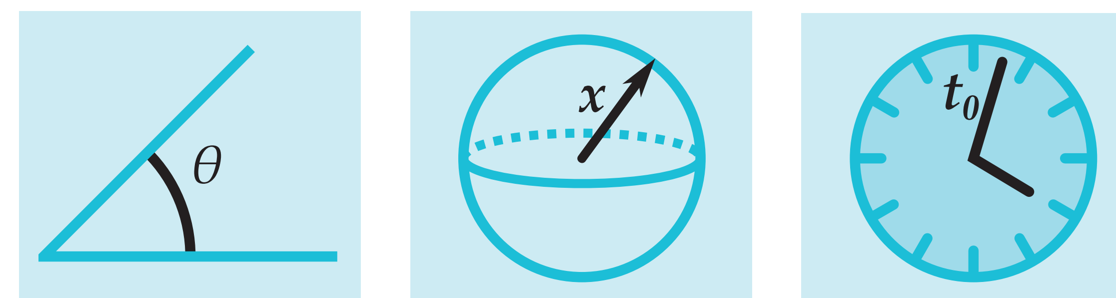

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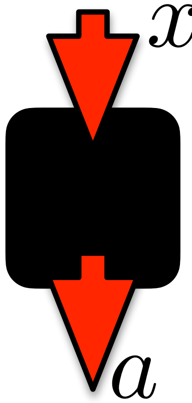

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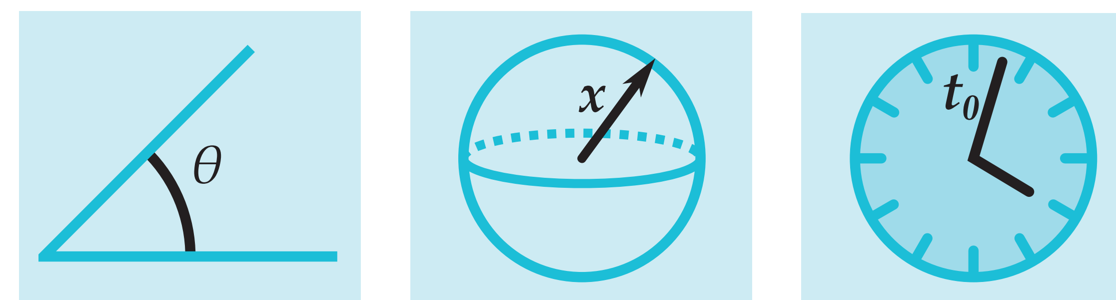

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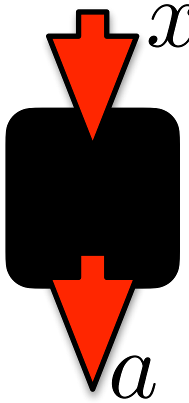

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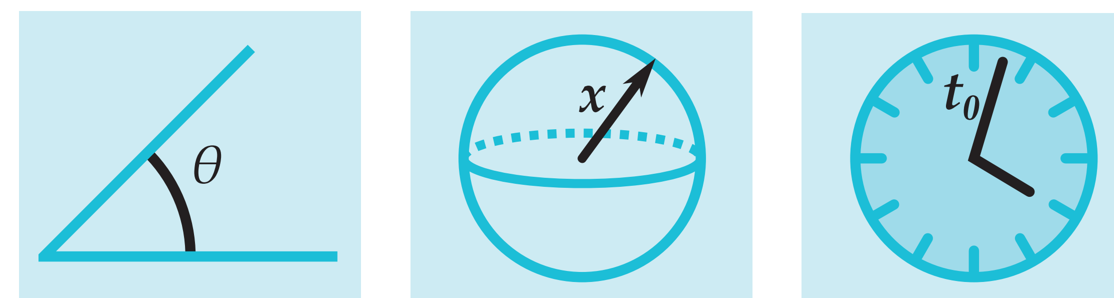

ANGLES DIRECTIONS DURATIONS

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- How could possible beyond-quantum physics fit into space and time?

Example: Stern-Gerlach experiment

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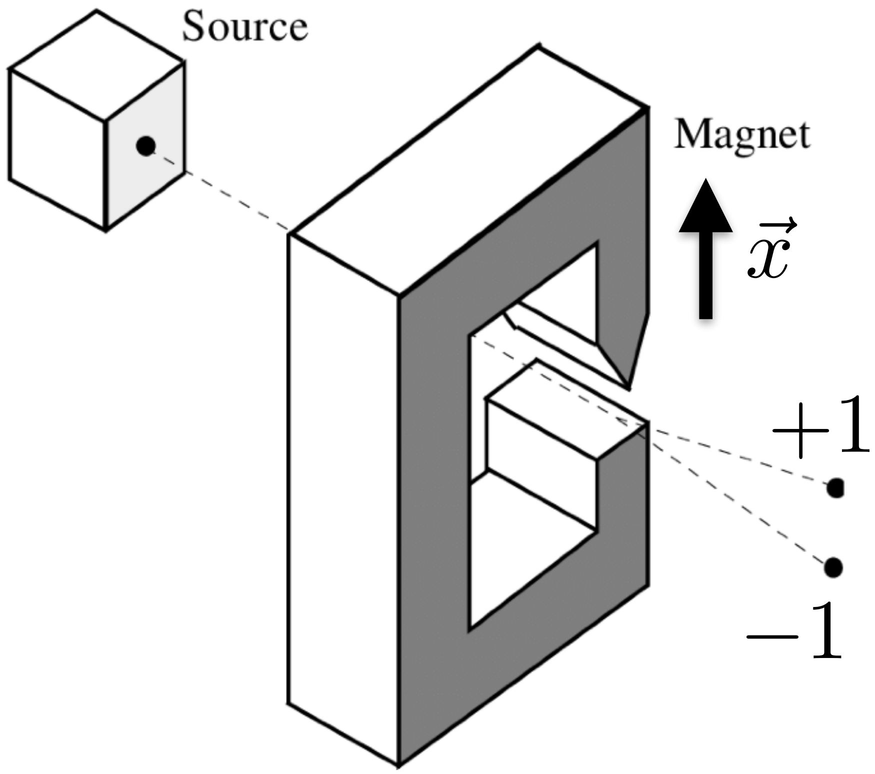

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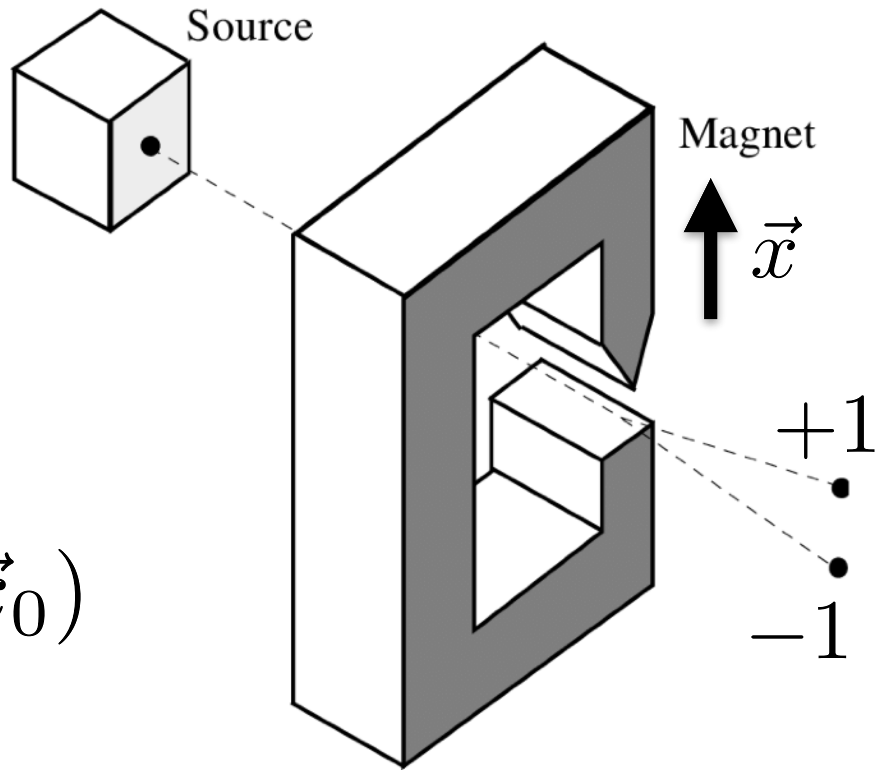
$$P(a|\vec{x})$$

$$= P(a|R\vec{x}_0)$$



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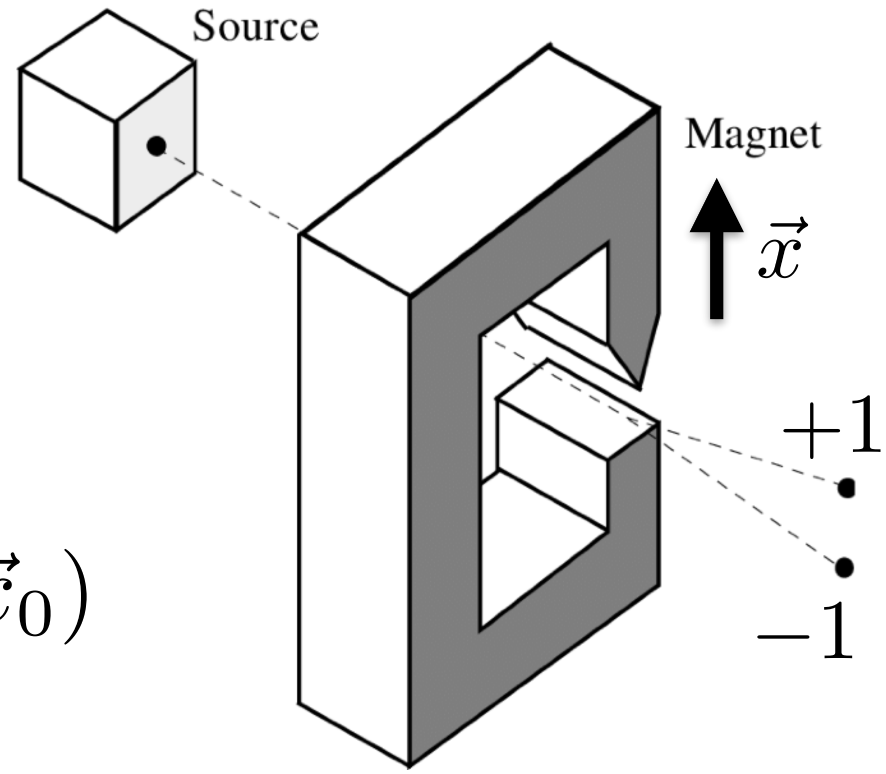

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- Default direction of inhomogeneity of field: $\vec{x}_0$.
- Spatial rotation applied to it: $R \in \mathcal{G} = \mathrm{SO}(3)$.

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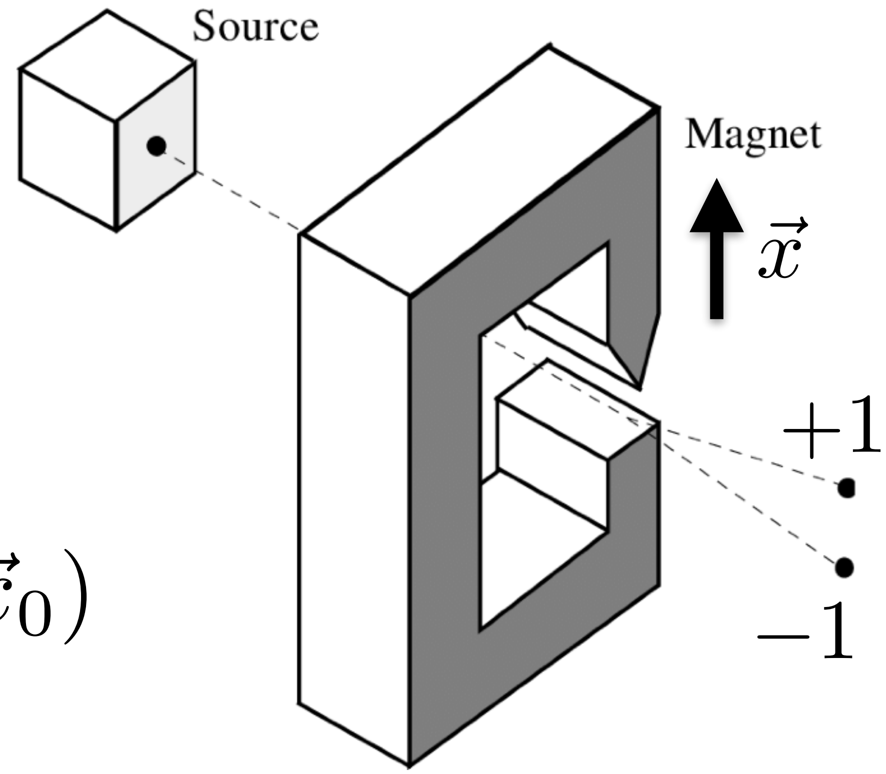

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$$|\vec{x}| = 1,$$
$$a \in \{-1, +1\}.$$

- Default direction of inhomogeneity of field: $\vec{x}_0$.
- Spatial rotation applied to it: $R \in \mathcal{G} = \mathrm{SO}(3)$.
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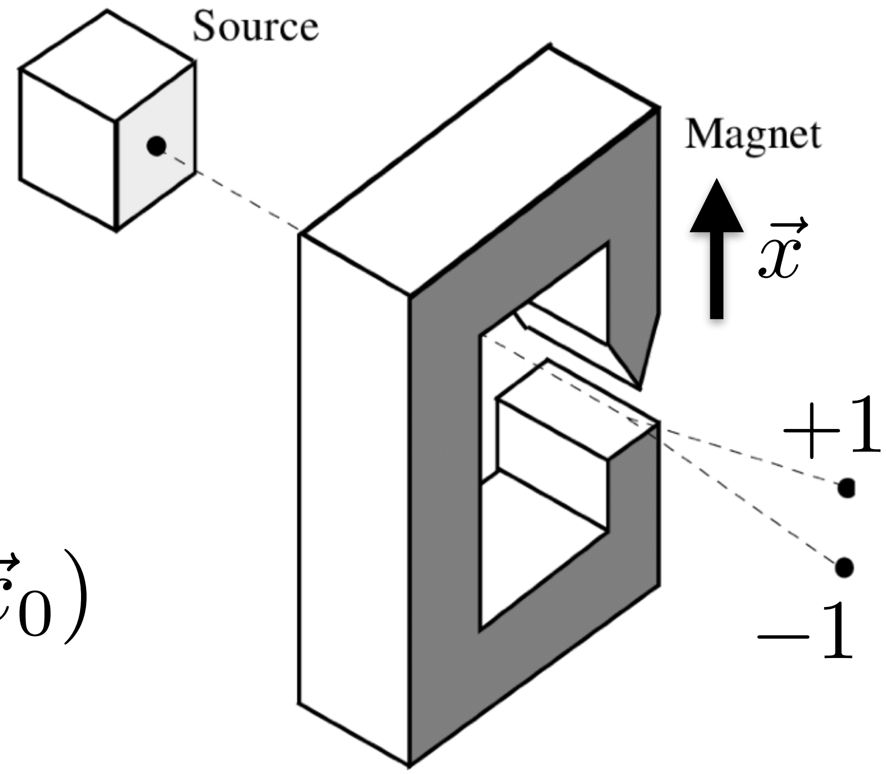
Example: Stern-Gerlach experiment



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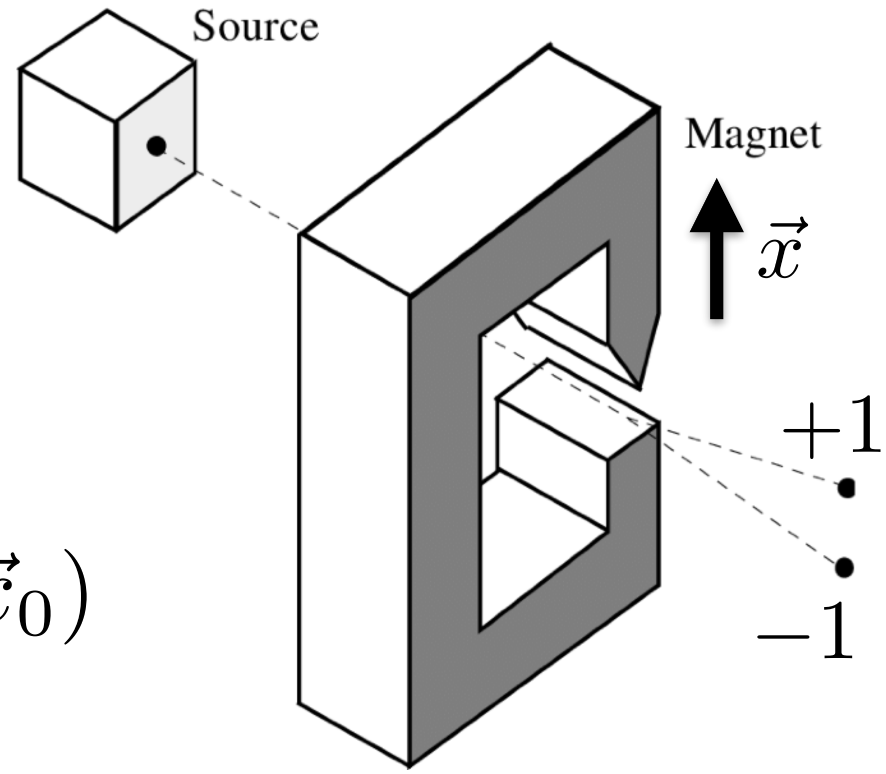

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- Manifold of inputs: the **unit sphere**, $S^2 = \mathrm{SO}(3)/\mathrm{SO}(2)$.
- In general, **inputs are elements of a homogeneous space,** $\mathcal{G}/\mathcal{H}$. Inputs are (partially) **symmetry-breaking** DOFs.

Spacetime boxes

A. J. P. Garner, M. Krumm, **MM**, Phys. Rev. Research **2**, 013112 (2020).

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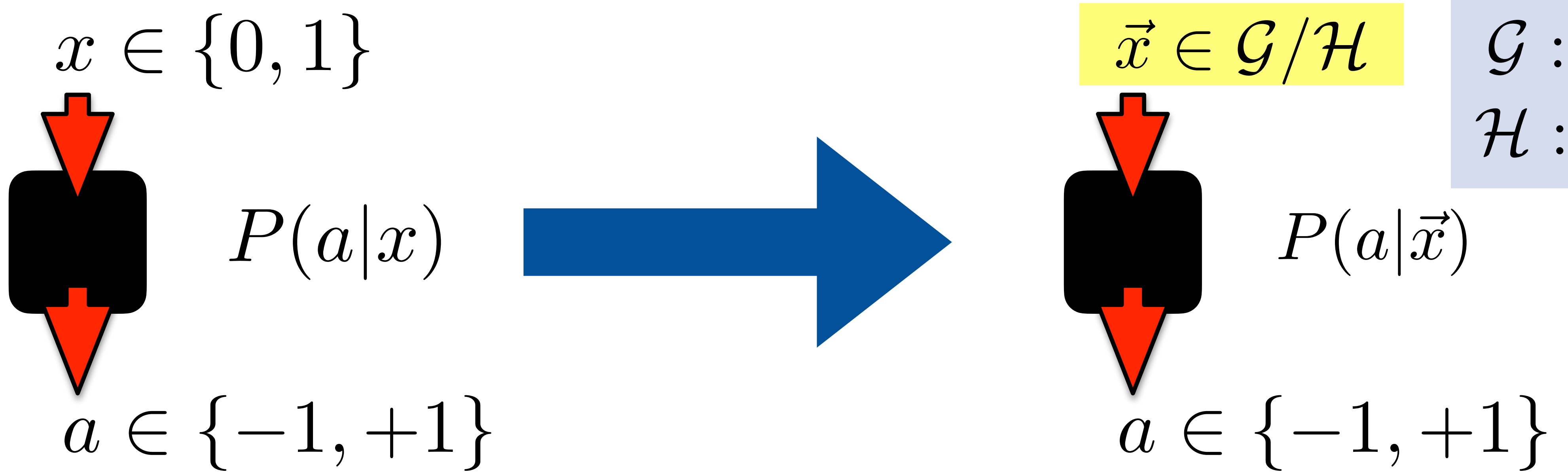

$\mathcal{G}$: symmetry group

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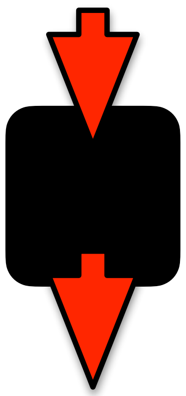
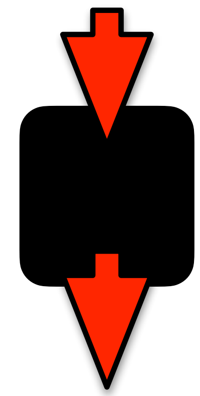
$x \in \{0, 1\}$



$P(a|x)$

$a \in \{-1, +1\}$

$\vec{x} \in \mathcal{G}/\mathcal{H}$



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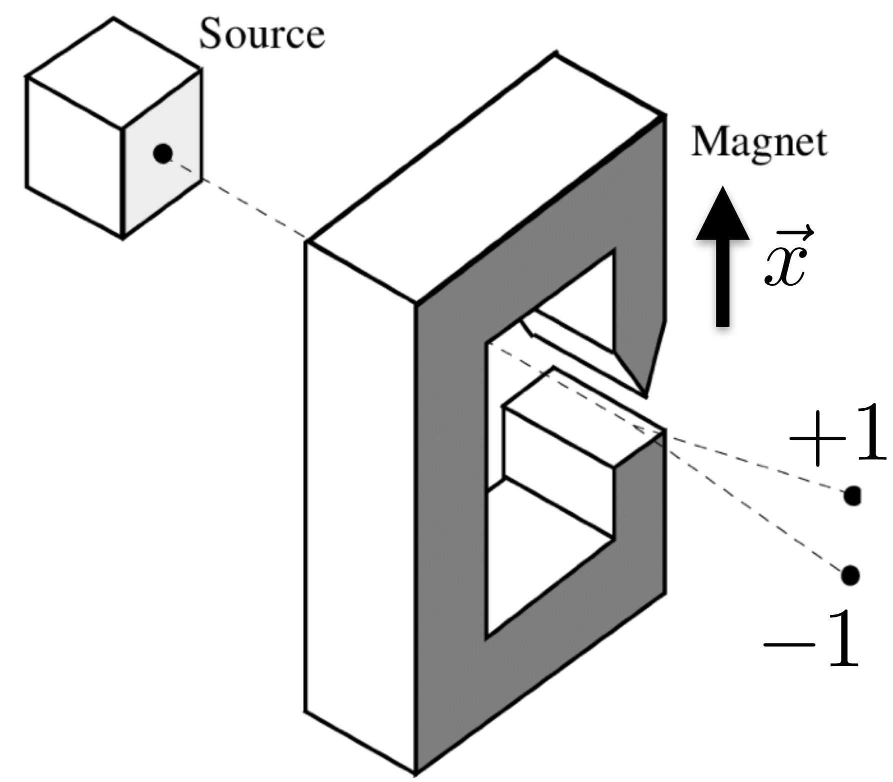
Example: Stern-Gerlach experiment

$\mathcal{G} = \mathrm{SO}(3)$ (spatial rotations)

$\mathcal{H} = \mathrm{SO}(2)$ (axial symmetry of magnetic field)

$\vec{x} \in \mathcal{G}/\mathcal{H} = S^2$ (unit vector: field direction)



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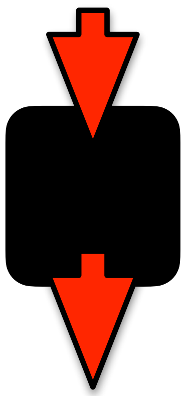

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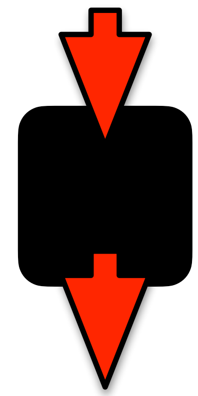

$P(a|\vec{x})$

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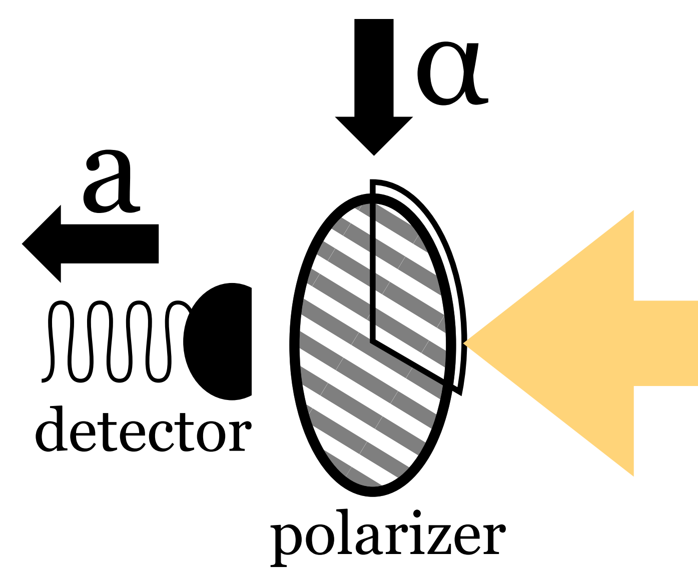
$\mathcal{G}$: symmetry group
$\mathcal{H}$: stabilizer subgroup

Example: Polarizer, $P(a|\alpha)$.

$\mathcal{G} = \mathrm{SO}(2)$ (rotations around beam axis)

$\mathcal{H} = \{\mathbf{1}\}$ (no additional symmetry)

$\alpha \in \mathcal{G}/\mathcal{H} = \mathrm{SO}(2)$.



click / no click: $a = \pm 1$.

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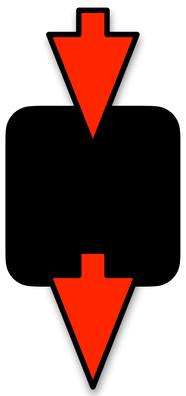

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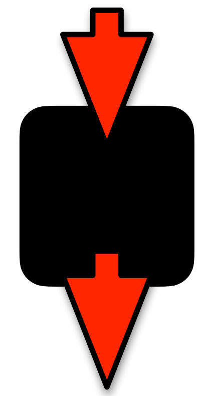

$P(a|\vec{x})$

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$\mathcal{G}$: symmetry group

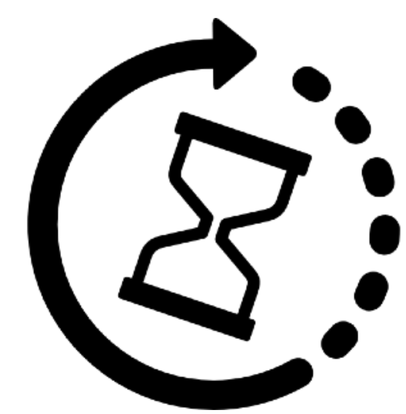
$\mathcal{H}$: stabilizer subgroup

Example: Input is time *t*, $P(a|t)$.

$\mathcal{G} = (\mathbb{R}, +)$ (group of time translations)

$\mathcal{H} = \{\mathbf{1}\}$ (no additional symmetry)

$\vec{x} = t \in \mathbb{R}$



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This must be true even if we do not assume that QT holds.

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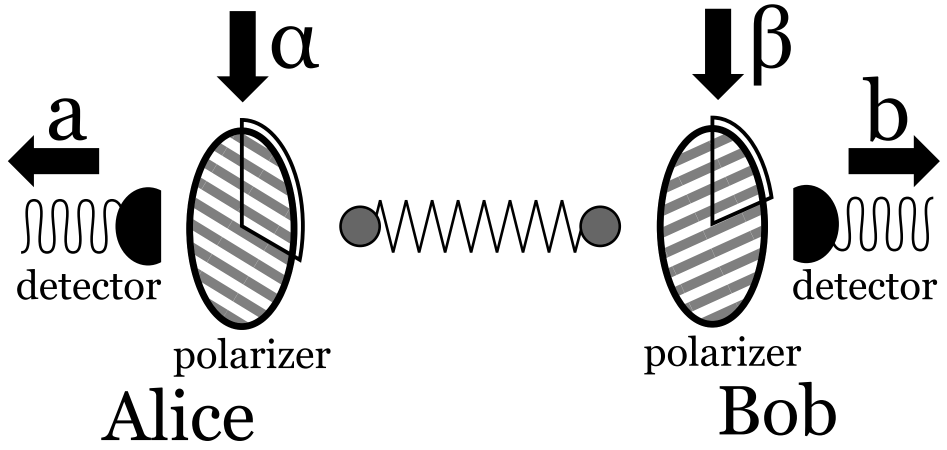

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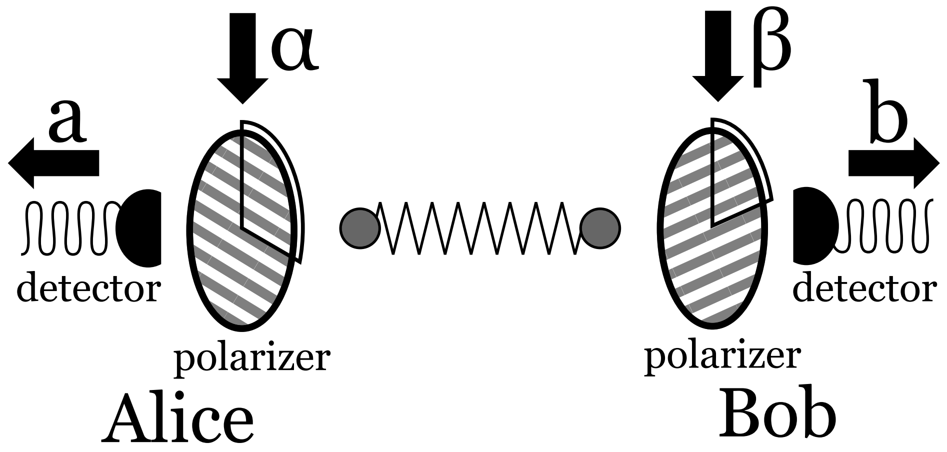

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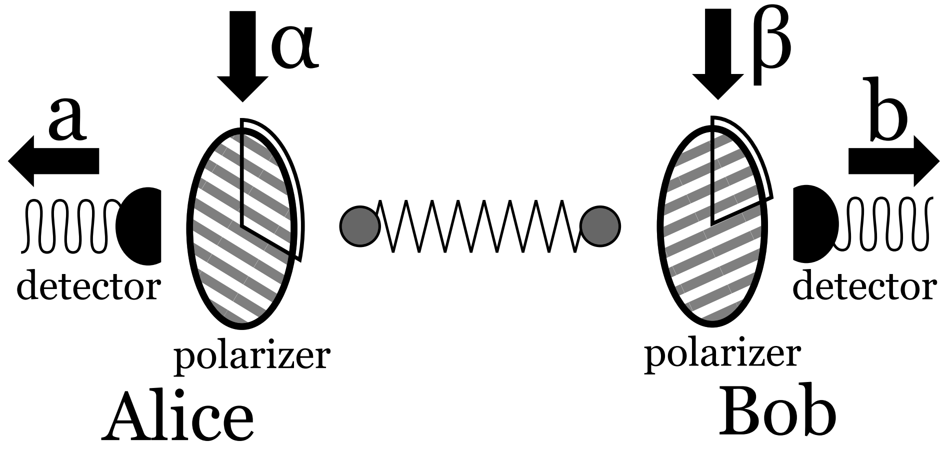

$$P(a,b|\alpha,\beta) := \sum_{m=0}^{2J}\sum_{n=-2J}^{2J} c_{mn}^{ab}\cos(m\alpha - n\beta) + s_{mn}^{ab}\sin(m\alpha - n\beta),$$

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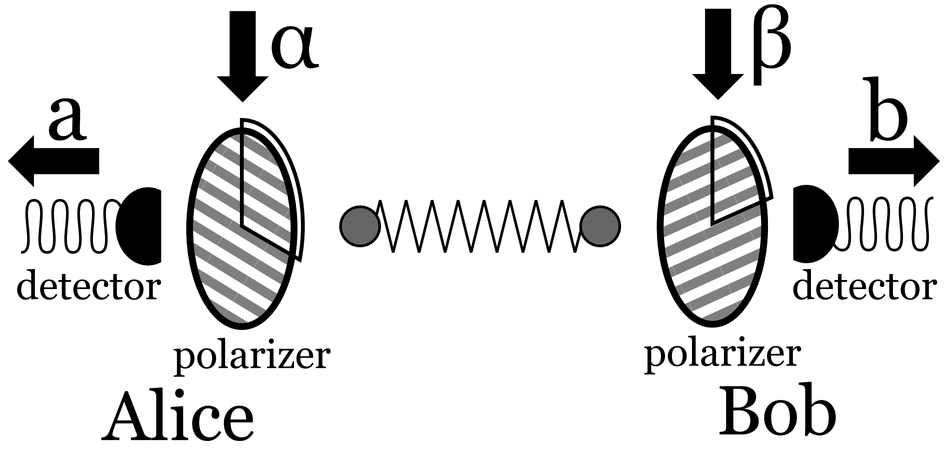

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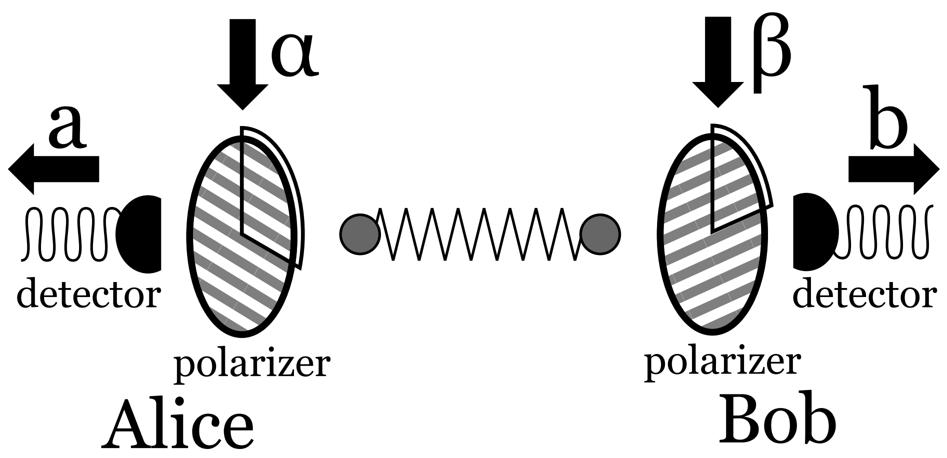

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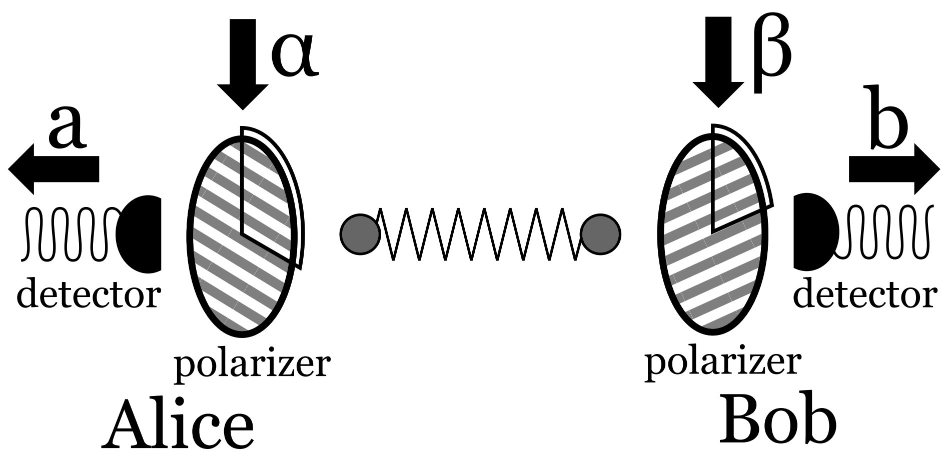

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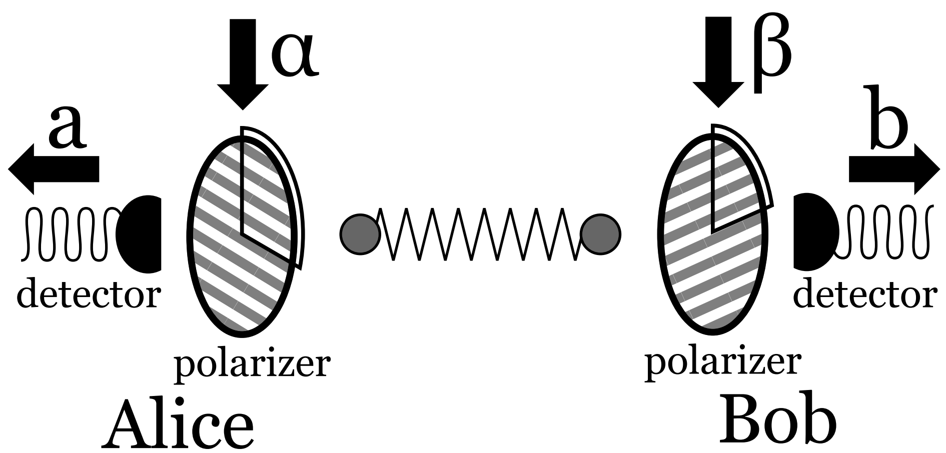

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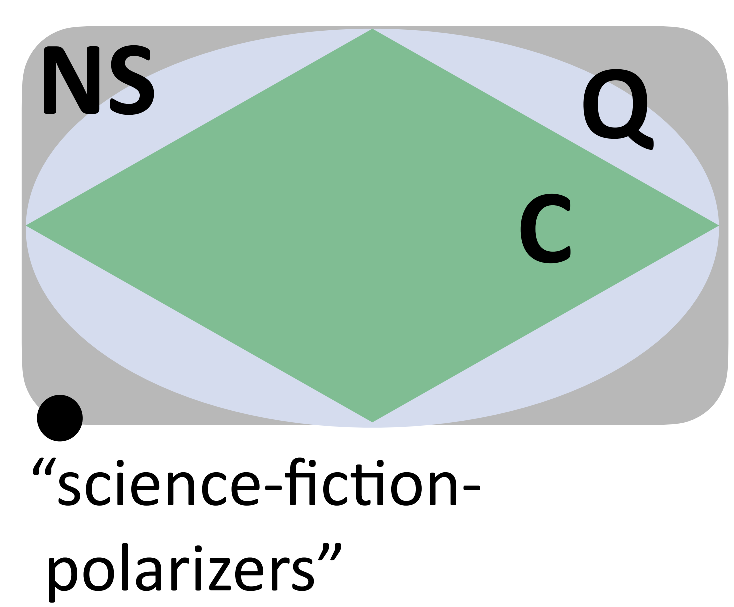

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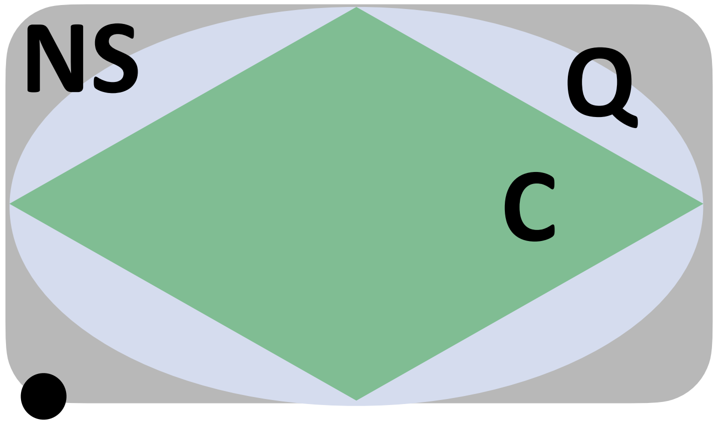

“science-fiction-polarizers”

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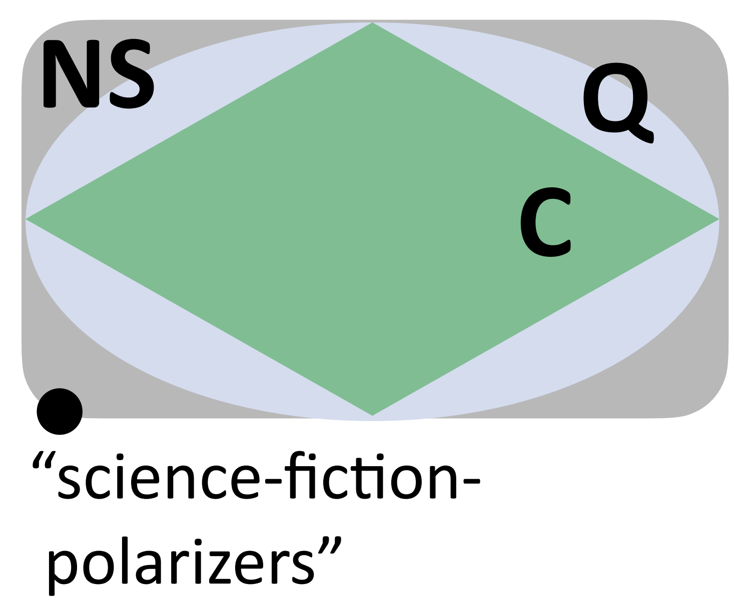

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$$C(\alpha,\beta)=\sum_{m=0}^{2J}\sum_{n=-2J}^{2J} c_{mn}\cos(m\alpha-n\beta)+s_{mn}\sin(m\alpha-n\beta)$$

Answer: No. If $\max_{\alpha,\beta}|C(\alpha,\beta)|\leq\sqrt{2}e^{-1}[4J(2J+1)]^{-3/2}$ then *C* admits of a local hidden-variable model. Likely true for other groups too.

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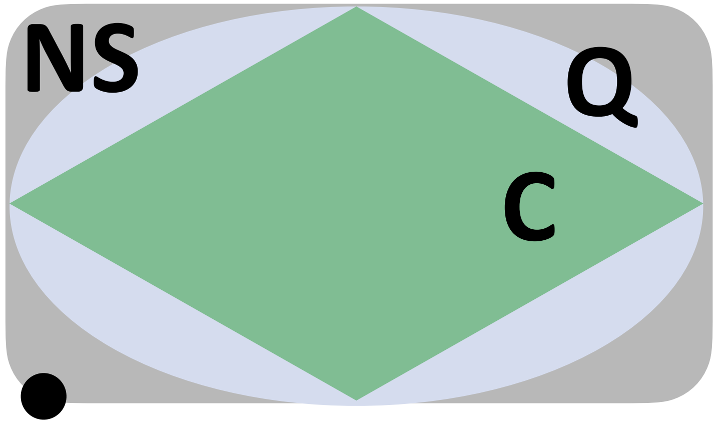
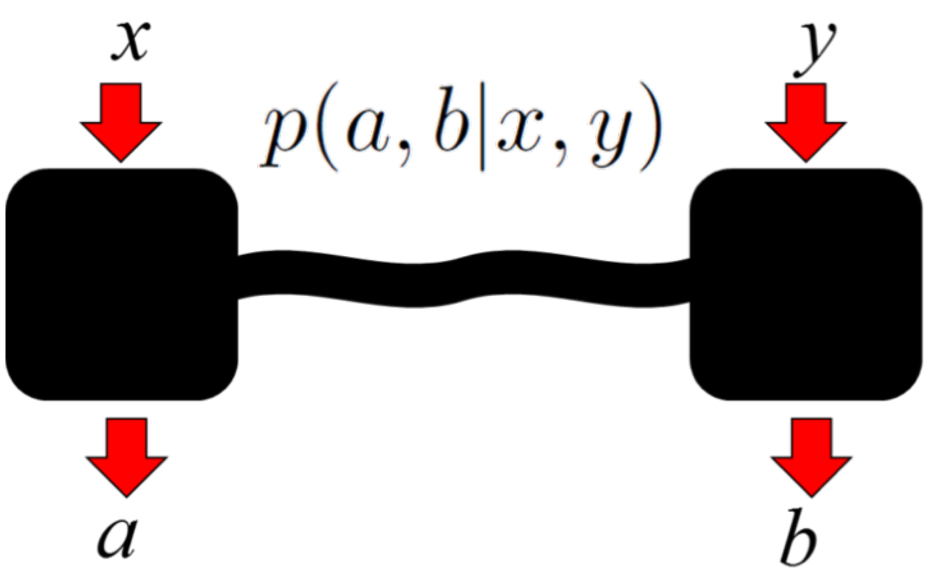


“science-fiction-polarizers”

1. General framework of "spacetime boxes"

2. Foundational insights



3. Towards novel protocols…

4. … and experimental tests of QT

Overview

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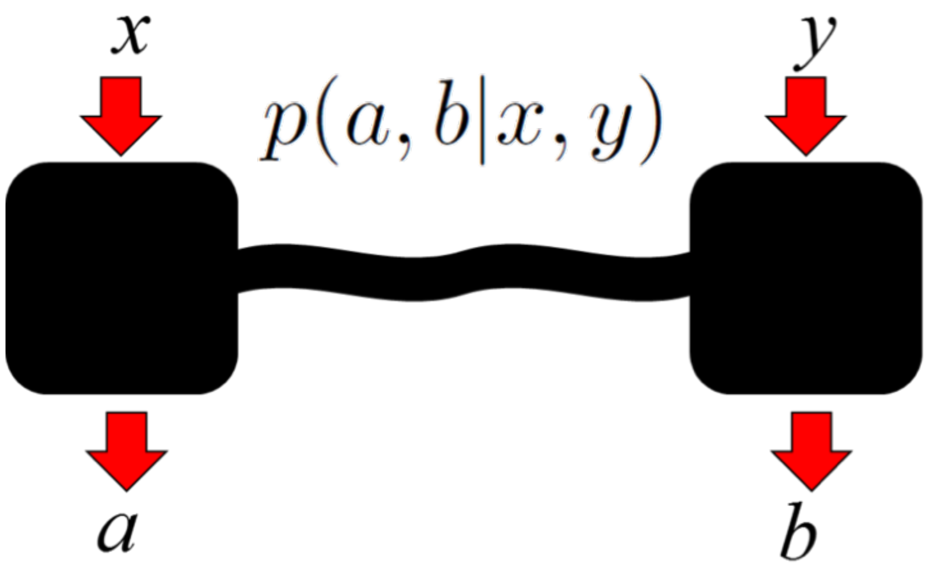

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Foundational consequences

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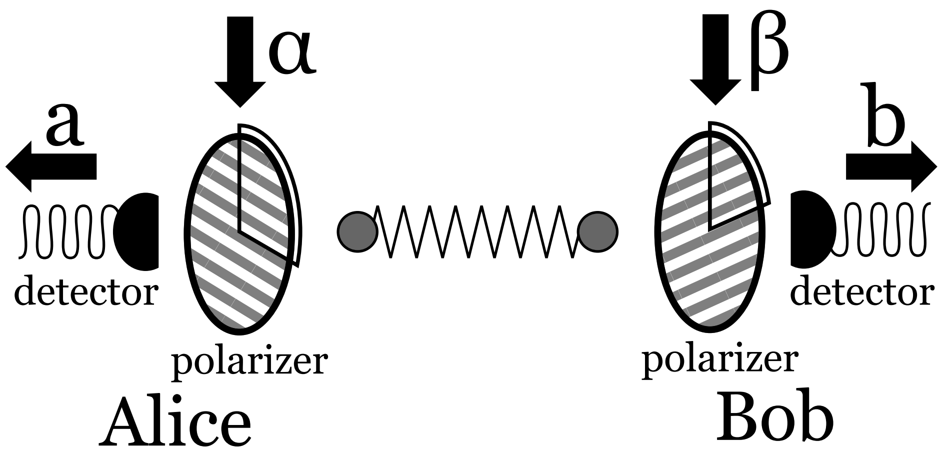

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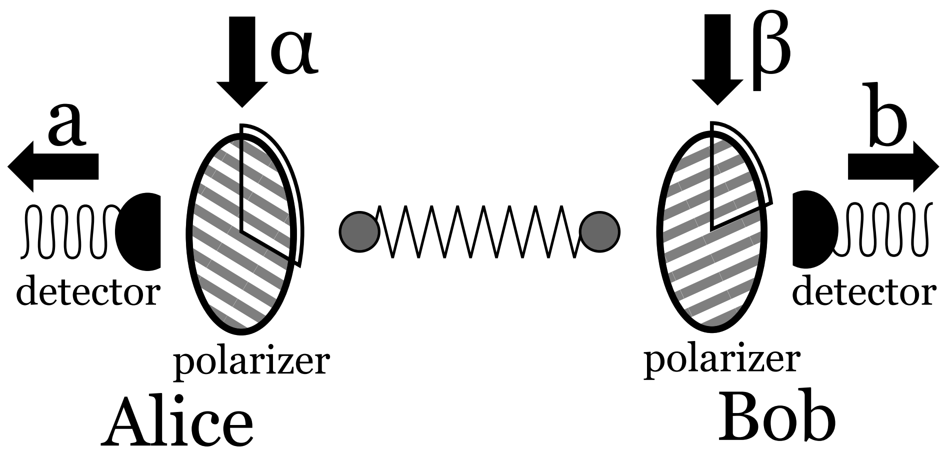

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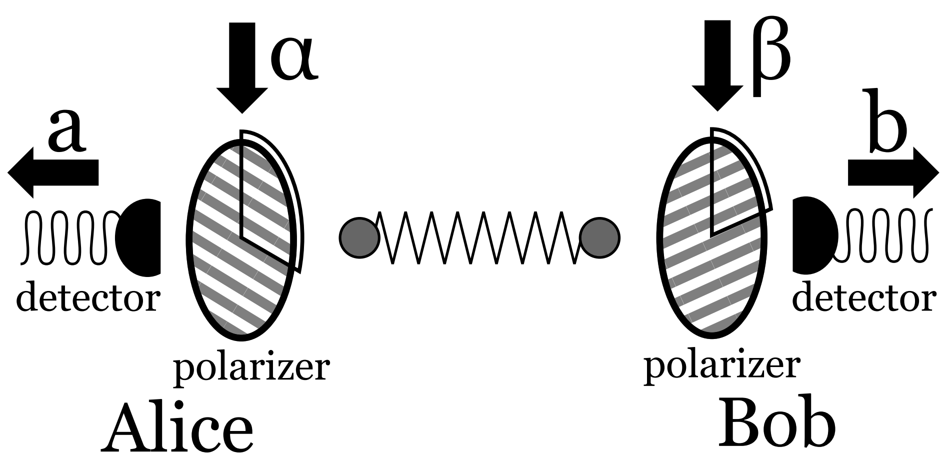

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More details:

Bob inputs $\vec{y}$, obtains outcome *b*, and tells Alice this

→ conditional box $P^A_{b,\vec{y}}(a|\vec{x}) = \dfrac{P(a,b|\vec{x},\vec{y})}{P_B(b|\vec{y})}$

transforms fundamentally *("like a [co-]vector")*.

Foundational consequences

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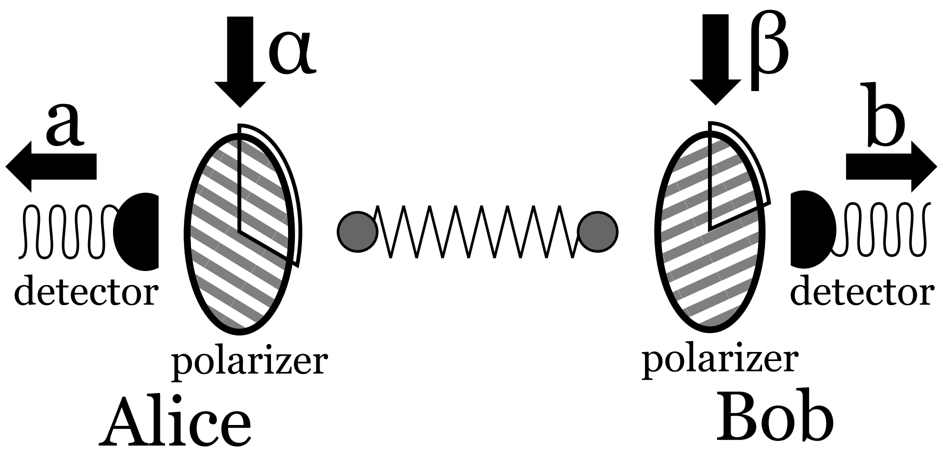

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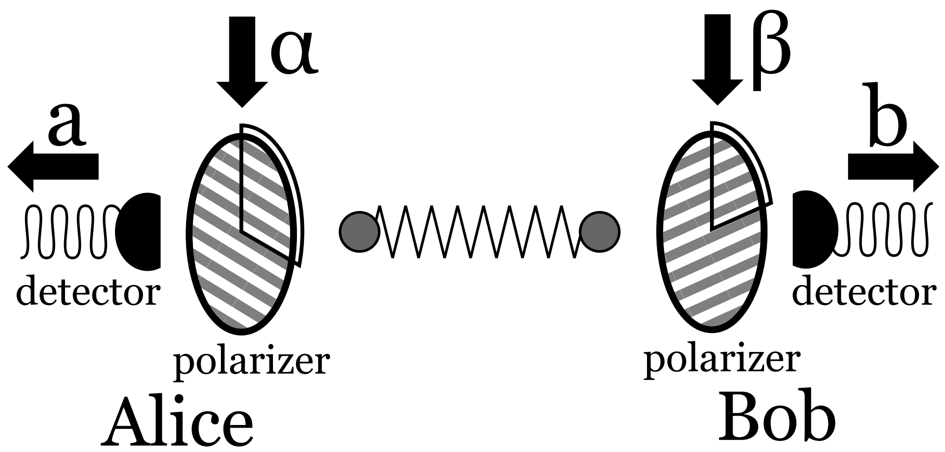

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Suppose *a* has **geometric interpretation** as "parallel or antiparallel to $\vec{x}$"

$\Rightarrow P^A(-a|\vec{x}) = P^A(a|-\vec{x})$

$\Rightarrow$ Local unbiasedness holds automatically.

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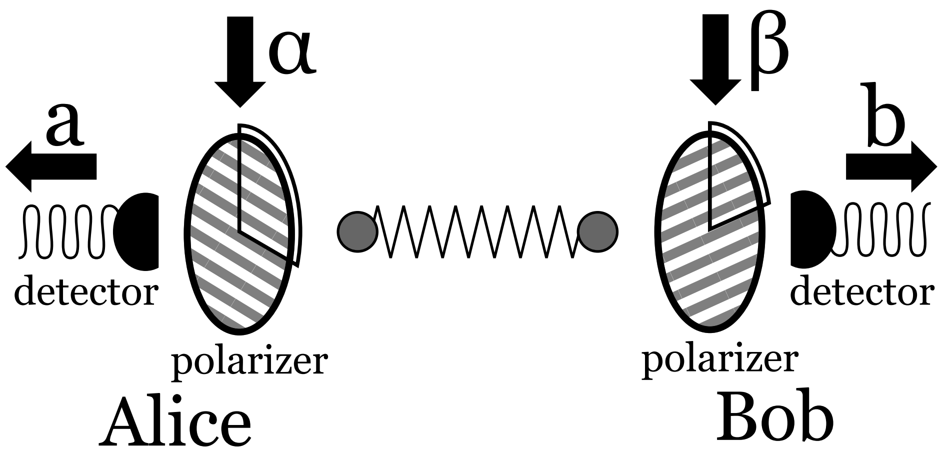

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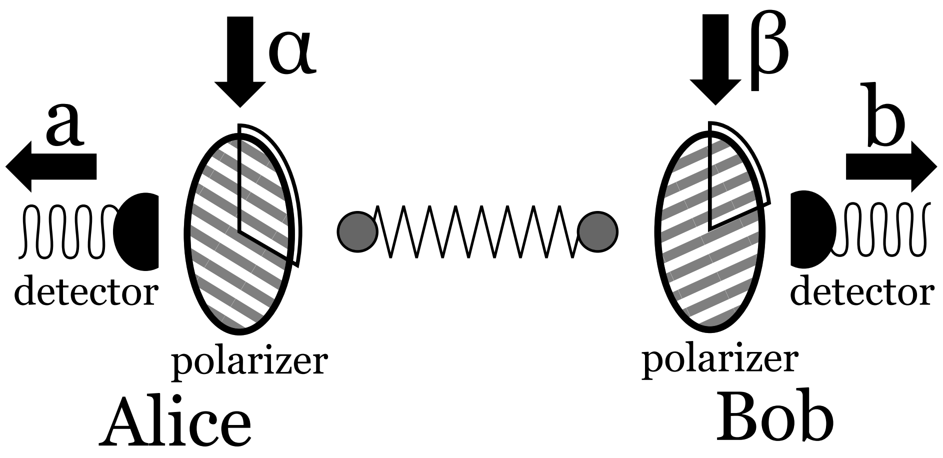
both for $a = +1, a = -1$ (similarly for *b*).

Theorem. In any world where these assumptions hold (**not assuming QT!**), Alice and Bob see **quantum correlations** (i.e. in **Q**).

Foundational consequences

A. J. P. Garner, M. Krumm, **MM**, Phys. Rev. Research **2**, 013112 (2020).



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Theorem: The quantum (2,2,2)-correlations **Q** are **exactly those** that can be obtained by $\mathrm{SO}(d) \times \mathrm{SO}(d)$-boxes that transform locally fundamentally and are locally unbiased, restricted to two inputs per party, and supplemented by shared randomness.

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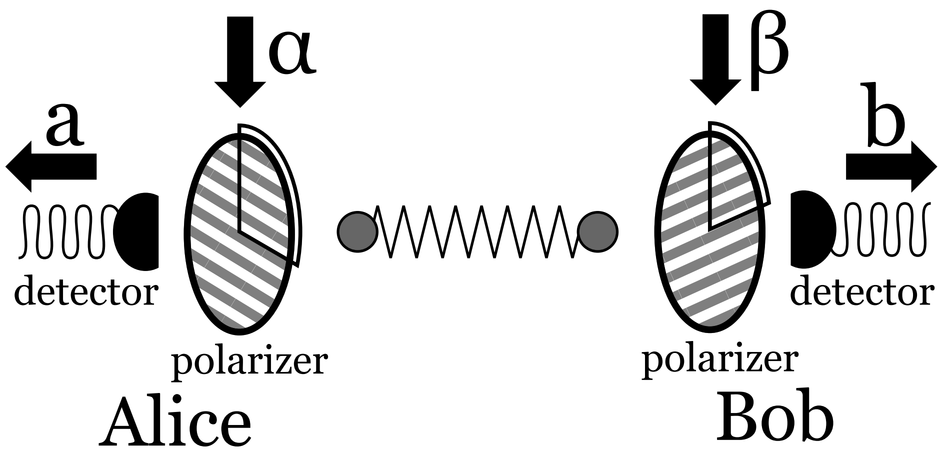

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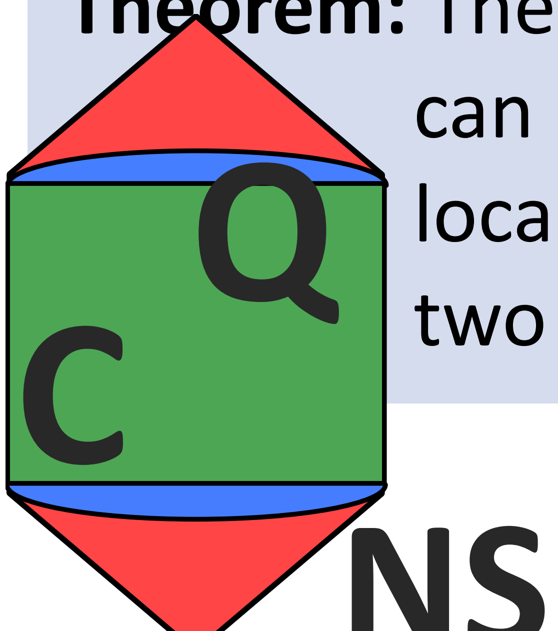

Fundamental relation between QT and space(time)?

Recall the *d=2* case

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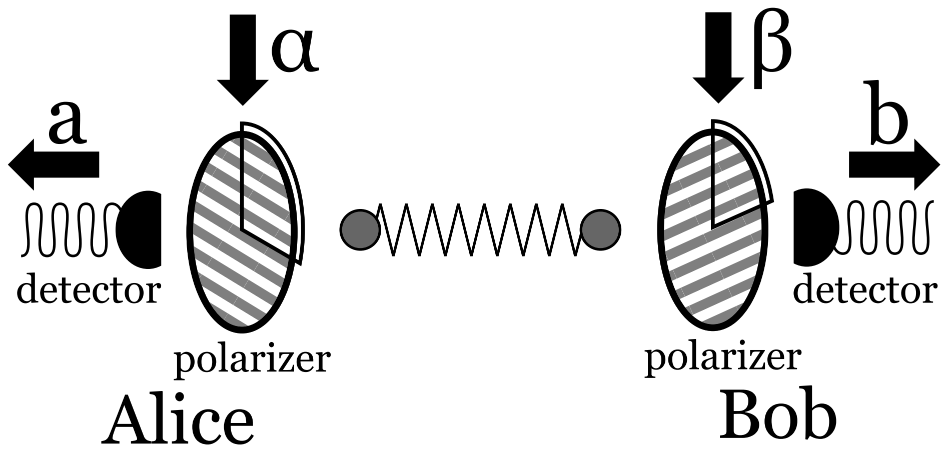

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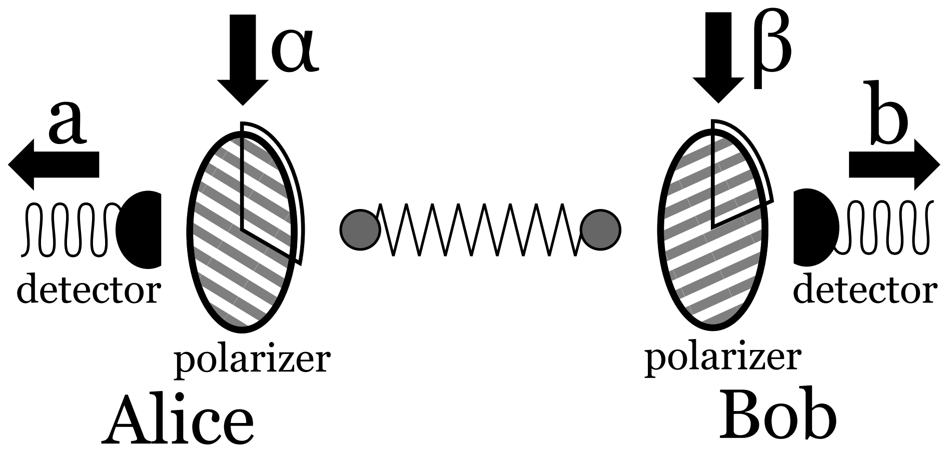

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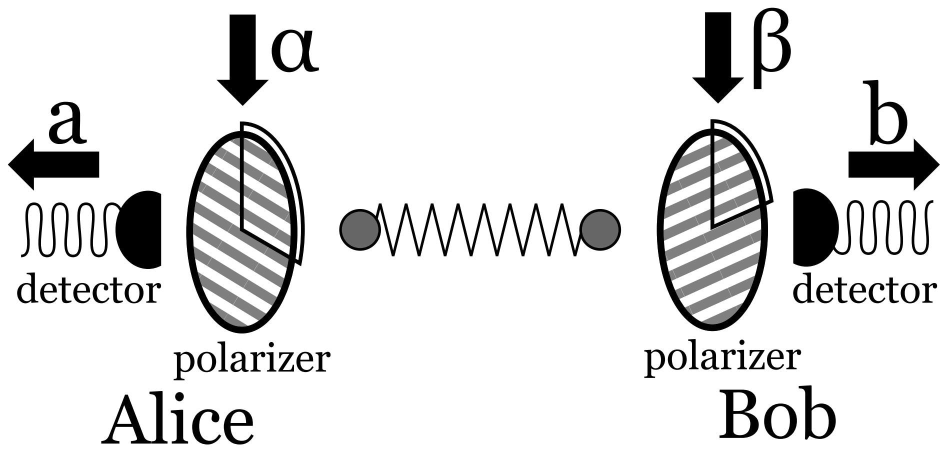

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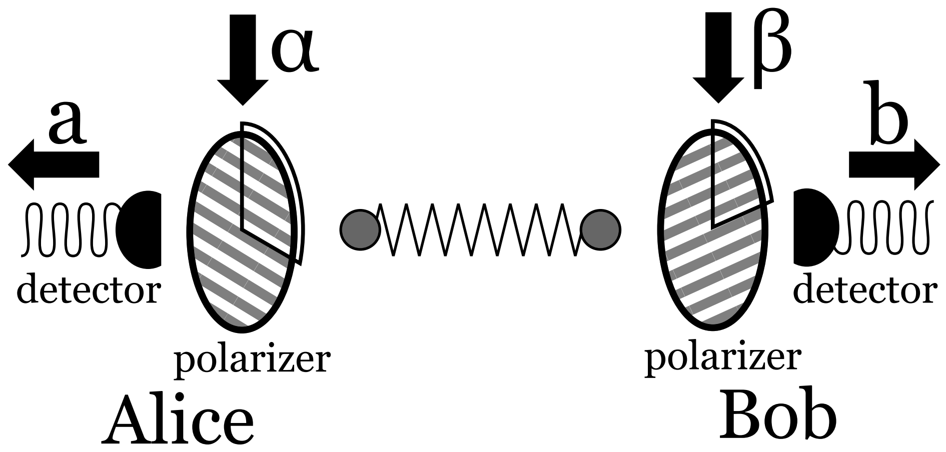

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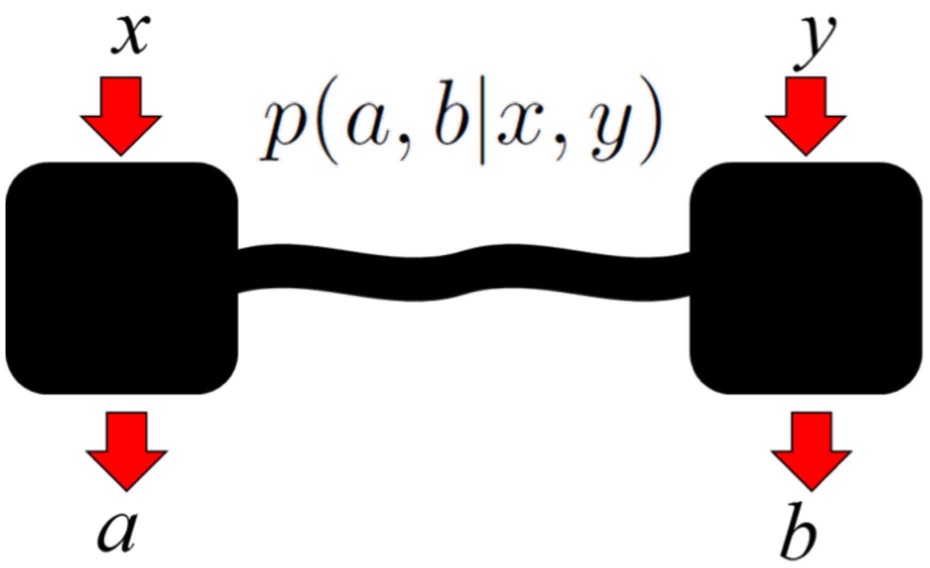
This amounts to an assumption of "how the devices respond to spatiotemporal symmetry transformations".

Idea: use this for **protocols**.

Overview

1. General framework of “spacetime boxes”

2. Foundational insights



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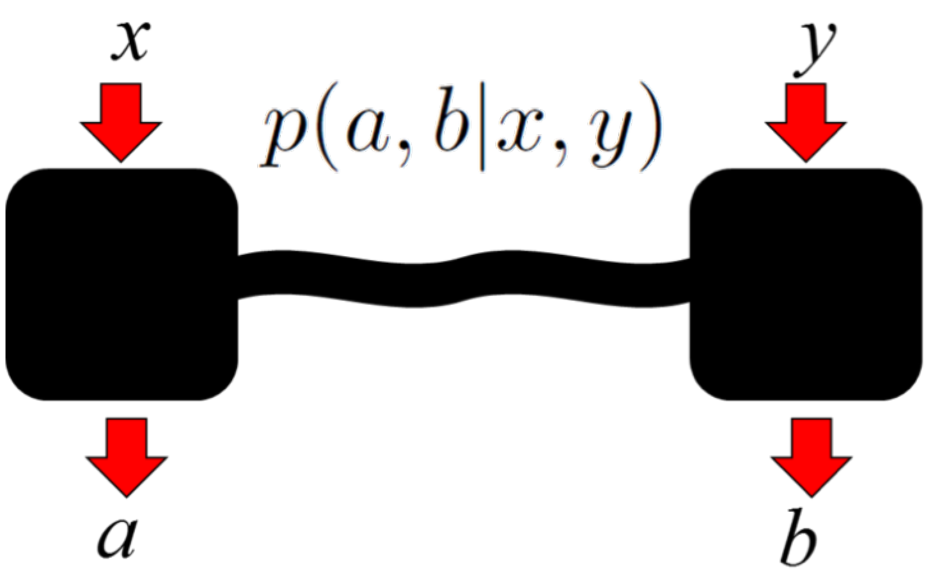

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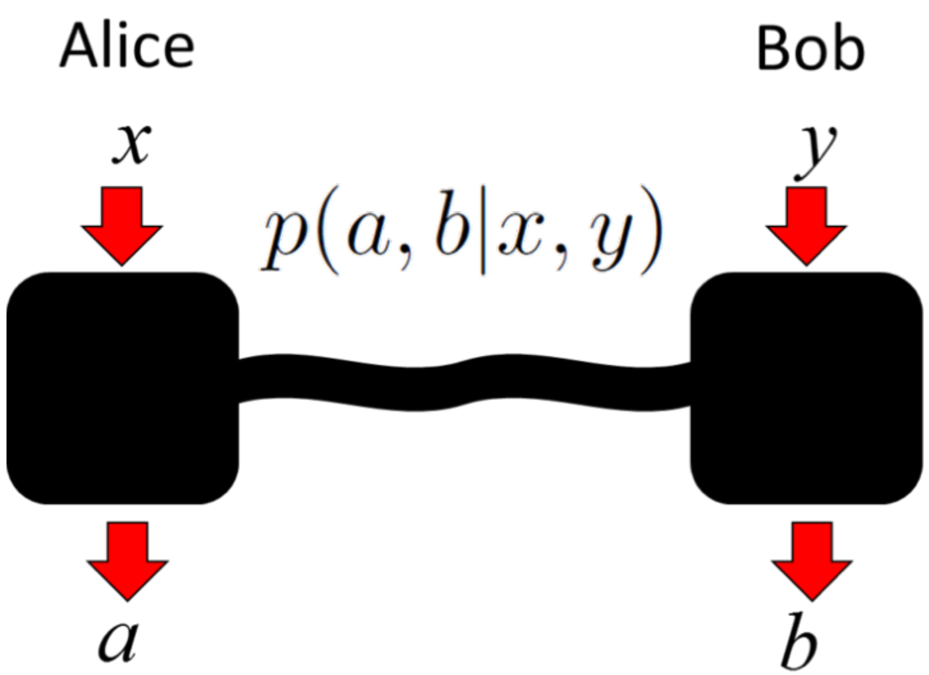
Towards protocols

Device-independent QIT:



Violation of a Bell inequality admits

- randomness expansion
- cryptography

even if **devices are untrusted**.

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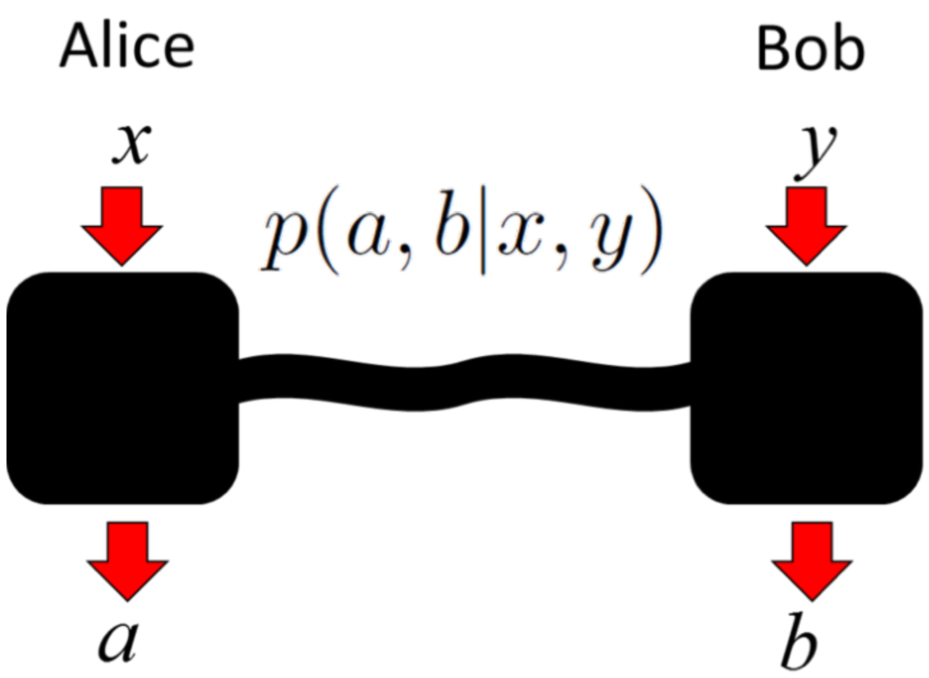

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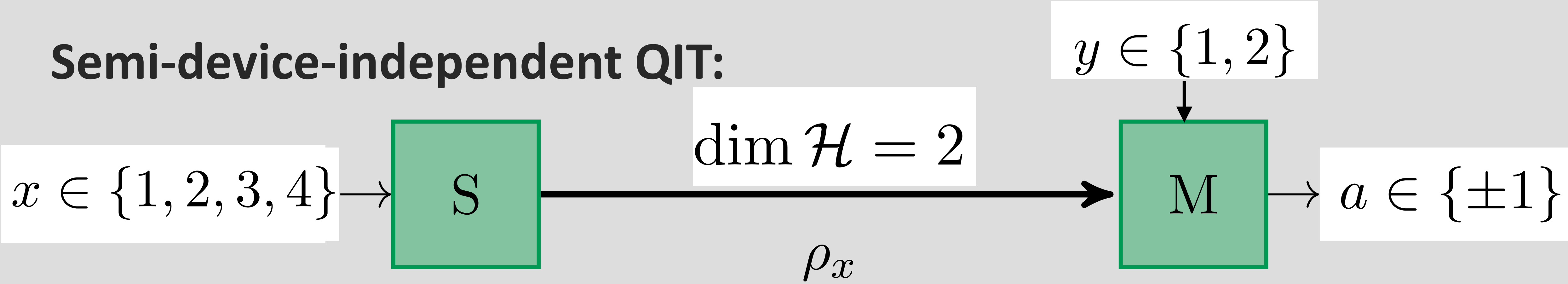

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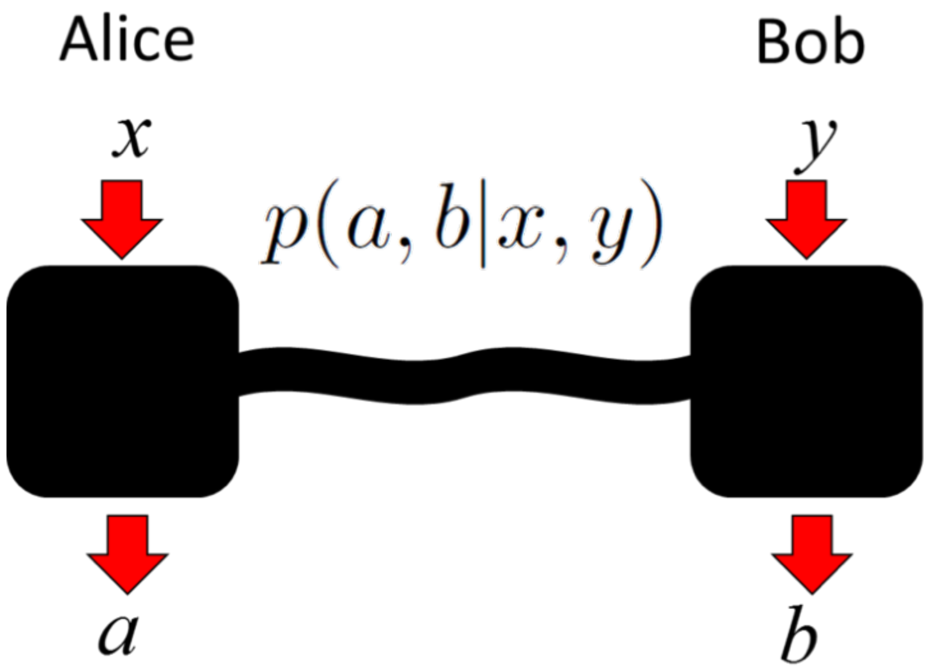

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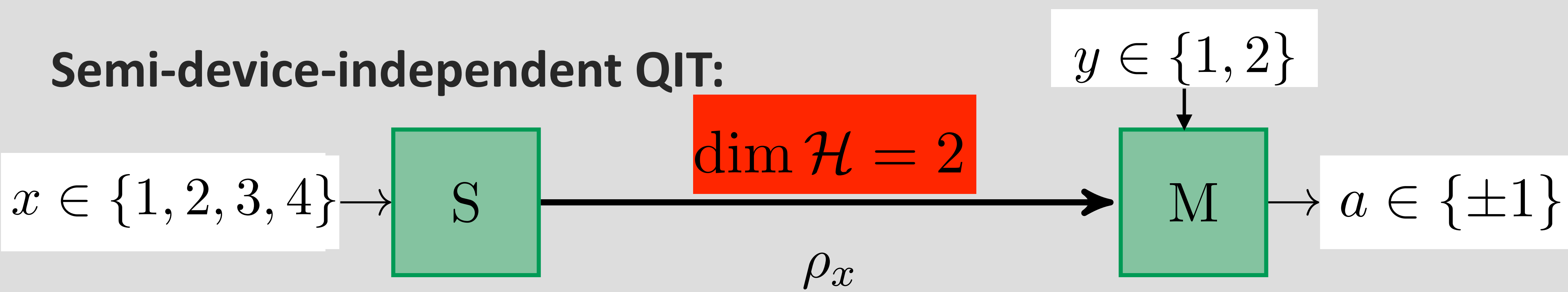

Physical motivation?

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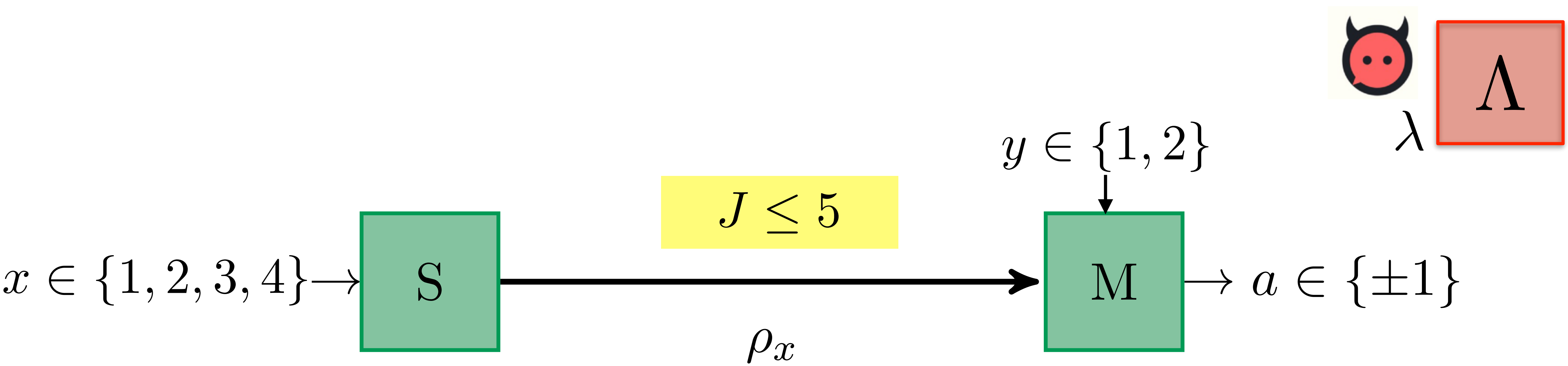
Idea: For SDI protocols, replace dimension bounds by **physically better motivated assumptions** on how systems respond to symmetries.



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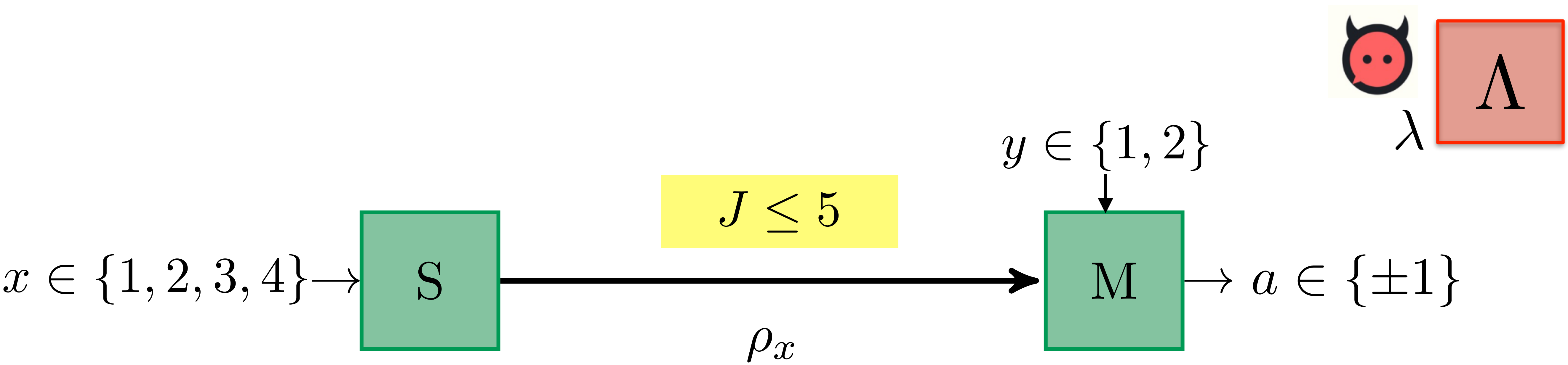

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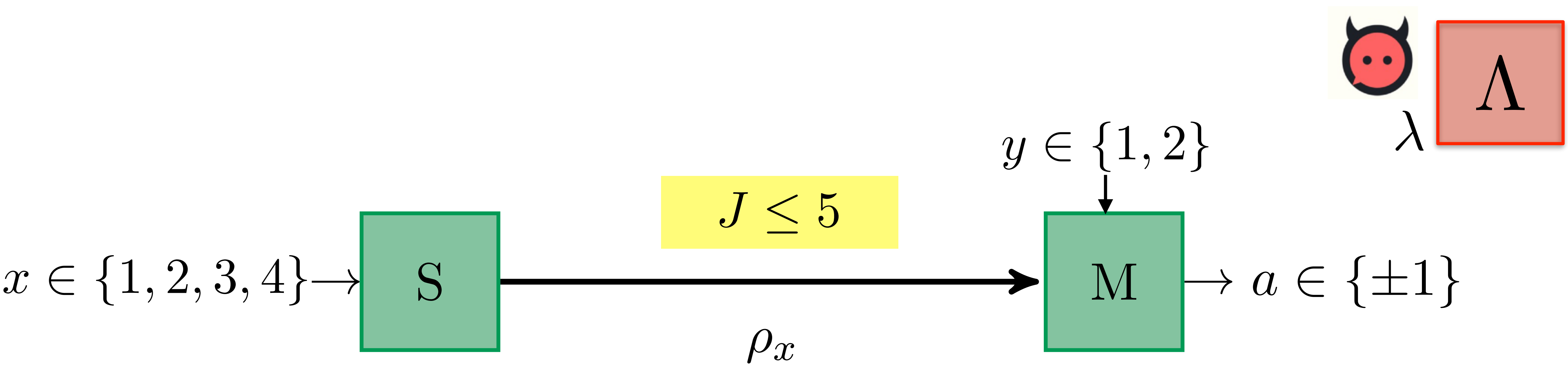

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Also, closer to **particle physics intuition**: don't count dimensions, but representation labels (of the Poincaré group).

Proof of principle for Bell witnesses

A. J. P. Garner, M. Krumm, **MM**, Phys. Rev. Research **2**, 013112 (2020).

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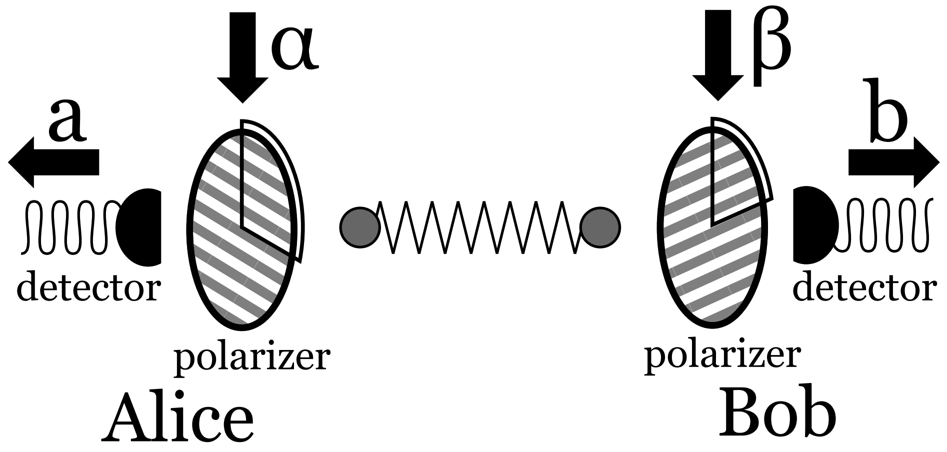

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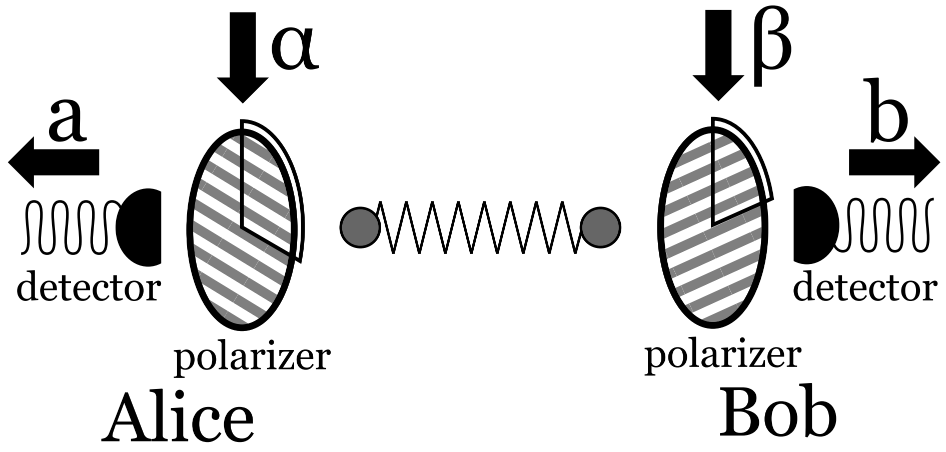

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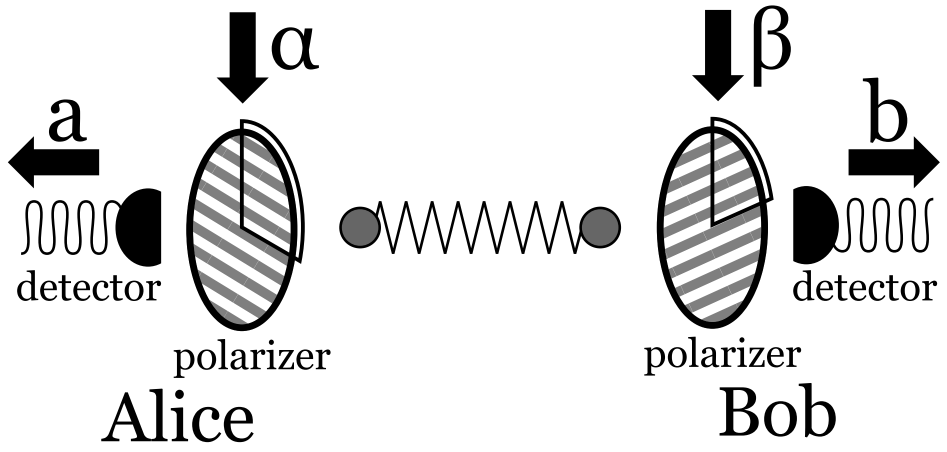

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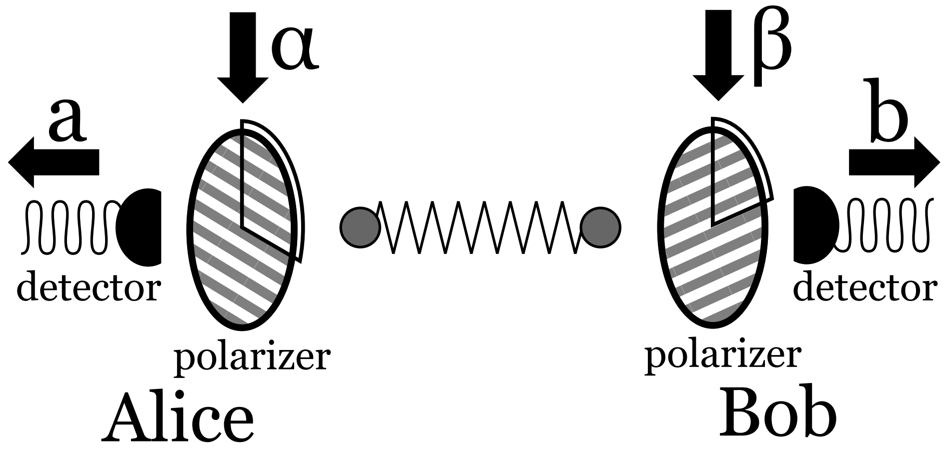

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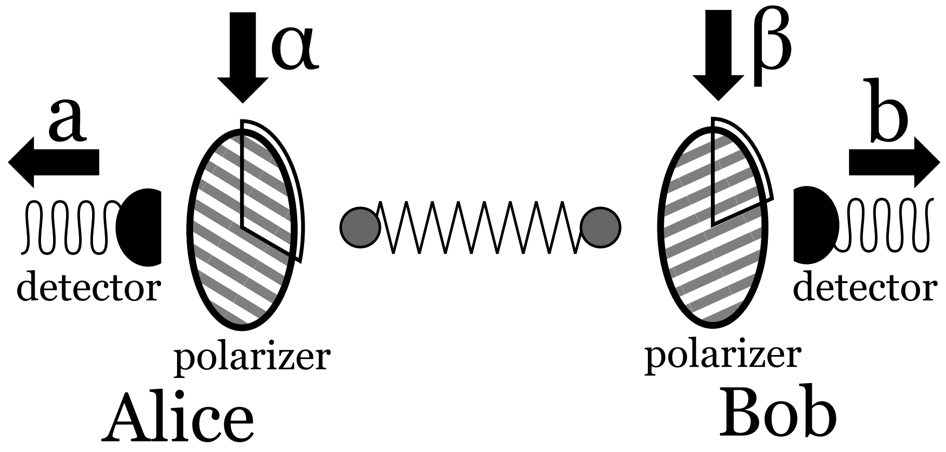

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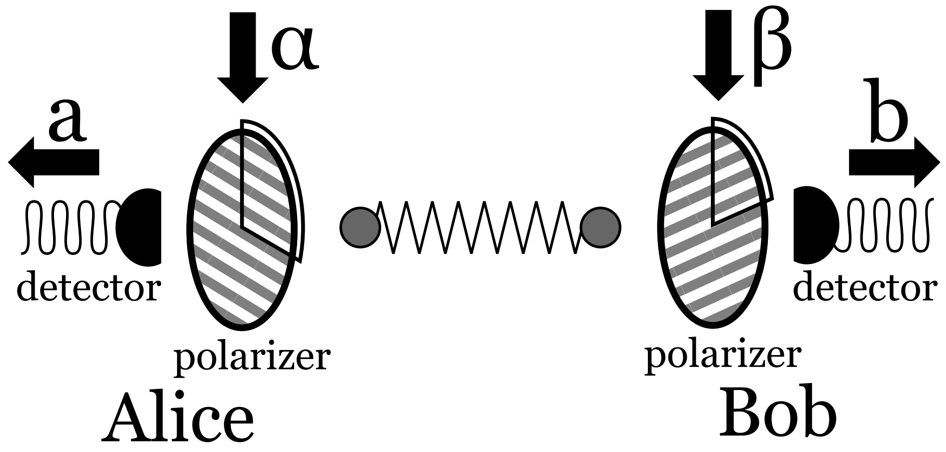

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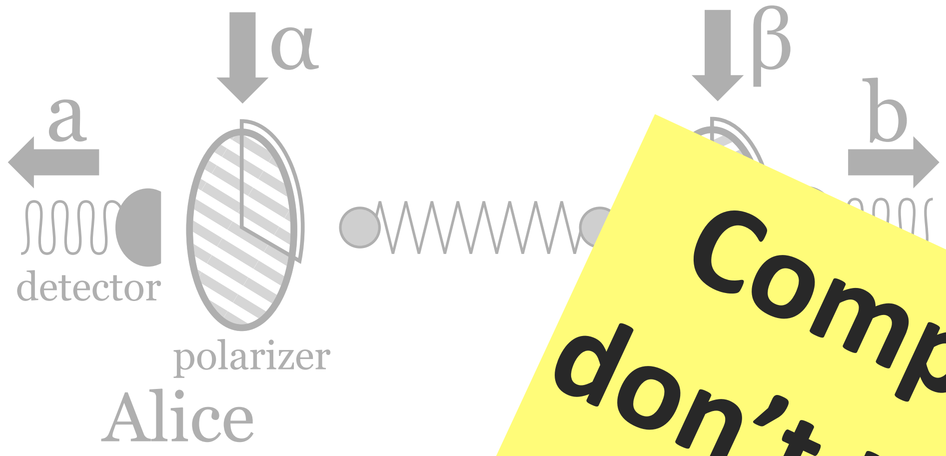

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Completely useless, don't try this at home!

But: proof of principle.

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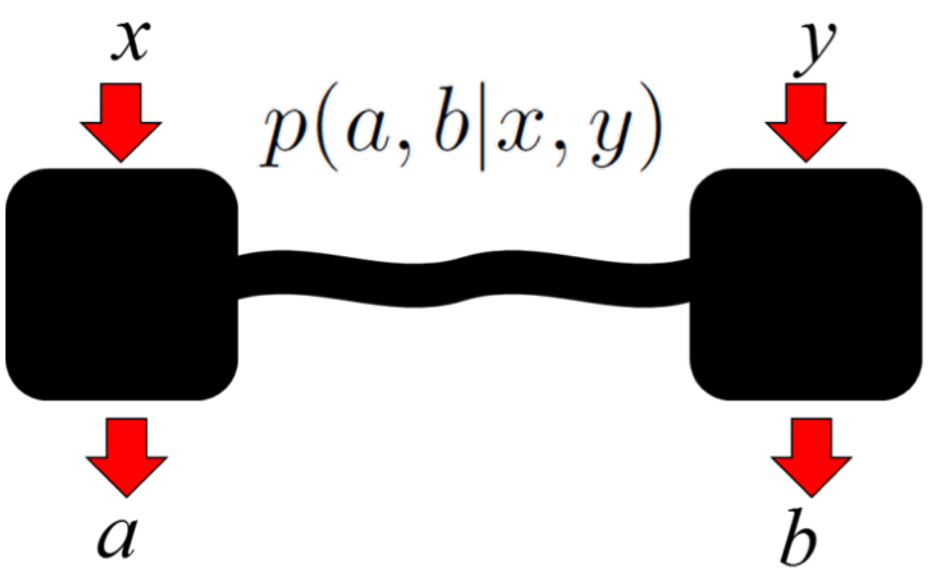

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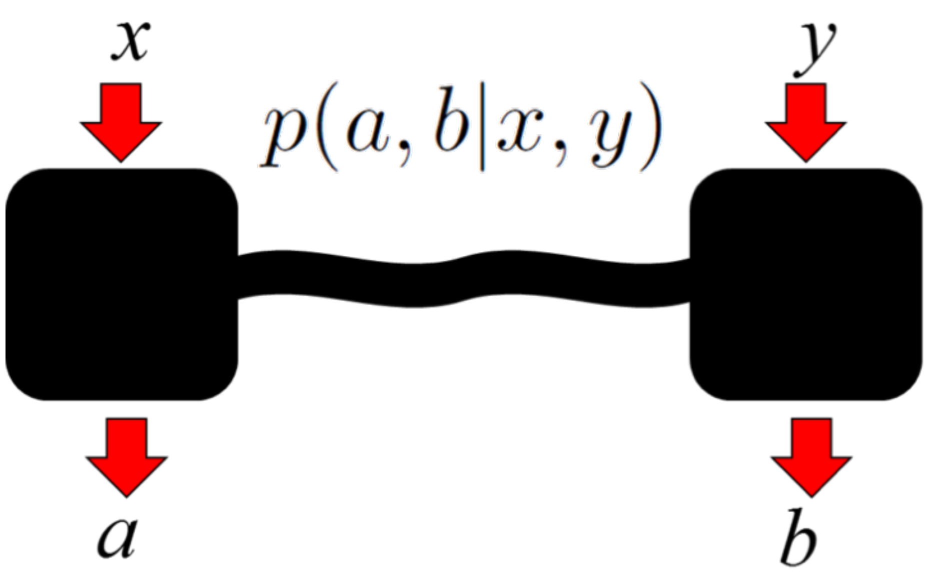

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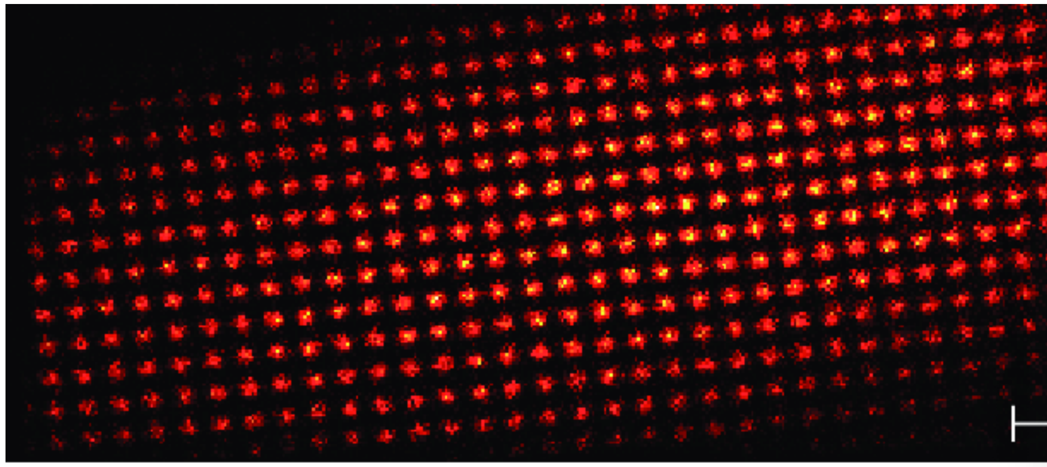
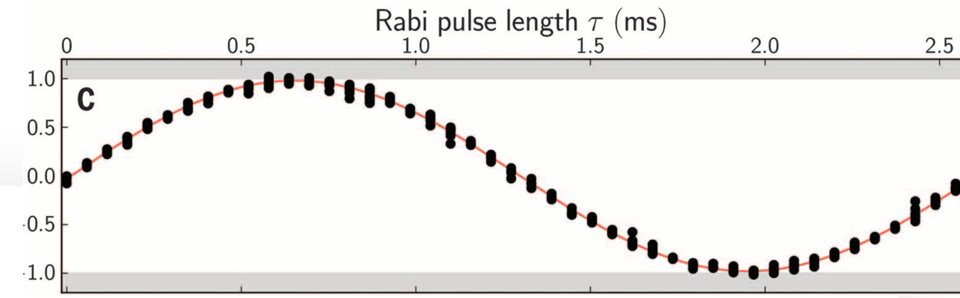
Experiments as “black boxes”





QUANTUM OPTICS

Bell correlations in a Bose-Einstein condensate

Roman Schmied,[1*] Jean-Daniel Bancal,[2,4*] Baptiste Allard,[1*] Matteo Fadel,[1]
Valerio Scarani,[2,3] Philipp Treutlein,[1†] Nicolas Sangouard[4†]

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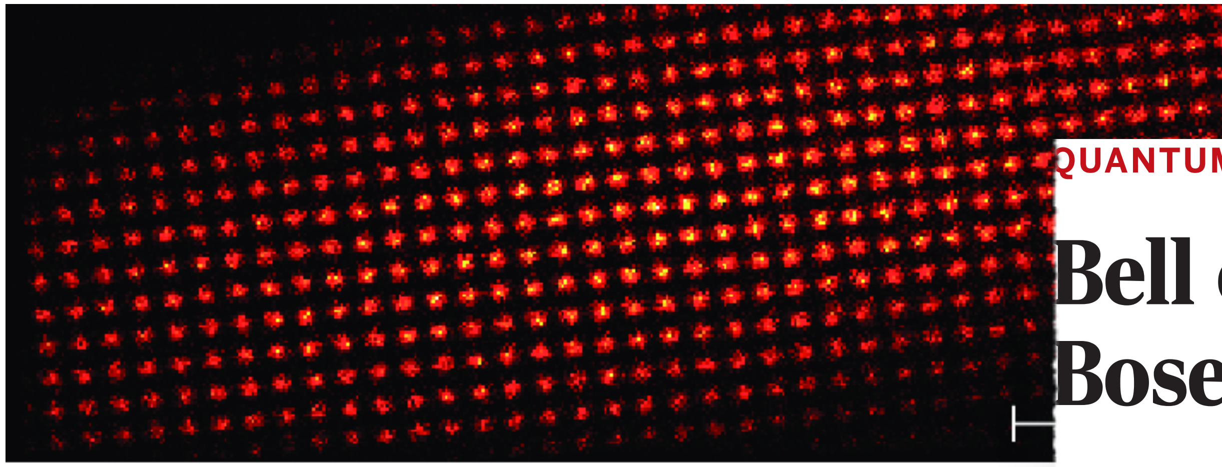

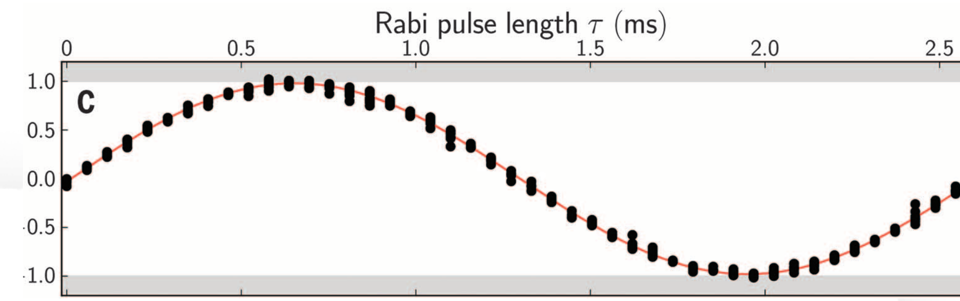

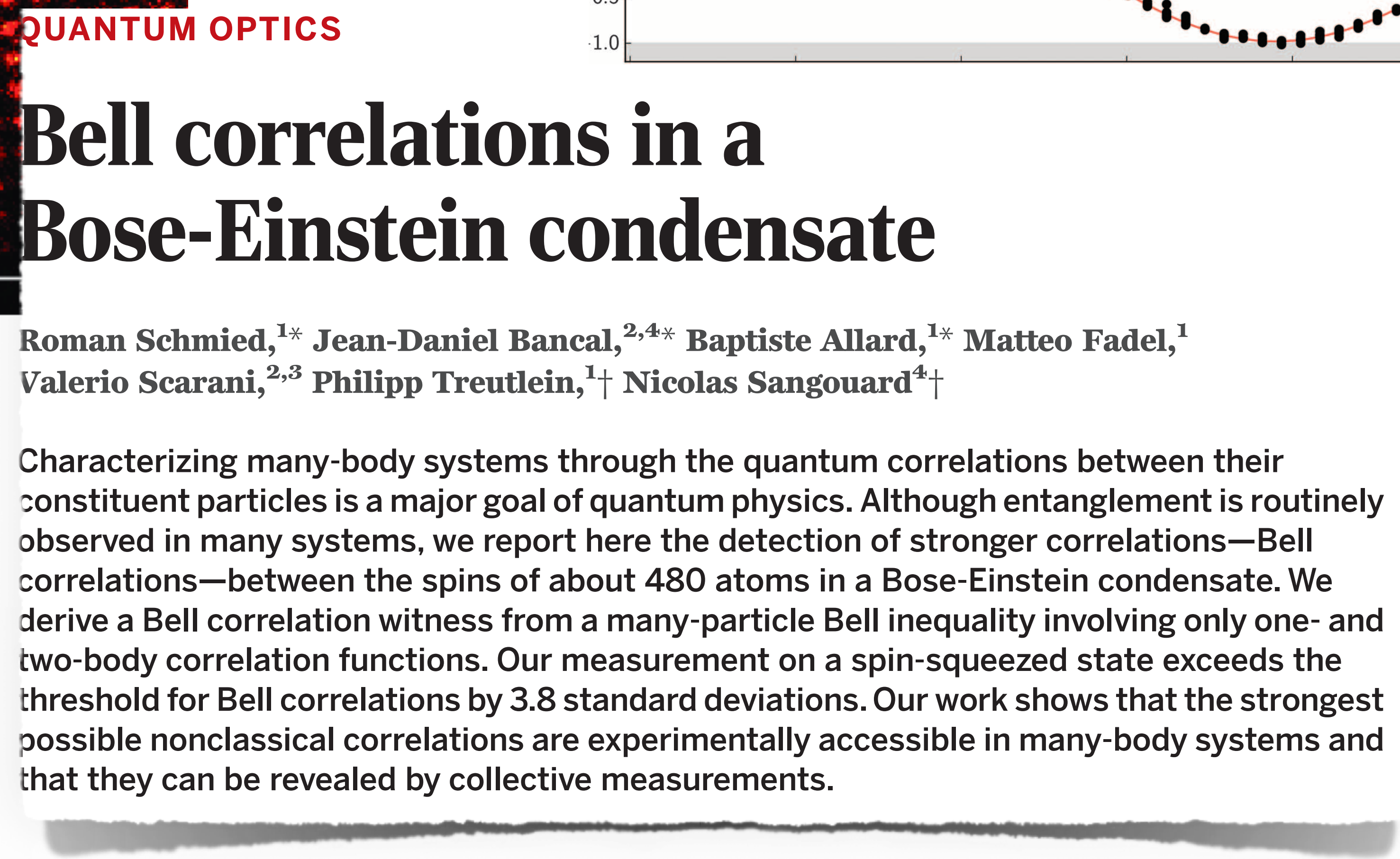

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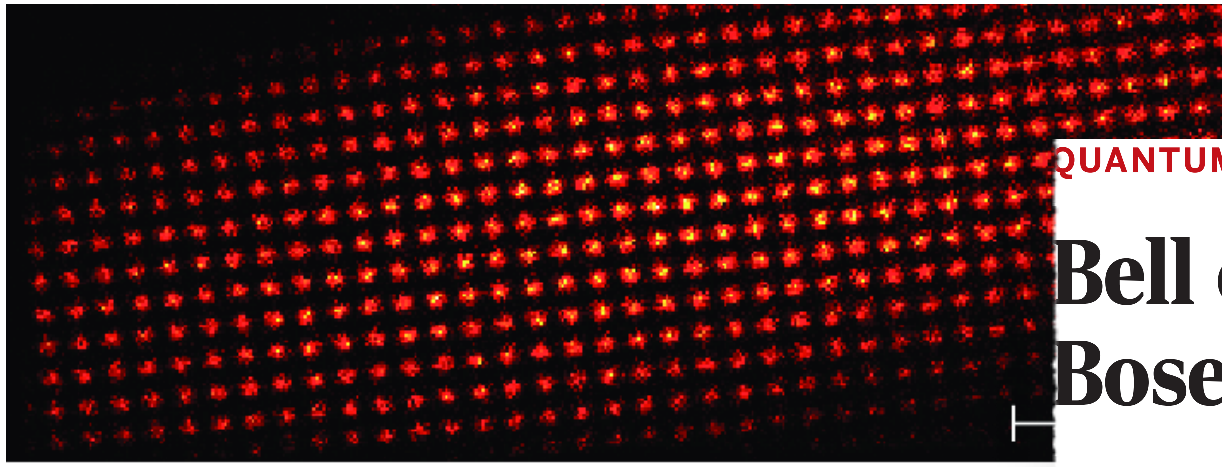

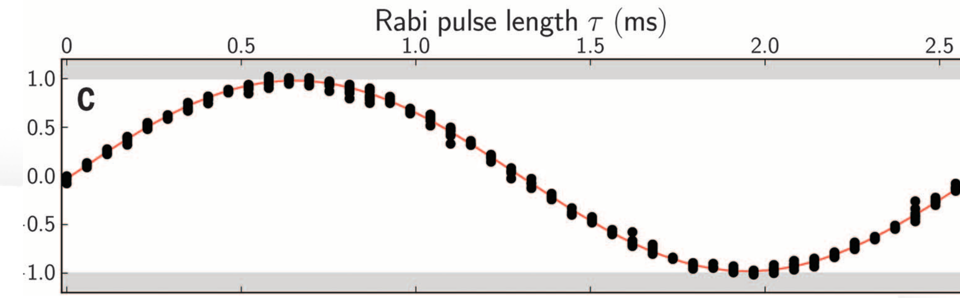

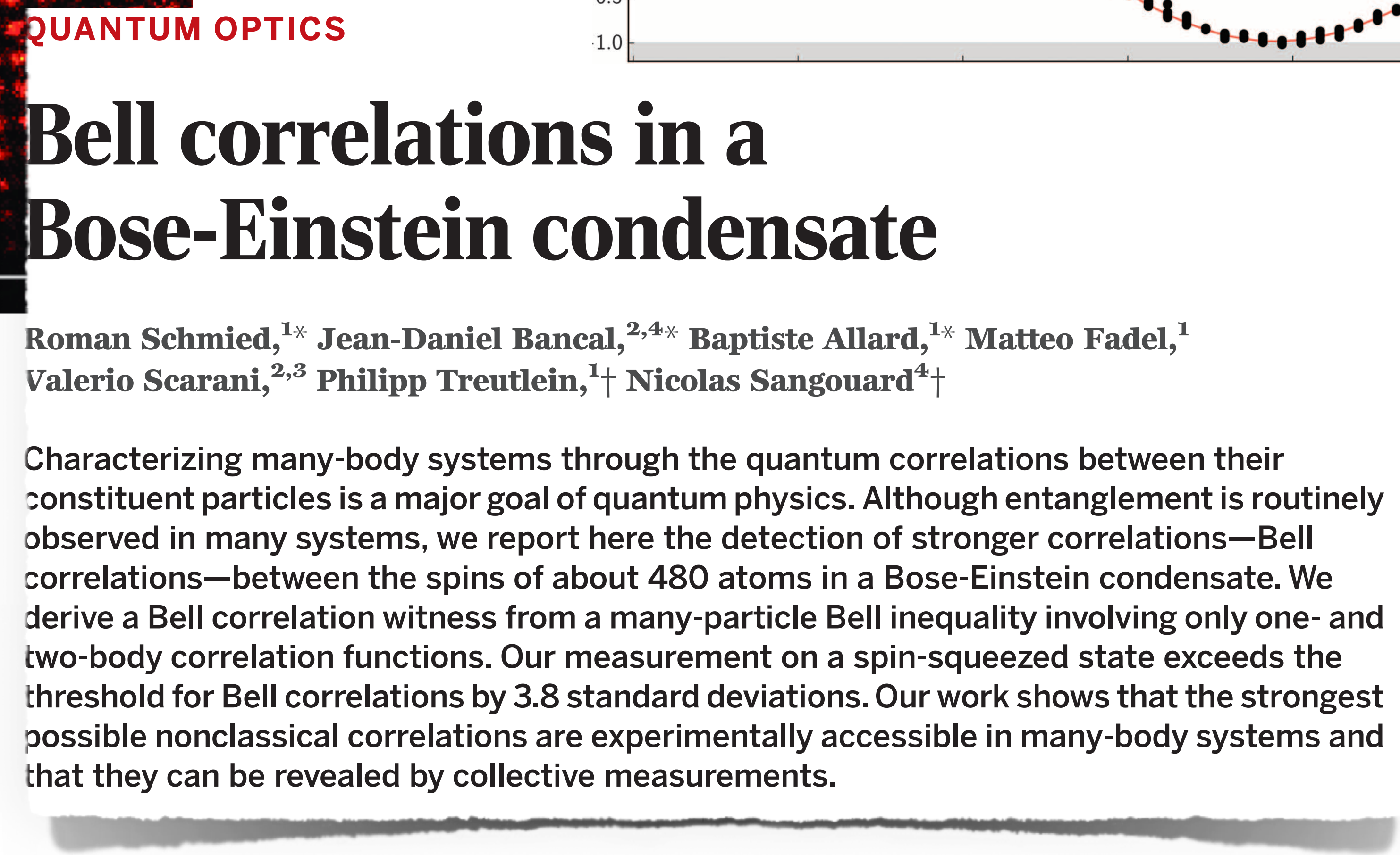

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Under what conditions could the result **falsify Quantum Theory**?

Conclusions

- "**Spacetime boxes**" via group representation theory.

- Foundational insights: study of **interplay probability vs. spacetime**, exact characterization of the **quantum (2,2,2)-correlations**.

- Towards protocols: **bounding representation labels** as a physically well-motivated assumption. "Proof of principle" nonlocality certification.

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