

Teletransporte quântico

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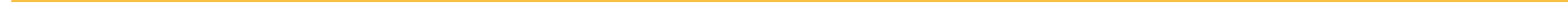
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01

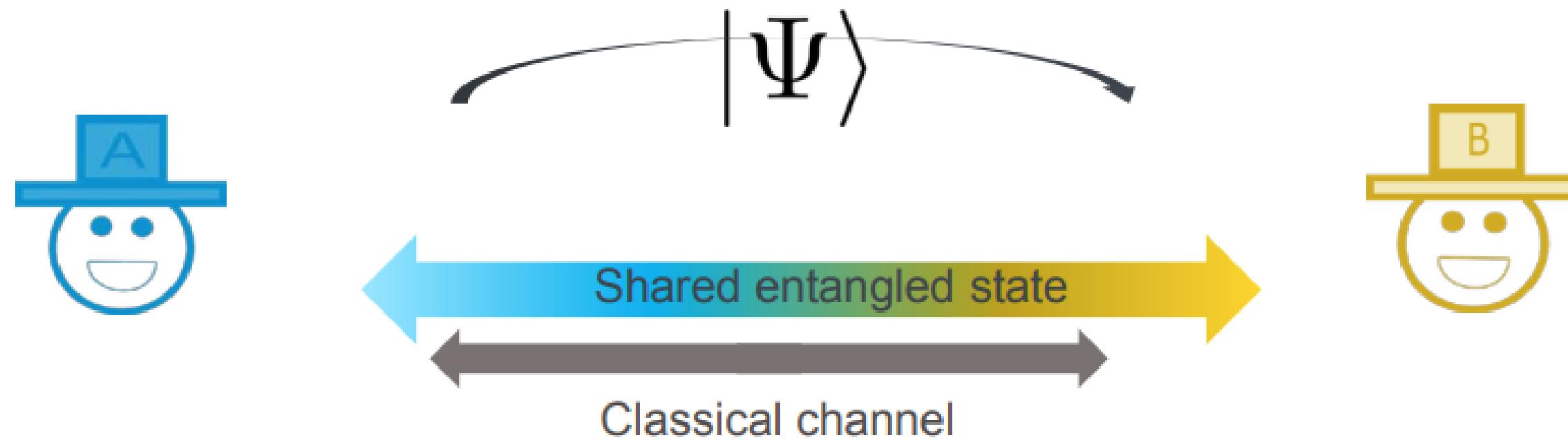


MOTIVAÇÃO E PASSO A PASSO



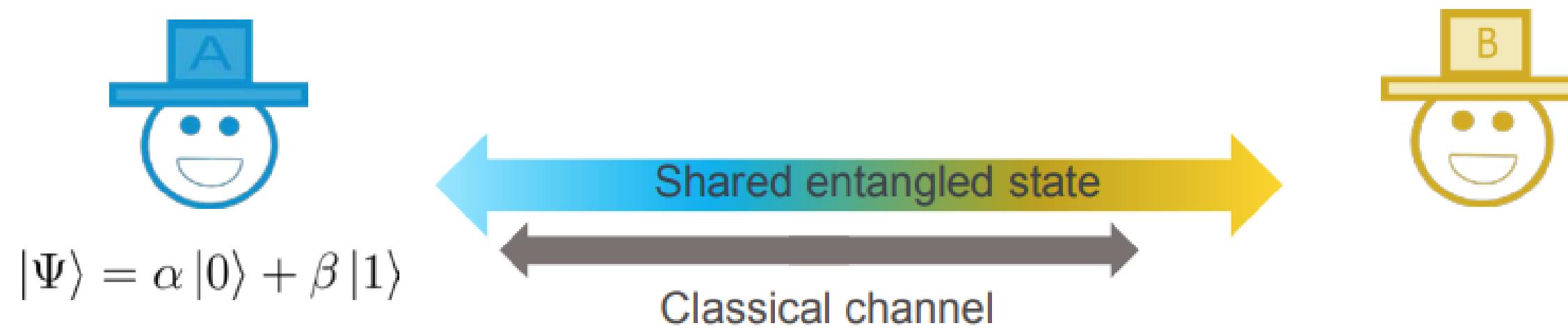
Esquematização

- *Objetivo:* Transmitir um estado quântico de A (Alice) para B (Bob) sem enviá-lo diretamente!



Source: Barz Group - University of Stuttgart

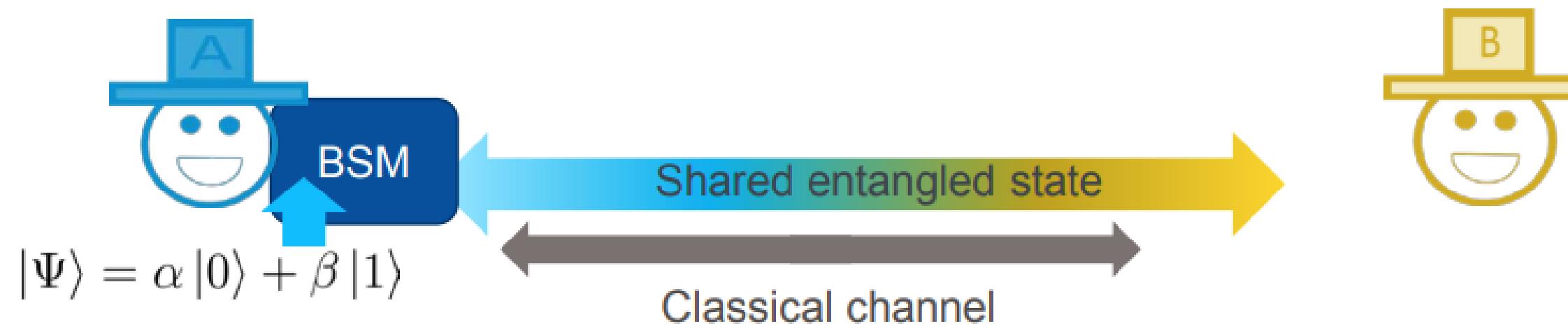
- Alice: Tem o estado quântico $|\Psi\rangle$ e uma metade de um estado emaranhado (ex. um fóton do estado de Bell)
- Bob: Tem a outra metade do estado emaranhado (o outro fóton do estado de Bell)



Source: Barz Group - University of Stuttgart

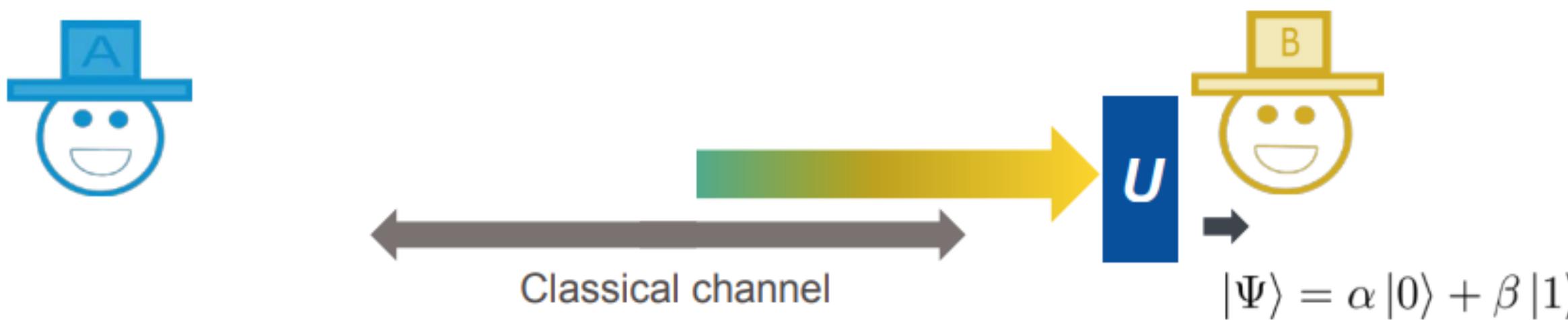
- Alice :

- Realiza uma medição de Bell (BSM) no estado e na sua metade do par emaranhado
- *Comunica o resultado a Bob (00, 01, 10, 11)*



Source: Barz Group - University of Stuttgart

- *Bob* :
 - Aplica um 'single-qubit correction U ' em seu estado, dependendo do resultado de Alice.
 - Obtém o estado $|\Psi\rangle$



02



ENTENDENDO O TELETRANSPORTE QUÂNTICO



Vamos mostrar como funciona o teletransporte quântico

Passo 1: Alice tem o estado $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

Passo 2: Alice e Bob partilham do estado emaranhado $|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|0\rangle_A|0\rangle_B + |1\rangle_A|1\rangle_B)$

Passo 3: O estado total é

$$\begin{aligned} |\psi\rangle \otimes |\Phi^+\rangle &= \frac{1}{\sqrt{2}}(\alpha|0\rangle \otimes (|00\rangle + |11\rangle) + \beta|1\rangle \otimes (|00\rangle + |11\rangle)) \\ &= \frac{1}{\sqrt{2}}(\alpha|000\rangle + \alpha|011\rangle + \beta|100\rangle + \beta|111\rangle) \end{aligned}$$

O estado total pode ser reescrito como

$$|\Psi_{\text{full}}\rangle = |\Psi\rangle |\Phi^+\rangle = \alpha |000\rangle + \alpha |011\rangle + \beta |100\rangle + \beta |111\rangle$$

Passo 4: Usando

$$\begin{aligned} |00\rangle &= \frac{1}{\sqrt{2}} (|\Phi^+\rangle + |\Phi^-\rangle) & |01\rangle &= \frac{1}{\sqrt{2}} (|\Psi^+\rangle + |\Psi^-\rangle) \\ |10\rangle &= \frac{1}{\sqrt{2}} (|\Psi^+\rangle - |\Psi^-\rangle) & |11\rangle &= \frac{1}{\sqrt{2}} (|\Phi^+\rangle - |\Phi^-\rangle) \end{aligned}$$

Temos

$$\begin{aligned} |\Psi_{\text{full}}\rangle &= \frac{1}{2} (|\Phi^+\rangle (\alpha |0\rangle + \beta |1\rangle) + |\Phi^-\rangle (\alpha |0\rangle - \beta |1\rangle) \\ &\quad + |\Psi^+\rangle (\alpha |1\rangle + \beta |0\rangle) + |\Psi^-\rangle (\alpha |1\rangle - \beta |0\rangle)) \end{aligned}$$

Em outras palavras

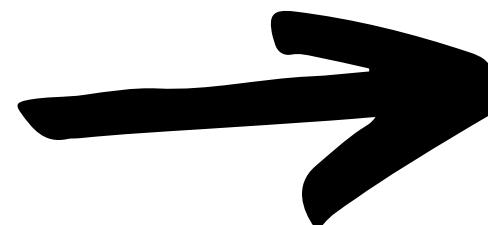
$$\begin{array}{cc}
 \textbf{Alice's 2-} & \textbf{Alice's 2-} \\
 \textbf{qubit state} & \textbf{qubit state} \\
 \textbf{Bob's qubit} & \textbf{Bob's qubit} \\
 \hline
 |\Psi\rangle = \frac{1}{2} \left[|\phi^+\rangle_{A'A} (\alpha|0\rangle_B + \beta|1\rangle_B) \right] + \frac{1}{2} \left[|\phi^-\rangle_{A'A} (\alpha|0\rangle_B - \beta|1\rangle_B) \right] \\
 + \frac{1}{2} \left[|\psi^+\rangle_{A'A} (\beta|0\rangle_B + \alpha|1\rangle_B) \right] + \frac{1}{2} \left[|\psi^-\rangle_{A'A} (-\beta|0\rangle_B + \alpha|1\rangle_B) \right]
 \end{array}$$

Alice's 2-	Bob's qubit	Alice's 2-	Bob's qubit
qubit state		qubit state	

Passo 5: Se Bob conhece o resultado de Alice, ele pode aplicar as correções e obter o estado original de entrada!

Bob's State	Gate Applied
$(\alpha 0\rangle + \beta 1\rangle)$	I
$(\alpha 1\rangle + \beta 0\rangle)$	X
$(\alpha 0\rangle - \beta 1\rangle)$	Z
$(\alpha 1\rangle - \beta 0\rangle)$	ZX

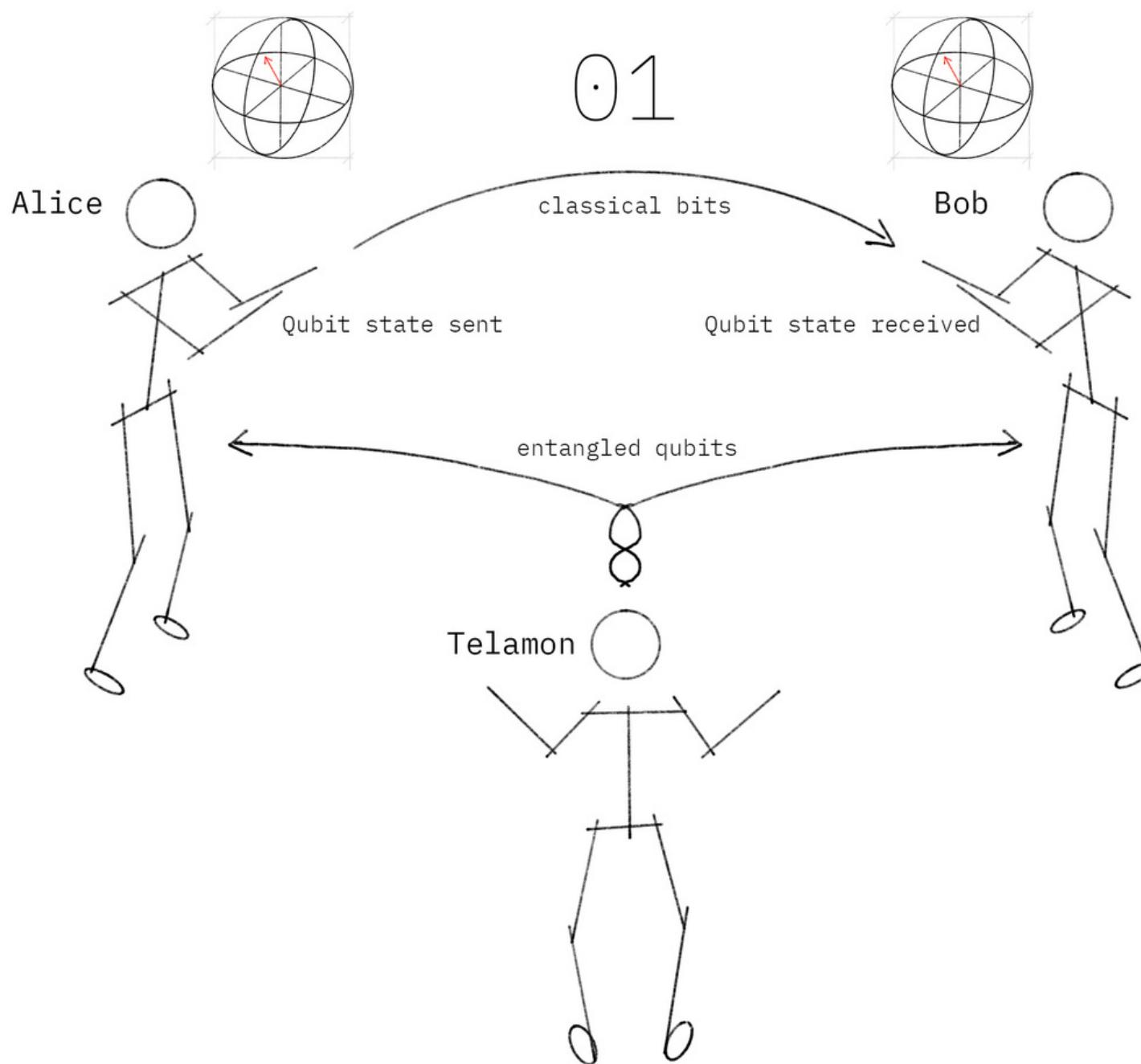
$$\begin{aligned}
(H \otimes I \otimes I)(CNOT \otimes I)(|\psi\rangle \otimes |e\rangle) &= (H \otimes I \otimes I)(CNOT \otimes I) \frac{1}{\sqrt{2}} (\alpha|000\rangle + \alpha|011\rangle + \beta|100\rangle + \beta|111\rangle) \\
&= (H \otimes I \otimes I) \frac{1}{\sqrt{2}} (\alpha|000\rangle + \alpha|011\rangle + \beta|110\rangle + \beta|101\rangle) \\
&= \frac{1}{2} (\alpha(|000\rangle + |011\rangle + |100\rangle + |111\rangle) + \beta(|010\rangle + |001\rangle - |110\rangle - |101\rangle))
\end{aligned}$$



$$\begin{aligned}
&= \frac{1}{2} (|00\rangle(\alpha|0\rangle + \beta|1\rangle) \\
&\quad + |01\rangle(\alpha|1\rangle + \beta|0\rangle) \\
&\quad + |10\rangle(\alpha|0\rangle - \beta|1\rangle) \\
&\quad + |11\rangle(\alpha|1\rangle - \beta|0\rangle))
\end{aligned}$$



Teletransporte quântico

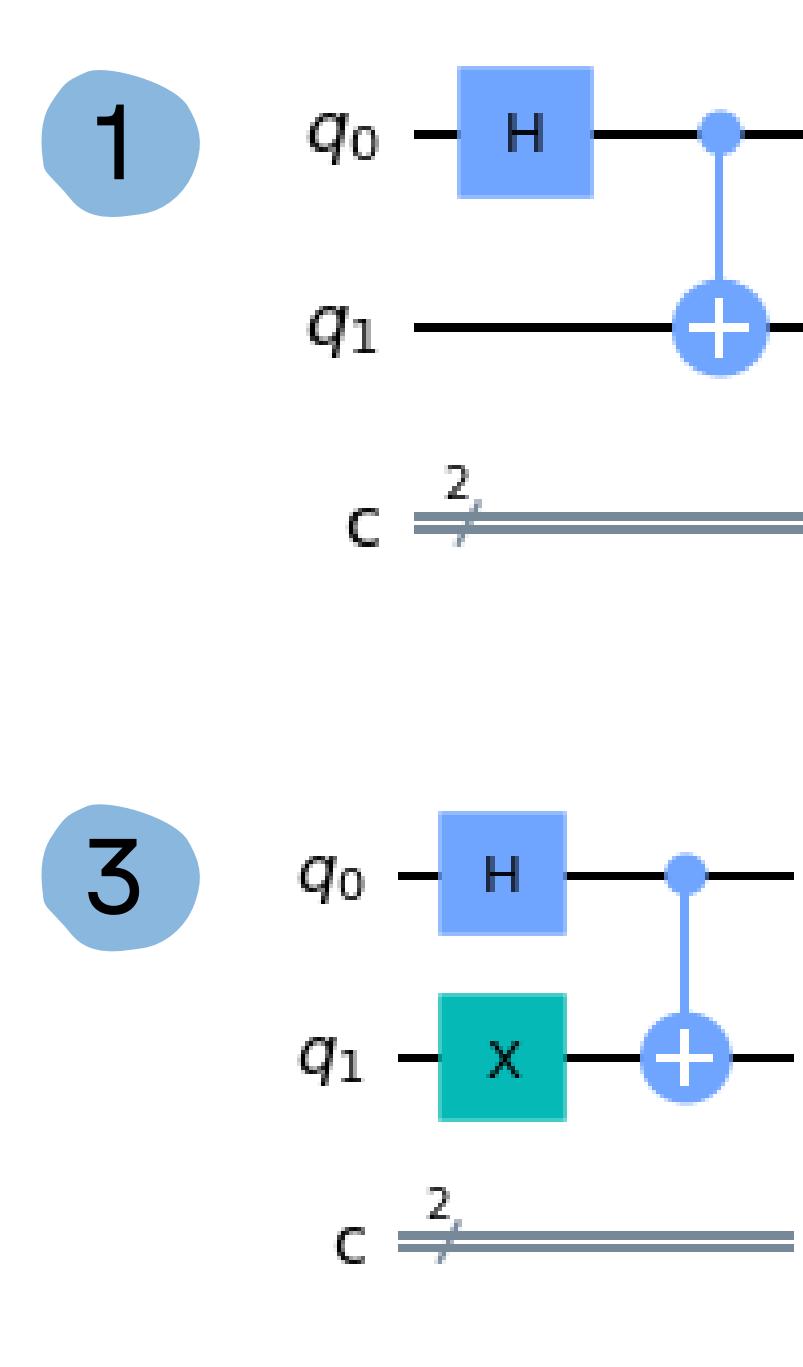


Source: Qiskit textbook



Estados de Bell

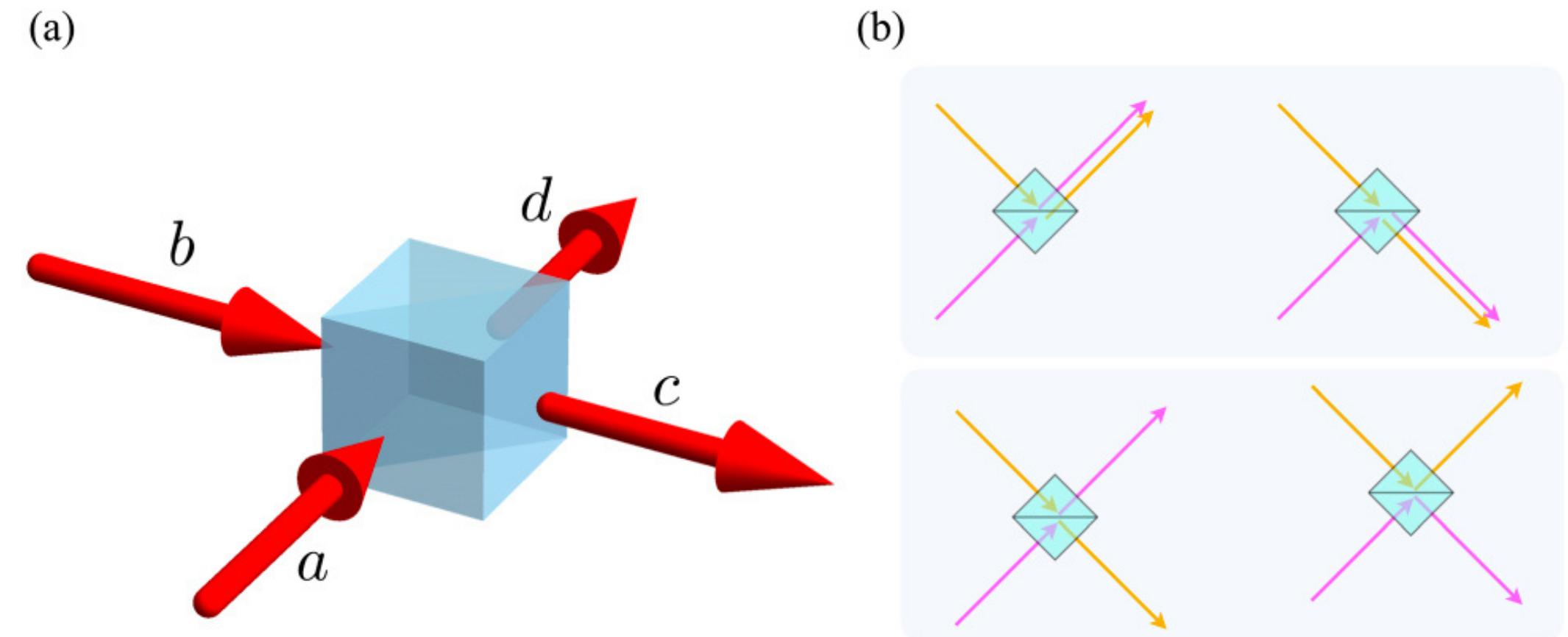
1. $|\Phi^+\rangle = \frac{1}{\sqrt{2}}[|00\rangle + |11\rangle]$
2. $|\Phi^-\rangle = \frac{1}{\sqrt{2}}[|00\rangle - |11\rangle]$
3. $|\Psi^+\rangle = \frac{1}{\sqrt{2}}[|01\rangle + |10\rangle]$
4. $|\Psi^-\rangle = \frac{1}{\sqrt{2}}[|01\rangle - |10\rangle]$



Medição fotônica de estados de Bell

1. $|\Phi^+\rangle = \frac{1}{\sqrt{2}}[|00\rangle + |11\rangle]$
2. $|\Phi^-\rangle = \frac{1}{\sqrt{2}}[|00\rangle - |11\rangle]$
3. $|\Psi^+\rangle = \frac{1}{\sqrt{2}}[|01\rangle + |10\rangle]$
4. $|\Psi^-\rangle = \frac{1}{\sqrt{2}}[|01\rangle - |10\rangle]$

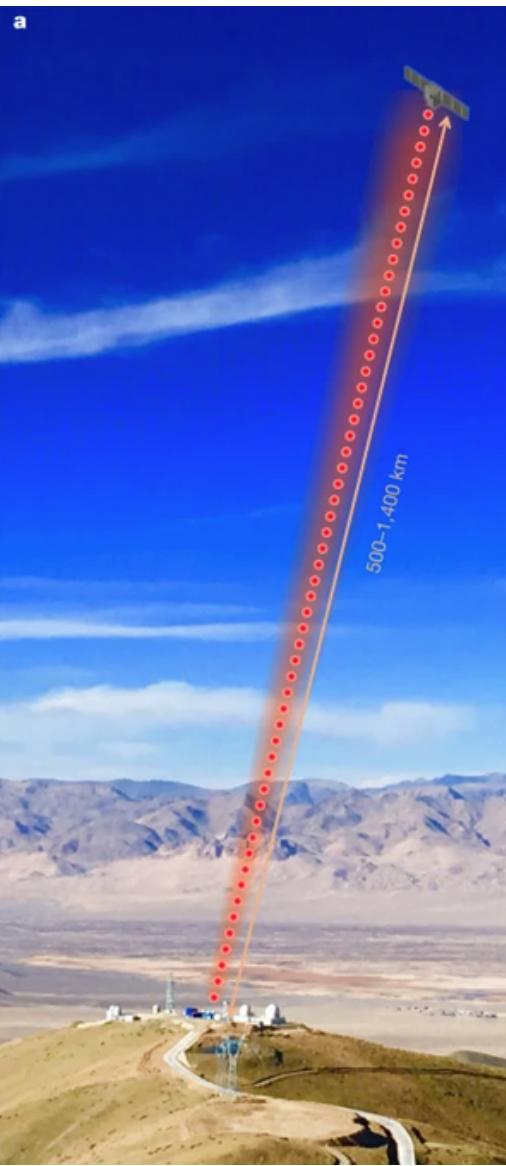
- *Hong-Ou-Mandel (HOM) effect*



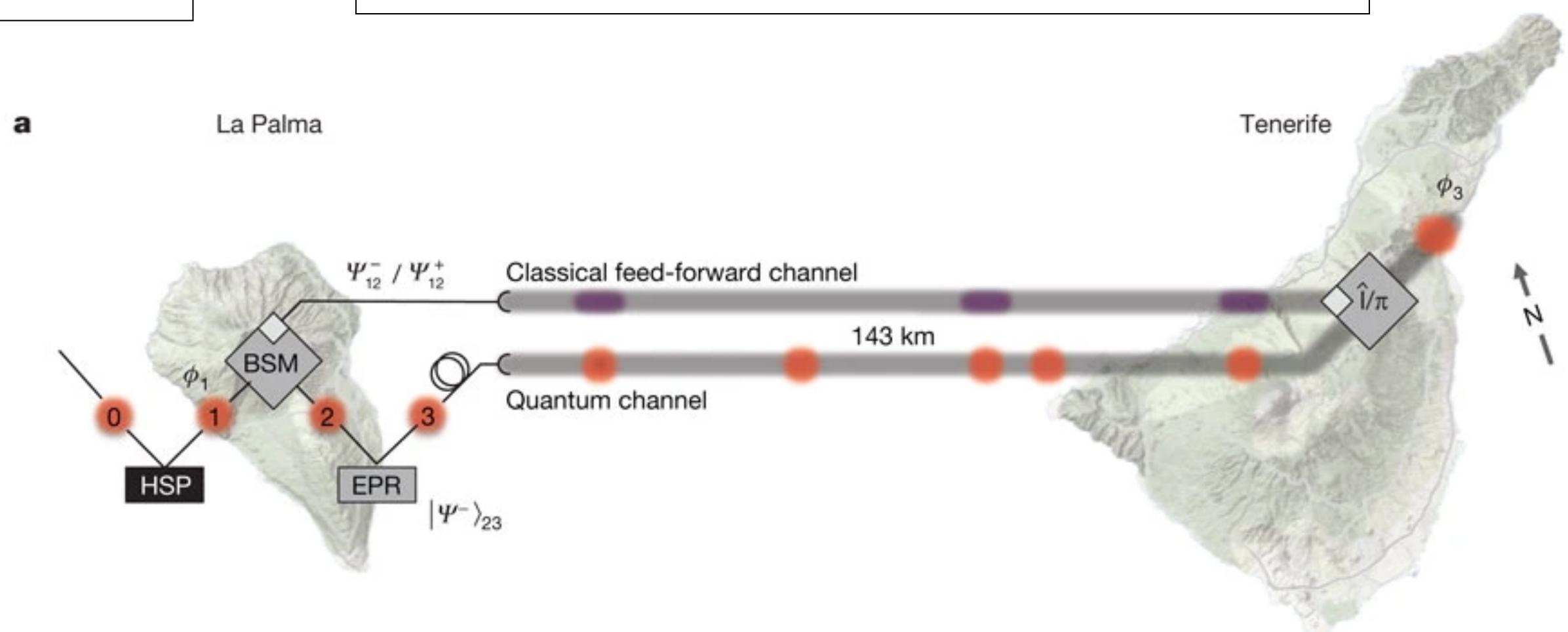
<https://iopscience.iop.org/article/10.1088/1361-6633/abcd7a>

Experimentos

Ground-to-satellite quantum teleportation
(em distâncias de até 1400 km)



Quantum teleportation over 143 kilometres
using active feed-forward



Ma et al., Nature 489, 269(2012)

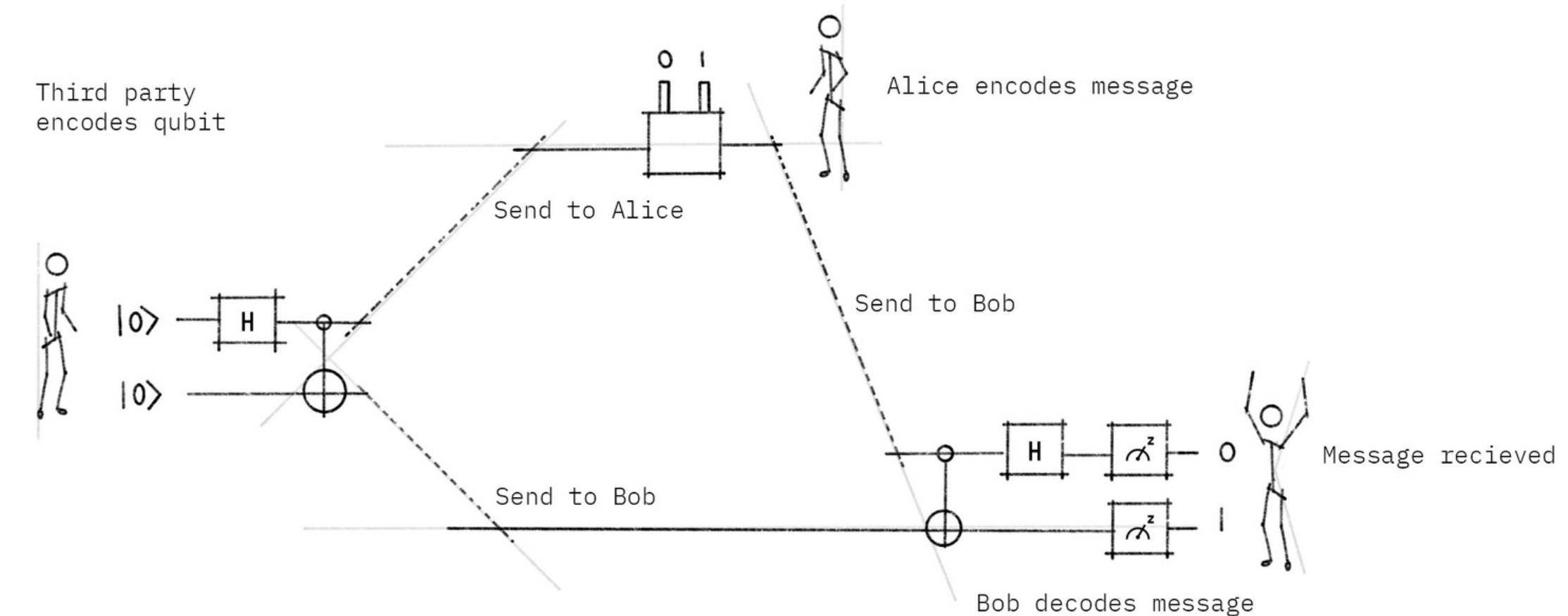
Ren at al., Nature 549, 70 (2017)



Teletransporte quântico

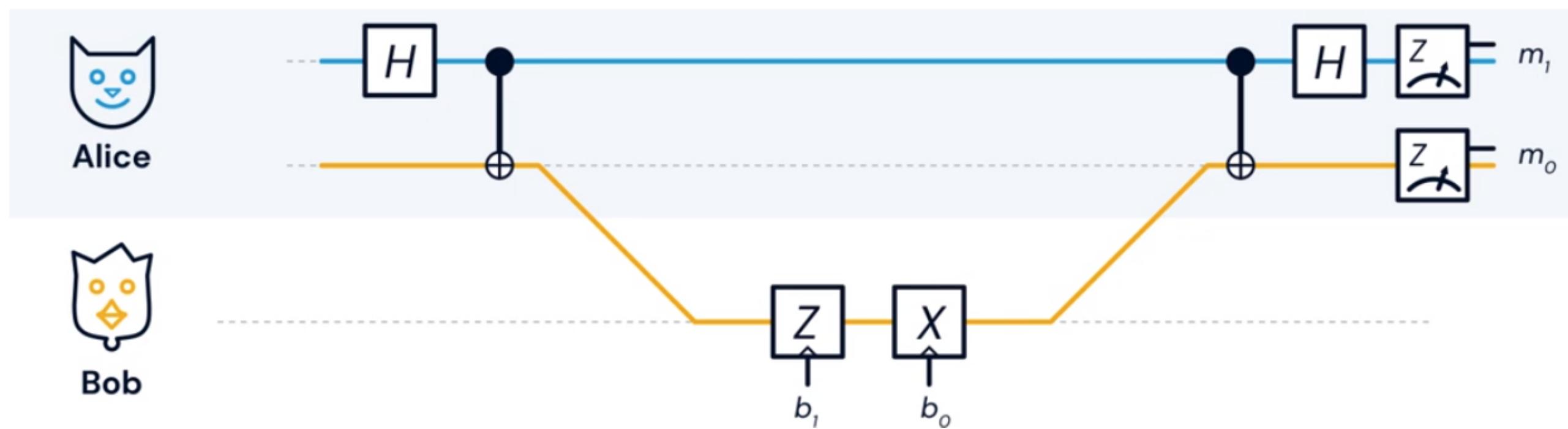
Codificação superdensa

Codificação superdensa



- A codificação superdensa é um protocolo de comunicação que permite que dois bits de informação sejam enviados usando um único qubit
- Como? Emaranhando, é claro!
- O protocolo de teleportação pode ser pensado como uma versão virada do protocolo de codificação superdensa, no sentido de que Alice e Bob simplesmente "trocaram seus equipamentos".

Source: Qiskit textbook



Source: QuTech Academy

3

Recap

Alice é capaz de teletransportar com sucesso um qubit para Bob.

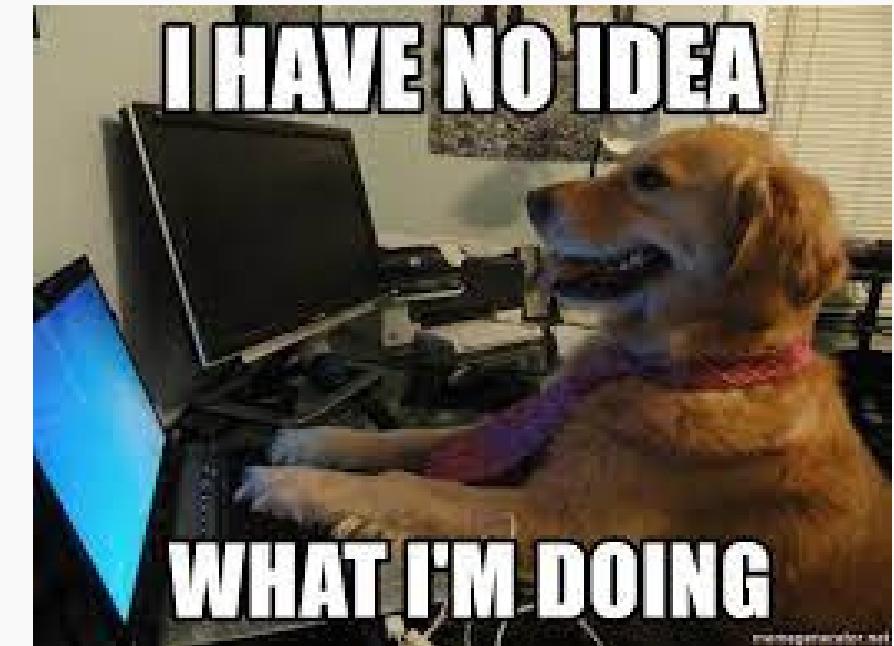
Alice e Bob não se comunicaram mais rápido do que a velocidade da luz. Alice teve que dizer a Bob quais eram suas duas medidas, e isto teve que ser feito através de algum canal de comunicação clássico, que por definição é mais lento do que a velocidade da luz.

Alice acaba destruindo seu qubit ao teletransportar as informações para Bob e, portanto, não violamos o teorema da não clonagem.

04



IMPLEMENTAÇÃO EM QISKit



05



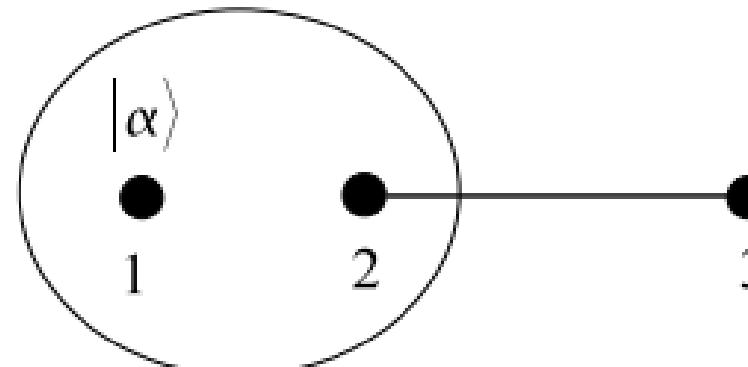
EXTRAS



1

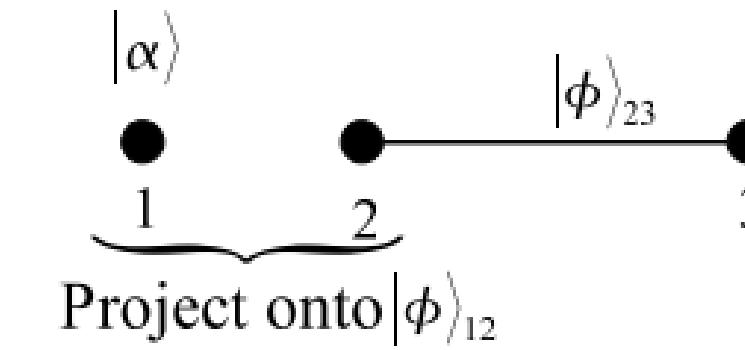
Computação quântica baseada em teletransporte

TQC



Bell measurement
outcome $|B_{cd}\rangle$

Teleported state
 $X^d Z^c |\alpha\rangle$



A projeção de $|\alpha\rangle_1 |\phi\rangle_{23}$ no $|\phi(U)\rangle_{12}$ resulta no estado $\frac{1}{d}U|\alpha\rangle_3$ no qubit 3



1WQC

qubit number	1	2	3	4	5
states	$ \psi\rangle$	$ +\rangle$	$ +\rangle$	$ +\rangle$	$ +\rangle$
entangle with CZ	*	●	●	●	●
measurements	X	$M(-\xi(-1)^{s_1})$	$M(-\eta(-1)^{s_2})$	$M(-\zeta(-1)^{s_1+s_3})$	
outcomes	s_1	s_2	s_3	s_4	

qubit 5 acquires the state
 $X^{s_2+s_4} Z^{s_1+s_3} U |\psi\rangle$

2

MBQC with Photons

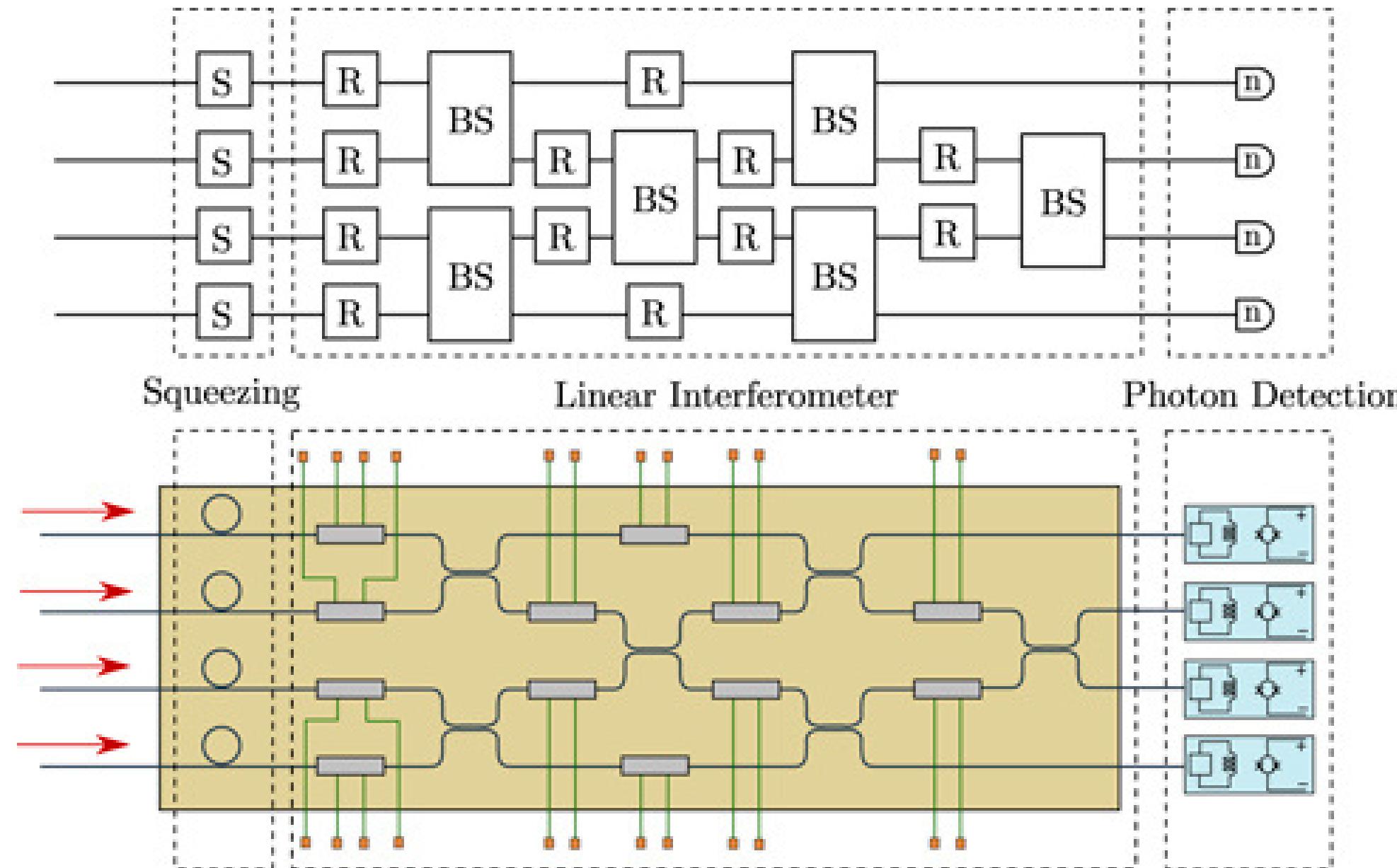
Blueprint for a Scalable Photonic Fault-Tolerant Quantum Computer

J. Eli Bourassa^{1,2,*}, Rafael N. Alexander^{1,3,4,*}, Michael Vasmer^{5,6}, Ashlesha Patil^{1,7}, Ilan Tzitrin^{1,2}, Takaya Matsuura^{1,8}, Daiqin Su¹, Ben Q. Baragiola^{1,4}, Saikat Guha^{1,7}, Guillaume Dauphinais¹, Krishna K. Sabapathy¹, Nicolas C. Menicucci^{1,4}, and Ish Dhand¹

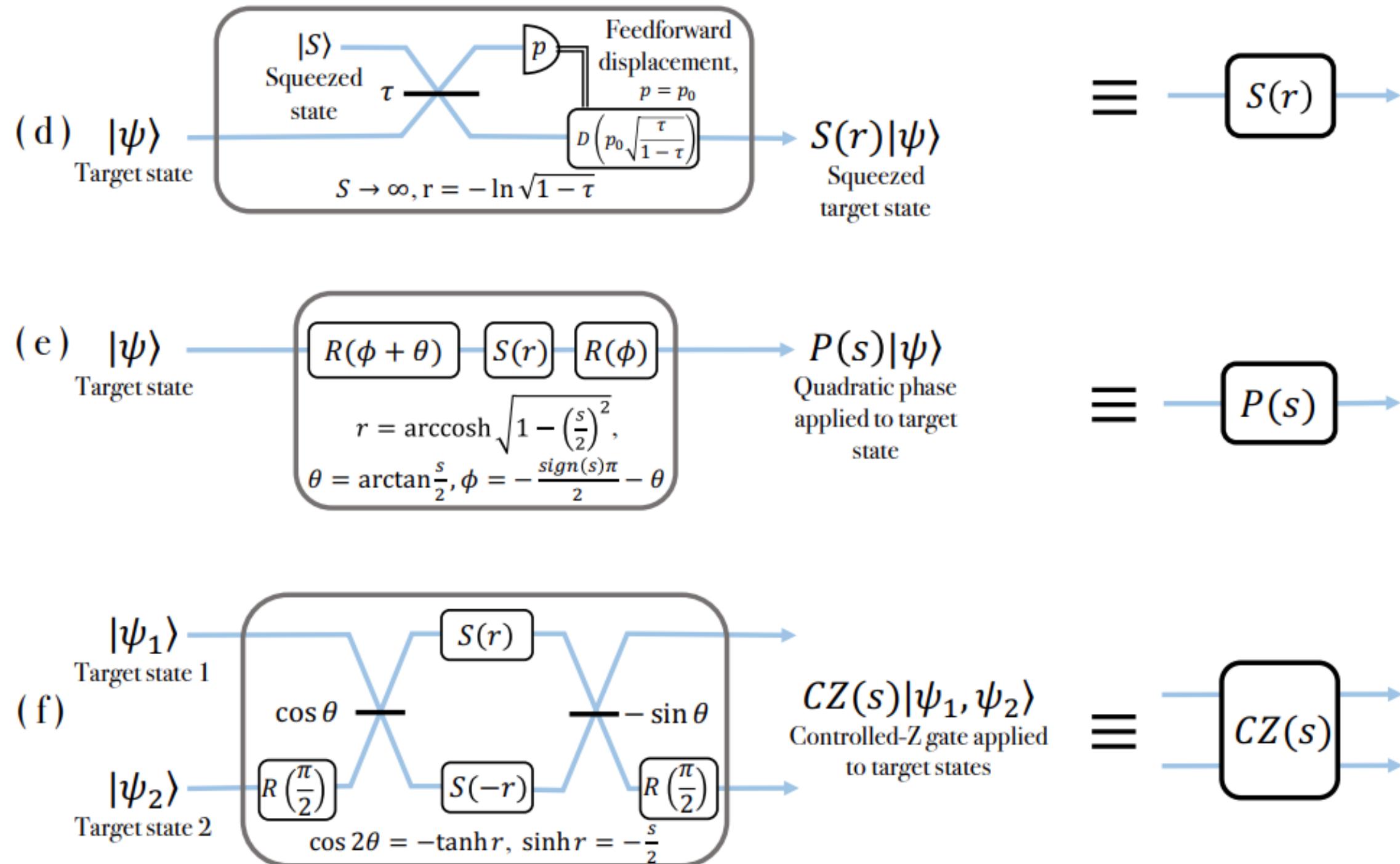
Fusion-based quantum computation

Sara Bartolucci, Patrick Birchall, Hector Bombin, Hugo Cable, Chris Dawson, Mercedes Gimeno-Segovia, Eric Johnston, Konrad Kieling, Naomi Nickerson, Mihir Pant, Fernando Pastawski, Terry Rudolph, Chris Sparrow

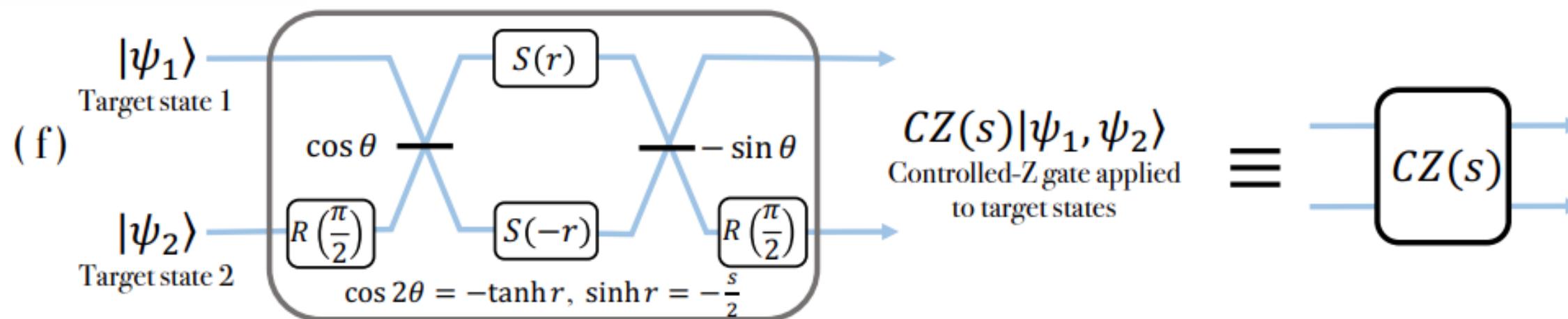
Esquematização do Chip da Xanadu



<https://iopscience.iop.org/article/10.1088/2058-9565/ab8504/meta>

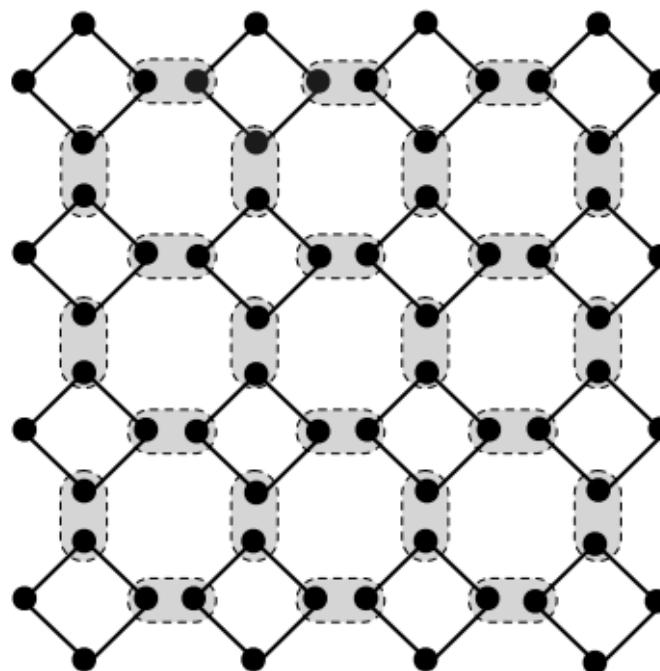


states	$ \psi\rangle$	$ +\rangle$	$ +\rangle$	$ +\rangle$	$ +\rangle$
entangle with CZ	*	●	●	●	●
measurements	X	$M(-\xi(-1)^{s_1})$	$M(-\eta(-1)^{s_2})$	$M(-\zeta(-1)^{s_1+s_3})$	
outcomes	s_1	s_2	s_3	s_4	

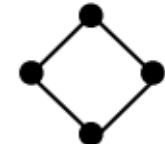


Esquematização do Chip da PsiQuantum

a) Fusion Network



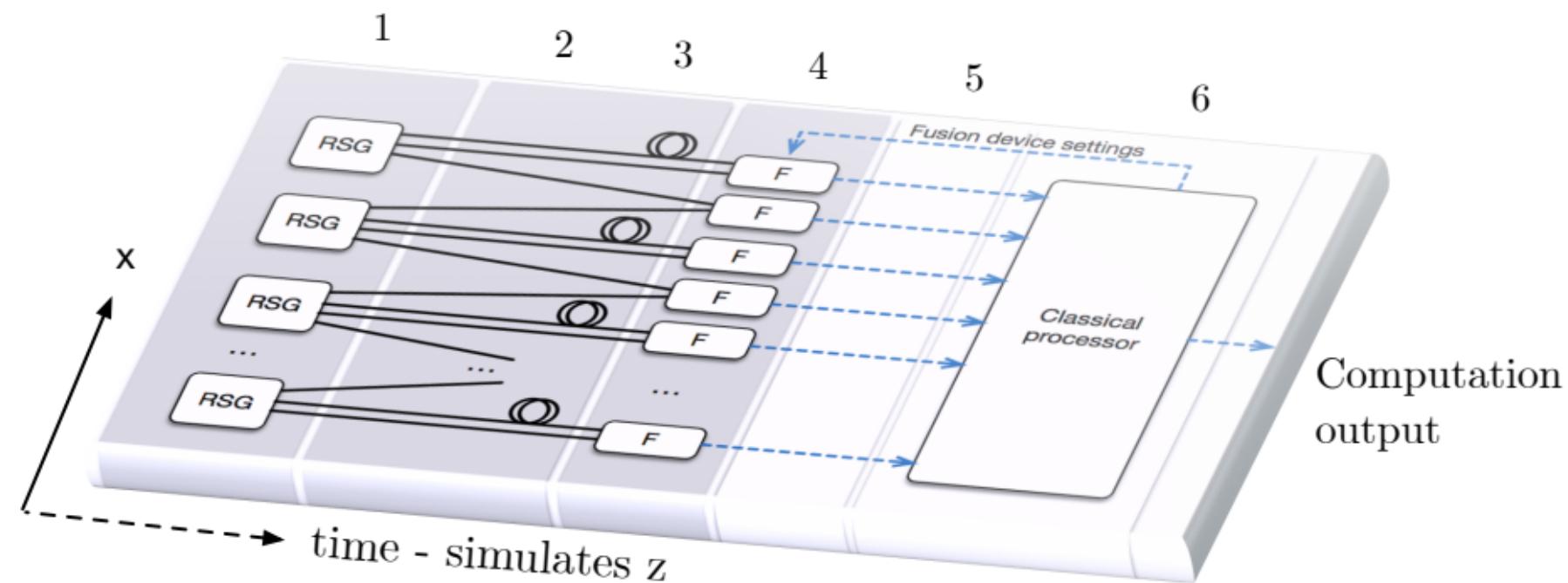
i) Resource states



ii) Fusion measurements



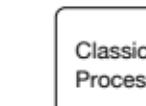
b) Fusion based quantum computing architecture



1. Resource state generators repeatedly create entangled states

2. Fusion network router sends qubits to fusion locations.

3. Delays - delay a qubit for one or more clockcycles.



4. Fusion devices perform reconfigurable measurements

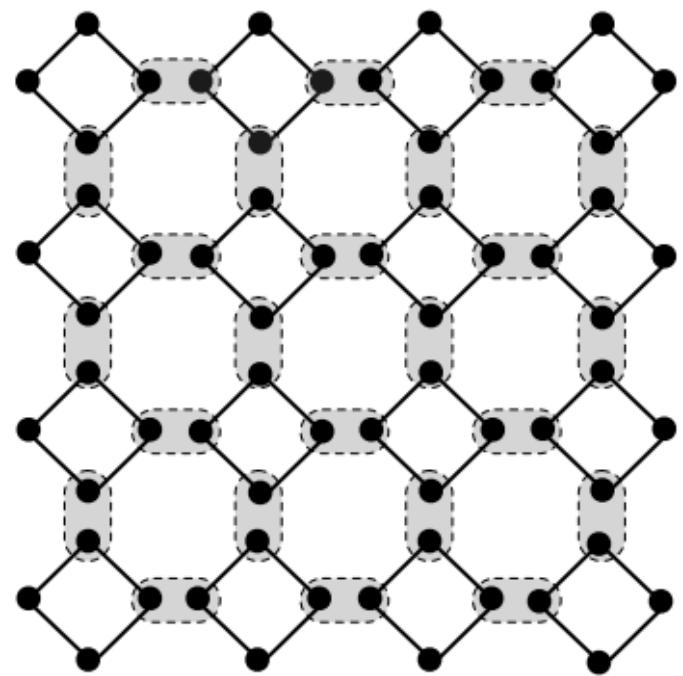
5. Classical signal transmission

6. Classical Processor - decoding and algorithm feedforward

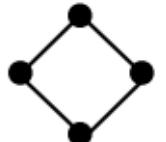


Esquematização do Chip da PsiQuantum

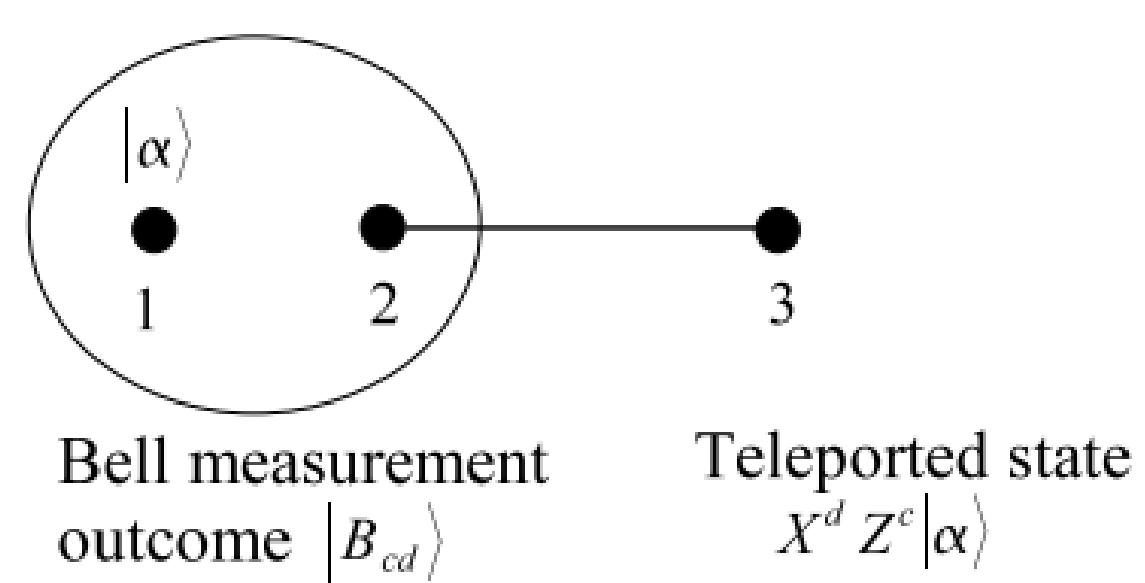
a) Fusion Network

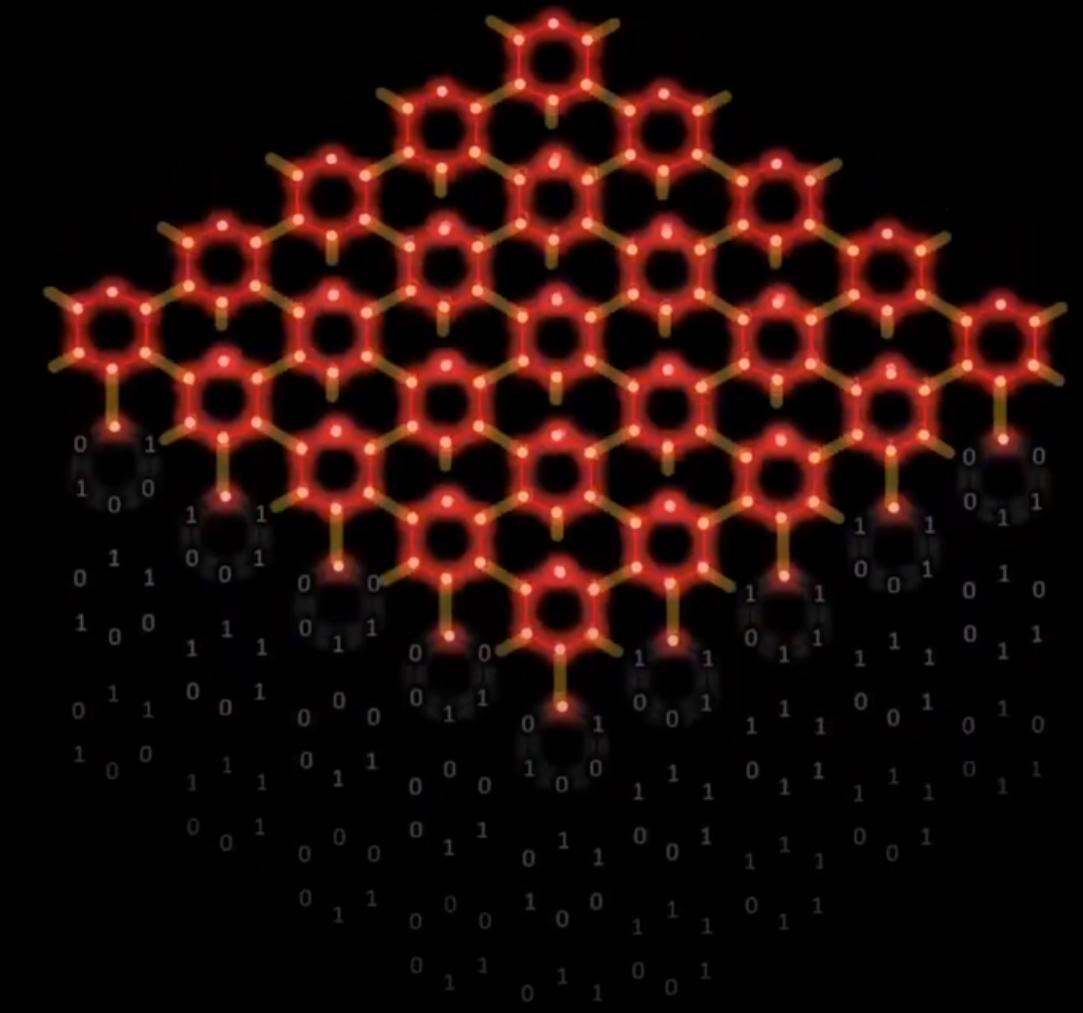
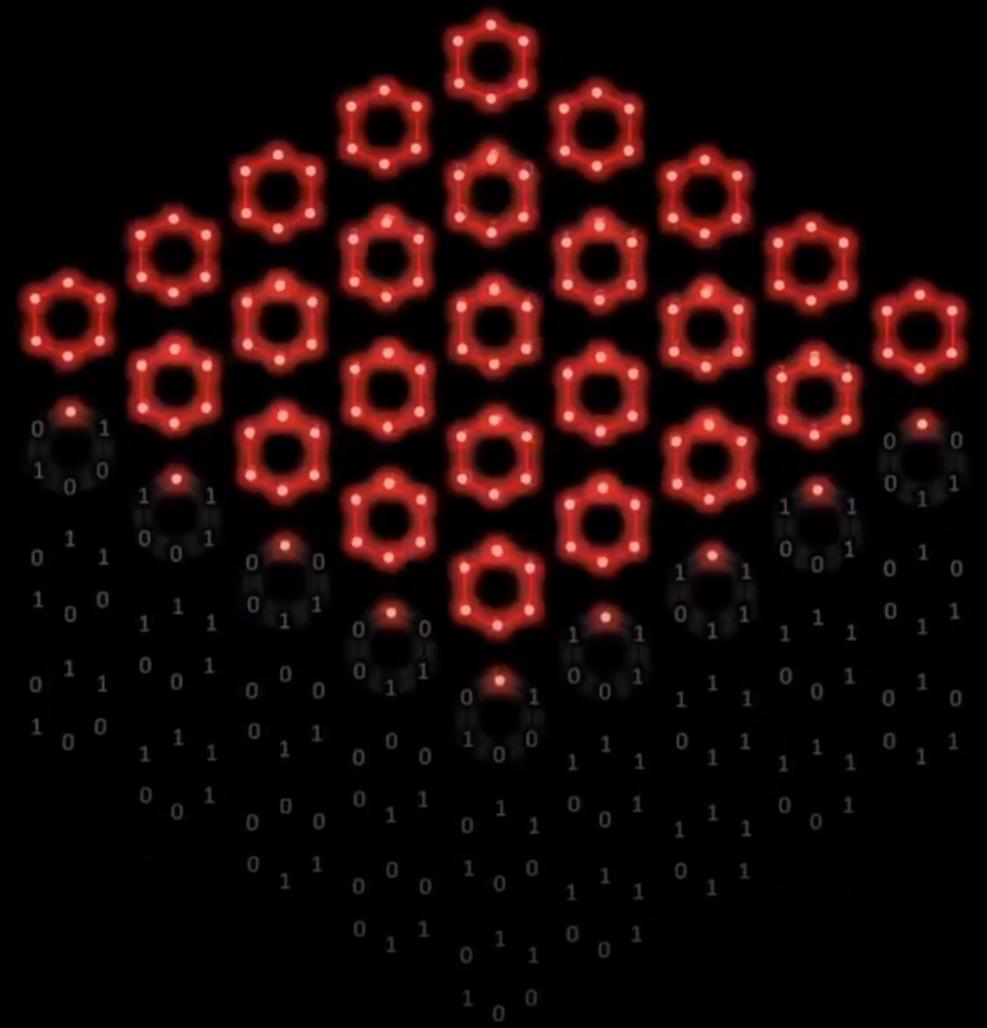
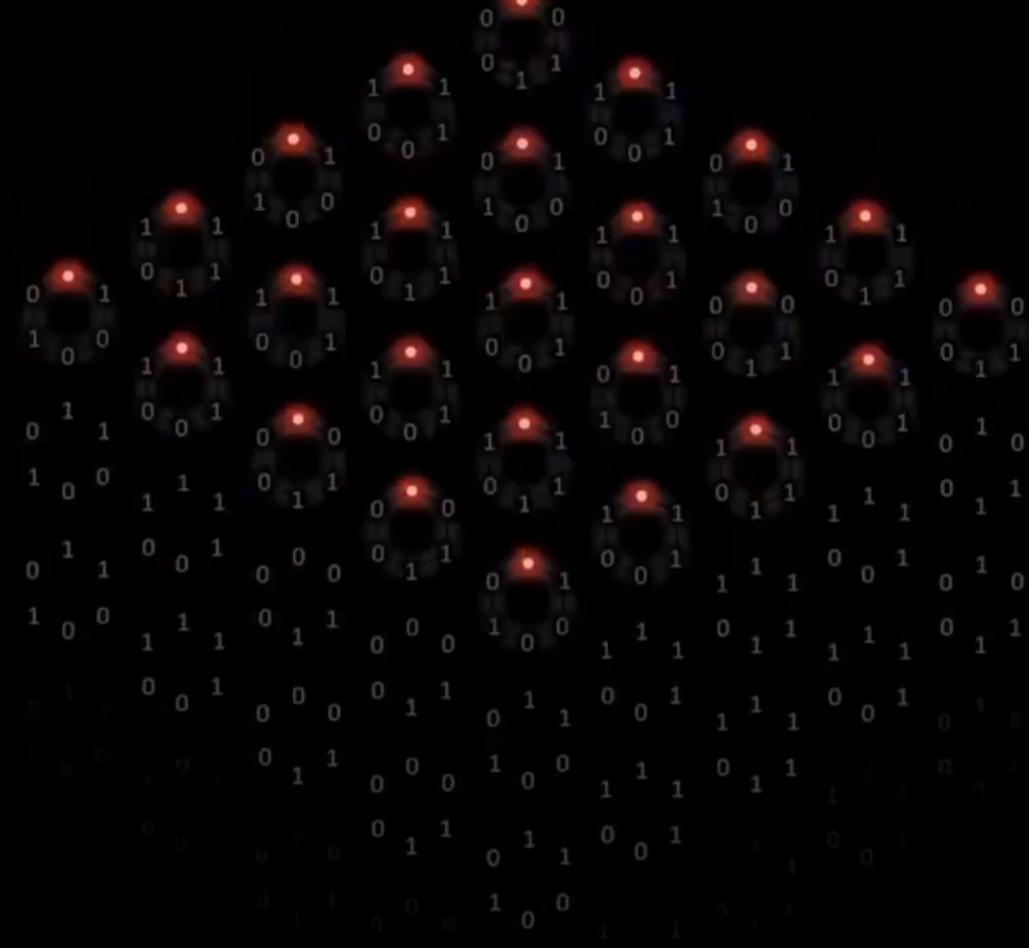


i) Resource states



ii) Fusion measurements

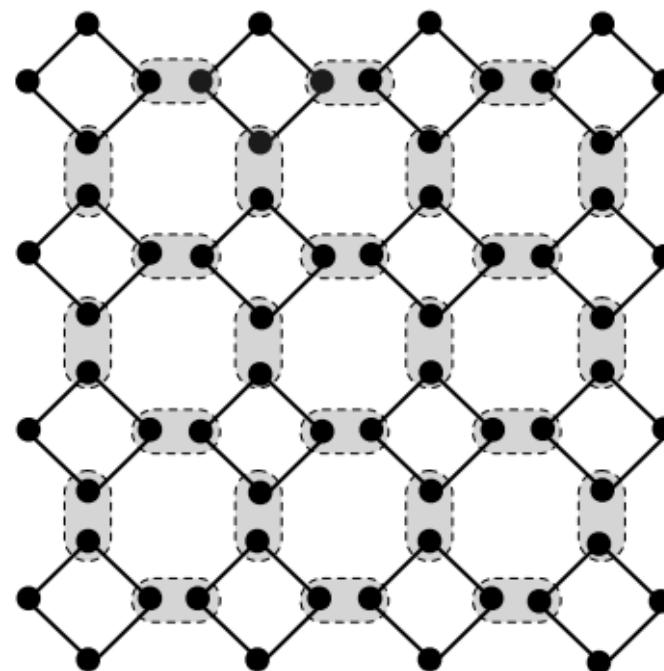




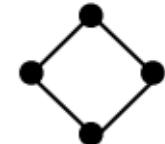
Source: PsiQuantum

Esquematização do Chip da PsiQuantum

a) Fusion Network



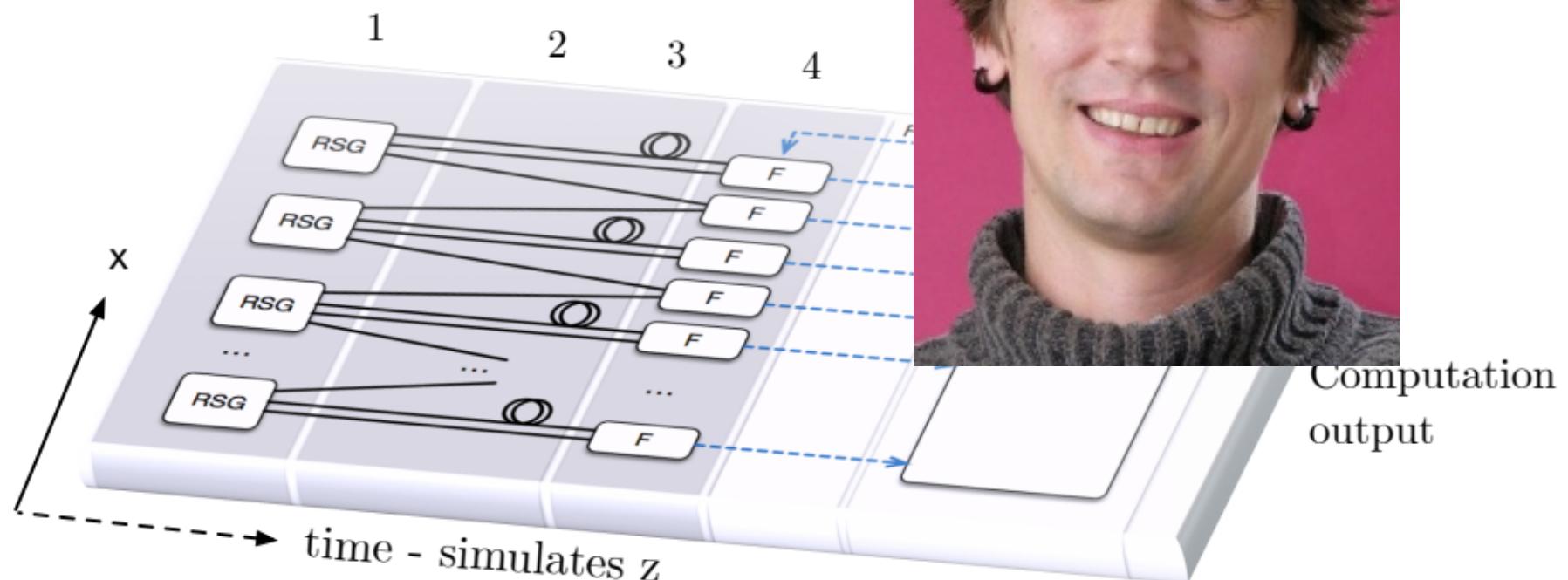
i) Resource states



ii) Fusion measurements



b) Fusion based quantum computing architecture



1. Resource state generators repeatedly create entangled states



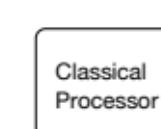
2. Fusion network router sends qubits to fusion locations.



3. Delays - delay a qubit for one or more clockcycles.



4. Fusion devices perform reconfigurable measurements

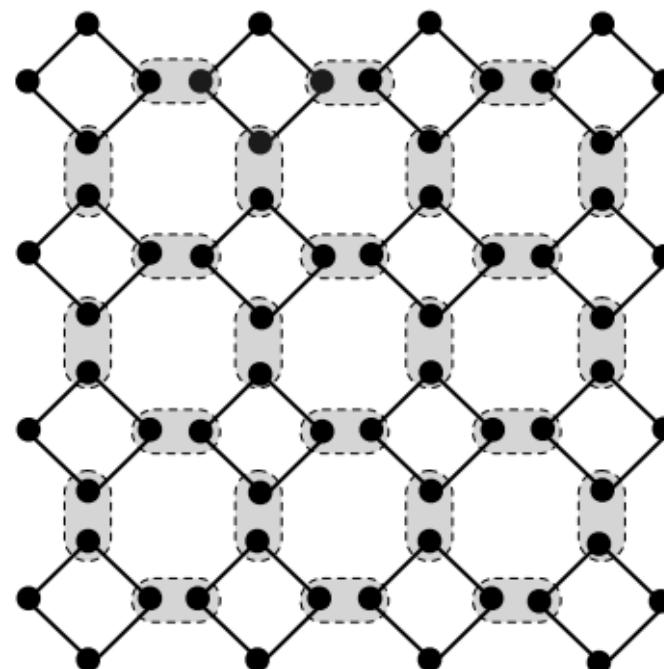


5. Classical signal transmission

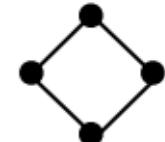
6. Classical Processor - decoding and algorithm feedforward

Esquematização do Chip da PsiQuantum

a) Fusion Network



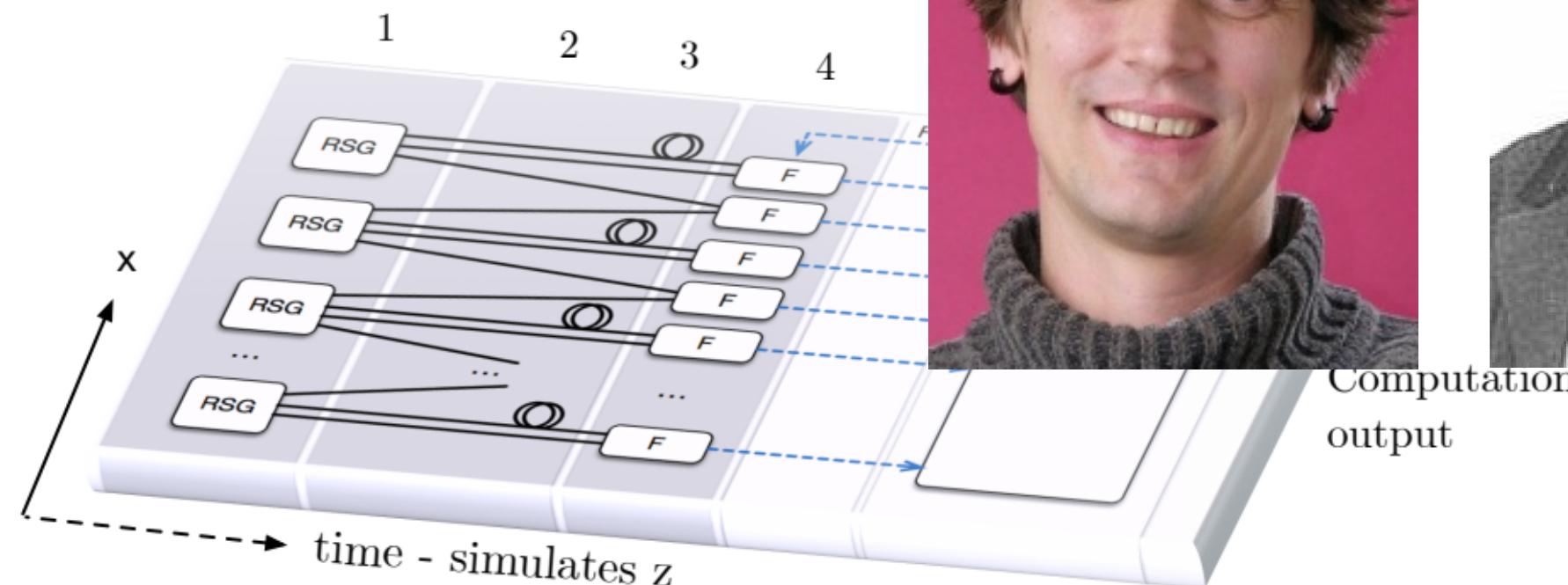
i) Resource states



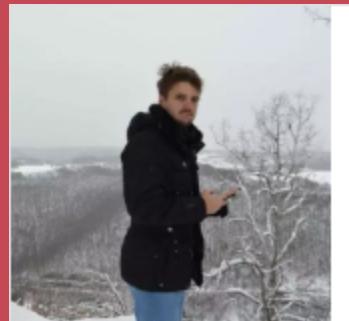
ii) Fusion measurements



b) Fusion based quantum computing architecture



-  1. Resource state generators repeatedly create entangled states
-  4. Fusion devices perform reconfigurable measurements
-  2. Fusion network router sends qubits to fusion locations.
-  5. Classical signal transmission
- 3. Delays - delay a qubit for one or more clockcycles.
- 6. Classical Processor - decoding and algorithm feedforward



arthurfaria - Overview

Ph.D. candidate in Quantum Thermodynamics. arthurfaria has 18 repositories available. Follow their code on GitHub.

 GitHub



smendoncabruna - Overview

Ph.D. Candidate - Topological Quantum Computing. smendoncabruna has 13 repositories available. Follow their code on GitHub.

 GitHub

OBRIGADO!

Perguntas?



ooo

Lemma 1

A projeção de $|\alpha\rangle_1 |\phi\rangle_{23}$ no $|\phi\rangle_{12}$ resulta no estado $\frac{1}{d} |\alpha\rangle_3$ no qubit 3

$$|\alpha\rangle = \sum a_j |j\rangle \quad |\phi\rangle = \frac{1}{\sqrt{d}} \sum_{i=0}^{d-1} |i\rangle |i\rangle$$

$$\frac{1}{d} \left(\sum_i \langle i | \langle i | \right) \left(\sum_{jk} a_j |j\rangle |k\rangle |k\rangle \right) = \frac{1}{d} \sum_{ijk} a_j \delta_{ij} \delta_{ik} |k\rangle = \frac{1}{d} \sum_k a_k |k\rangle$$

Lemma 2

A projeção de $|\alpha\rangle_1 |\phi\rangle_{23}$ no $|\phi(U)\rangle_{12}$ resulta no estado $\frac{1}{d} U |\alpha\rangle_3$ no qubit 3

$$|U^\dagger a\rangle = U^\dagger |a\rangle \longrightarrow \langle U^\dagger a | b \rangle = \langle a | U b \rangle$$