RESOURCE-CONSTRAINED ENTANGLEMENT DISTRIBUTION AND QUANTUM COMPILATION

PhD Thesis

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1st of September, 2026

SUPERVISOR

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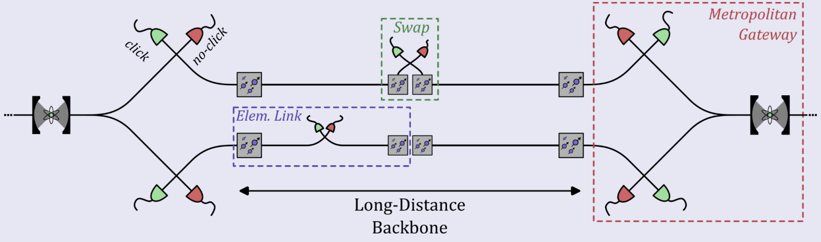
JURY MEMBERS

Sébastien Tanzilli (President), Mario Krenn (Referee), Wolfgang Dür (Referee), Hanna Le Jeannic (Examiner)

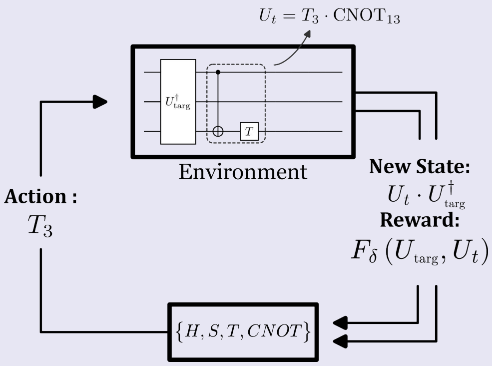
PhD Thesis:

Resource-Constrained

Entanglement Distribution *and* ***Quantum Compilation***



QUANTUM NETWORKS



QUANTUM CIRCUIT SYNTHESIS

Quantum Network

The QIA project

→ **The QIA project**

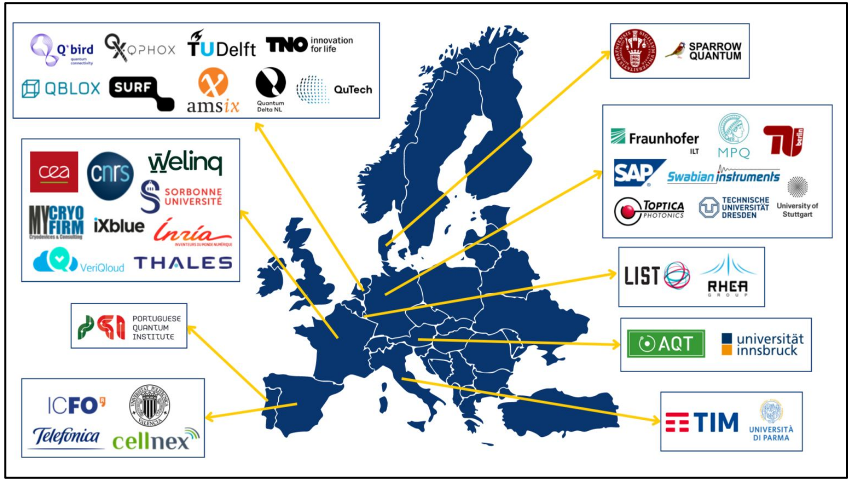
→ Brief introduction

→ Study of an elementary link

→ Entanglement witness

→ Short conclusion

QN - *The QIA Project*



QUANTUM INTERNET ALLIANCE

*Born of the desire of **sharing entanglement** between big cities in Europe*

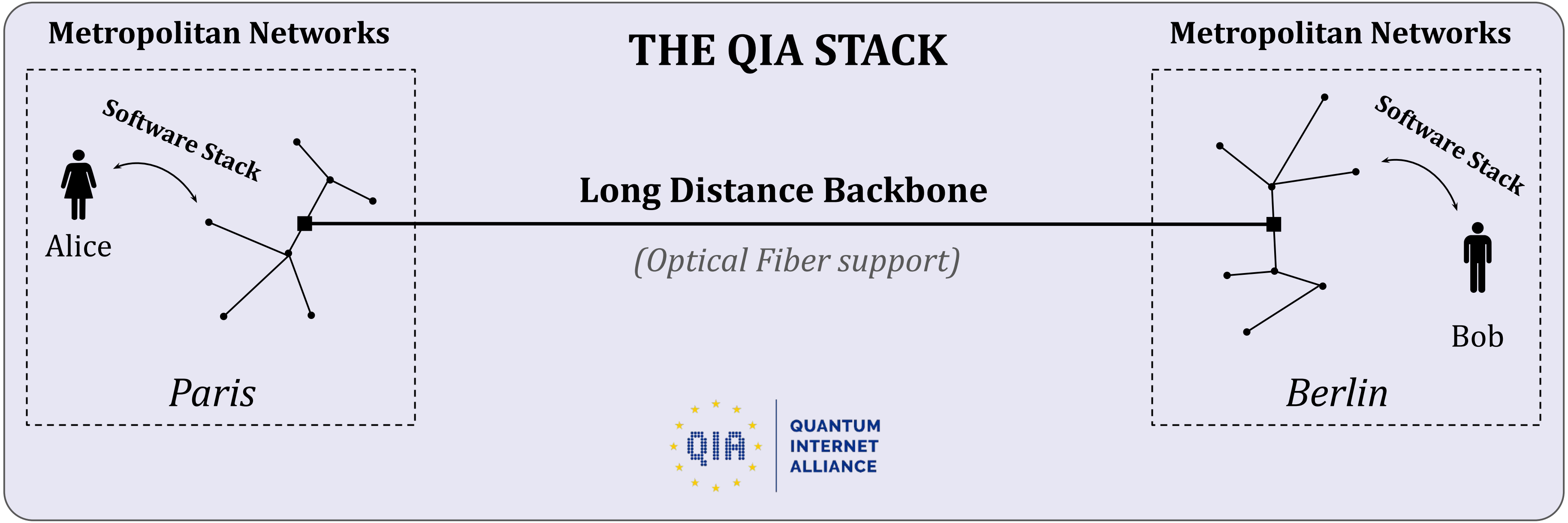
*Ambition to build a working 1^{st} generation quantum repeater **by 2030***

https://quantuminternetalliance.org

PURPOSE

Distribute a Bell pair between Alice and Bob

$$|\Psi^+\rangle = |10\rangle + |01\rangle$$



https://quantuminternetalliance.org

Quantum Network

Brief introduction

→ The QIA project

→ **Brief introduction**

→ Study of an elementary link

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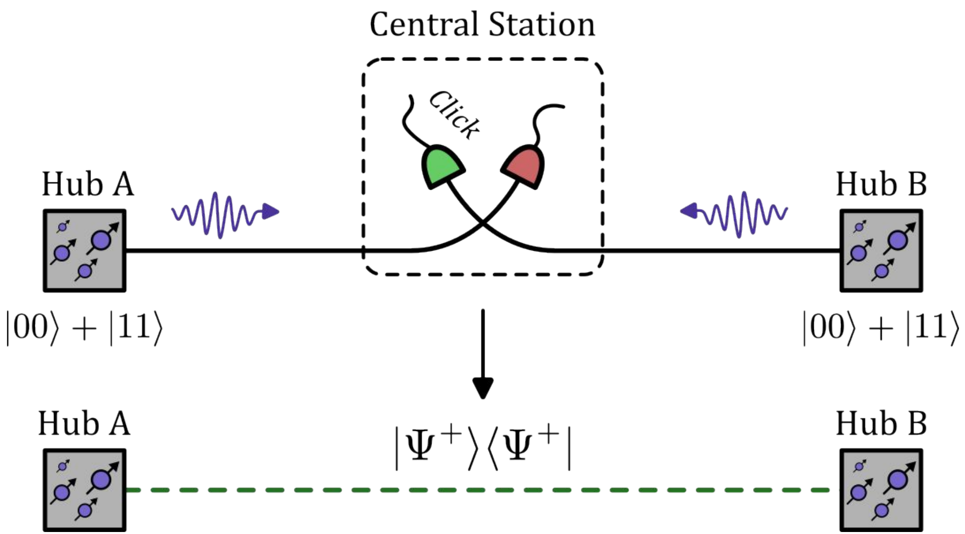
→ Short conclusion

GENERATING LONG-DISTANCE ENTANGLEMENT

Detection-in-mid-point

local Bell pair prepared in each hub



The single-click swaps the local entanglement to the remote hubs

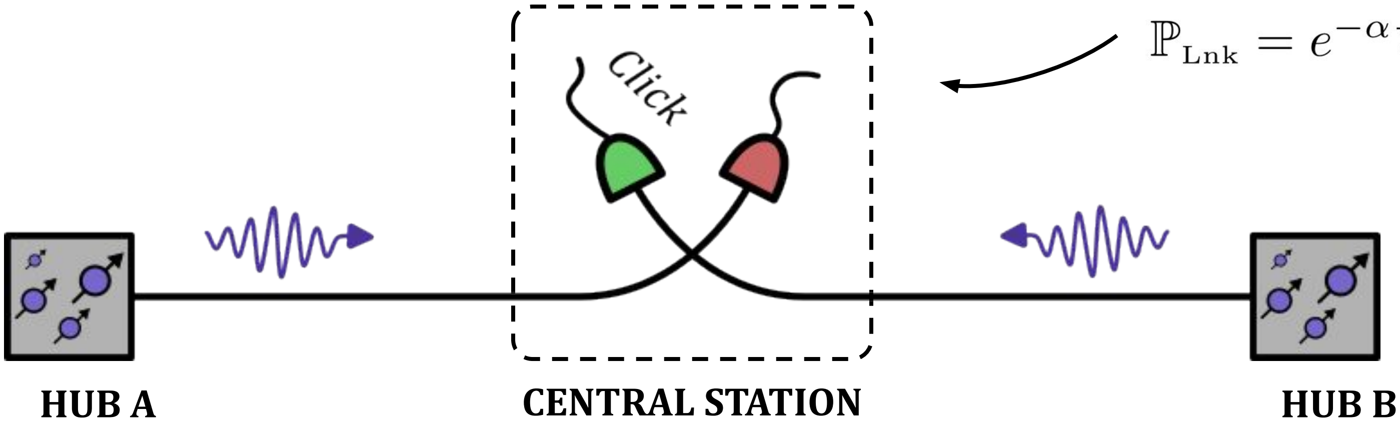
Sangouard, Simon, Riedmatten, and Gisin - Reviews of Modern Physics 83, 33 (2011)

GENERATING LONG-DISTANCE ENTANGLEMENT

Detection-in-mid-point

heralding based on single-photon propagation

$$\mathbb{P}_{\mathrm{Lnk}} = e^{-\alpha \frac{L}{10}}$$



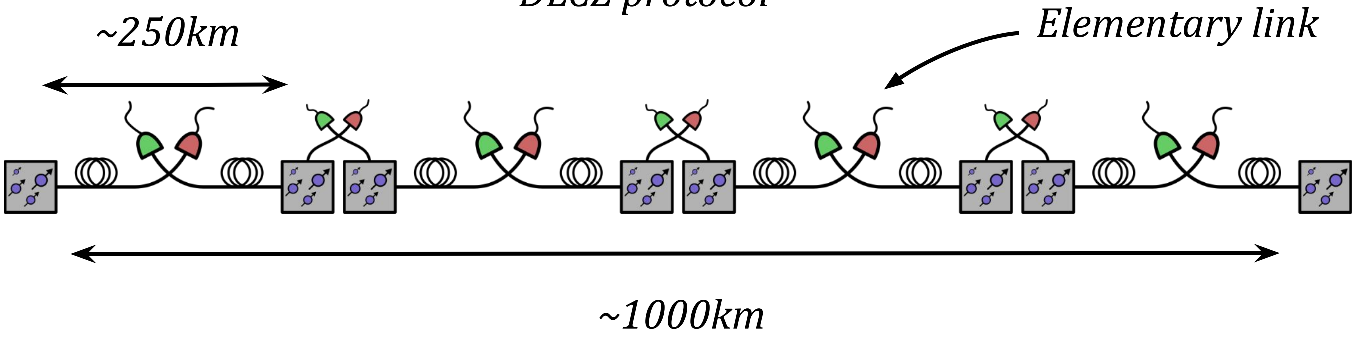
$$\textbf{Country-Scale:} \quad \mathbb{P}_{200\,\mathrm{km}} \approx 10^{-4} \rightarrow 1\,\mathrm{GHz} \cdot 10^{-4} \rightarrow 10\ \mu\mathrm{s}$$

$$\textbf{Continent-Scale:} \quad \mathbb{P}_{1000\,\mathrm{km}} \approx 10^{-20} \rightarrow 1\,\mathrm{GHz} \cdot 10^{-20} \rightarrow 10^{3}\ \mathrm{years}$$

Sangouard, Simon, Riedmatten, and Gisin - Reviews of Modern Physics 83, 33 (2011)

GENERATING LONG-DISTANCE ENTANGLEMENT

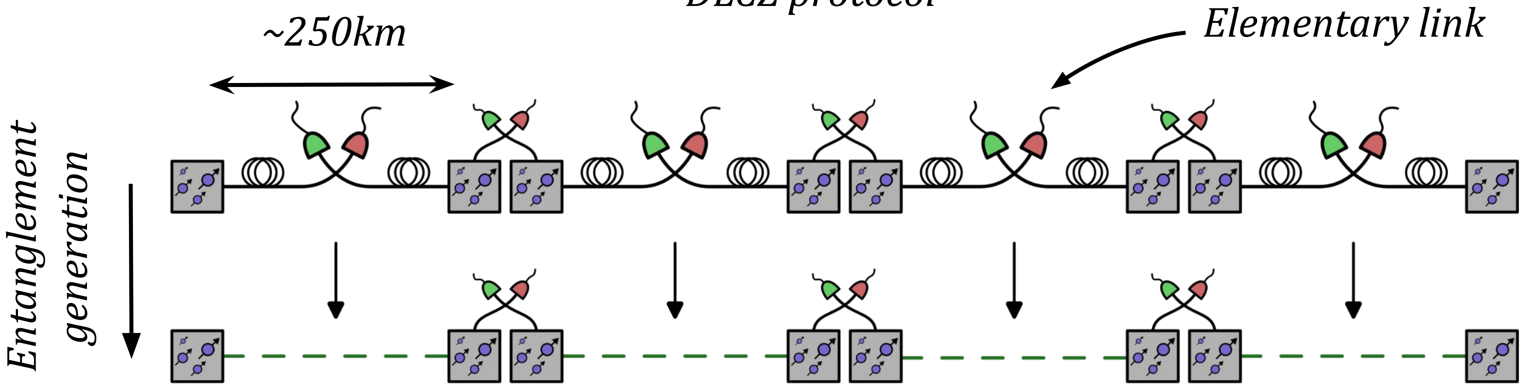
DLCZ protocol



Sangouard, Simon, Riedmatten, and Gisin - Reviews of Modern Physics 83, 33 (2011)

GENERATING LONG-DISTANCE ENTANGLEMENT

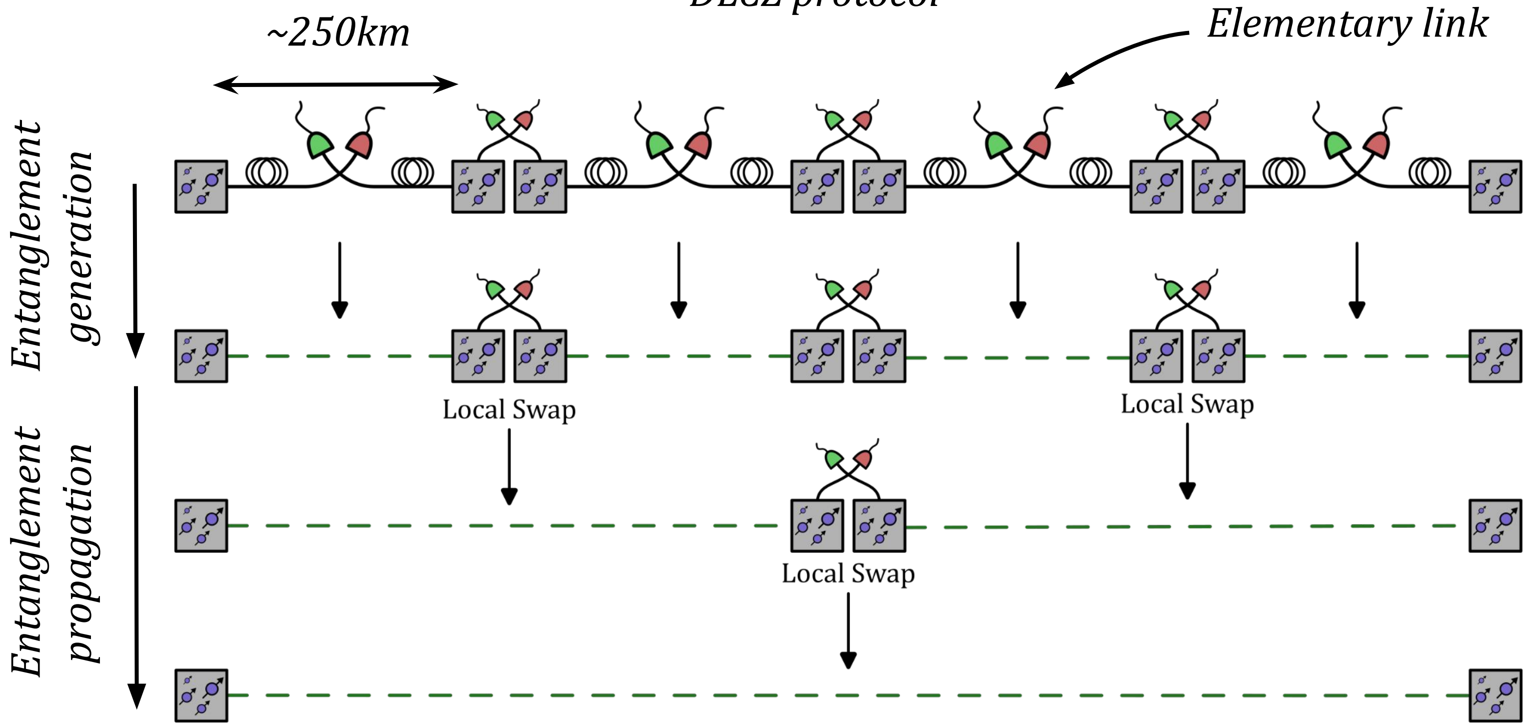
DLCZ protocol



Sangouard, Simon, Riedmatten, and Gisin - Reviews of Modern Physics 83, 33 (2011)

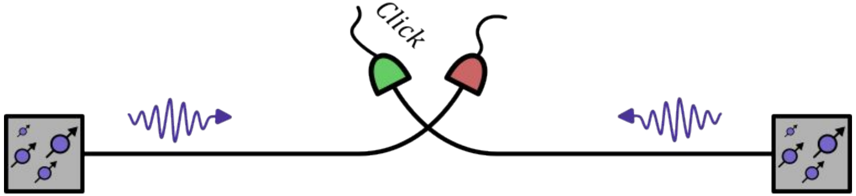
GENERATING LONG-DISTANCE ENTANGLEMENT

DLCZ protocol



Sangouard, Simon, Riedmatten, and Gisin - Reviews of Modern Physics 83, 33 (2011)

DIFFERENT PLATFORMS



Colored Defect
Lukin
Knaut et al., Nature 629, 573 (2024)

Atomic Ensemble
De Reidmatten
Hanni et al. PRX 15, 041003 (2025)

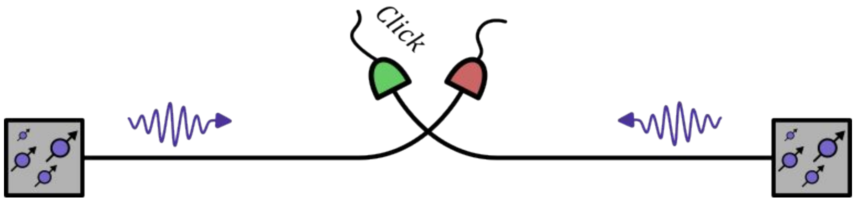
Trapped Ion
Northup and Lanyon
Krutyanskiy et al., PRL 130, 050803 (2023)

Single atom
Pan and Bao
Lu et al., Science 391, 592 (2026)

QUANTUM INTERNET ALLIANCE

THIS TALK

Theoretical Study of an Elementary Link



EXPERIMENTAL COLLABORATION

ICFO

The Institute of Photonic Sciences

Barcelona

De Riedmatten's group

✅ **CURRENT STATUS**

Experimental implementation of a working elementary link

Hanni, Rodriguez-Moldes, Appas et al.
Physical Review X 15, 041003 (2025)

⌛ **NEXT STEP**

Working 2-repeater link

MY WORK: *Bring theoretical support*

→ **Beyond perturbative modeling**

high pump regime for high entanglement distribution rate

→ **Witnessing entanglement**

develop an entanglement witness suited for the elementary link

Quantum Network

Study of an Elementary Link

→ The QIA project

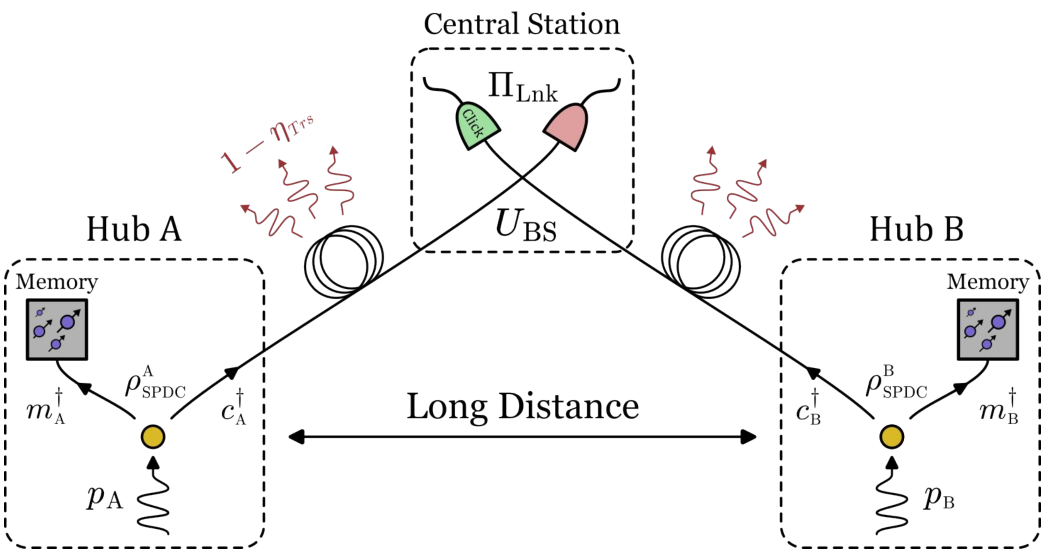
→ Brief introduction

→ **Study of an elementary link**

→ Entanglement witness

→ Short conclusion

CONSIDERED OPTICAL SETUP



$$\mathcal{E}_{\mathrm{Lnk}} : \rho_{\mathrm{SPDC}} \longmapsto \mathrm{TR}_{c_{\mathrm{A}},c_{\mathrm{B}}} \left[\sqrt{\Pi_{\mathrm{Lnk}}}\, U_{\mathrm{BS}}\, \rho_{\mathrm{SPDC}}\, U^\dagger_{\mathrm{BS}} \sqrt{\Pi_{\mathrm{Lnk}}} \right]$$

HERALDED STATE:

$$\rho_{\mathrm{Lnk}} = \frac{1}{\mathcal{N}}\, \mathcal{E}_{\mathrm{Lnk}} \left(\rho_{\mathrm{SPDC}} \right)$$

FIGURES OF MERIT:

→ Fidelity with a Bell-Pair

$$\mathcal{F}_{\mathrm{Lnk}} = \langle \Psi^+ | \, \rho_{\mathrm{Lnk}} \, | \Psi^+ \rangle$$

entanglement quality

→ Heralding Probability

$$\mathbb{P}_{\mathrm{Lnk}} = \mathrm{Tr} \left[\mathcal{E}_{\mathrm{Lnk}} \left(\rho_{\mathrm{SPDC}} \right) \right]$$

distribution rate

→ **TRADE-OFF**

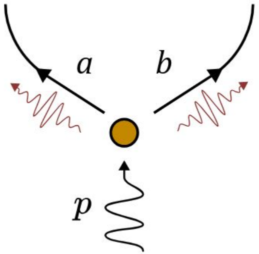
Sangouard, Simon, Riedmatten, and Gisin - Reviews of Modern Physics 83, 33 (2011)

FOCUS ON THE SPDC SOURCE

$$\rho_{\mathrm{SPDC}} = \sqrt{1-p}\ \exp\left[\sqrt{p}\ a^{\dagger} b^{\dagger}\right]\ |00\rangle \xrightarrow{p \ll 1} \sum_{n=0}^{N} p^{n/2}\ |nn\rangle + \mathrm{o}\,(N)$$

1^{st} Order Approximation

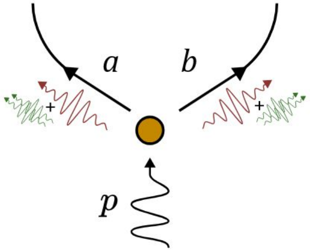
$$|00\rangle + \sqrt{p}\,|11\rangle$$



Purpose: standard regime in labs

2^{nd} Order Approximation:

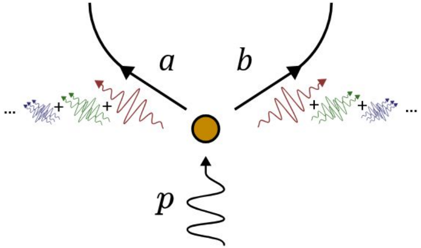
$$|00\rangle + \sqrt{p}\,|11\rangle + p\,|22\rangle$$



Purpose: influence of the two-photons term

Exact Derivation:

$$\sqrt{1-p}\ \exp\left[\sqrt{p}\ a^{\dagger} b^{\dagger}\right]\ |00\rangle$$



Purpose: explore high-pump regime for high-rate distribution

Sangouard, Simon, Riedmatten, and Gisin - Reviews of Modern Physics 83, 33 (2011)

1st ORDER EXPANSION

$$\rho_{\mathrm{SPDC}} = |00\rangle + \sqrt{p}\,|11\rangle + \mathrm{o}\,(p) \quad \xrightarrow{\mathcal{E}_{\mathrm{Lnk}}} \quad \rho_{\mathrm{Lnk}} = |\Psi^+\rangle\,\langle\Psi^+| + \mathrm{o}\,(1)$$

HERALDING PROBABILITY *(distribution rate)*

$$\mathbb{P}_{\mathrm{Lnk}} = \eta_{\mathrm{Trs}} \cdot p + \mathrm{o}\,(p)$$

→ Low probability

BELL FIDELITY *(entanglement quality)*

$$\mathcal{F}_{\mathrm{Lnk}} = 1 + \mathrm{o}\,(1)$$

→ Pure Bell state

Get a **fully entangled state** at the cost of **low distribution rate**

rate-quality trade-off

2nd ORDER EXPANSION

1-photon contribution

2-photon contribution "noise"

$$\rho_{\mathrm{Lnk}} = \left|\Psi_1^+\right\rangle\left\langle\Psi_1^+\right| + \left(\alpha\cdot\left|\Psi_1^+\right\rangle\left\langle\Psi_1^+\right| + \beta\cdot\left|\Psi_2^+\right\rangle\left\langle\Psi_2^+\right| + \gamma\cdot\left|\Psi_{12}^+\right\rangle\left\langle\Psi_{12}^+\right|\right)\cdot p + \mathrm{o}\left(p\right)$$

QUBIT SPACE — **MULTI-PHOTONS**

HERALDING PROBABILITY *(distribution rate)*

1-photon contribution

$$\mathbb{P}_{\mathrm{Lnk}} = \eta_{\mathrm{Trs}}\, p + \eta_{\mathrm{Trs}}(1 - 2\eta_{\mathrm{Trs}})\, p^2 + \mathrm{o}\left(p^2\right)$$

2-photon contribution

BELL FIDELITY *(entanglement quality)*

1-photon contribution

$$\mathcal{F}_{\mathrm{Lnk}} = 1 - (3 - 2\eta_{\mathrm{Trs}})\, p + \mathrm{o}\left(p\right)$$

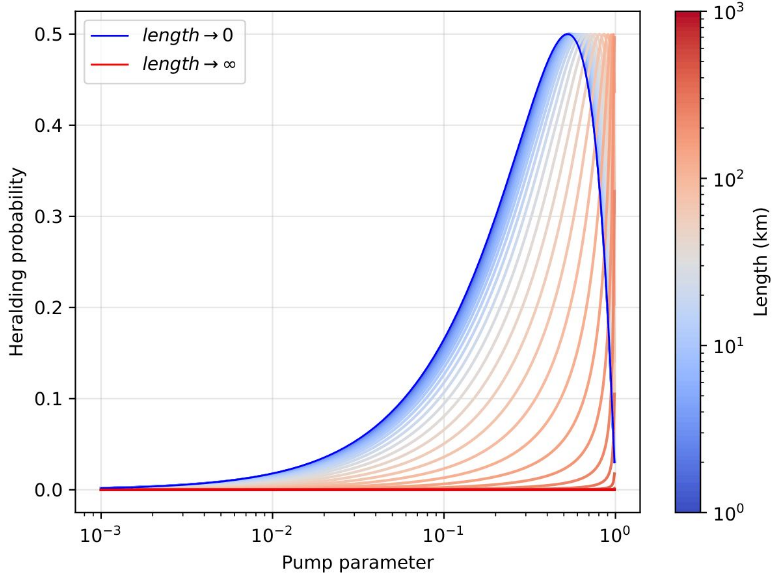
2-photon contribution

*The 2-photon contribution **increases the distribution rate** at the cost of **a lower purity***

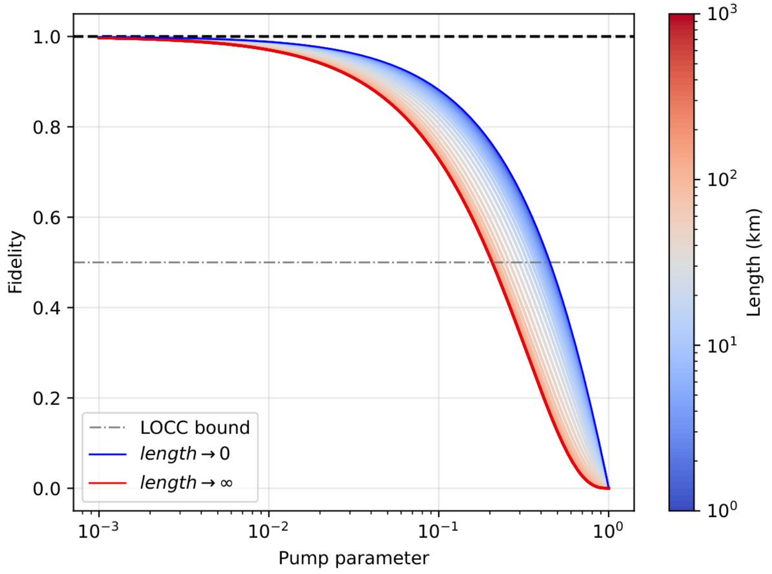
EXACT DERIVATION

$$\rho_{\text{Lnk}} = \frac{1}{1-\xi} \cdot \rho_{\text{Therm}}^{m_\sigma^+}(\sigma_+) \otimes \rho_{\text{Therm}}^{m_\sigma^-}(\sigma_-) - \frac{\xi}{1-\xi} \cdot \rho_{\text{Therm}}^{m_\omega^+}(\omega_+) \otimes \rho_{\text{Therm}}^{m_\omega^-}(\omega_-)$$

HERALDING PROBABILITY *(distribution rate)*



BELL FIDELITY *(entanglement quality)*



Quantum Network

Entanglement witness

→ The QIA project

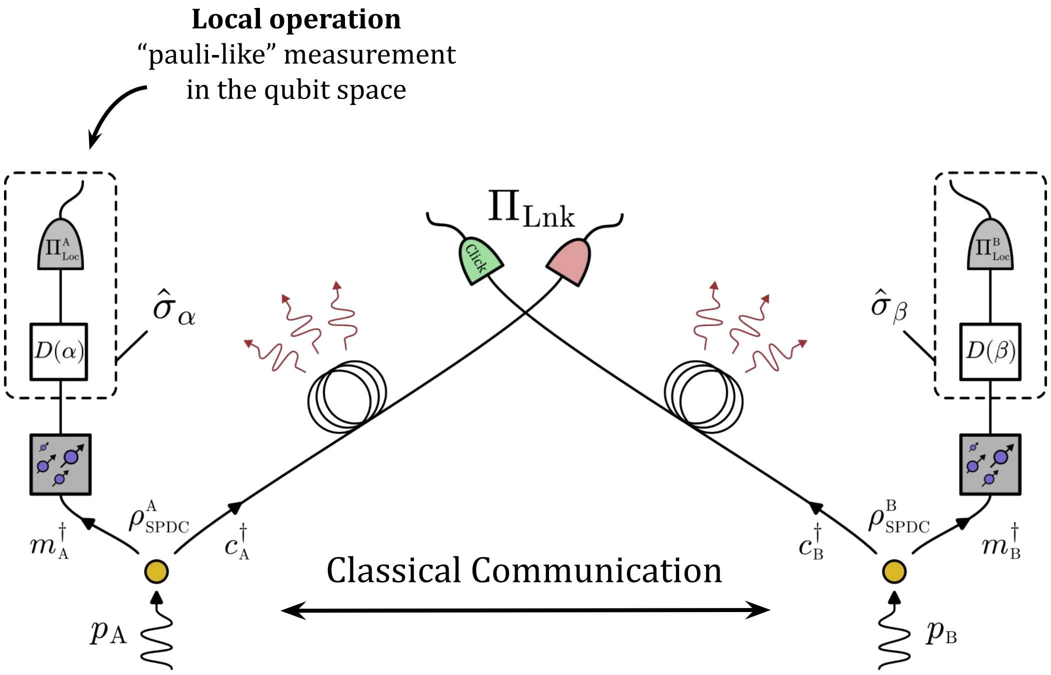
→ Brief introduction

→ Study of an elementary link

→ **Entanglement witness**

→ Short conclusion

QN - *Certifying Entanglement*



LOCC-BASED WITNESS

SPECIFICITY

→ **Focus on qubit space**

entanglement lives in the qubit-space

$$\langle \sigma_\alpha \otimes \sigma_\beta \rangle < {}^{\text{In}}w_{\text{PPT}} + {}^{\text{Out}}w_{\text{multi}}$$

Non-local boundary
PPT in the qubit-space

Correction boundary
multi-photon contribution

→ **Memory-loss "aware"**

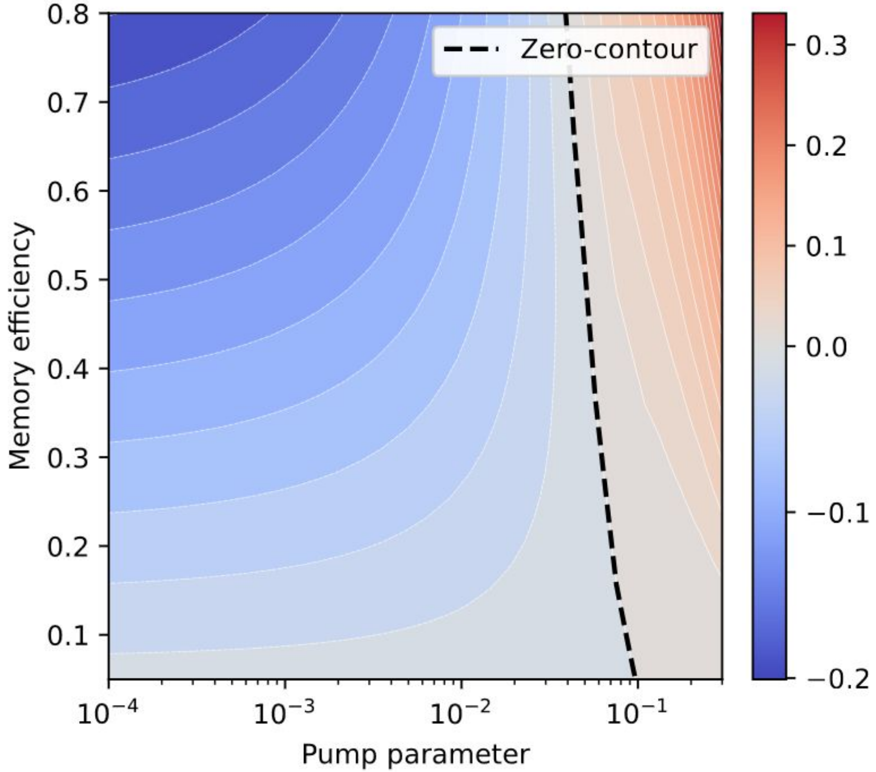
must be robust against memory losses

$$(\rho_{\text{Lnk}})_{i,i} = \mathbb{P}^{i,i}_{\text{Loc}}$$

Caspar et al. - Phys. Rev. Lett. 125, 110506 (2020)
Vivoli et al. - New Journal of Physics 17, 023023 (2015)

Witnesses entanglement for any memory loss

$$(\rho_{\mathrm{Lnk}})_{i,i} = \mathbb{P}^{i,i}_{\mathrm{Loc}}$$



negative** means **non-separable

Witness according to the **pump parameter** and **memories efficiency**

(250km link, optimized over displacement)

Quantum Network

Short Conclusion

→ The QIA project

→ Brief introduction

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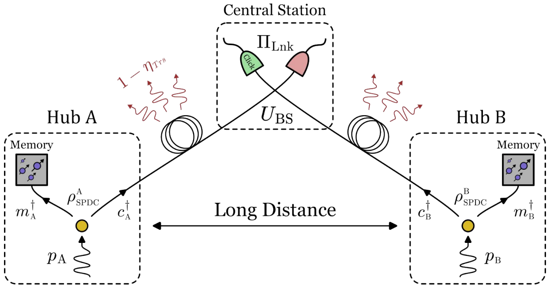
→ **Short conclusion**

MY CONTRIBUTION

in a nutshell

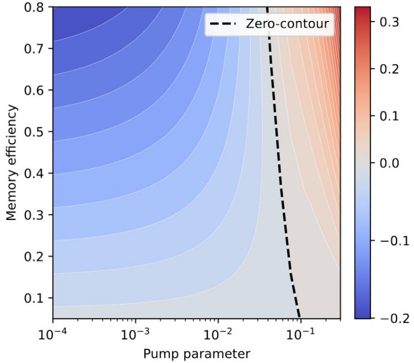
ELEMENTARY LINK

Non-perturbative *study of an elementary link for quality-speed trade-off*



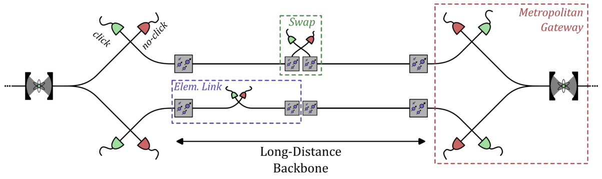
ENTANGLEMENT WITNESS

Development of a ***LOCC loss-aware*** *witness certifying entanglement in the qubit subspace*



FULL REPEATER

Full repeater architecture under ***realistic conditions*** *toward a European quantum network*

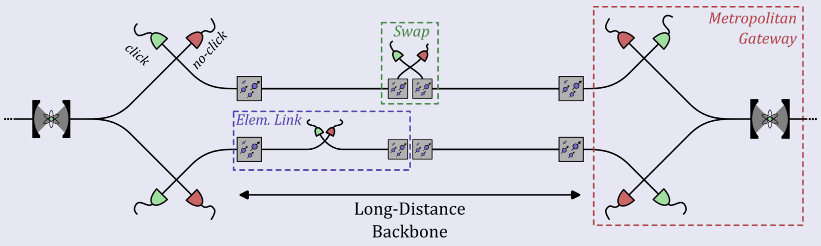


Cussenot et al., Phys. Rev. Lett. 135, 240803 (2025)

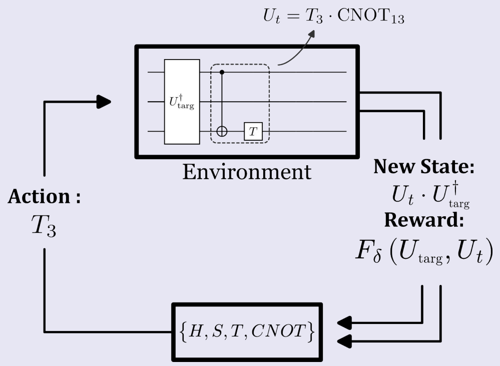
PhD Thesis:

Resource-Constrained

Entanglement Distribution** and **Quantum Compilation



QUANTUM NETWORKS



QUANTUM CIRCUIT SYNTHESIS

Quantum Circuit Synthesis

Quantum Circuit Synthesis

What is Quantum Circuit Synthesis ?

→ **What is Quantum Circuit Synthesis ?**

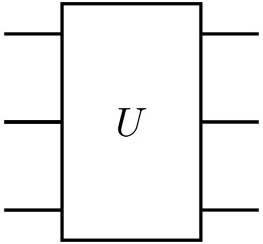
→ How hard is it ?

→ Synthesis as a RL single player game

→ Results

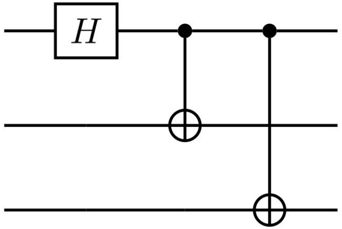
→ Short conclusion

QCS - *Brief introduction*



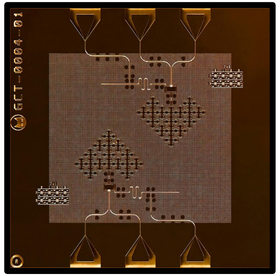
Circuit implementation

Saving 50% Toffoli on Addition
(Gidney - Quantum 2, 74 - 2018)
Ancilla for subroutine T-count optimization
(Khattar, Gidney - arXiv:2407.17966 - 2024)



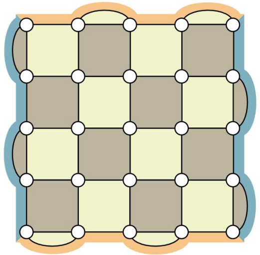
Magic state cultivation
(Gidney - arXiv:2409.17595 - 2024)
Space-Time trade-off on surface code
(Litinski - Quantum 3, 128 - 2019)

QEC implementation



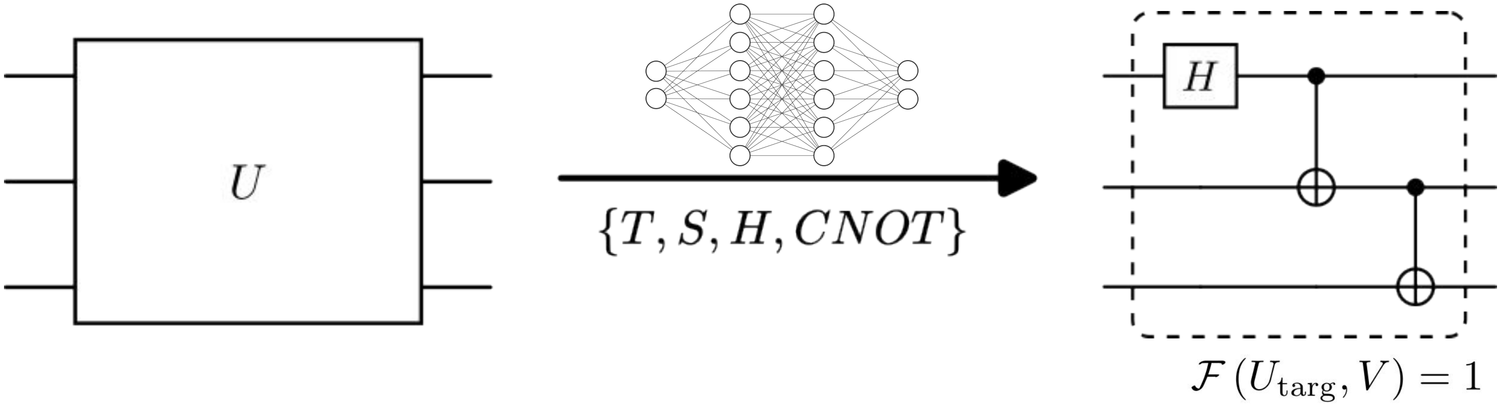
Physical Implementation

Hardware below the threshold
(Google Quantum AI Nature 638, 920 2025)
(Amazon: Putterman et al. Nature 638, 927 2025)



EXACT DISCRETE SYNTHESIS

MACHINE LEARNING



Find the the exact decomposition of a unitary U
for a given universal gate-set

IA-empowered Quantum circuit synthesis and compilation optimization: Overview and prospects
Yan et al., IEEE Trans. Pattern Anal. Mach. Intell, 2026

Quantum Circuit Synthesis

How hard is it ?

→ What is Quantum Circuit Synthesis ?

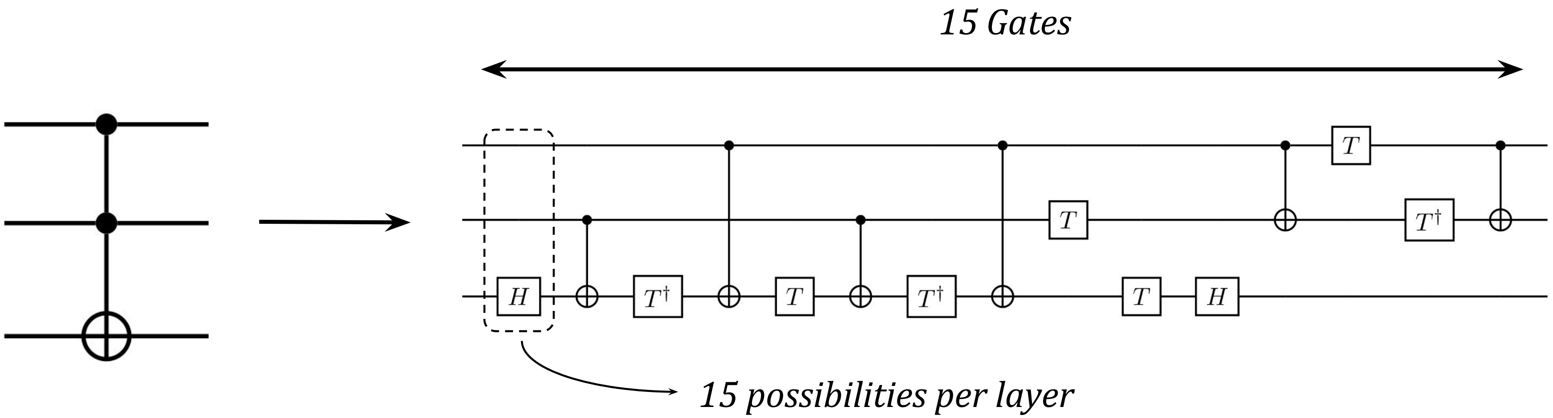
→ **How hard is it ?**

→ Synthesis as a RL single player game

→ Results

→ Short conclusion

QCS - *How hard is it ?*



GATE SET

$$\mathcal{G} = \{H, S, T, CNOT\}$$

$$\tilde{\mathcal{G}} = \{H_1, H_2, S_1, S_2, S_3, T_1, \cdots\}$$

with qubit position

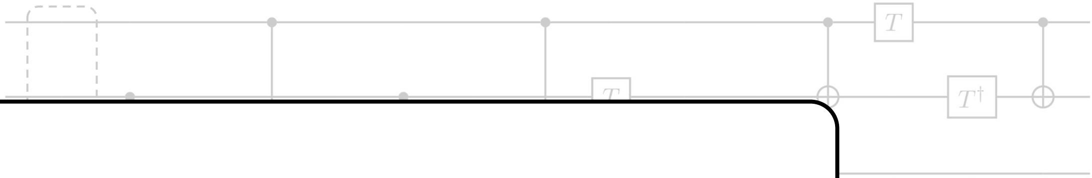
NUMBER OF POSSIBLE CIRCUITS

$$(\#\ \text{gates})^{(\#\ \text{layers})} = 15^{15} \approx 2 \cdot 10^{16}$$

1 GHz try → ½ year

QCS - *How hard is it ?*

15 Gates



Not only a search problem: **an optimization problem inside a search problem**

find the decomposition and pay as little as possible

GATE SET

LE CIRCUITS

$$\mathcal{G} = \{H, S, T, CNOT\}$$

$$\tilde{\mathcal{G}} = \{H_1, H_2, S_1, S_2, S_3, T_1, \cdots\}$$

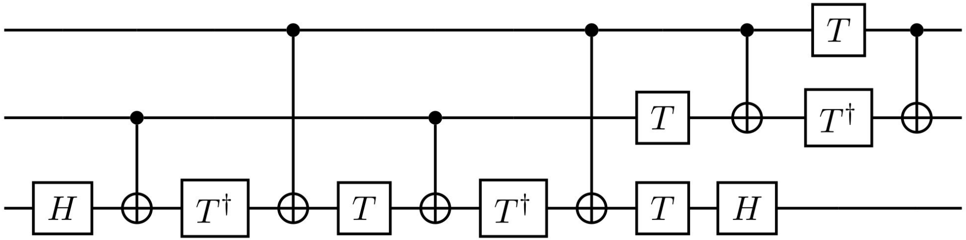
with qubit position

$$(\#\ \text{gates})^{(\#\ \text{layers})} = 12^{15} \approx 2 \cdot 10^{16}$$

1 GHz try $\longrightarrow$ ½ year

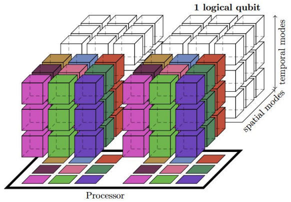
GATE RESOURCE CONSTRAINT

T-count: 7
T-depth: 5



GATE-COUNT: number of gates

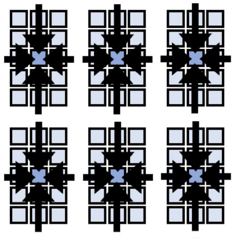
non-parallelizable QPU architecture



Example:
Memory-based QPU
(Gouzien, Sangouard arXiv:2103.06159)

GATE-DEPTH: number of “gate-layers”

parallelizable QPU capabilities



Example:
Multiple T-factories QPU
(Beverland et al. arXiv:2211.07629)

Quantum Circuit Synthesis

Synthesis as a RL single player game

→ What is Quantum Circuit Synthesis ?

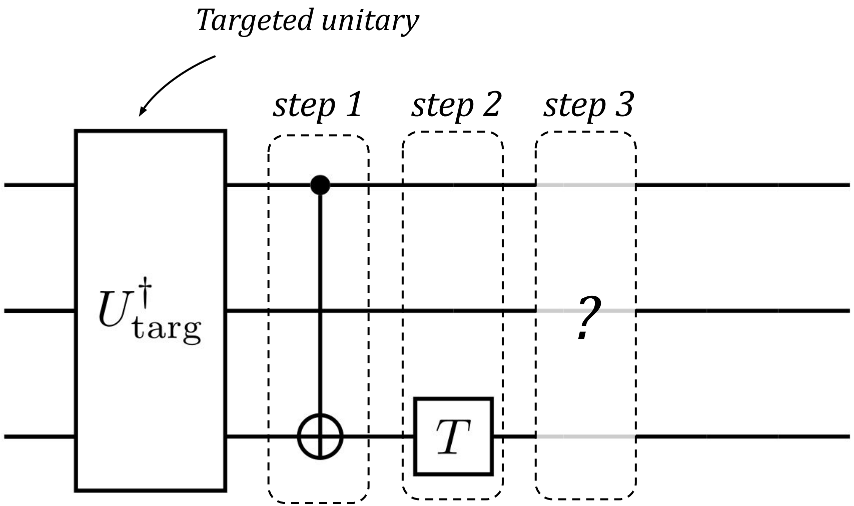
→ How hard is it ?

→ **Synthesis as a RL single player game**

→ Results

→ Short conclusion

QCS - *Synthesis as a RL Single-player Game*



Starting from ***U*** † ***targ***
every step *the player adds* ***one gate***
aiming to ***reach identity***

STATE OF THE GAME

$$\hat{U}_0 = \mathbb{1} \cdot U^\dagger_{\text{targ}}$$
$$\hat{U}_1 = \text{CNOT}_{13} \cdot U^\dagger_{\text{targ}}$$
$$\hat{U}_2 = T_3\ \text{CNOT}_{13} \cdot U^\dagger_{\text{targ}}$$

$g_1 = \text{CNOT}_{13}$

$g_2 = T_3$

Circuit synthesis in progress

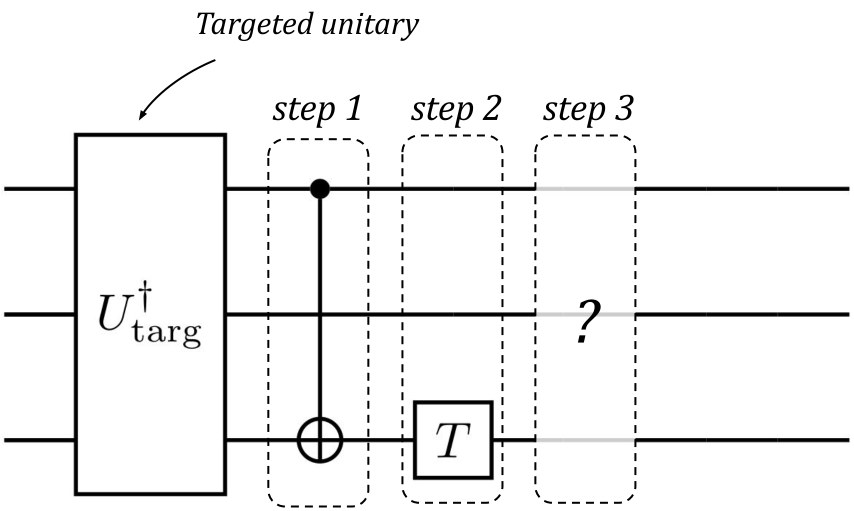
Same target for every unitary

END GAME

$$\text{Success} \rightarrow \hat{U}_t = \mathbb{1}$$
$$\text{Failure} \rightarrow t \geq d_{\text{max}}$$

Valcarce, Grivet and Sangouard - arXiv:2508.21217v

QCS - *Synthesis as a RL Single-player Game*

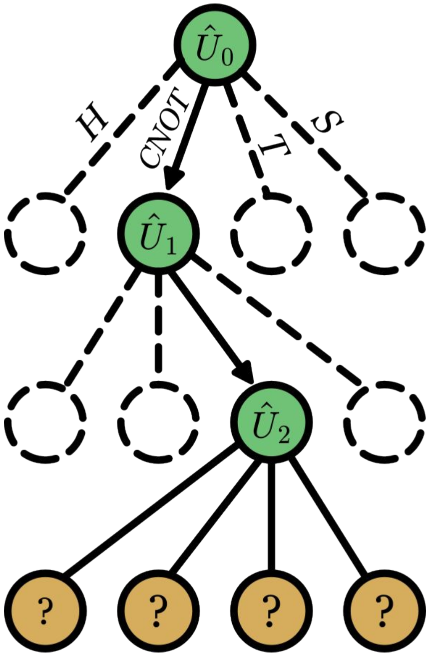


Starting from $\boldsymbol{U^{\dagger}_{targ}}$

every step** the player adds **one gate

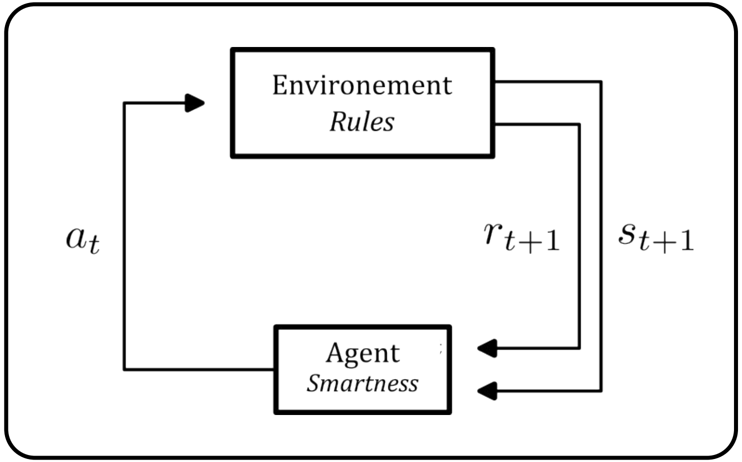
*aiming to **reach identity***

DECISION TREE REPRESENTATION

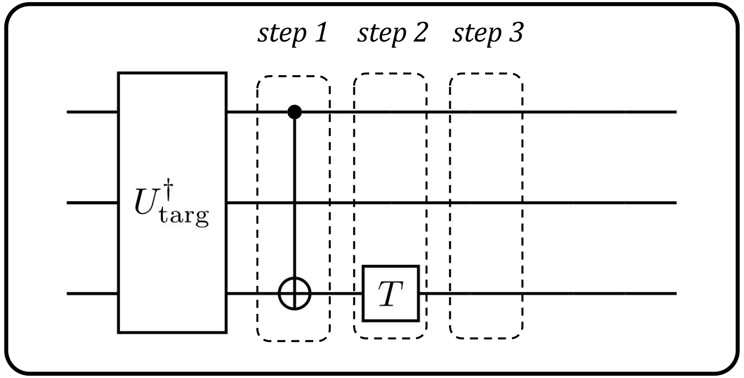


Valcarce, Grivet and Sangouard - arXiv:2508.21217v

QCS - *Synthesis as a RL Single-player Game*



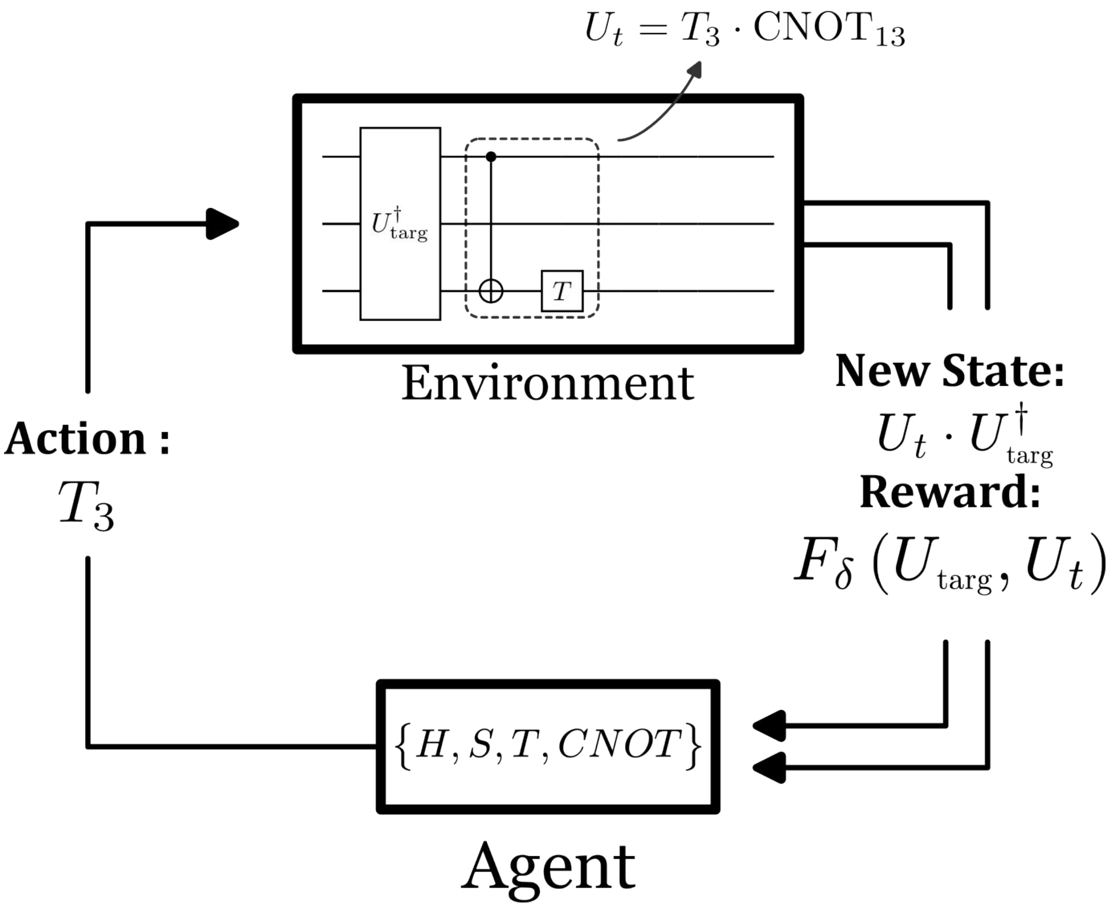
Reinforcement Learning



Single player
Quantum Circuit Synthesis

Reinforcement Learning: An Introduction (Richard S. Sutton and Andrew G. Barto)

QCS - *Synthesis as a RL Single-player Game*

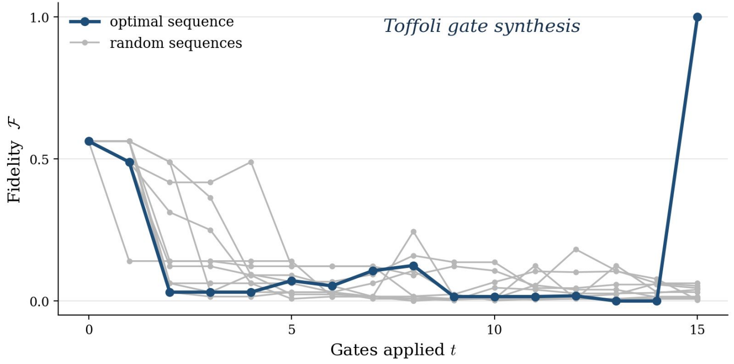


Valcarce, Grivet and Sangouard - arXiv:2508.21217v

A SUITED REWARD FOR THE AGENT

Fidelity

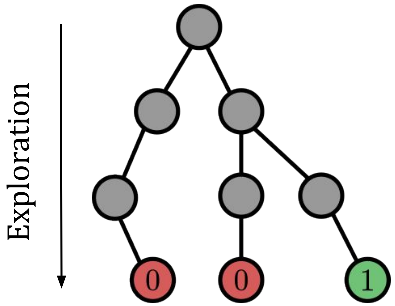
$$r_t = \mathcal{F}\left(U_t, U_{\text{targ}}\right) = \frac{\left|\text{Tr}(U_t \cdot U_{\text{targ}}^\dagger)\right|}{2^n}$$



Fidelity does not provide a suitable score for intermediate states

Binary Fidelity

$$r_t = \mathcal{F}_\delta\left(U_t, U_{\text{targ}}^\dagger\right) = \begin{cases} 1 & \text{if } U_t = U_{\text{targ}} \\ 0 & \text{else} \end{cases}$$



Binary Fidelity provides a strong signal to the agent at the end of the game

Valcarce, Grivet and Sangouard - arXiv:2508.21217v

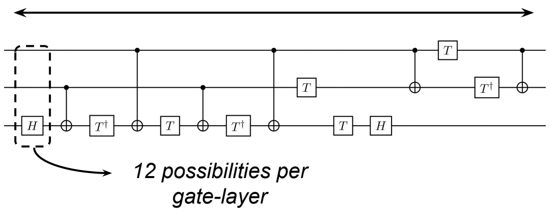
A SUITED AGENT FOR THE PROBLEM

handles

robust to

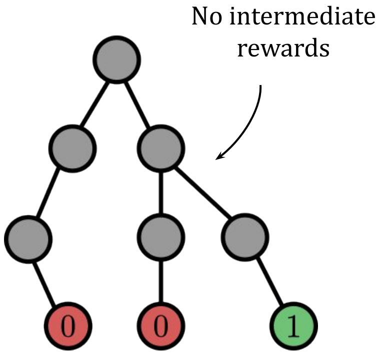
requires

LARGE SPACE

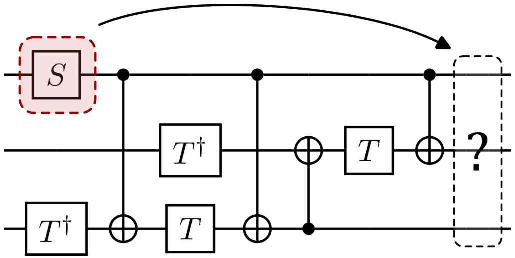


$$(\# \text{ gates})^{(\# \text{ layers})} = 12^{15} \approx 2 \cdot 10^{16}$$

SPARSE REWARD



LONG-HORIZON PLANNING



wrong early gate may impact the overall synthesis

Matsuno, Amano - arXiv:0806.3834

Valcarce, Grivet and Sangouard - arXiv:2508.21217v

A SUITED AGENT FOR THE PROBLEM

handles

robust to

requires

LARGE SPA

IZON PLANNING

15 Gates

12 possibilities per gate-layer

$$(\#\ \text{gates})^{(\#\ \text{layers})} = 12^{15} \approx 2 \cdot 10^{16}$$

COMPUTER SCIENCE

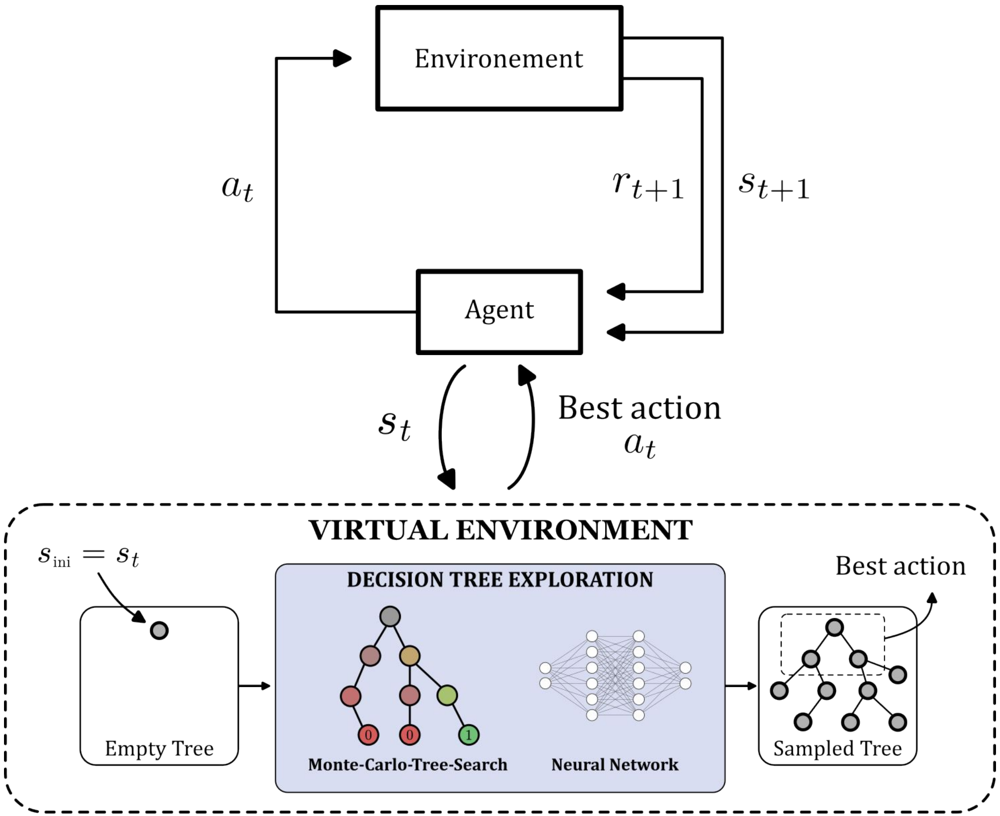
A general reinforcement learning algorithm that masters chess, shogi, and Go through self-play

David Silver[1,2]*†, Thomas Hubert[1]*, Julian Schrittwieser[1]*, Ioannis Antonoglou[1], Matthew Lai[1], Arthur Guez[1], Marc Lanctot[1], Laurent Sifre[1], Dharshan Kumaran[1], Thore Graepel[1], Timothy Lillicrap[1], Karen Simonyan[1], Demis Hassabis[1]†

wrong early gate may impact the overall synthesis

Matsuno, Amano - arXiv:0806.3834

Valcarce, Grivet and Sangouard - arXiv:2508.21217v

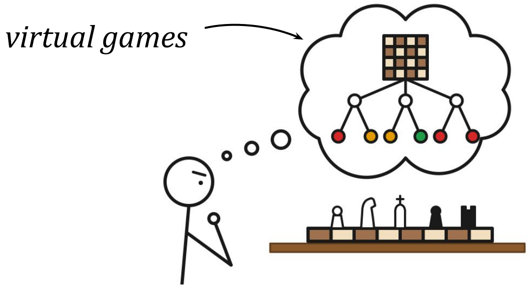


MODEL-BASED AGENT

Every step the agent:

→ Open a virtual environment
→ Plays virtual games
→ Evaluates moves ahead
→ Picks the best action

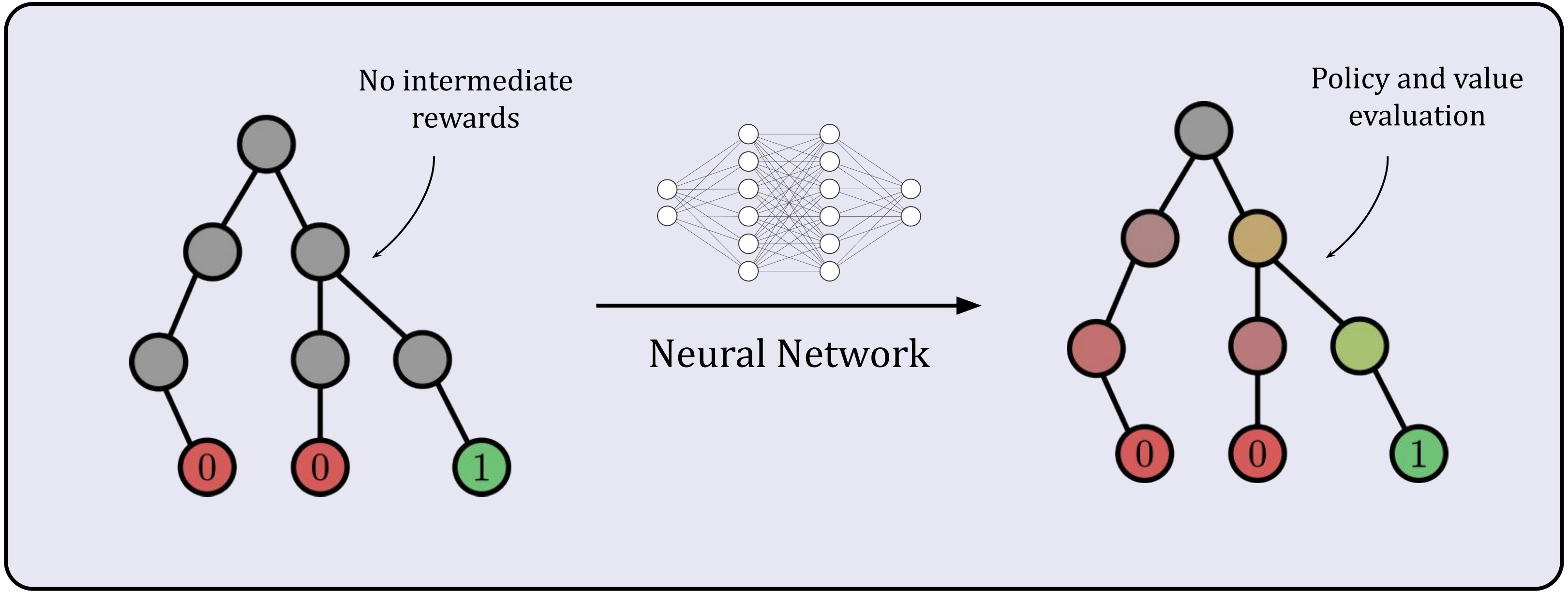
ANALOGY



Chess player thinking of potential next strategies before committing the move

Silver et al. - Science Vol 362, pages 1140-1144 (2018)

QCS - *Synthesis as a RL Single-player Game*



The neural network helps the tree search with
intermediate evaluation of the states

Silver et al. - Science Vol 362, pages 1140-1144 (2018)

Quantum Circuit Synthesis

Results

→ What is Quantum Circuit Synthesis ?

→ How hard is it ?

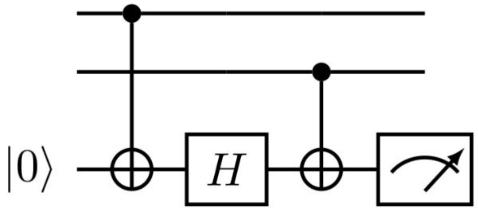
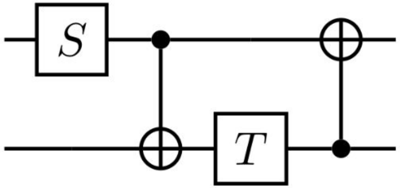
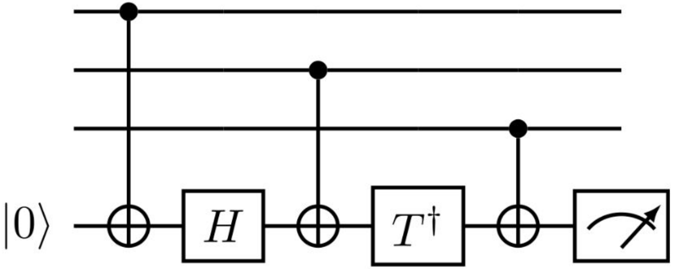
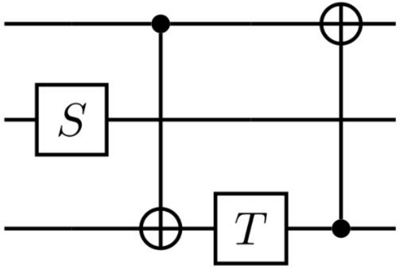
→ Synthesis as a RL single player game

→ **Results**

→ Short conclusion

QUBIT CONNECTIVITIES

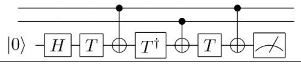
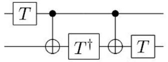
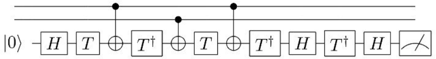
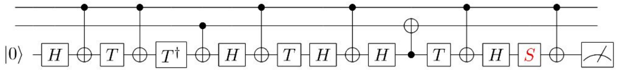
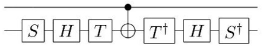
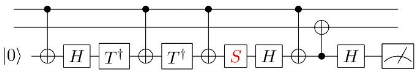
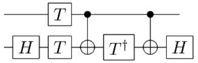
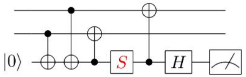
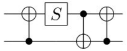
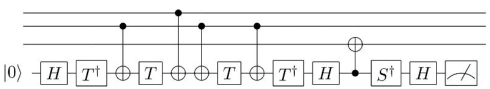
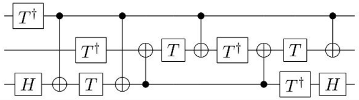
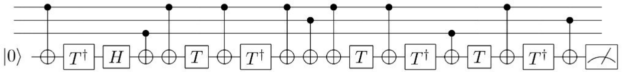
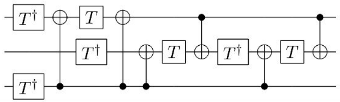
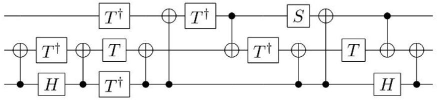
QUBITS

	$n+1$, $\{H, T, CNOT\}$	**all-to-all**, $\{H, S, T, CNOT\}$
2		
3		

→ ***4 agents trained:*** *2 settings × 2 circuit sizes*

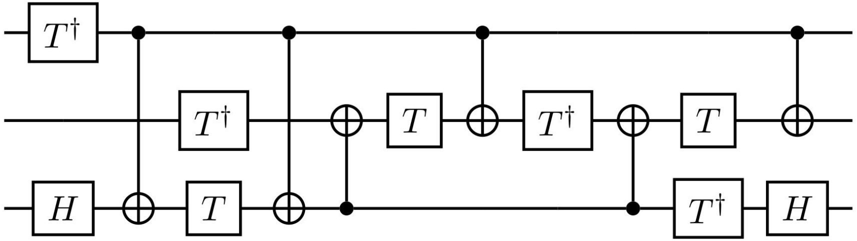
Valcarce, Grivet and Sangouard - arXiv:2508.21217v1

QUALITATIVE BENCHMARK

Qubits	Unitary	$n+1$, $\{H, T, \text{CNOT}\}$	**all-to-all**, $\{H, S, T, \text{CNOT}\}$
	CS		
	CT		*No circuit found*
2	CH		
	CV		
	iSWAP		
	Toffoli		
3	CCZ		
	Fredkin	*No circuit found*	

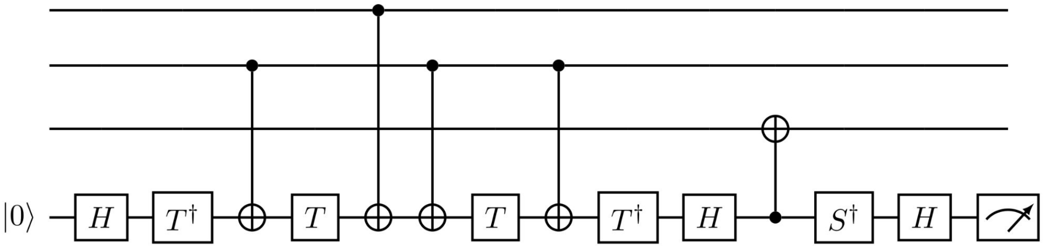
Valcarce, Grivet and Sangouard - arXiv:2508.21217v1

TOFFOLI - *All-to-All*



→ Optimal T-count *(without ancilla)*

TOFFOLI - *n+1*



→ Optimal T-count *(with ancilla)*

Gosset, Kliuchnikov, Mosca, and Russo - arXiv:1308.4134

Quantum Circuit Synthesis

Short Conclusion

→ What is Quantum Circuit Synthesis ?

→ How hard is it ?

→ Synthesis as a RL single player game

→ Results

→ **Short conclusion**

QCS - *Short Conclusion*

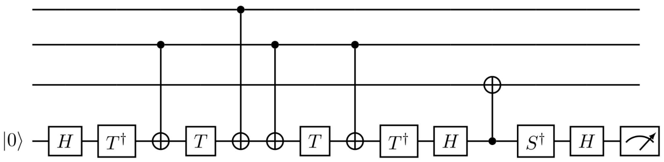
RESULTS

→ Proof of concept

Ability of RL technique for quantum circuit synthesis for different qubit connectivities

→ Subroutines synthesis

*Toffoli, CCZ, Fredkin, etc. in **few seconds***
*Optimal decomposition requires **few days***
(e.g. Gouzien, Sangouard arXiv:2103.06159)

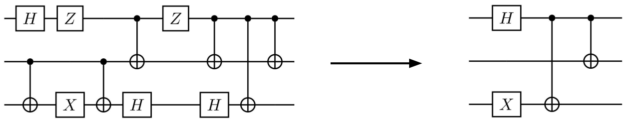


Optimal T count

PERSPECTIVE

→ Training set improvement

Non-trivial circuits generation of the training set



randomly generated *after simplification*

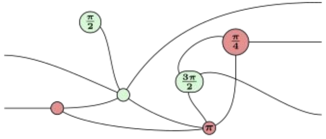
→ Clifford-awareness

Add non-clifford information in the state (e.g. SDE)

$$\mathrm{sde}(z) \;=\; \min\left\{ k \in \mathbb{N} \;:\; \sqrt{2}^{\,k} z \in \mathbb{Z}[\omega] \right\}$$

→ Scaling

State use encoded as unitary → 2^{2n} matrix size



Thank you!

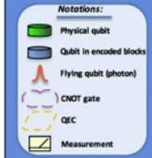
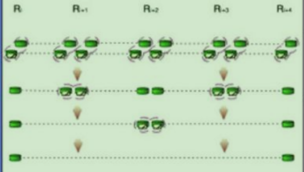
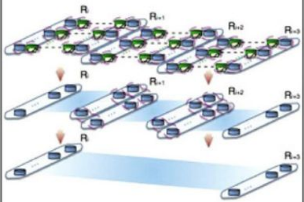
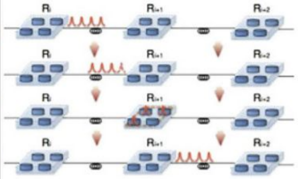
RESSOURCES

RESSOURCES

Study of an Elementary Link

Muralidharan Nomenclature

Muralidharan et al. Nature Sci Rep 6, 20463 (2016)

	First Generation QR	Second Generation QR	Third Generation QR
Schematic Architecture 			
Loss Error	HEG (two-way signaling)	HEG (two-way signaling)	QEC (one-way signaling)
Operation Error	HEP (two-way signaling)	QEC (one-way signaling)	QEC (one-way signaling)
Procedure	1. Create entangled pairs over L_0 between adjacent stations 2. At *k*-th level, connect two pairs over L_k and extend to $L_{k+1}=2L_k$, followed by HEP. 3. After *n* nesting levels, obtain high-fidelity pair over $L_{tot}=2^n \times L_0$	1. Prepare encoded states $\|0\rangle_L$ and $\|+\rangle_L$ 2. Use teleportation-based non-local CNOT gates to create encoded Bell pairs between adjacent stations. 3. Connect intermediate stations to create long distance encoded Bell pair	1. Encode information with a block of qubits that are sent through a lossy channel 2. Use QEC to correct both loss and operation errors 3. Relay the encoded information to the next station; and repeat steps 2 & 3.
Characteristic time scale	$\mathrm{Max}(L_{tot}/c, t_0)$	$\mathrm{Max}(L_0/c, t_0)$	t_0
Cost Coefficient (C')	$\mathrm{Poly}(L_{tot})$	$\mathrm{PolyLog}(L_{tot})$	$\mathrm{PolyLog}(L_{tot})$

Muralidharan et al. - Scientific Reports 6, 20463 (2016)

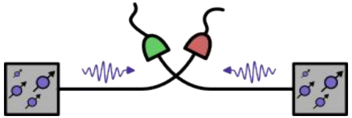
Beukers Nomenclature

Beukers et al. PRX QUANTUM 5, 010202 (2024)

Layer 1

Network Topology

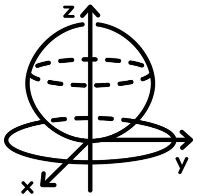
Detection-in-mid-point



Layer 2

Encoding

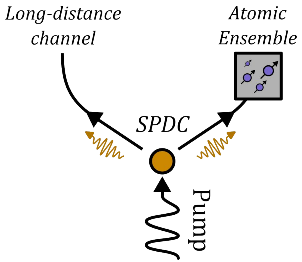
Photon Number
(qubit space)



Layer 3

Source

Photon-pair
Atomic ensemble



Layer 4

Modeling

Full Fock space

QUBIT SPACE

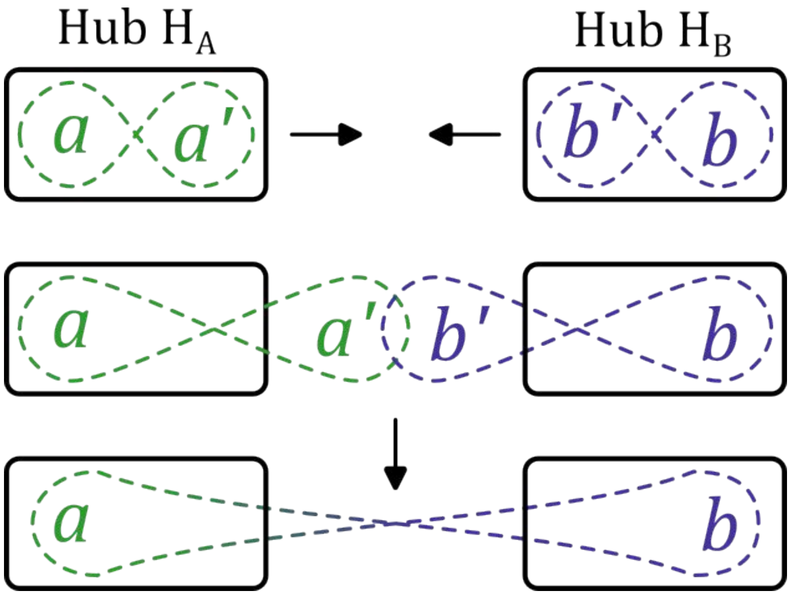
$$\begin{pmatrix} p^0\,\rho^{(0)}_{\mathrm{Lnk}} & 0 & 0 & \cdots \\ 0 & p^1\,\rho^{(1)}_{\mathrm{Lnk}} & 0 & \cdots \\ 0 & 0 & p^2\,\rho^{(2)}_{\mathrm{Lnk}} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

MULTI-PHOTONS

ENTANGLEMENT SWAPPING

General Mechanics

each hub locally generates a bipartite entangled state



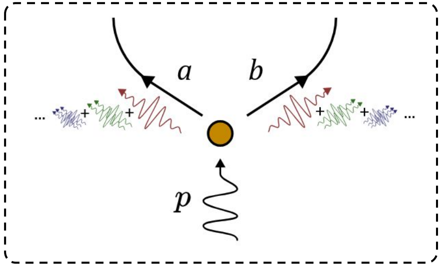
measurement on a' and b' swap the entanglement to a and b

Entanglement swapping allows to **generate entanglement** between **two distant hubs** that have never interacted

Zukowiski et al. - Phys. Rev. Lett. 71, 4287

QIA - *Study of an Elementary Link*

SPDC STATE



$$\sqrt{1-p}\cdot\exp\left[\sqrt{p}\cdot a^\dagger b^\dagger\right]$$

↓ *cut-off*

$$|00\rangle + \sqrt{p}\,|11\rangle + \cdots + p^{\frac{N}{2}}\,|NN\rangle + o\,(N)$$

Quantum Channel

$$\mathrm{Tr}_{c_A,c_B}\left[\sqrt{\Pi_{\mathrm{Lnk}}}\,U_{\mathrm{BS}}\,\rho_{\mathrm{SPDC}}\,U_{\mathrm{BS}}^\dagger\sqrt{\Pi_{\mathrm{Lnk}}}\right]$$

HERALDED STATE

$$\rho_{\mathrm{Lnk}} = \mathcal{E}_{\mathrm{Lnk}}\left(\rho_{\mathrm{SPDC}}\right)$$

$$\mathcal{F}_{\mathrm{Lnk}} = \langle\Psi^+|\,\rho_{\mathrm{Lnk}}\,|\Psi^+\rangle$$

$$\mathbb{P}_{\mathrm{Lnk}} = \mathrm{Tr}\left[\Pi_{\mathrm{Lnk}}\cdot\rho_{\mathrm{Lnk}}\right]$$

FRICTION: *SPDC Gaussian VS POVM Fock-diagonal*

FIX: *expand in p → Fock-compatible + valide with p<<1*

Sangouard, Simon, Riedmatten, and Gisin - Reviews of Modern Physics 83, 33 (2011)

QUANTUM INTERNET ALLIANCE

cea

INITIAL STATE

$$\rho_{\text{ini}} = \sum_{i=0}^{N} p^i \, \rho_{\text{ini}}^{(i)} + \rho_{\text{ini}}^{\star}(p) + o\left(p^N\right)$$

QUBIT SPACE

$$\begin{pmatrix} p^0 \, \rho_{\text{ini}}^{(0)} & \star & \star & \cdots \\ \star & p \, \rho_{\text{ini}}^{(1)} & \star & \cdots \\ \star & \star & p^2 \, \rho_{\text{ini}}^{(2)} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

MULTI-PHOTONS

crossed terms

HERALDED STATE

$$\rho_{\text{Lnk}} = \sum_{i=0}^{N} p^i \, \mathcal{E}_{\text{Lnk}}\left(\rho_{\text{ini}}^{(i)}\right) + \mathcal{E}_{\text{Lnk}}\left(\rho_{\text{ini}}^{\star}(p)\right) + o\left(p^N\right)$$

QUBIT SPACE

$$\begin{pmatrix} p^0 \, \mathcal{E}_{\text{Lnk}}\left(\rho_{\text{ini}}^{(0)}\right) & 0 & 0 & \cdots \\ 0 & p \, \mathcal{E}_{\text{Lnk}}\left(\rho_{\text{ini}}^{(1)}\right) & 0 & \cdots \\ 0 & 0 & p^2 \, \mathcal{E}_{\text{Lnk}}\left(\rho_{\text{ini}}^{(2)}\right) & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

MULTI-PHOTONS

crossed terms does not contribute

$$\mathcal{E}_{\text{Lnk}}\left(\rho_{\text{ini}}^{\star}(p)\right) = 0$$

Each diagonal block carries *n* photons within the subspace:

$$\tilde{\mathcal{H}}(n) = \text{Span}\left\{ |ij\rangle \;\; \text{s.t.}\; i + j = n \right\}$$

N$^{\text{th}}$ ORDER EXPANSION

dilutes the Bell pair

$$\rho_{\mathrm{Lnk}} = \underbrace{\tilde{\rho}^{(0)}_{\mathrm{Lnk}} + p \cdot \tilde{\rho}^{(1)}_{\mathrm{Lnk}}}_{\text{QUBIT SPACE}} + \underbrace{\sum_{i=0}^{N} p^i \, \tilde{\rho}^{(i)}_{\mathrm{Lnk}}}_{\text{MULTI-PHOTONS}} + \mathrm{O}\left(p^N\right)$$

HERALDING PROBABILITY *(distribution rate)*

Qubit Space

$$\mathbb{P}_{\mathrm{Lnk}} = \tilde{\mathbb{P}}_{\mathrm{Lnk}} \cdot p + \sum_{i=2}^{N} p^i \, \tilde{\mathbb{P}}^{(i)}_{\mathrm{Lnk}} + \mathrm{O}\left(p^N\right)$$

Multi Photon

BELL FIDELITY *(entanglement quality)*

Qubit Space

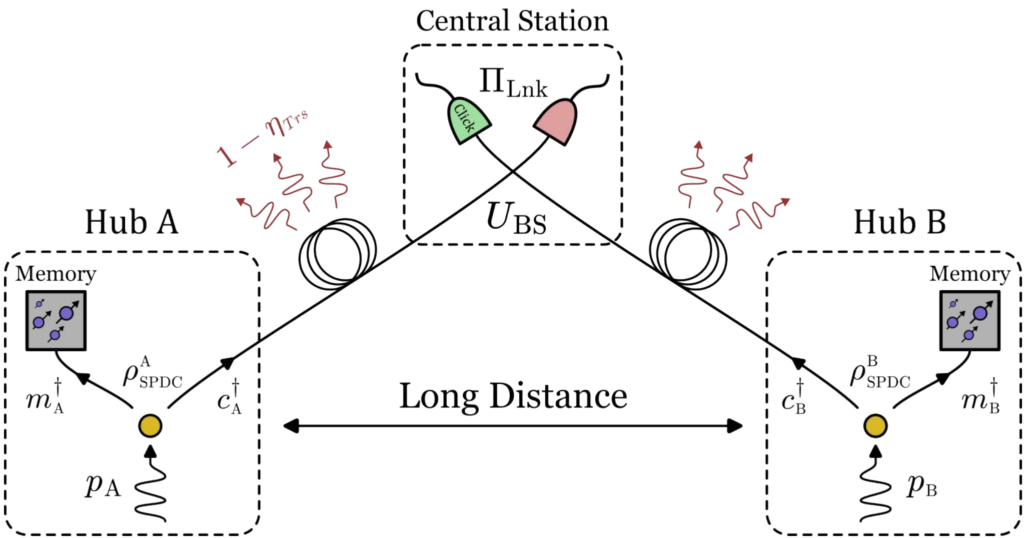
$$\mathcal{F}_{\mathrm{Lnk}} = 1 - \sum_{i=1}^{N} p^i \, \tilde{\mathcal{F}}^{(i)}_{\mathrm{Lnk}} + \mathrm{O}\left(p^N\right)$$

Multi Photons

The ***multi-photons contribution dilutes*** *the desired Bell pair*

RESSOURCES

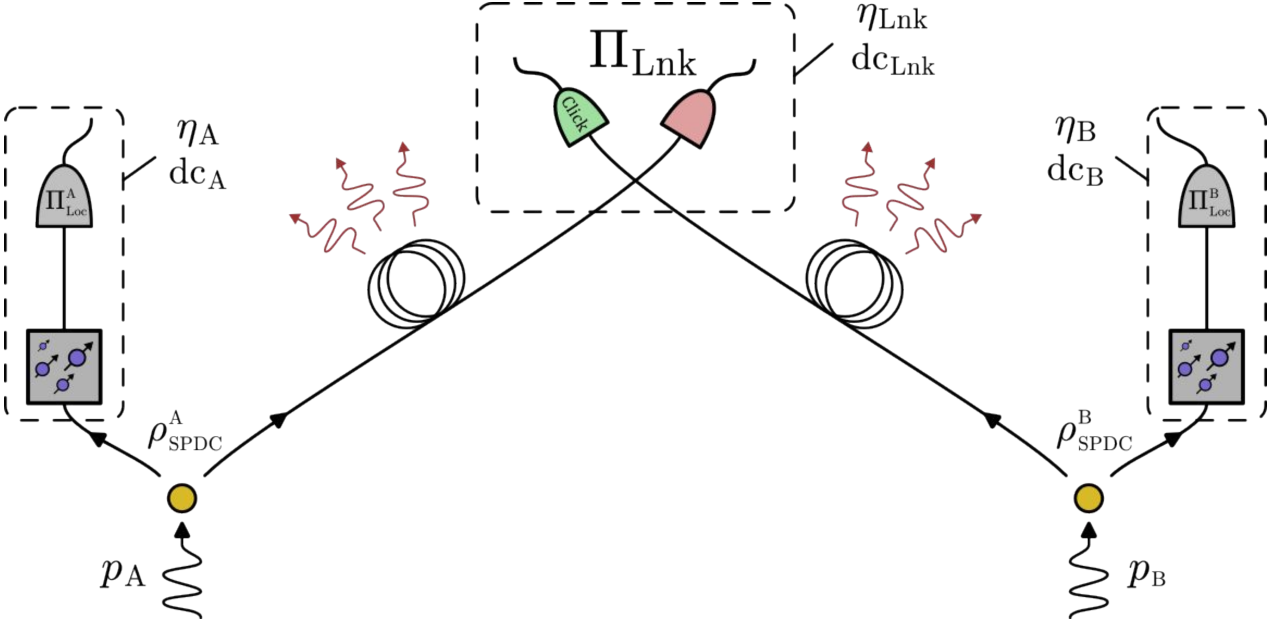
Experimental Fit



NUMERICAL VALUES

Pump parameter	0.05
Link length	250 km
Detector efficiency	0.9

	$\mathcal{F}_{\mathrm{Lnk}}$		$\mathbb{P}_{\mathrm{Lnk}}$	
	value	err.	value	err.
Pert. $N=1$	1.0	+17%	2.7×10^{-4}	9%
Pert. $N=2$	0.95	+11%	2.8×10^{-4}	5%
Exact	0.86	—	3.0×10^{-4}	—

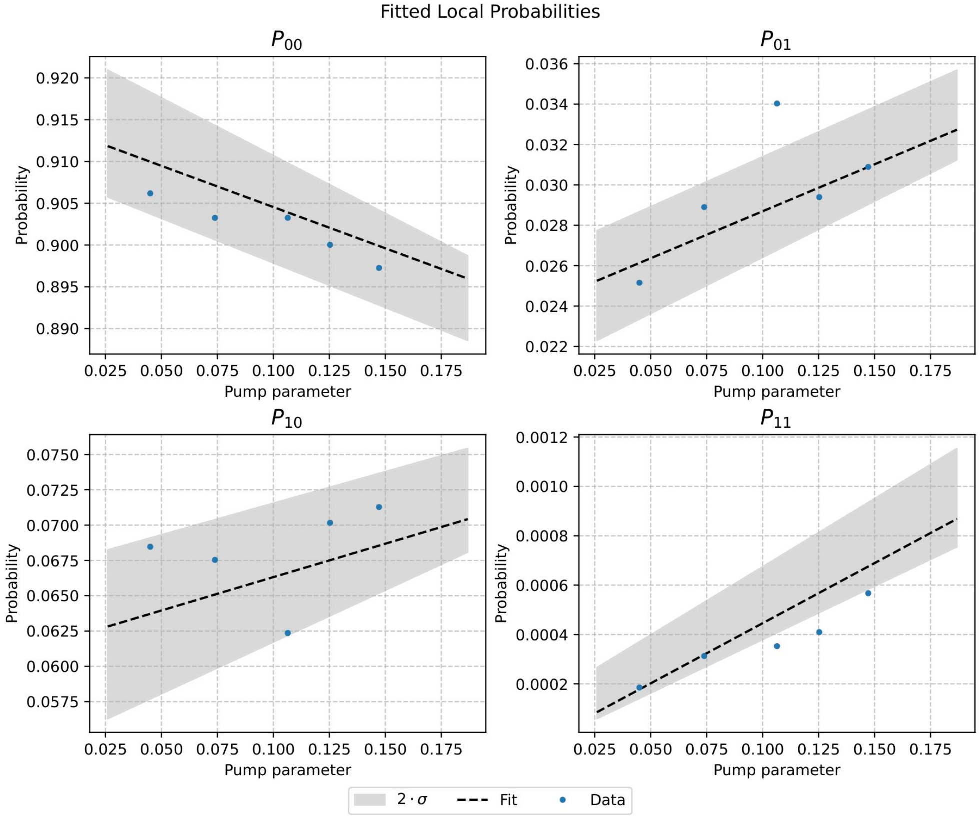


LOCAL PROBABILITIES

(local click/no-click)

Data from ICFO (unpublished)

QIA - *Fit with Experimental Data*

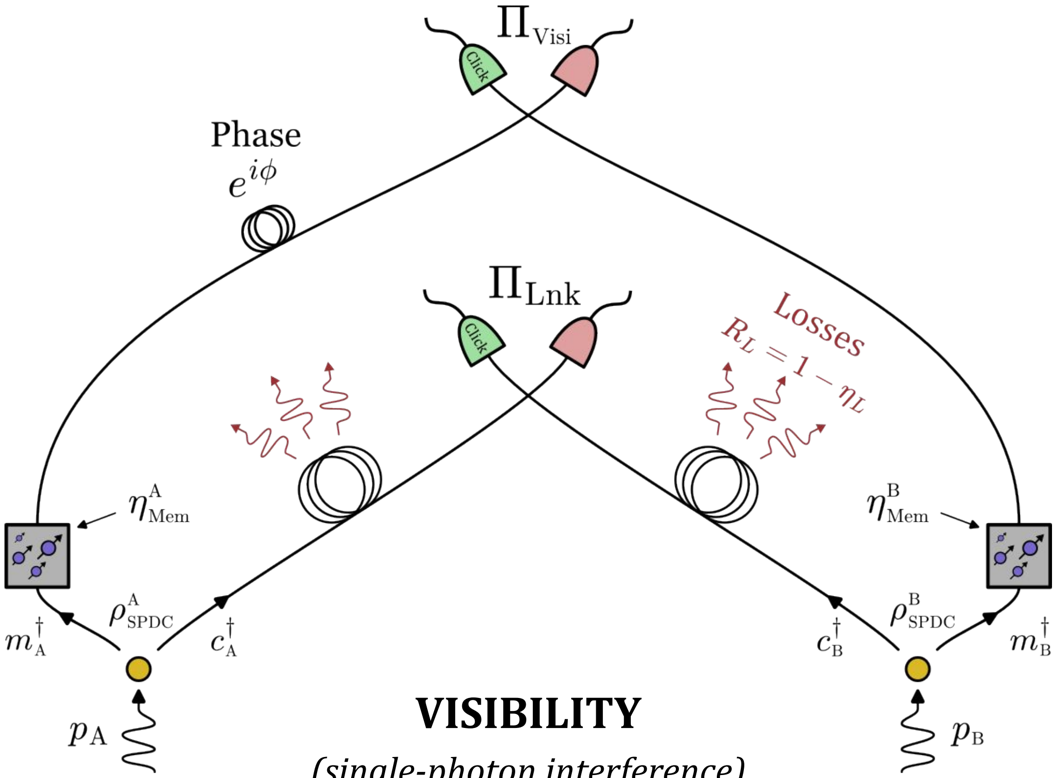


FIT - LOCAL PROBABILITIES

	Sym.	Asym.
Efficiency		
η_{Lnk}	$0.8^{\pm 0.15}$	$0.86^{\pm 0.04}$
η_{A}	$0.062^{\pm 0.003}$	$0.138^{\pm 0.002}$
η_{B}		$0.045^{\pm 0.001}$
Dark counts		
$\mathrm{dc}_{\mathrm{Lnk}}$	$2.0 \cdot 10^{-7}\,^{\pm 0.8}$	$3.6 \cdot 10^{-4}\,^{\pm 0.5}$
dc_{A}	$3.2 \cdot 10^{-4}\,^{\pm 0.4}$	$1.8 \cdot 10^{-4}\,^{\pm 0.5}$
dc_{B}		$1.1 \cdot 10^{-4}\,^{\pm 0.4}$
MSE	$1.0^{\pm 0.03}$	$3.4 \cdot 10^{-2}\,^{\pm 0.4}$

Data from ICFO (unpublished)

QIA - *Fit with Experimental Data*

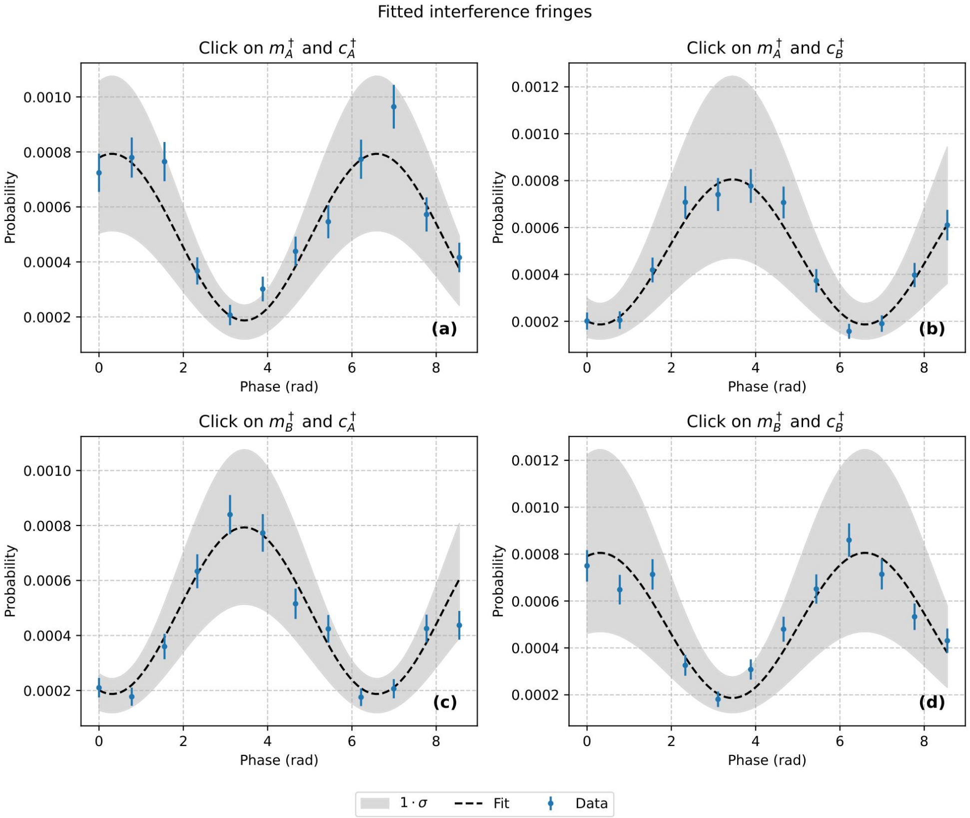


VISIBILITY

(single-photon interference)

Hanni, Rodriguez-Moldes, Appas et al. - Physical Review X 15, 041003 (2025)

QIA - *Fit and Numerical Study*



FIT - VISIBILITY

	Fit	*Hanni et al. 2015*
Efficiency		
η_{Lnk}	$0.099^{\pm 0.050}$	0.20
η_{A}	$0.13^{\pm 0.067}$	$4.4 \cdot 10^{-3}$
η_{B}	$0.12^{\pm 0.066}$	$6.1 \cdot 10^{-3}$
Dark counts		
$\mathrm{DC}_{\mathrm{Lnk}}$	$6.2 \cdot 10^{-3\, \pm 0.3}$	n.p.
DC_{A}	$9.0 \cdot 10^{-3\, \pm 0.3}$	n.p.
DC_{B}	$9.4 \cdot 10^{-3\, \pm 0.3}$	n.p.

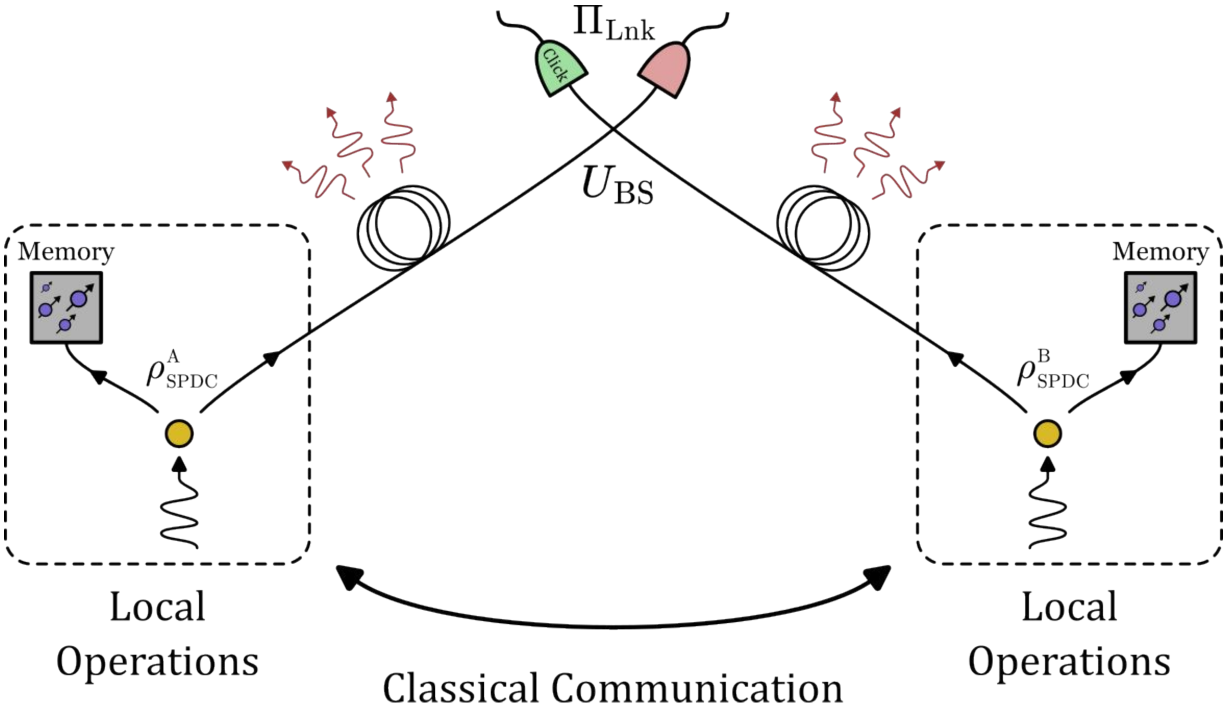
Hanni, Rodriguez-Moldes, Appas et al. - Physical Review X 15, 041003 (2025)

RESSOURCES

Entanglement Witness

GOAL

Develop a LOCC-based witness suitable for the elementary link



QIA - *Certifying Entanglement*

INPUT: $\{a_1, a_2\}$

e.g. X and Z

ALICE QUBIT

$$\begin{pmatrix} \gamma_A & \delta_A \\ \delta_A^\star & 1-\gamma_A \end{pmatrix}$$

OUTPUT: *{+1, -1}*

The inputs label two
non-commuting local observables

$$\mathbb{E}\left[a,b\right] = \left\langle \hat{A}(a) \otimes \hat{B}(b) \right\rangle_{\rho_{AB}}$$

INPUT: $\{b_1, b_2\}$

BOB QUBIT

$$\begin{pmatrix} \gamma_B & \delta_B \\ \delta_B^\star & 1-\gamma_B \end{pmatrix}$$

OUTPUT: *{+1, -1}*

CHSH SCORE

$$S = \left|\mathbb{E}\left[a_1,b_1\right] + \mathbb{E}\left[a_1,b_2\right] + \mathbb{E}\left[a_2,b_1\right] - \mathbb{E}\left[a_2,b_2\right]\right|$$

Local Bound

$$|0\rangle\langle 0| + |1\rangle\langle 1|$$

$$2 < S \leq 2\sqrt{2}$$

Saturation

$$|\Psi^+\rangle\langle\Psi^+|$$

Clauser, Horne, Shimony, and Holt. - Physical Review Letters 23, 880 (1969)

INPUT: $\{a_1, a_2\}$

e.g. X and Z

ALICE Q

OUTPUT:

INPUT: $\{b_1, b_2\}$

QUBIT

T: $\{+1, -1\}$

How to perform Pauli-like measurement in the full Fock space ?

QUBIT SPACE

$$\begin{pmatrix} p^0\,\rho^{(0)}_{\mathrm{Lnk}} & 0 & 0 & \cdots \\ 0 & p^1\,\rho^{(1)}_{\mathrm{Lnk}} & 0 & \cdots \\ 0 & 0 & p^2\,\rho^{(2)}_{\mathrm{Lnk}} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

MULTI-PHOTONS

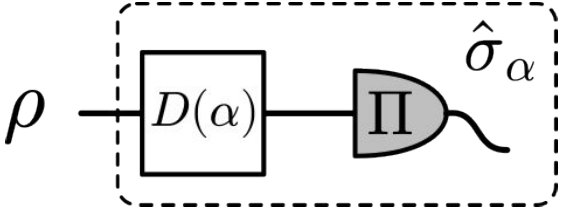
Local Bound

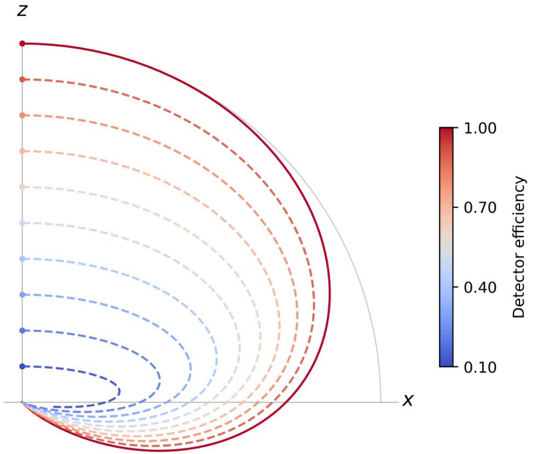
$|0\rangle\langle 0| + |1\rangle\langle 1|$

$$2 < S \leq 2\sqrt{2}$$

Saturation

$|\Psi^+\rangle\langle\Psi^+|$





Bloch-Sphere representation of ***n*** as a function of ***α***

The displacement allow to perform a **projected measurement in the Bloch** along the vector:

$$\vec{n} \propto \begin{pmatrix} -\,e^{-\eta|\alpha|^2}\ |\alpha|\ \eta \cos\left(\delta\right) \\ e^{-\eta|\alpha|^2}\ |\alpha|\ \eta \sin\left(\delta\right) \\ \frac{1}{2}e^{-\eta|\alpha|^2}\eta\left(1-|\alpha|^2\eta\right) \end{pmatrix}$$

$\alpha = 0$ → **Z measurement**

$\alpha = \frac{1}{\sqrt{\eta}}$ → **X measurement**

Vivoli et al. - New Journal of Physics 17, 023023 (2015)

QIA - *Certifying Entanglement*

INPUT: $X, Z \rightarrow \alpha_1, \alpha_2$

↓

ALICE STATE

$$\left(\begin{array}{c|c} |0\rangle, |1\rangle & \star \\ \hline \star & |n\rangle \end{array}\right)$$

↓

OUTPUT: *{+1, -1}*

INPUT: $X, Z \rightarrow \beta_1, \beta_2$

↓

BOB STATE

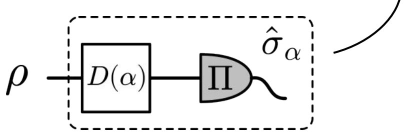
$$\left(\begin{array}{c|c} |0\rangle, |1\rangle & \star \\ \hline \star & |n\rangle \end{array}\right)$$

↓

OUTPUT: *{+1, -1}*

The displacements α and β allows
pauli-like measurement

$$\mathbb{E}[\alpha, \beta] = \langle \hat{o}_\alpha \otimes \hat{o}_\beta \rangle_{\rho_{\mathrm{AB}}}$$



$$S = |\mathbb{E}[\alpha_1, \beta_1] + \mathbb{E}[\alpha_1, \beta_2] + \mathbb{E}[\alpha_2, \beta_1] - \mathbb{E}[\alpha_2, \beta_2]|$$

In practice α and β are optimized to reach a maximum

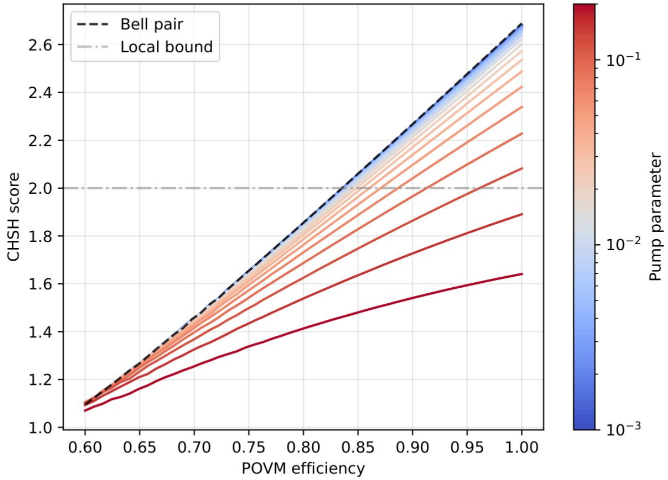
Vivoli et al. - New Journal of Physics 17, 023023 (2015)

TWO ISSUES

→ "General" witness

CHSH: witness non-locality of the state

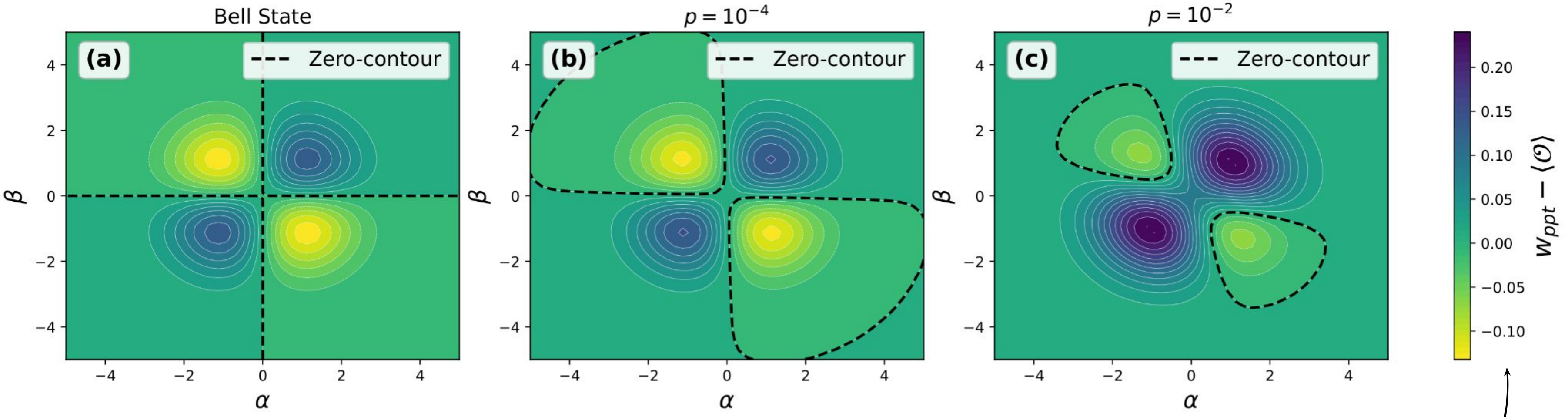
WANTED: non-separability in the qubit subspace



→ Losses

The witness is **sensitive to memory-loss**: must reach a **0.8 efficiency** while optimistic value is around **0.5 efficiency**

Vivoli et al. - New Journal of Physics 17, 023023 (2015)



negative $\rightarrow$ *non-separable*

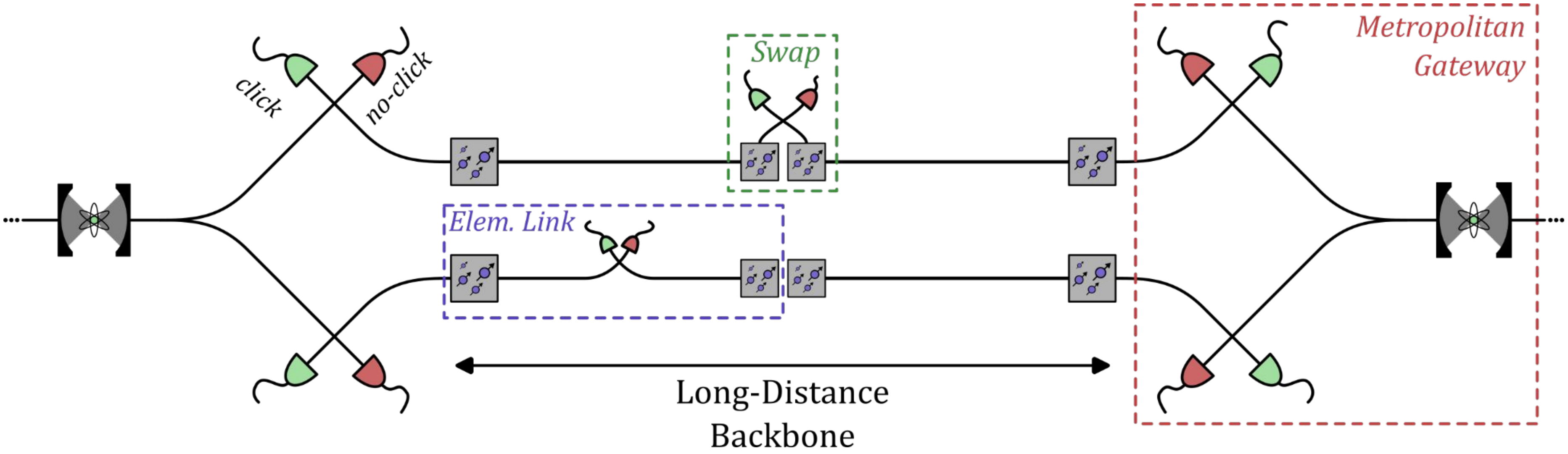
Witness according to the **displacements**
for different values of the pump parameter

(250km link, no dark-count)

RESSOURCES

Full Repeater Link

QIA - *Full Link Architecture*



ACTUAL STUDIED REPEATER

Dual-rail multi-elementary-link chain with a heterogeneous interface

Cussenot et al. - Physical Review Letters 135, 240803 (2025)

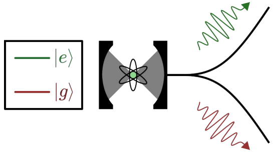
QIA - *Full Link Architecture*

Vacuum component **growing linearly** with the number of swaps:

$$\left(1-\frac{2}{2^n\cdot(2-\eta_S)+\eta_S}\right)|00\rangle\langle 00| + \frac{2}{2^n\cdot(2-\eta_S)+\eta_S}|\Psi^+\rangle\langle\Psi^+|$$

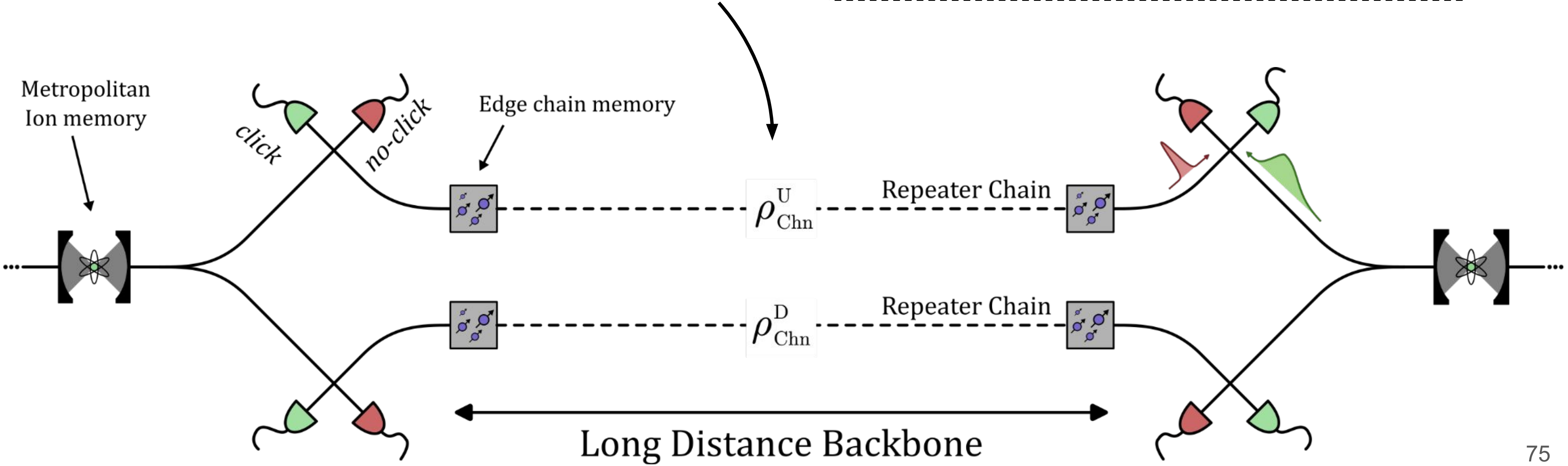
4 Clicks

1-click per ion

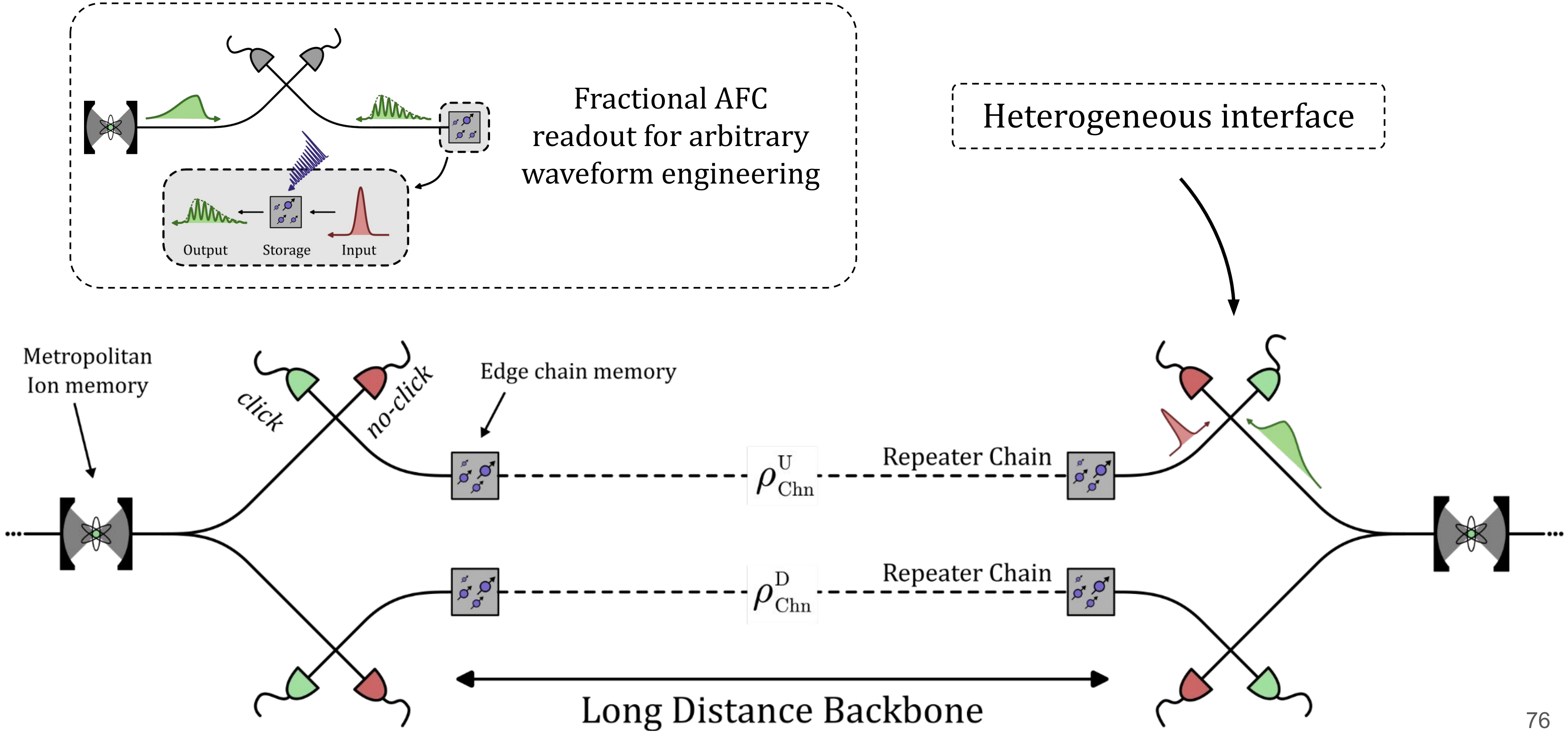


1-click per chain

$$\alpha\ |00\rangle\langle 00| + \beta\ |\Psi^+\rangle\langle\Psi^+|$$

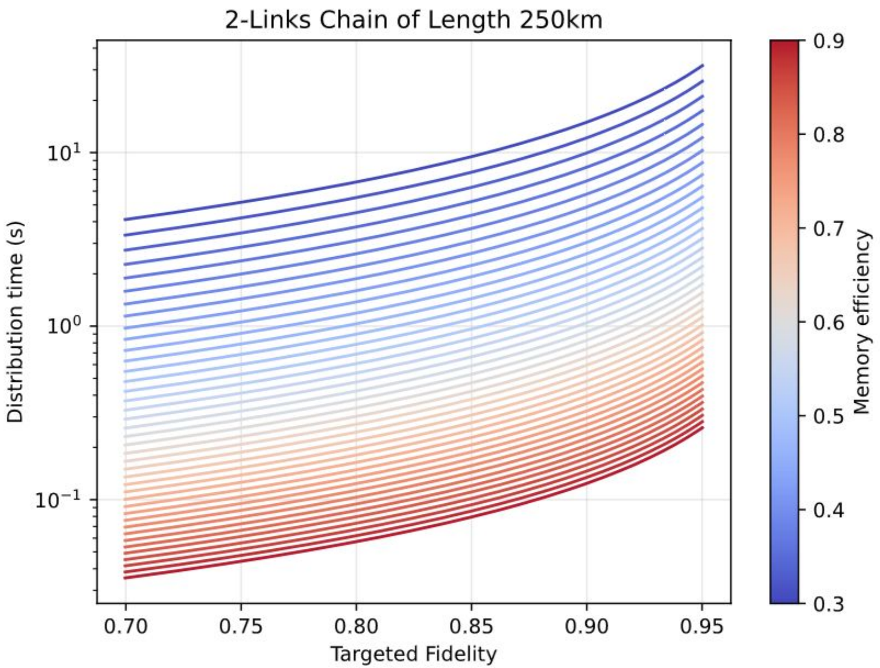


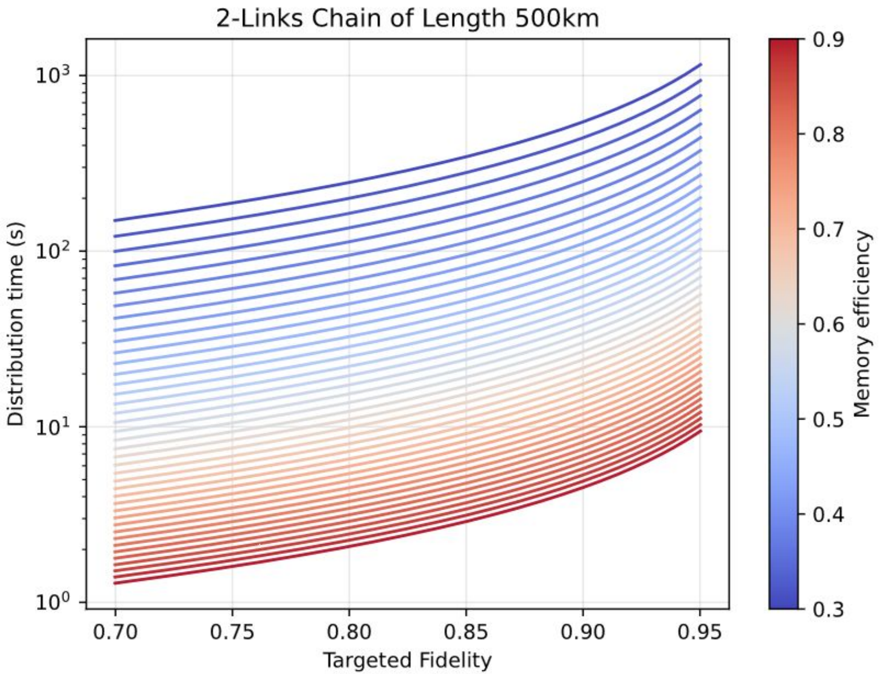
QIA - *Full Link Architecture*



Cussenot et al. - Physical Review Letters 135, 240803 (2025)

QIA - *Full Link Architecture*



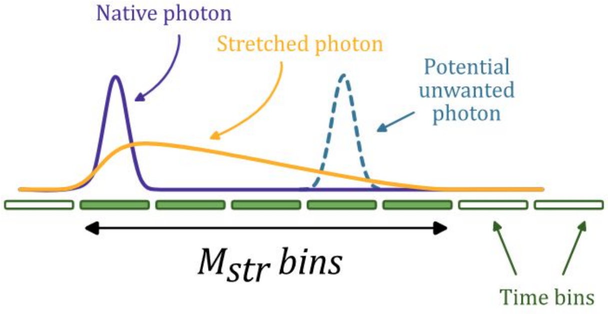


Entanglement distributed in **~0.5 s** over **250 km**, with **0.5 efficient memories** and a **0.9 target fidelity**

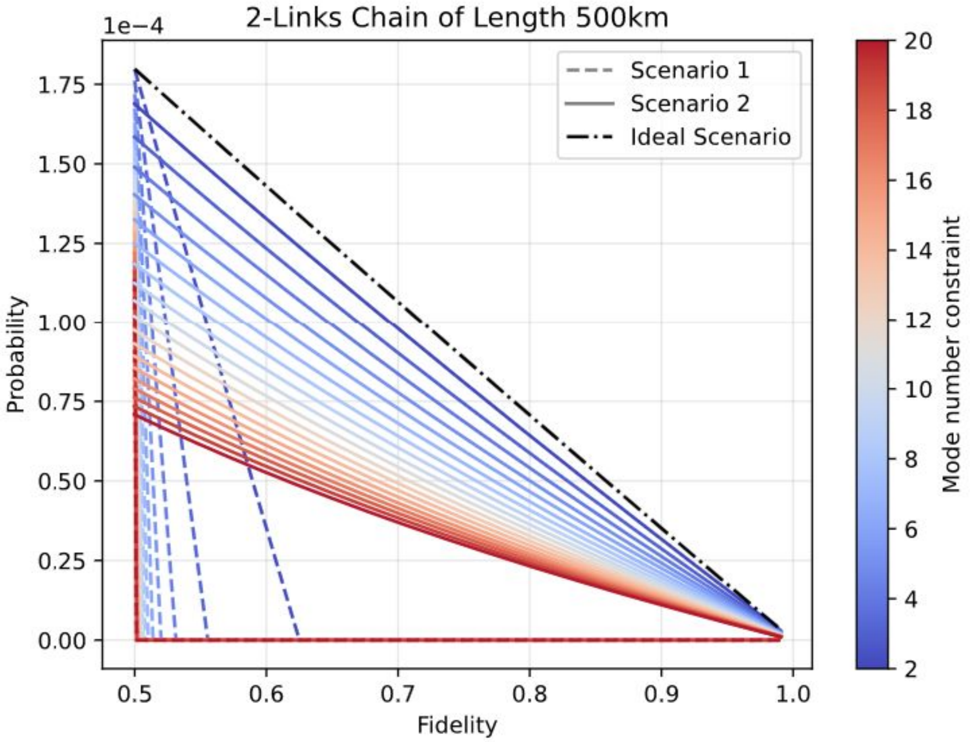
Entanglement distributed in **~10 s** over **500 km**, with **0.5 efficient memories** and a **0.9 target fidelity**

Cussenot et al. - Physical Review Letters 135, 240803 (2025)

QIA - *Full Link Architecture*



*Impact of the photon shaping on the **temporal multimode capabilities** of the repeater*



Cussenot et al. - Physical Review Letters 135, 240803 (2025)

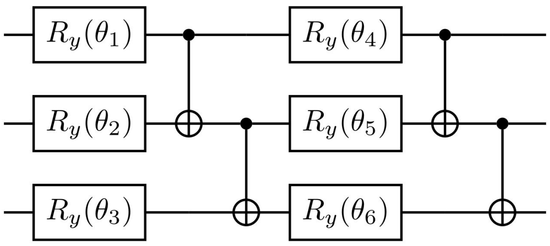
RESSOURCES

Quantum Circuit Synthesis

QCS - *What is Quantum Circuit Synthesis ?*

SYNTHESIS

CONTINUOUS

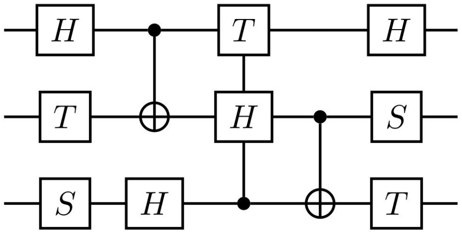


Optimizing continuous parameters on ***a given ansatz***

NOTES:

→ Continuous optimisation problem
→ Difficulty: *Barren Plateau*
→ NISQ paradigm

DISCRETE



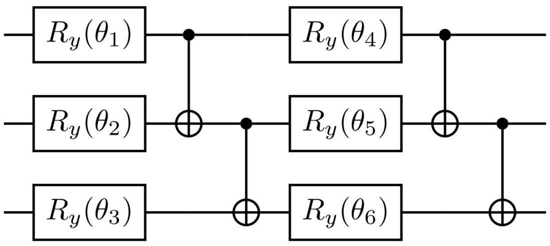
Finding a gate-combinaison from ***a given gate set***

NOTES:

→ Combinatorial problem
→ Difficulty: *Large Space*
→ FTQC paradigm

SYNTHESIS

CONTINUOUS



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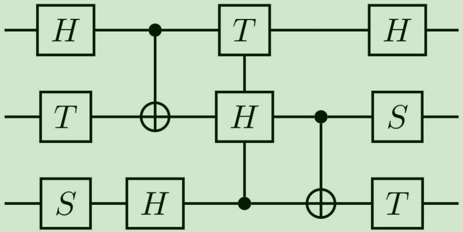

Finding a gate-combinaison from
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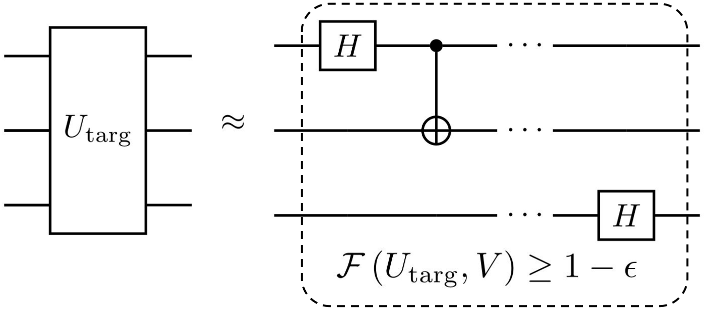
→ FTQC paradigm

DISCRETE SYNTHESIS

APPROXIMATE



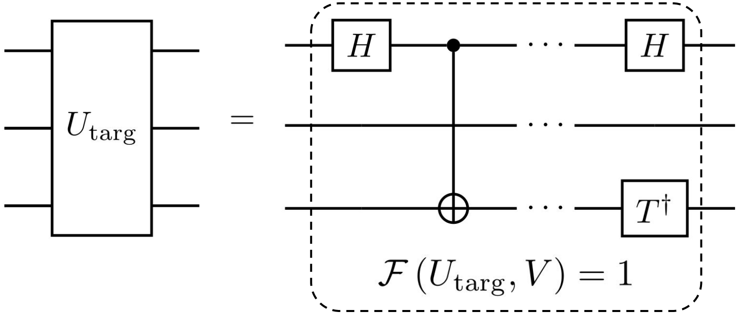
*Finding a decomposition **up to ε***

$U(2^n) = \overline{\mathcal{G}_n}$

NOTES:

→ Always exist *(Solovay-Kitaev)*
→ FTQC parametrized gates *(e.g. θ-rotation)*
→ Historical quantum compilation

EXACT



*Finding an **exact** decomposition*

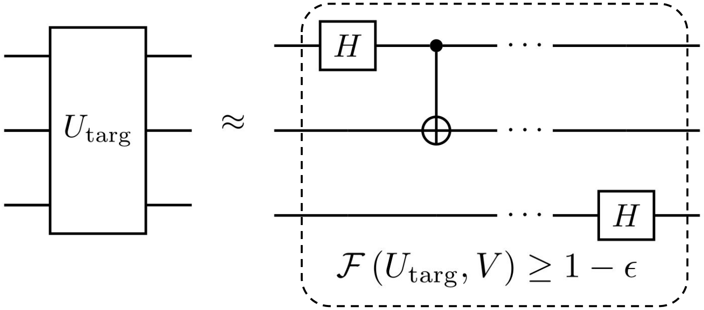
$\mathbb{Z}\left[\frac{1}{\sqrt{2}}, i\right]$

NOTES:

→ May not exist *(Giles-Selinger)*
→ FTQC aglebric subroutine *(e.g. addition)*
→ Modern quantum compilation

DISCRETE SYNTHESIS

APPROXIMATE



Finding a decomposition ***up to ε***

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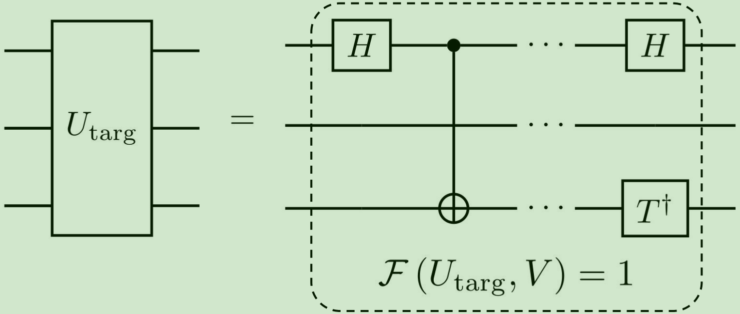
EXACT



Finding an ***exact*** *decomposition*

$\mathbb{Z}\left[\frac{1}{\sqrt{2}}, i\right]$

NOTES:

→ May not exist *(Giles-Selinger)*
→ FTQC aglebric subroutine *(e.g. addition)*
→ Modern quantum compilation

WHICH METHOD ?

OPTIMAL

$$\left[\bigvee_{j} x_{i,j}\right] \wedge \left[\bigwedge_{j_1,j_2} \neg x_{i,j_1} \vee \neg x_{i,j_2}\right]$$

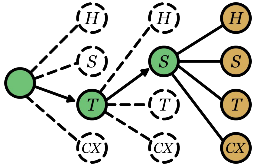
*Finding decomposition under constraint with **optimality***

- ✔ *optimality*
- ✖ *heavy computation requirement*

EXAMPLES:

→ Meet-in-the-middle
→ SAT Solver

HEURISTIC



*Finding decomposition under constraint with **satisfied criterion***

- ✔ *light computation requirement*
- ✖ *no optimality*

EXAMPLES:

→ Greedy technique
→ Stochastic methods
→ Machine Learning

WHICH METHOD ?

OPTIMAL

$$\left[\bigvee_j x_{i,j}\right] \wedge \left[\bigwedge_{j_1,j_2} \neg x_{i,j_1} \vee \neg x_{i,j_2}\right]$$

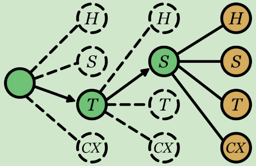
*Finding decomposition under constraint with **optimality***

- ✔ *optimality*
- ✖ *heavy computation requirement*

EXAMPLES:

- → Meet-in-the-middle
- → SAT Solver

HEURISTIC



*Finding decomposition under constraint with **no optimality guarantee***

- ✔ *light computation requirement*
- ✖ *no optimality*

EXAMPLES:

- → Greedy technique
- → Stochastic methods
- → Machine Learning

RESSOURCES

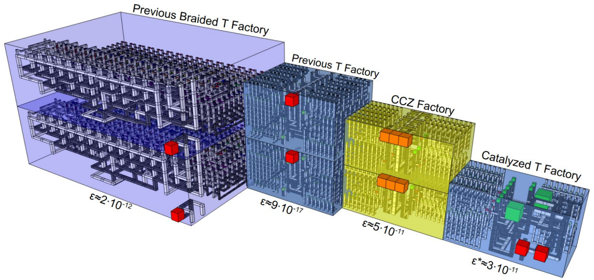
Resource Optimization

GATES COST

Some gates are more expensive than others

Examples:

→ 2D QEC: T-gate and Toffoli-gate
→ 3D QEC: H-gate



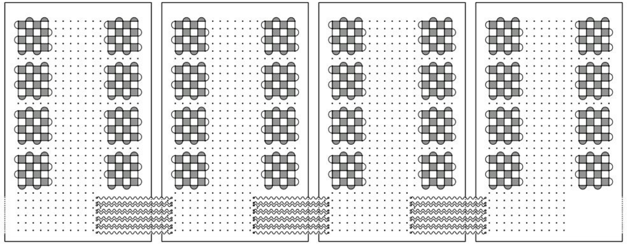
Gidney and Fowler - Quantum 3, 135 (2019)

QUBIT CONNECTIVITY

Hardware constrains the available qubit connectivity

Examples:

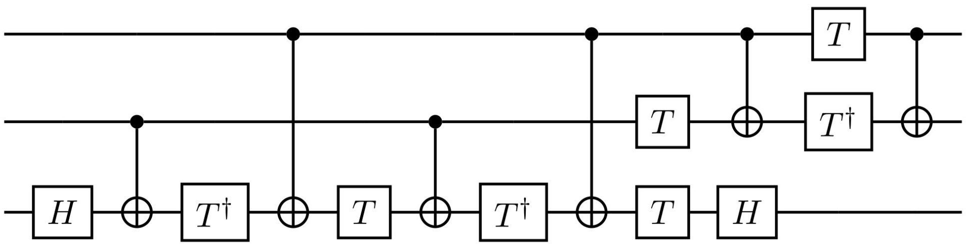
→ All-to-all: *Trapped ions*
→ Neighbors: *Transmon*
→ Star-topology: *NV-center*



Jacinto et al. - Physical Review Research 8, 013205 (2026)

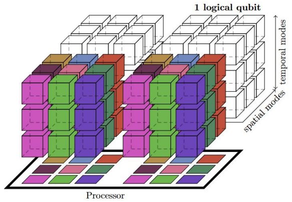
GATE RESOURCE CONSTRAINT

T-count: 7
T-depth: 5



GATE-COUNT: number of gates

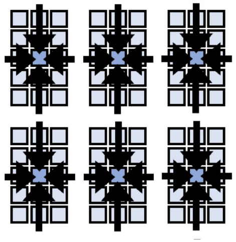
non-parallelizable QPU architecture



Example:
Memory-based QPU
(Gouzien, Sangouard arXiv:2103.06159)

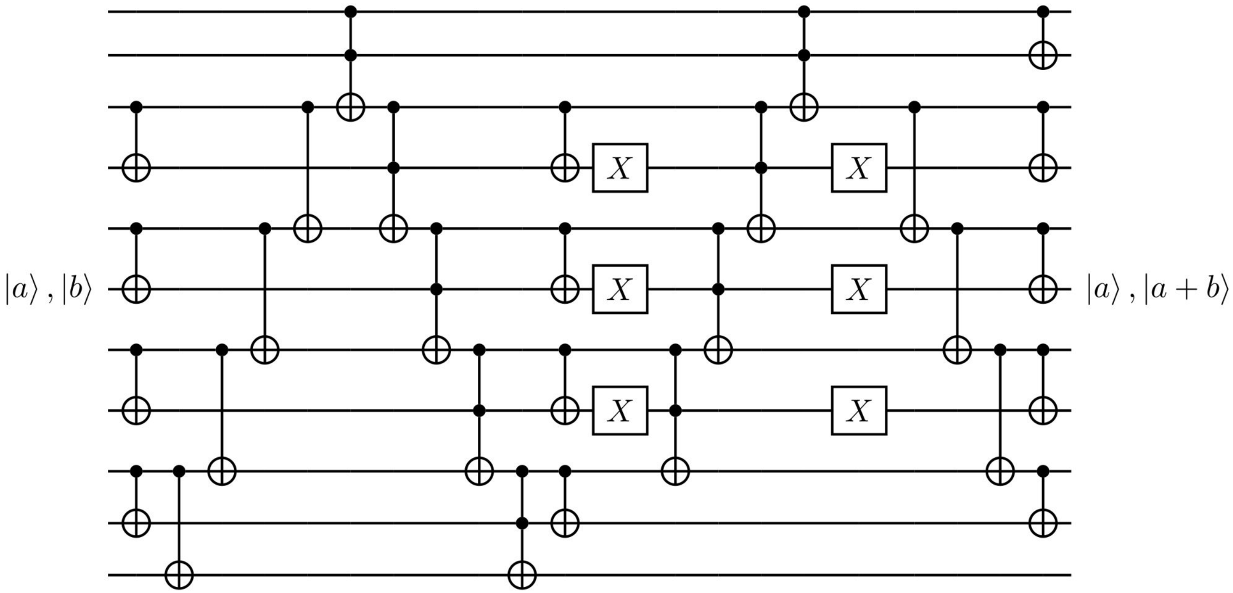
GATE-DEPTH: number of "gate-layers"

parallelizable QPU capabilities



Example:
Multiple T-factories QPU
(Beverland et al. arXiv:2211.07629)

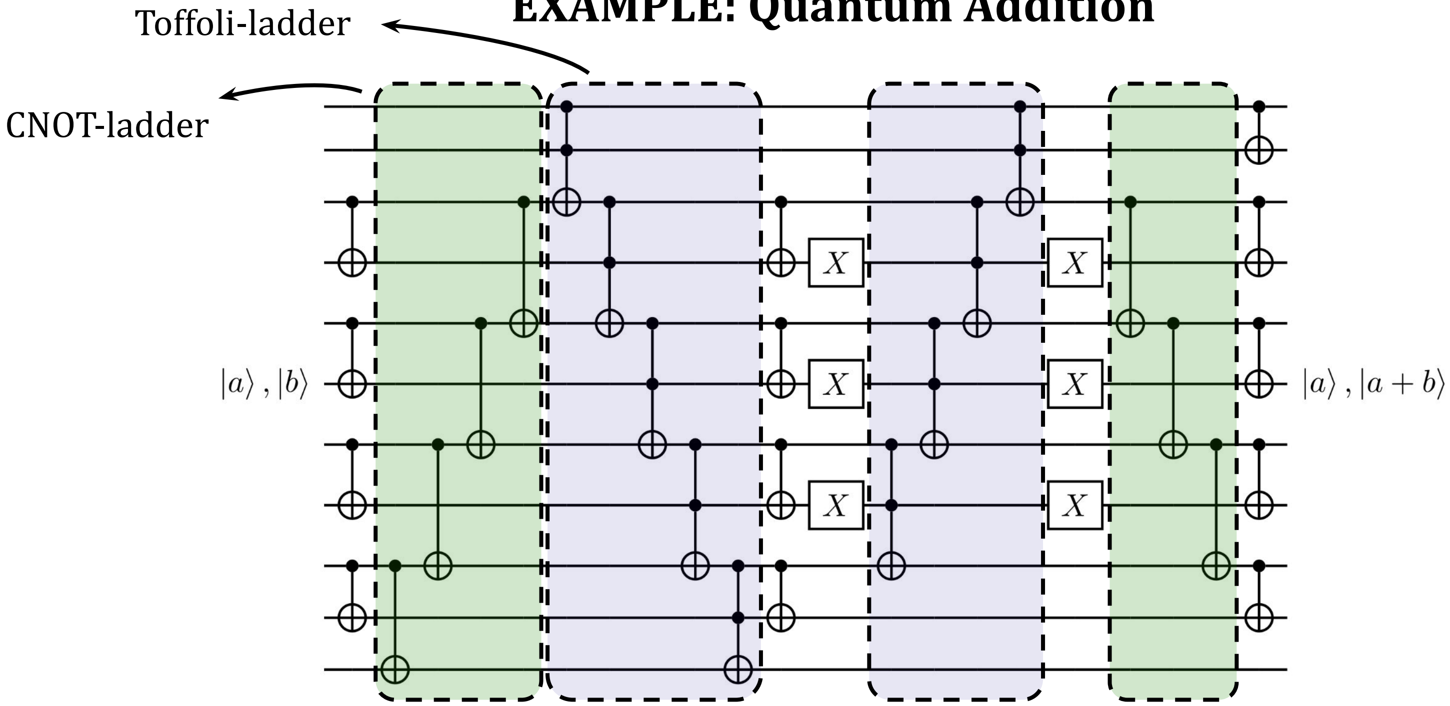
EXAMPLE: Quantum Addition



General Quantum Addition Structure from Remaud et al.

Remaud et al. - arXiv:2510.00840

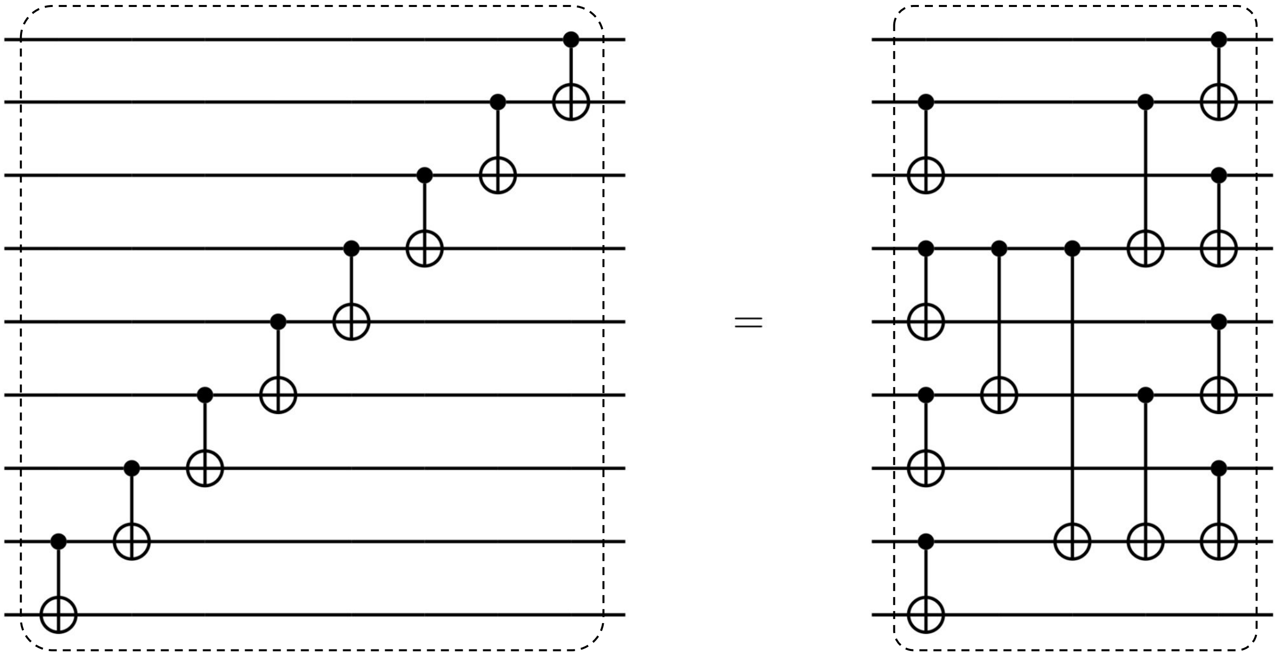
EXAMPLE: Quantum Addition



General Quantum Addition Structure from Remaud et al.

(arXiv:2510.00840)

QCS - *Resource Optimization*



CX-depth: 8
CX-count: 8

CNOT-COUNT OPTIMIZATION

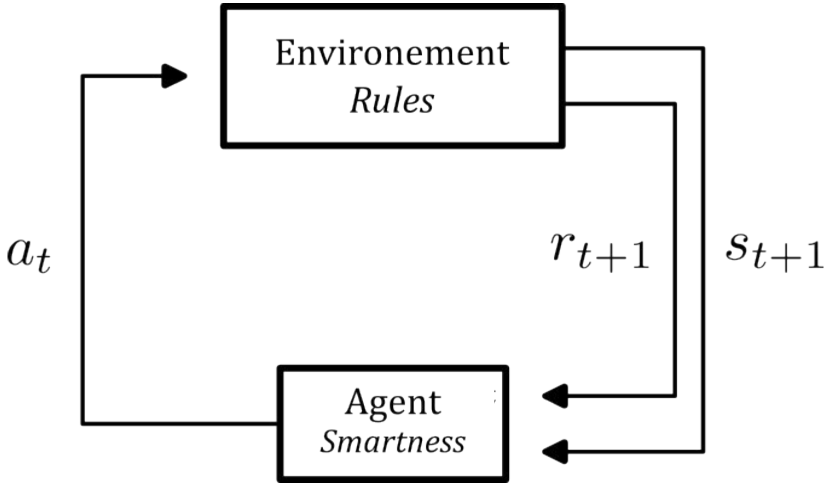
CX-depth: 5
CX-count: 12

CNOT-DEPTH OPTIMIZATION

Remaud et al. - arXiv:2510.00840

RESSOURCES

Reinforcement Learning



POLICY - *smartness*

$$\pi\left(a|s_t\right) = \mathbb{P}\left(a|s_t\right)$$

VALUE FUNCTION - *purpose*

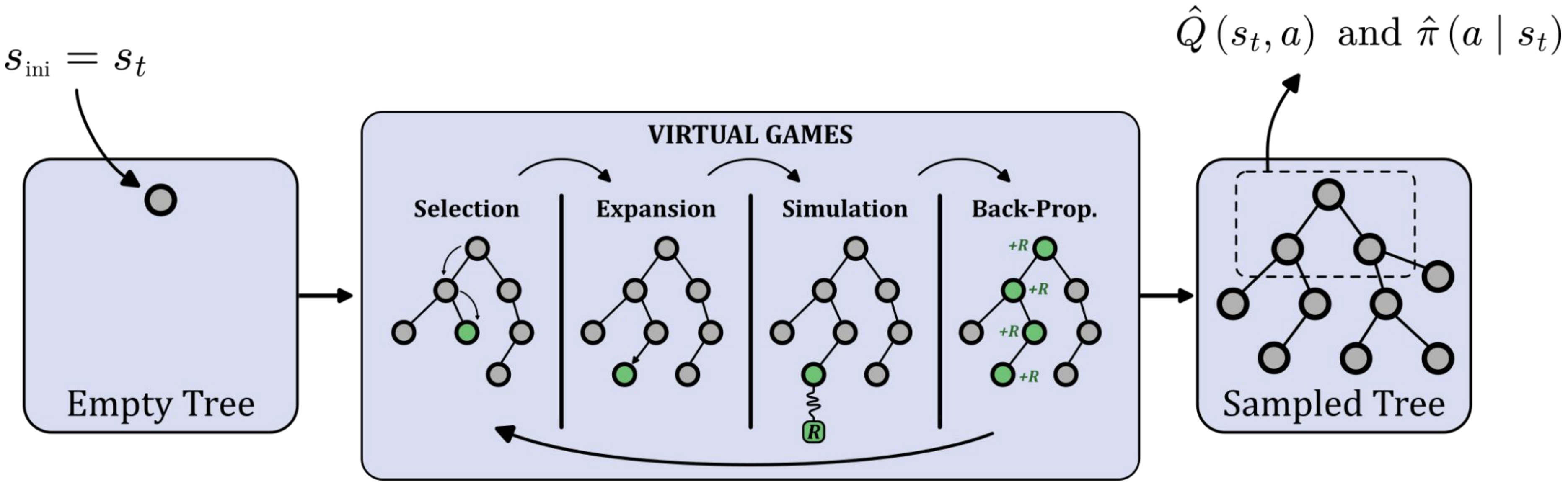
$$V^{\pi}(s) = \mathbb{E}_{\pi}\left[\sum_{k=0}^{\infty} \gamma^k \cdot r_{k+1} \mid s_0 = s\right]$$

BEST POLICY - *optimization*

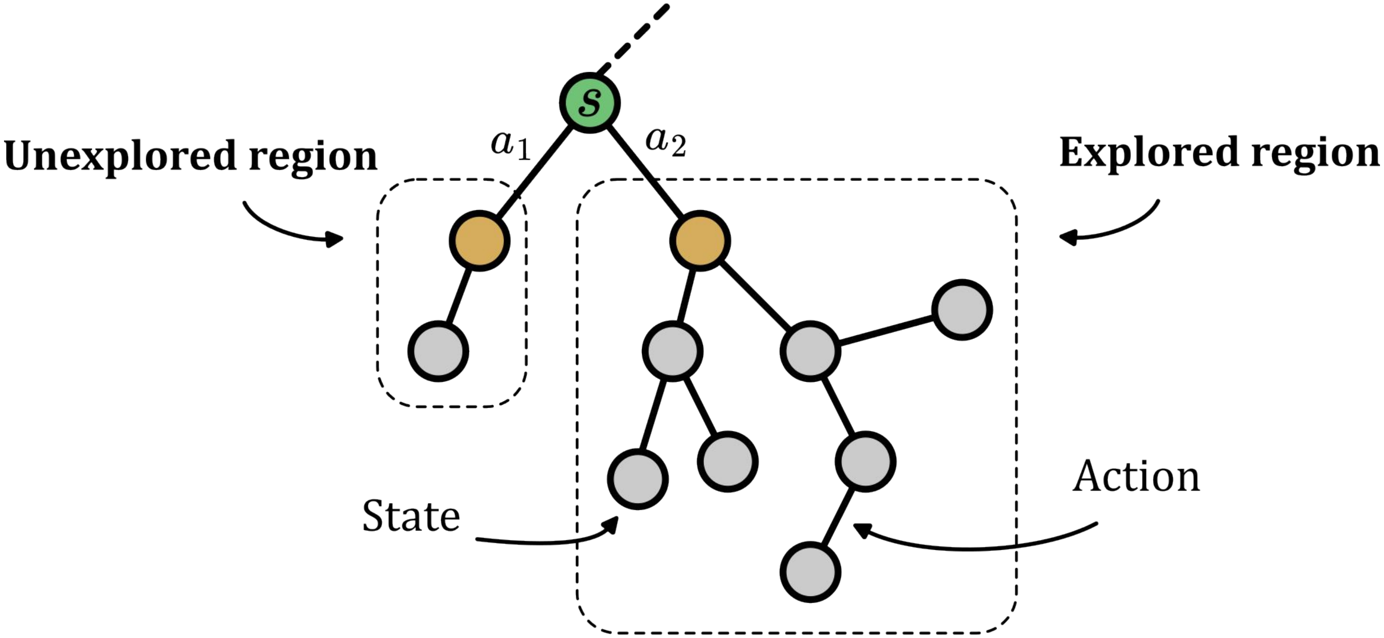
$$\pi^{\star} \in \arg\max_{\pi} V^{\pi}(s), \quad \forall s \in \mathcal{S}$$

*We call **agent** the **algorithm** that **approximates** the **best policy***

Reinforcement Learning: An Introduction (Richard S. Sutton and Andrew G. Barto)

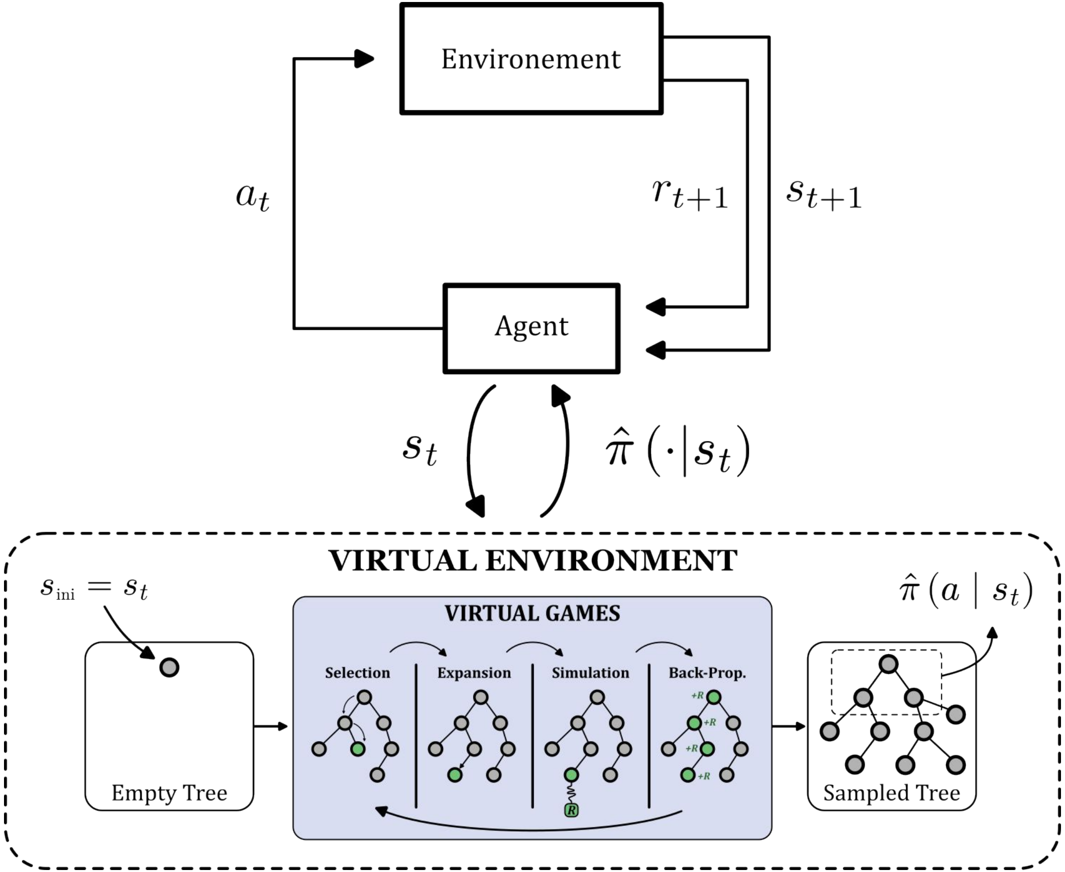

$s_{\text{ini}} = s_t$
Empty Tree
VIRTUAL GAMES
Selection
Expansion
Simulation
Back-Prop.
R
+R
+R
+R
+R
Sampled Tree
$\hat{Q}(s_t, a)$ and $\hat{\pi}(a \mid s_t)$

QCS - *Reinforcement Learning*

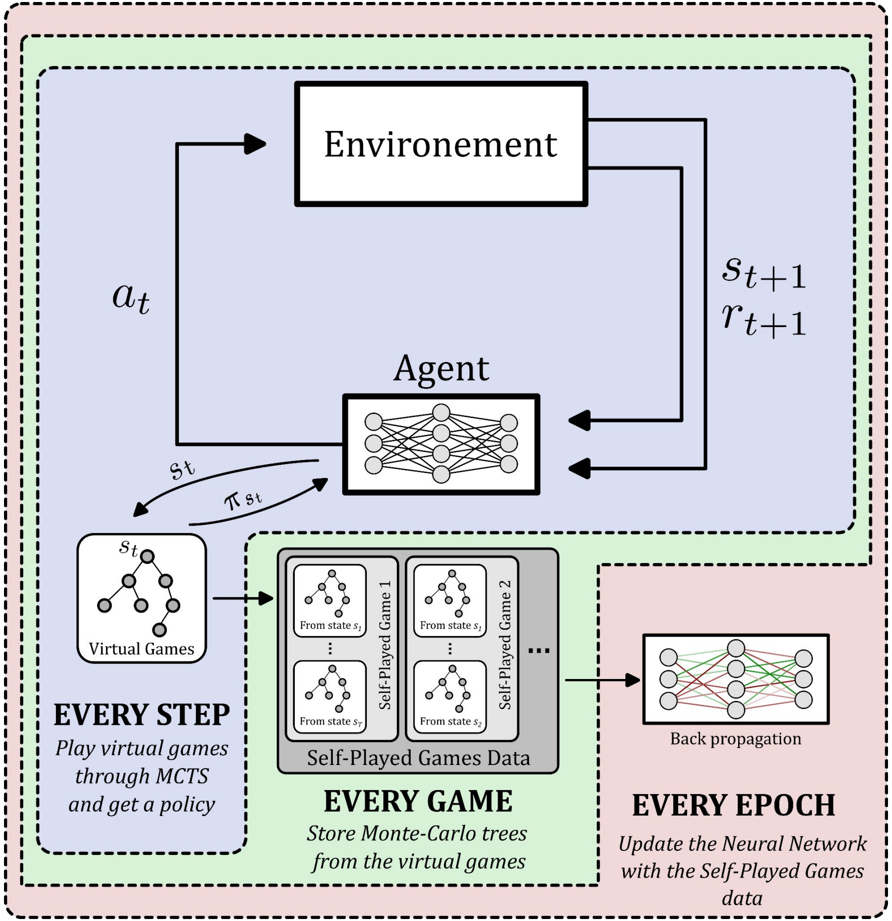


$$\mathrm{PUCT}(s,a) = \hat{Q}(s,a) + C_{PUCT}\,\tilde{\pi}(a \mid s) \cdot \frac{\sqrt{N(s)}}{N(s,a)+1}$$

QCS - *Reinforcement Learning*



QCS - *Results*



MAIN IDEA

reinforcement loop

- Self-played game *(training unitary)*
- Store decision tree statistics
- Update the neural network

PRACTICAL NUMBERS

→ 2x NVIDIA Titan XP *(no Tensor Cores and FP16)*

→ ~4 days of training

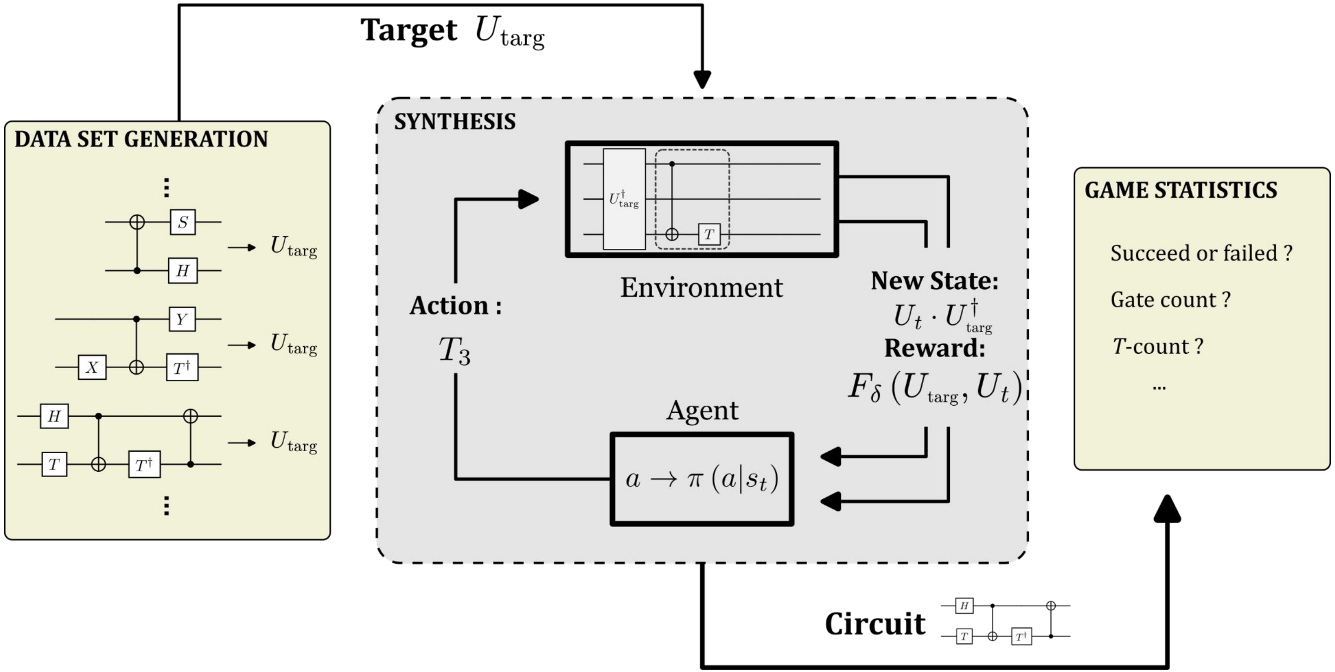
→ 10^5 self-played game

RESSOURCES

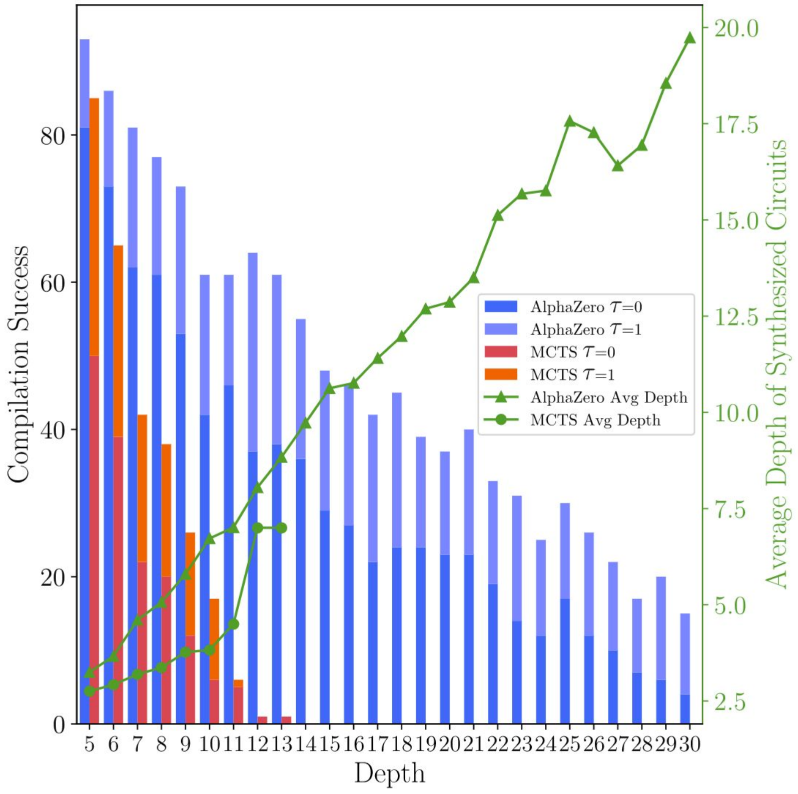
Results

QUANTITATIVE BENCHMARK

random circuit → target unitary → can the agent find a circuit?



QCS - *Results*



2+1 architecture

PROTOCOL

Success:

$$U_{\text{targ}}^{\dagger} \cdot U_t = \mathbb{1} \qquad \text{and} \qquad t \leq d_{\text{targ}}$$

Search-Protocol:

U_{targ} → Deterministic **τ=0** *1 run* → *failed* → Stochastic **τ=1** *10 runs*

100 circuits per depth

BRIEF ANALYSIS

→ **MCTS alone:** dies for depth-12 unitaries

→ **MCTS + NN:** up to depth-30 unitaries

→ **Stochasticity:** helps the synthesis

Valcarce, Grivet and Sangouard - arXiv:2508.21217v1

Experimental and Theoretical progress

HARDWARE - Below threshold

Transmon-based QPU (2025)

Google AI Quantum

→ Surface code (d=7)
→ 101 physical qubits

Google Quantum AI Nature 638, 920 (2025)

Cat-state-based QPU (2025)

→ Repetition code (d=5)
→ Cat state with 1.5 photons

Putterman et al. Nature 638, 927 (2025)

Amazon BraKet

SOFTWARE - Reducing the cost

Circuit-Implementation Side

→ Saving 50% Toffoli on Addition
(Gidney - Quantum 2, 74 - 2018)

→ Ancilla for subroutine T-count optimization
(Khattar, Gidney - arXiv:2407.17966 - 2024)

→ Formal synthesis methods
(Gouzien, Sangouard - arXiv:2503.15452 - 2025)

QEC-Implementation Side

→ Space-Time trade-off on surface code
(Litinski - Quantum 3, 128 - 2019)

→ Magic state cultivation: making T-gates cheaper
(Gidney - arXiv:2409.17595 - 2024)

→ Resource Estimation on Neutral Atom QPU
(Cain, Xu - arXiv:2603.28627 - 2026)

STATE OF THE RESEARCH

Lu et al., Science 391, 592 (2026) - *Bao/Pan, USTC*

Focus on long-distance capabilities:

→ *Practical* ***DI-QKD at 11km*** *(distant hubs, 3.6 bits/min)*
→ *Asymptotic key distribution* ***up to 100km*** *(in laboratory)*

Hanni et al. Physical Review X 15, 041003 (2025) - *De Riedmatten, ICFO*

Focus on scalability capabilities:

→ ***Multimode*** *capabilities (15 modes)*
→ *"Feed-forward"* ***real-time control*** *(on-which-detector correction)*

Stas et al. Nature 651, 326 (2026) - *Lukin, Harvard*

Toward non-cryptographic applications:

→ *Non-local* ***optical interferometry*** *for astronomy (Gottesman/Jennewein/Croke 2012)*
→ ***Quantum Internet*** *for real-world application (Kimble 2008)*