

Enhanced Fault-tolerance in Photonic Quantum Computing: Comparing the Honeycomb Floquet Code and the Surface Code in Tailored Architecture

Théo Dessertaine^{*,1}, Boris Bourdoncle¹, Pierre Colonna d'Istria¹, Aurélie Denys¹, Grégoire de Gliniasty^{1,2}, Gerard Valenti-Rojas^{3,4}, Shane Mansfield¹, **Paul Hilaire**^{1,5}

¹Quandela, ²LIP6, ³Naquidis Center, ⁴IMB, ⁵LTCl, Inria Télécom Paris

June 25, 2026





Théo Dessertaine



Boris Bourdoncle



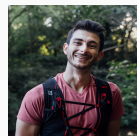
Pierre Colonna d'Istria



Aurélie Denys



Grégoire de Glinasty



Gerard Valentí-Rojas



Shane Mansfield

Enhanced **Fault-tolerance** in Photonic Quantum Computing: Comparing the Floquet Code and the Surface Code in Tailored Architecture

- **Fault-tolerant quantum computing**

Enhanced **Fault-tolerance** in **Photonic Quantum Computing**: Comparing the Floquet Code and the Surface Code in Tailored Architecture

- **Fault-tolerant quantum computing**
- **Spin-Optical Quantum Computing (SPOQC) architecture**

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- Spin-Optical Quantum Computing (SPOQC) architecture
- Quantum Error Correcting (QEC) codes

Enhanced Fault-tolerance in Photonic Quantum Computing: Comparing the Floquet Code and the Surface Code in Tailored Architecture

- Fault-tolerant quantum computing
- Spin-Optical Quantum Computing (SPOQC) architecture
- Quantum Error Correcting (QEC) codes
- Optimizing hardware with QEC

Main challenge: **Physical Noise**

QEC: Physical noise $\neq$ Logical noise

$\Rightarrow$ Need for Fault-Tolerant Quantum Computers.

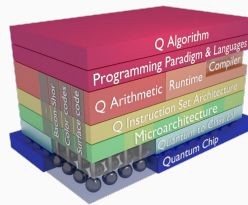
FTQC architecture

An FTQC architecture:

- Hardware (physical gate / noise)
- QEC code
- Decoder
- FT gates

⇒ **Co-design for efficient FTQC.**

All these elements should be optimized jointly for an efficient architecture.



credit: QuTech

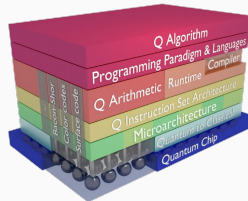
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All these elements should be optimized jointly for an efficient architecture.



credit: QuTech

- **Similar work** [1] Chan *et al.*, ArXiv 2410.06784 (2024)
- Walking cat architecture (IonQ)
- Measurement-free FT (Neqxt)
- Directional codes (Riverlane)

Enhanced Fault-tolerance in Photonic Quantum Computing: Floquet Code Outperforms Surface Code in Tailored Architecture

*A photonic architecture exploiting spin quantum
emitter sources*



- **Advantages:**
 - Fast clock rate
 - High-fidelity single-qubit gates
 - Long-range interaction

Photonic Quantum Information Processing



- **Advantages:**
 - Fast clock rate
 - High-fidelity single-qubit gates
 - Long-range interaction
- **Challenges:**
 - Probabilistic entangling gates with linear optics
 - Photon loss

Photonic Quantum Information Processing



- **Advantages:**

- Fast clock rate
- High-fidelity single-qubit gates
- Long-range interaction

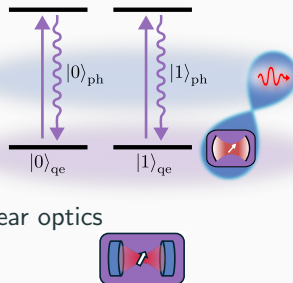
- **Challenges:**

- Probabilistic entangling gates with linear optics
- Photon loss

- **Current experimental developments:**

- Quantum emitters with spin degree of freedom
- Spin-entangled photon generation

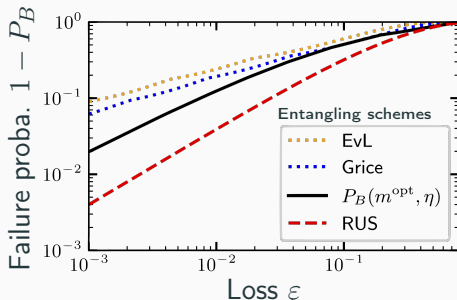
Spin quantum emitter



- [1] Coste *et al.*, Nat. Photon., 2023
- [2] Thomas *et al.*, Nature, 2022
- [3] Cogan *et al.*, Nat. Photon, 2023
- [4] Huet *et al.*, ArXiv, 2024

Entangling operations in Photonics

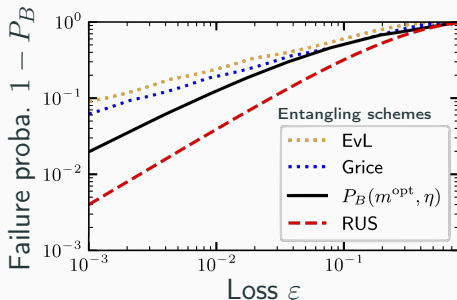
Successful entangling
gate probability P_B



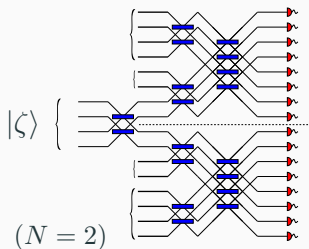
- [1] Ewert and van Look, Phys. Rev. Lett. (2014)
- [2] Grice, Phys. Rev. A (2011)
- [3] Hilaire et al., Quantum (2023)
- [4] Lee et al., Phys. Rev. A (2019)
- [5] Lim et al., Phys. Rev. Lett. (2005)

Entangling operations in Photonics

Successful entangling
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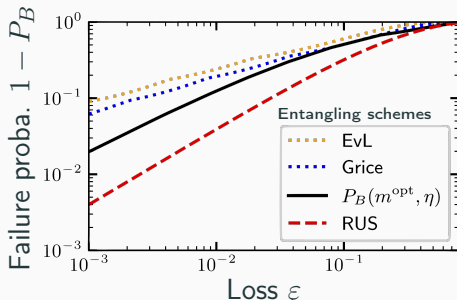
EvL [1] / Grice [2] schemes:
Ancilla-assisted entangling gates



- [1] Ewert and van Look, Phys. Rev. Lett. (2014)
- [2] Grice, Phys. Rev. A (2011)
- [3] Hilaire *et al.*, Quantum (2023)
- [4] Lee *et al.*, Phys. Rev. A (2019)
- [5] Lim *et al.*, Phys. Rev. Lett. (2005)

Entangling operations in Photonics

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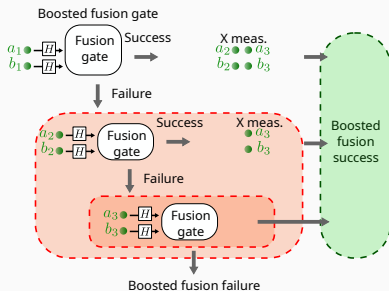
- [1] Ewert and van Look, Phys. Rev. Lett. (2014)
- [2] Grice, Phys. Rev. A (2011)
- [3] Hilaire *et al.*, Quantum (2023)
- [4] Lee *et al.*, Phys. Rev. A (2019)
- [5] Lim *et al.*, Phys. Rev. Lett. (2005)

Boosted fusion [3,4]

Photonic gate.

Requires:

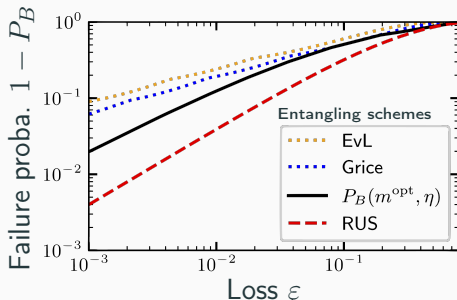
Spin-entangled photon generation



$$P_B(m, \eta) = (1 - 2^{-m}) \eta^{2m}$$

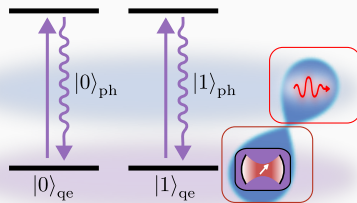
Entangling operations in Photonics

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Repeat-Until-Success gate [5]

Spin-spin gate.



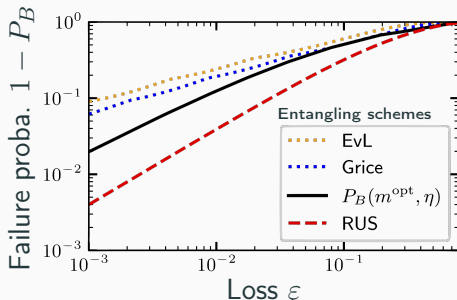
⇒ Idea of the “SPOQC” architecture

For SPin-Optical Quantum Computing

- [1] Ewert and van Look, Phys. Rev. Lett. (2014)
- [2] Grice, Phys. Rev. A (2011)
- [3] Hilaire et al., Quantum (2023)
- [4] Lee et al., Phys. Rev. A (2019)
- [5] Lim et al., Phys. Rev. Lett. (2005)

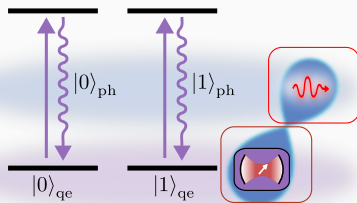
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⇒ Idea of the “SPOQC” architecture

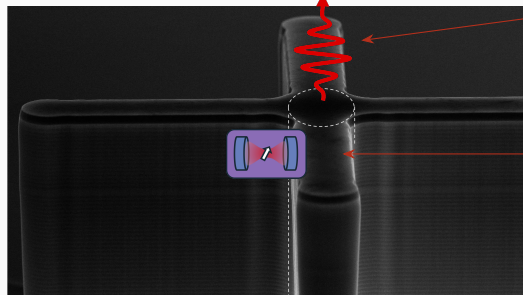


- [1] Ewert and van Look, Phys. Rev. Lett. (2014)
- [2] Grice, Phys. Rev. A (2011)
- [3] Hilaire et al., Quantum (2023)
- [4] Lee et al., Phys. Rev. A (2019)
- [5] Lim et al., Phys. Rev. Lett. (2005)

Physical Qubits in SPOQC

Physical Qubits

Semiconductor Quantum Dot



Photonic Qubit

Spin Qubit

Spin-Optical
Quantum Computing

Computation
Spin Qubit

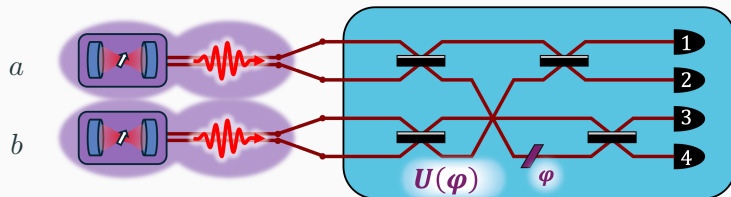
+

Communication
Photonic Qubit

Repeat-Until-Success (RUS): a Spin-Photon Hybrid Scheme

(1) Emission

$$\rho \mapsto K\rho K^\dagger$$



$$K = |0_s, 0_{ph}\rangle \langle 0_s| + |1_s, 1_{ph}\rangle \langle 1_s|$$

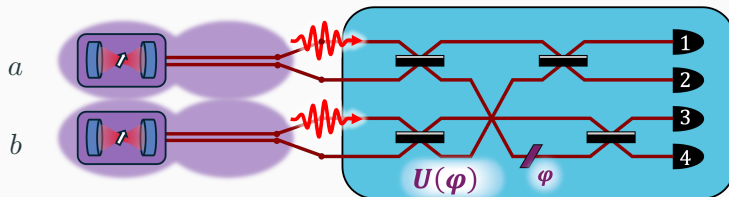
Repeat-Until-Success (RUS): a Spin-Photon Hybrid Scheme

(1) Emission

$$\rho \mapsto K\rho K^\dagger$$

(2) LO Transformation

$$U(\varphi)$$



Creation operators $\Rightarrow$ LO Transformation

$$\begin{aligned} \left| 0_{\text{ph}}^a \right\rangle &\rightarrow a_0^\dagger \\ \left| 1_{\text{ph}}^a \right\rangle &\rightarrow a_1^\dagger \\ \left| 0_{\text{ph}}^b \right\rangle &\rightarrow a_2^\dagger \\ \left| 1_{\text{ph}}^b \right\rangle &\rightarrow a_3^\dagger \end{aligned}$$

$$a_i^\dagger \rightarrow \sum_j U(\varphi)_{ij} a_j^\dagger$$

Repeat-Until-Success (RUS): a Spin-Photon Hybrid Scheme

(1) Emission

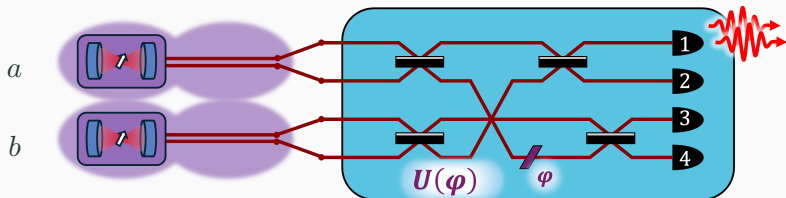
$$\rho \mapsto K\rho K^\dagger$$

(2) LO Transformation

$$U(\varphi)$$

(3) Detection

$$\pi$$



Bunch $\pi \in \left\{ \begin{array}{l} (2, 0, 0, 0) \\ (0, 2, 0, 0) \\ (0, 0, 2, 0) \\ (0, 0, 0, 2) \end{array} \right\}$

Identity on the Quantum Emitters
(up to single-qubit spin corrections)

$$\rho \mapsto \rho$$

Information is unaltered

Repeat-Until-Success (RUS): a Spin-Photon Hybrid Scheme

(1) Emission

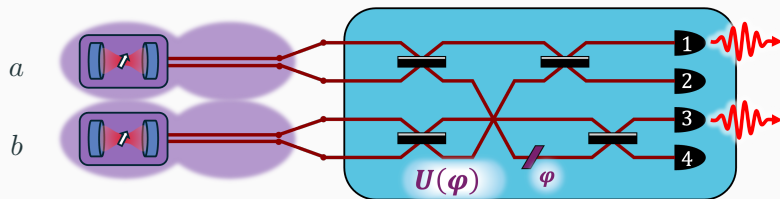
$$\rho \mapsto K\rho K^\dagger$$

(2) LO Transformation

$$U(\varphi)$$

(3) Detection

$$\pi$$



Success $\pi \in \left\{ \begin{array}{l} (1, 0, 1, 0) \\ (1, 0, 0, 1) \\ (0, 1, 1, 0) \\ (0, 1, 0, 1) \end{array} \right\}$

$$\varphi = \pi/2 \quad \rho \mapsto CZ_{ab}\rho CZ_{ab}$$

$$\varphi = 0 \quad \rho \mapsto M_{ZZ}(\rho)$$

Entanglement

Repeat-Until-Success (RUS): a Spin-Photon Hybrid Scheme

(1) Emission

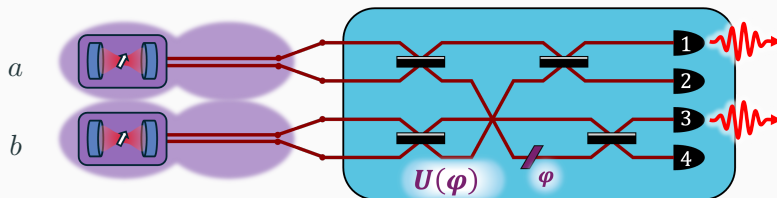
$$\rho \mapsto K\rho K^\dagger$$

(2) LO Transformation

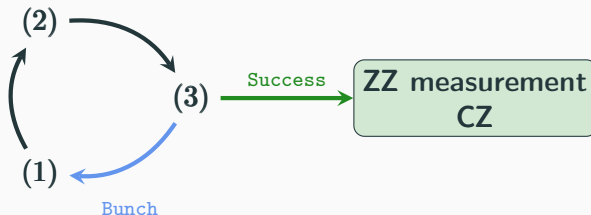
$$U(\varphi)$$

(3) Detection

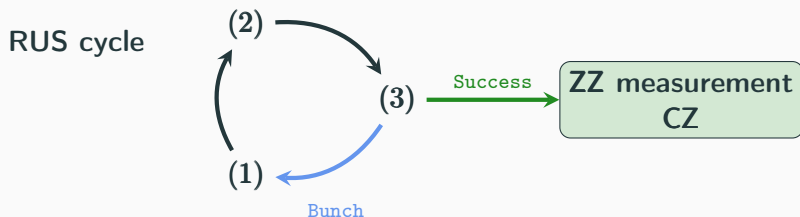
$$\pi$$



RUS cycle



Repeat-Until-Success (RUS): a Spin-Photon Hybrid Scheme



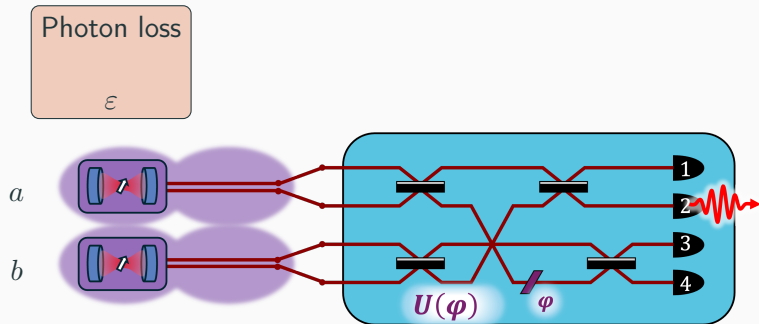
Probability to succeed after T cycles

$$p_s(T) = 1 - \frac{1}{2^T}$$

99.9% success probability after $T = 10$ cycles

$\implies$ (Almost) Deterministic entanglement

Noisy Repeat-Until-Success

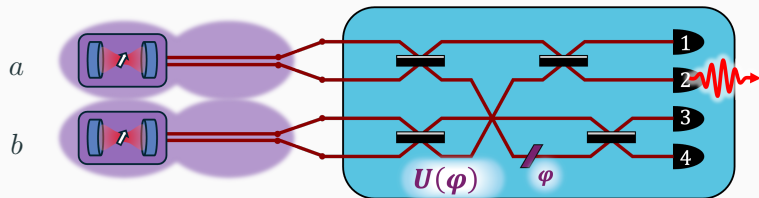


Noisy Repeat-Until-Success

Photon loss

ε

$$\mathcal{C}_i[\rho] = (\rho + Z_i \rho Z_i) / 2 \quad \text{Full dephasing}$$



$$\text{Loss}_1 \quad \pi \in \left\{ \begin{array}{l} (1, 0, 0, 0) \\ (0, 1, 0, 0) \\ (0, 0, 1, 0) \\ (0, 0, 0, 1) \end{array} \right\}$$

$$\rho \mapsto \frac{\mathcal{C}_a[\rho] + \mathcal{C}_b[\rho]}{2}$$

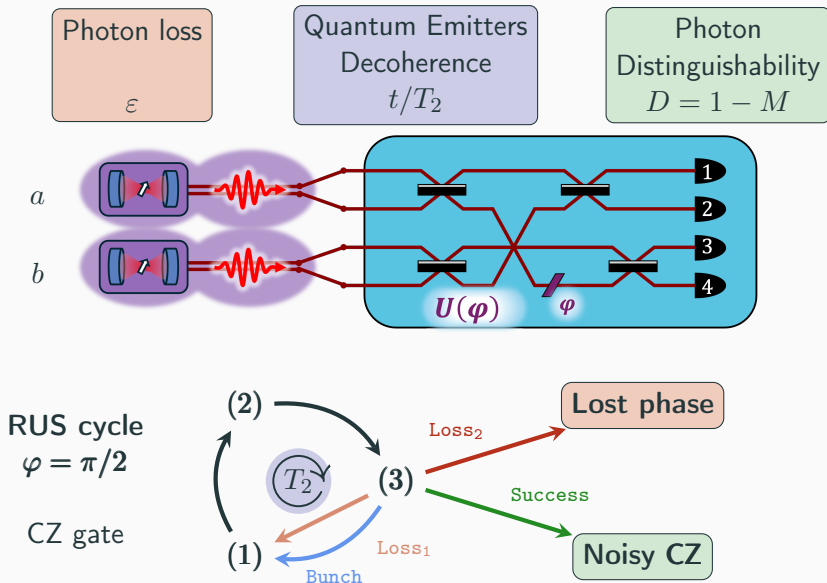
Lost phase on
one emitter

$$\text{Loss}_2 \quad \pi = (0, 0, 0, 0)$$

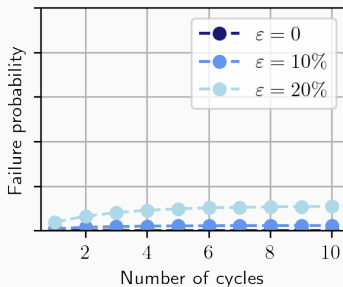
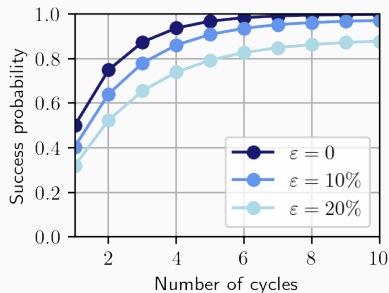
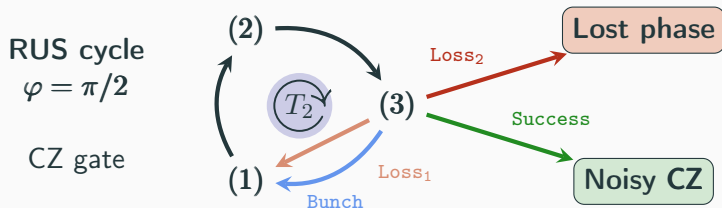
$$\rho \mapsto \mathcal{C}_a \circ \mathcal{C}_b[\rho]$$

Lost phase on
both emitters

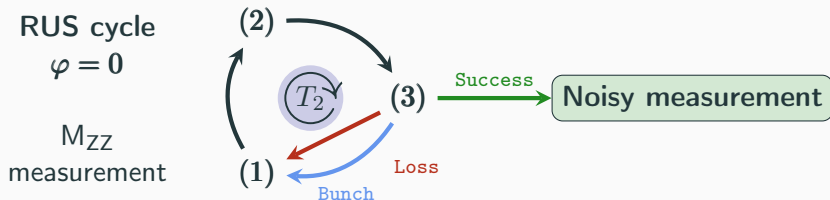
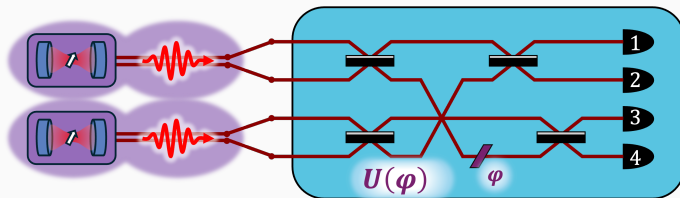
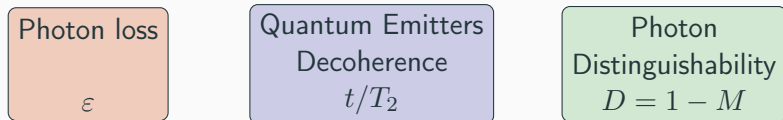
Noisy Repeat-Until-Success



Noisy Repeat-Until-Success



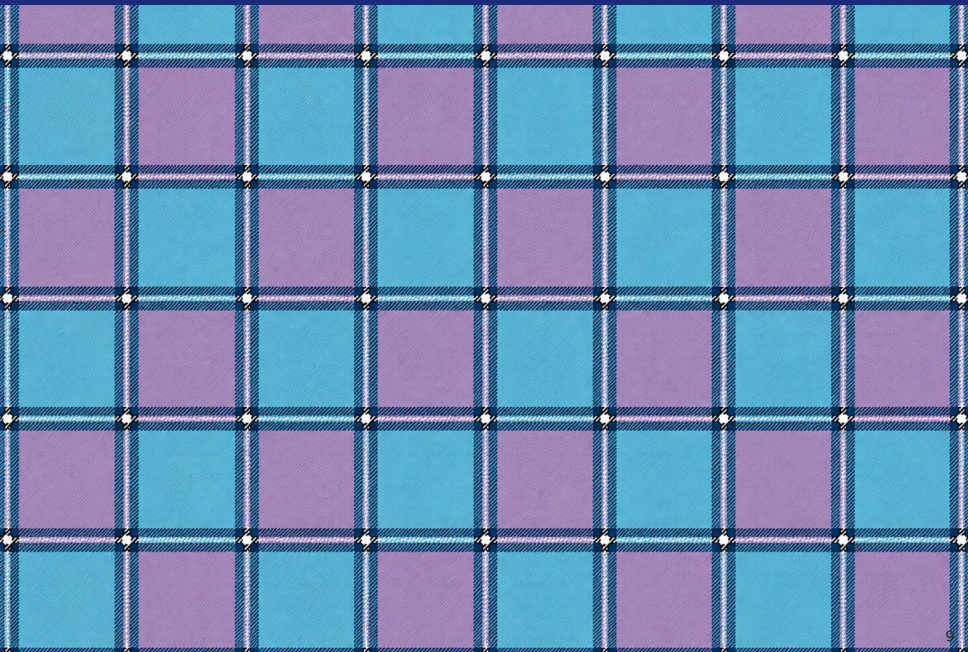
Noisy Repeat-Until-Success



Enhanced Fault-tolerance in Photonic Quantum Computing: Floquet Code Outperforms Surface Code in Tailored Architecture

Two types of quantum error correcting codes

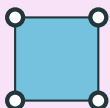
Rotated Surface Code

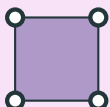


Rotated Surface Code

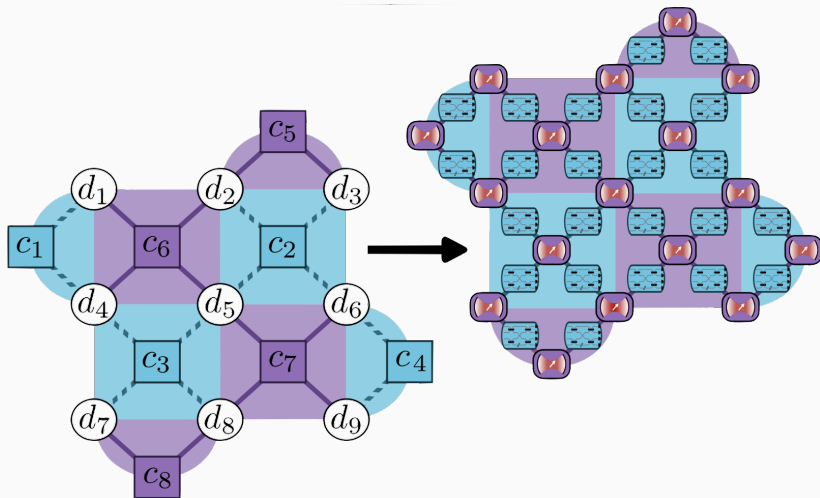
Associated stabilizer operators

$$\forall |\psi\rangle_L, g_i |\psi\rangle_L = + |\psi\rangle_L$$


$$\longleftrightarrow g_Z = Z_a Z_b Z_c Z_d$$


$$\longleftrightarrow g_X = X_a X_b X_c X_d$$

Rotated Surface Code layout in the SPOQC architecture



Honeycomb Floquet Code

Floquet / Dynamical code

No fixed logical subspace

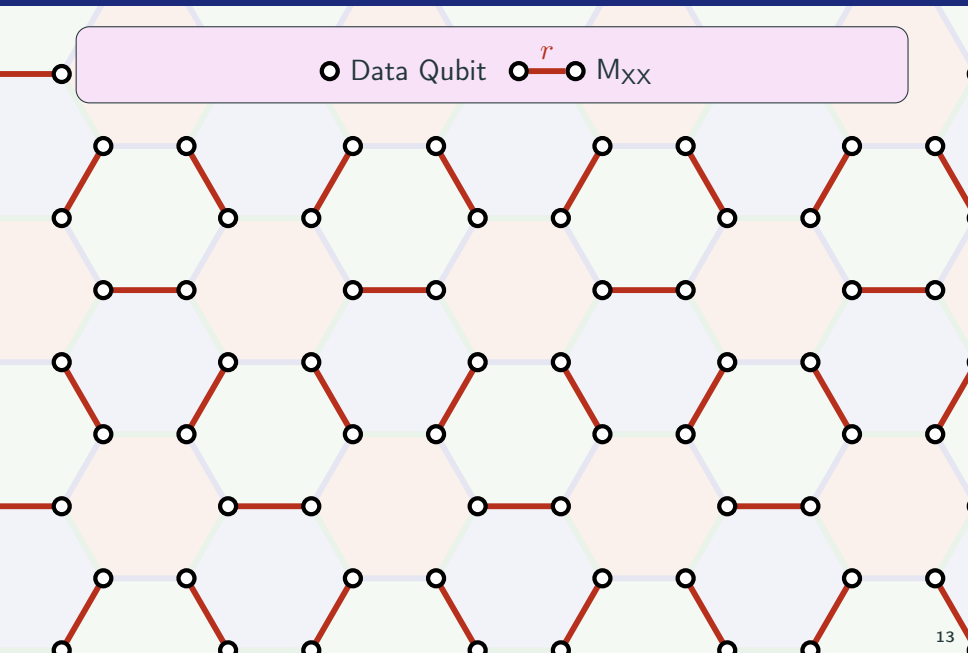
“Dynamical version” of the surface code

Implementation through **weight-2** measurements

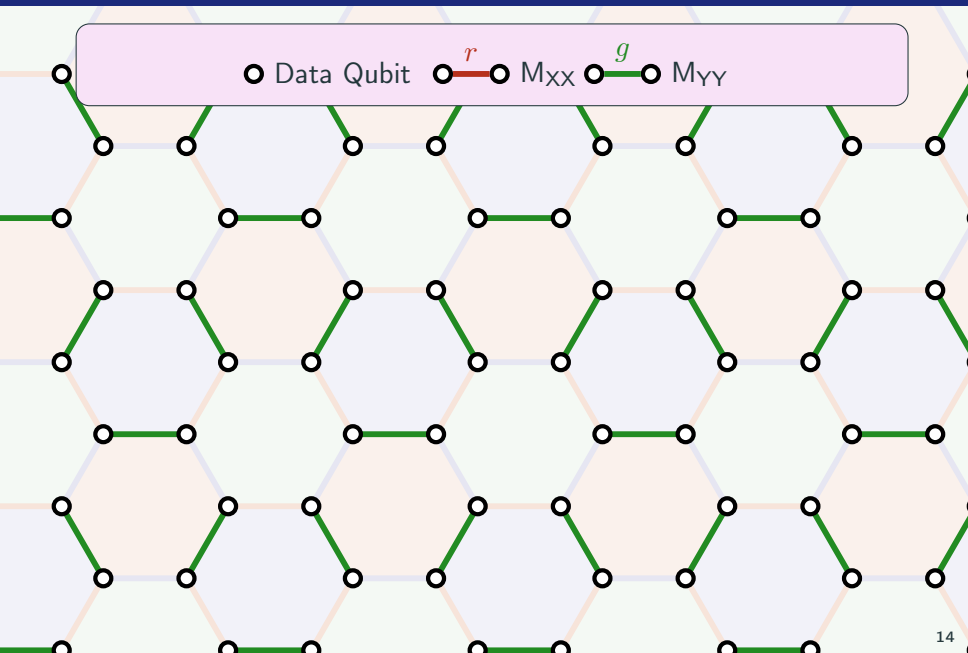
[1] Hastings and Haah, Quantum, 2021

[2] Floquet code's talk by Bhargavi Jonnadula

Honeycomb Floquet Code

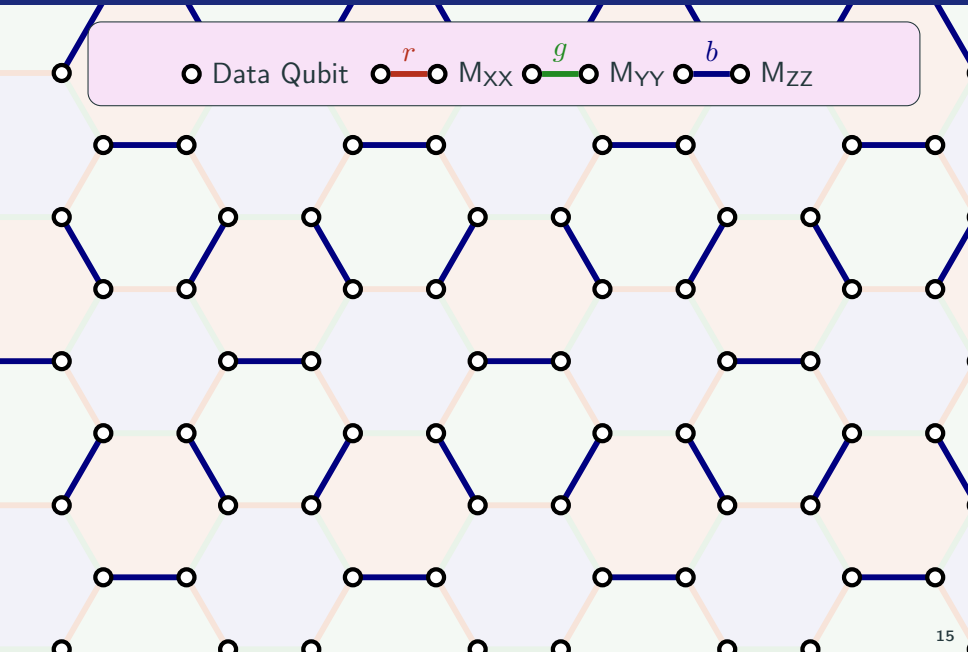


Honeycomb Floquet Code



Honeycomb Floquet Code

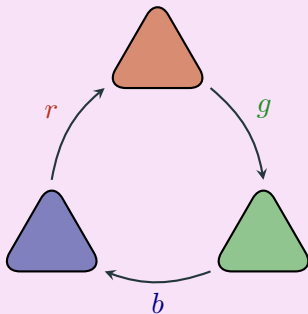
○ Data Qubit r M_{XX} g M_{YY} b M_{ZZ}



Honeycomb Floquet Code

○ Data Qubit r M_{XX} g M_{YY} b M_{ZZ}

Measurement schedule
 $\mathcal{M} = \{r, g, b, r, g, b, \dots\}$

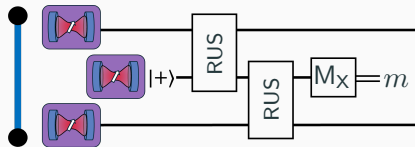
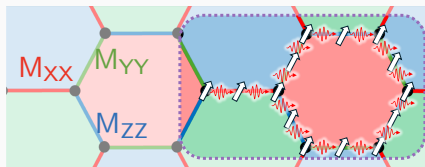


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*Evaluating the performance of a tailored
architecture*

Honeycomb Floquet Code with RUS gates

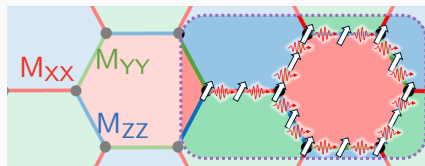
CZ-SPOQC



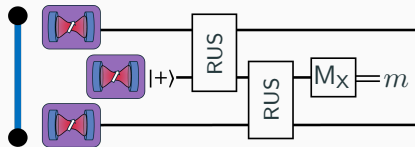
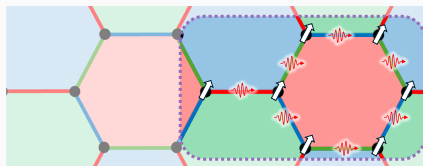
$$\varphi = \pi/2$$

Honeycomb Floquet Code with RUS gates

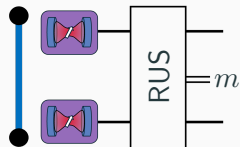
CZ-SPOQC



M_{zz} -SPOQC



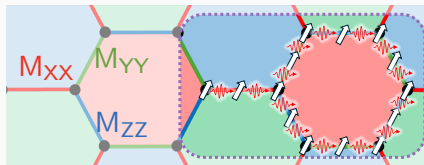
$$\varphi = \pi/2$$



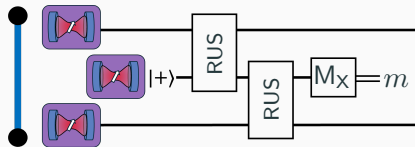
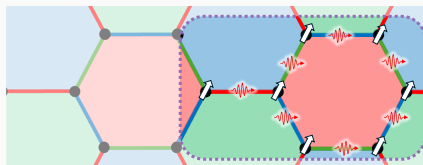
$$\varphi = 0$$

Honeycomb Floquet Code with RUS gates

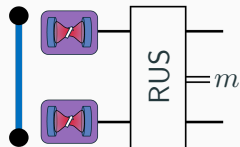
CZ-SPOQC



M_{zz} -SPOQC



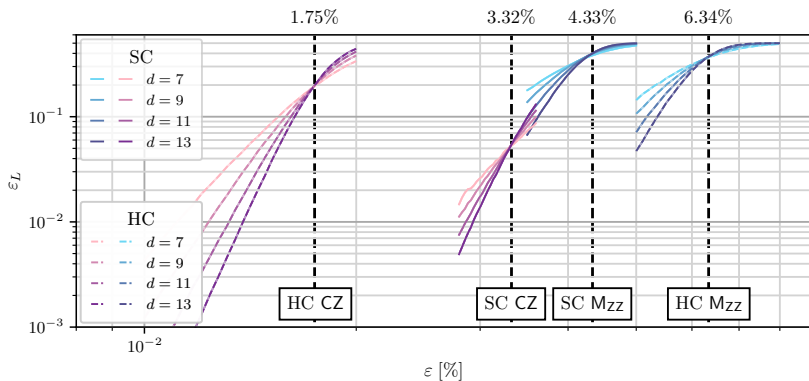
$$\varphi = \pi/2$$



$$\varphi = 0$$

⇒ M_{zz} -SPOQC: less resource intensive for Floquet codes
Fault-tolerant thresholds?

Thresholds for Surface Codes and Honeycomb Codes Quantum Memories



Thresholds for Surface Codes and Honeycomb Codes

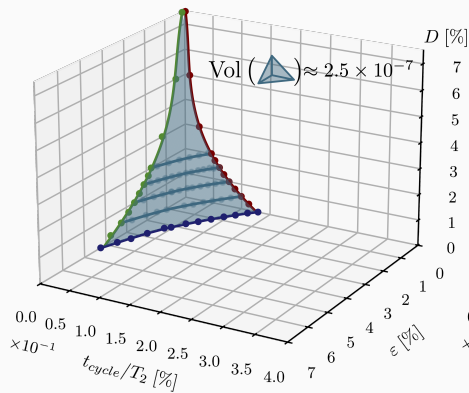
Quantum Memories

Code	Architecture	ϵ	D	t_{RUS}/T_2
Surface code	CZ-based	3.3%	2.2%	2.5%
	M_{ZZ} -based	4.3%	*	1.2%
Honeycomb Floquet code	CZ-based	1.6%	0.8%	0.6%
	M_{ZZ} -based	6.4%	2.4%	2.3%

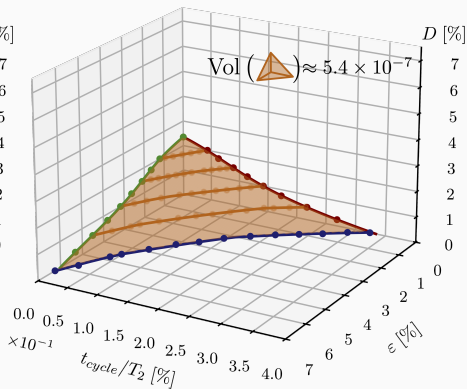
Thresholds for Surface Codes and Honeycomb Codes

Quantum Memories

(a) Pentagon tiling Surface code



(b) Honeycomb Floquet code



Conclusion

Discussions, perspectives

- Floquet code outperforms a Surface code in a concrete architecture and for a concrete noise model.

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- “Floquetification”: get dynamical versions of static codes for better performances? [1] Rodatz *et al.*, ArXiv, 2410.17240 (2024)

Discussions, perspectives

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- More accurate error model. Add specific errors (other photonic errors such as photon impurity, $g^{(2)}$ and spin errors)...

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THANK YOU !



Link to the paper

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THANK YOU !



Link to the paper



New paper highlighting
architecture-algorithm co-design

Two layers, no swaps:
Biplanar SPOQC Architecture Improves
Runtime of Fermi-Hubbard Simulation

Shameless advertisement

Job post:

- 1 postdoc position in Early-FTQC, jointly with Mike Vasmer.
- 1 postdoc position in photonic FTQC architecture.
- 1 PhD position in photonic FTQC.

Contact me at *paul.hilaire@telecom-paris.fr*

QMI Master program (IP Paris / Paris Saclay):

- Opened last year.
- Focus on Mathematical and Computer Science aspects of Quantum Information.
- We are quite happy about it.

