QUANDELA

Calculating resource overheads for fault-tolerant photonic quantum computing

TQCI – PALAISEAU – 24 JUNE 2025

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Motivation: what matters for reaching fault-tolerance

We need an FTQC roadmap with

- High threshold

  $\Longrightarrow$ Tolerate more errors

- Low space and time overhead

  $\Longrightarrow$ Reduce hardware footprint and wall-clock time

How to evaluate and compare FTQC roadmaps

Low-level → High-level

- Error thresholds
  Good to test a QEC code, but doesn't say anything about sub-threshold behaviour
- Logical qubit footprint
  Good for quantum memory, but doesn't say anything about the overhead of performing logical operations
- End-to-end resource estimation for an algorithm
  Good benchmark, but optimisation problem of very high dimension

What I focus on today

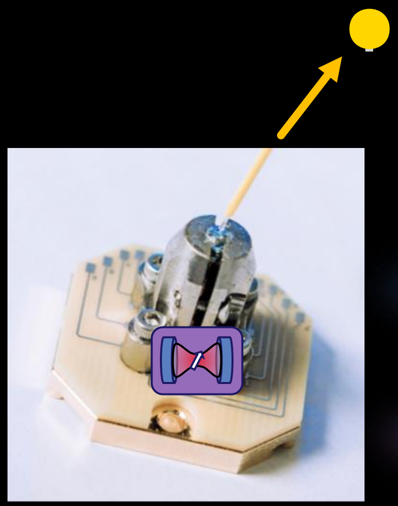
Low-level resource comparison for

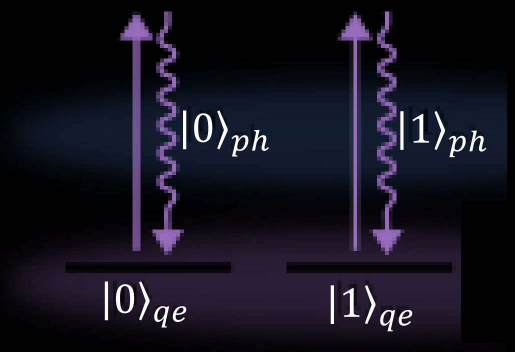
One model of FTQC: fusion-based quantum computing (FBQC)

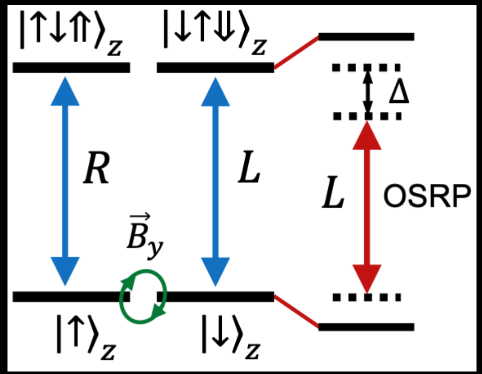
One step of FBQC: resource state generation

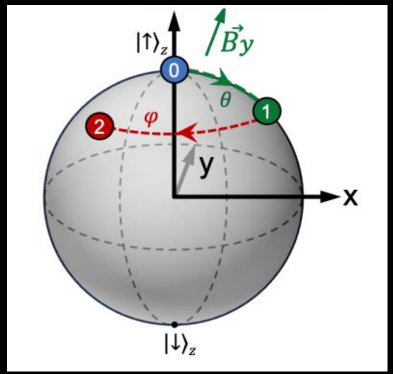
For three types of single-photon sources

Quandela's hardware







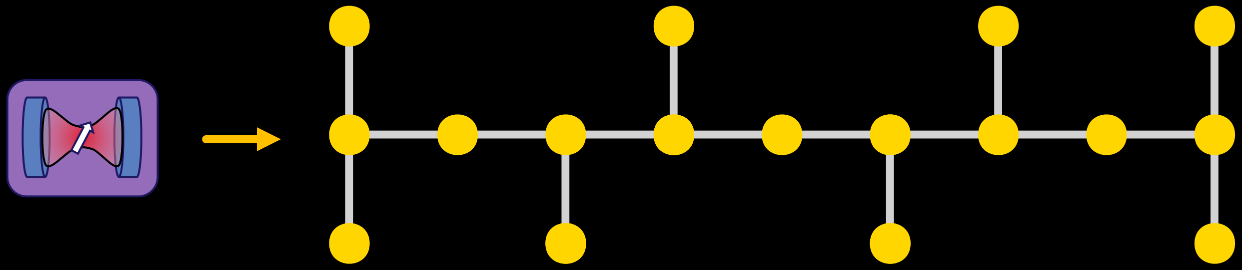


$$|0\rangle_{\mathrm{qe}} + |1\rangle_{\mathrm{qe}} \xrightarrow{\text{Emission}} |0\rangle_{\mathrm{qe}}|0\rangle_{\mathrm{ph1}} + |1\rangle_{\mathrm{qe}}|1\rangle_{\mathrm{ph1}}$$

$$\xrightarrow{\text{Emission}} |0\rangle_{\mathrm{qe}}|0\rangle_{\mathrm{ph1}}|0\rangle_{\mathrm{ph2}} + |1\rangle_{\mathrm{qe}}|1\rangle_{\mathrm{ph1}}|1\rangle_{\mathrm{ph2}}$$

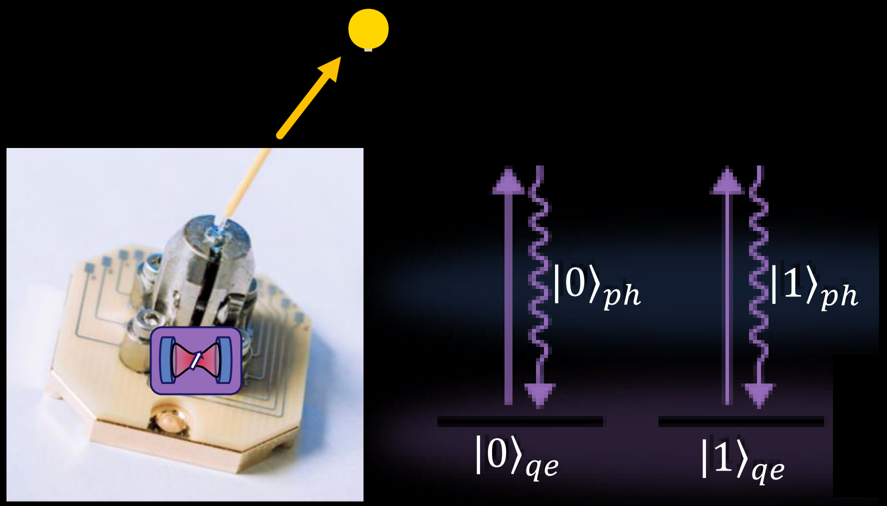
$$|0\rangle_{\mathrm{qe}} + |1\rangle_{\mathrm{qe}} \xrightarrow{\text{Emission}} |0\rangle_{\mathrm{qe}}|0\rangle_{\mathrm{ph}} + |1\rangle_{\mathrm{qe}}|1\rangle_{\mathrm{ph}}$$

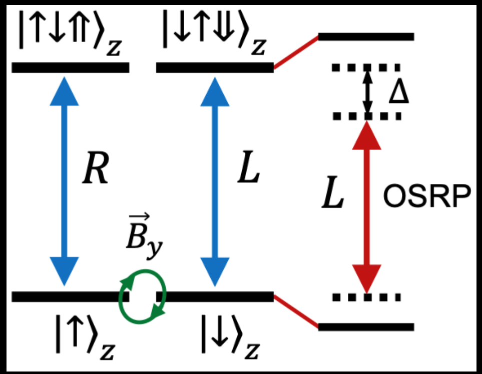
$$\xrightarrow{H_{\mathrm{qe}}} \mathrm{CZ}(|+\rangle_{\mathrm{qe}}|+\rangle_{\mathrm{ph}})$$

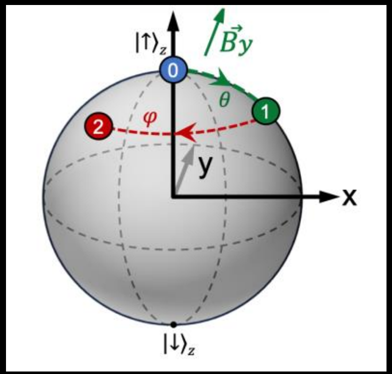


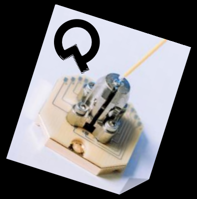
N. Lindner, T. Rudolph. Proposal for Pulsed On-Demand Sources of Photonic Cluster State Strings, *Phys. Rev. Lett.* **103**, 113602 (2009)
Somaschi *et al.* Near-optimal single-photon sources in the solid state. *Nature Photon* **10**, 340–345 (2016)
H. Huet *et al.* Deterministic and reconfigurable graph state generation with a single solid-state quantum emitter, arXiv:2410.23518 (2024)

Quandela's hardware

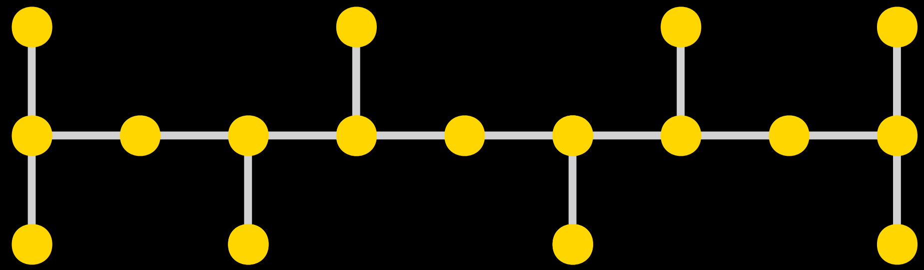


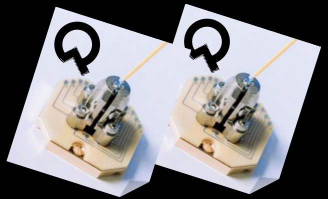




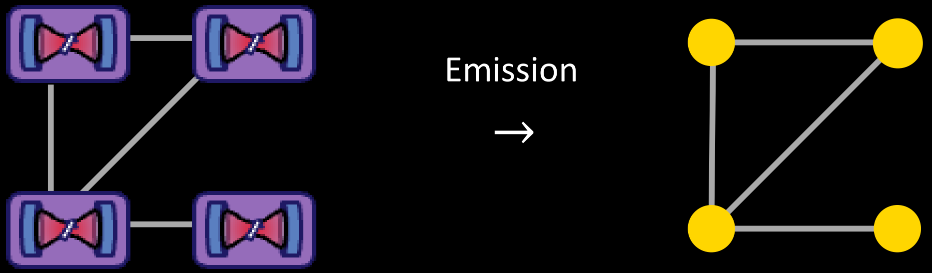


States that can be created with one source





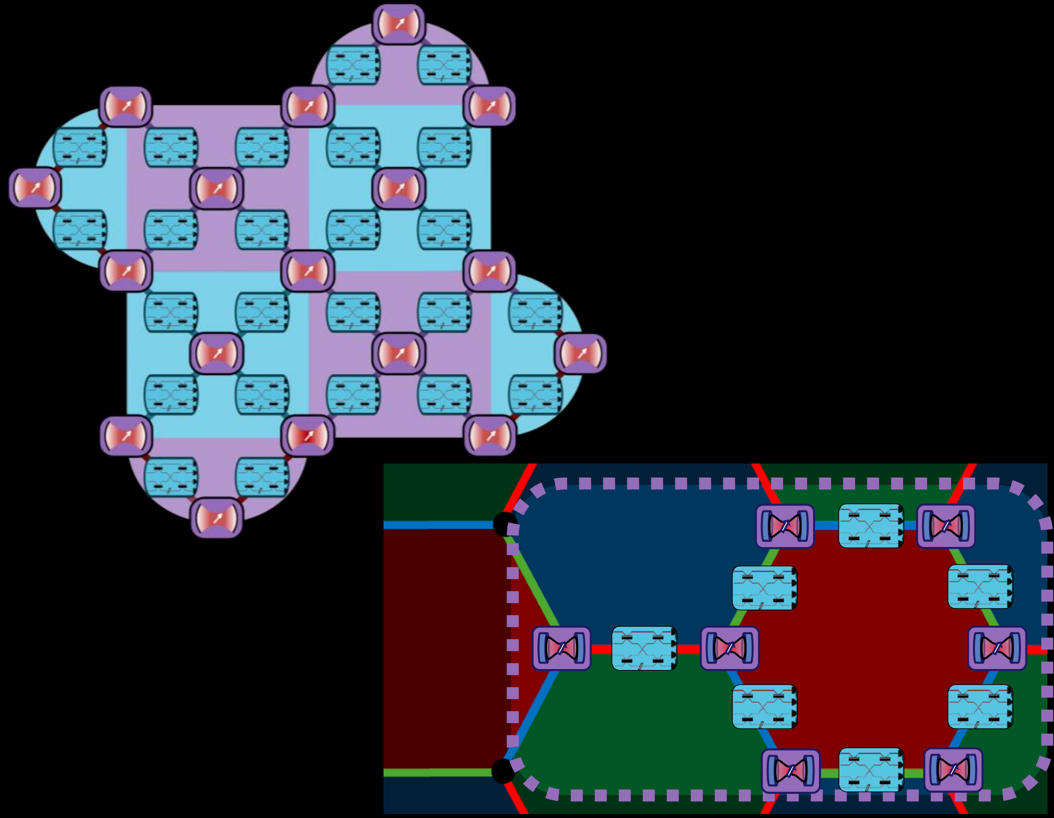
States that can be created with multiple sources



Y. L. Lim et al., Repeat-until-success quantum computing using stationary and flying qubits, *Phys. Rev. A* **73**, 012304 (2006)

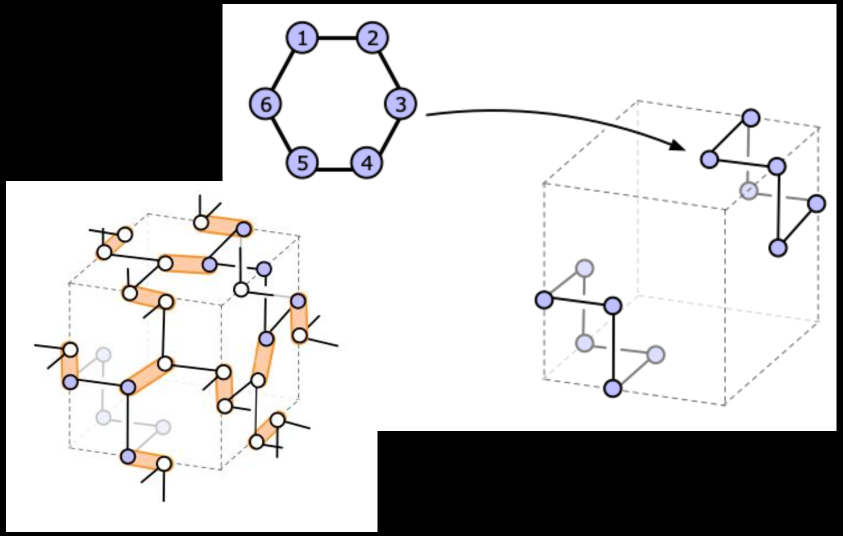
Comparing our options for FTQC

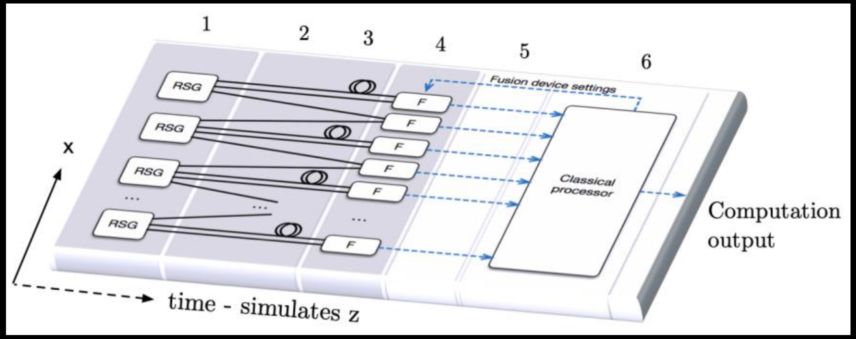
SPOQC – Spin-optical quantum computing



G. De Gliniasty *et al.* A Spin-Optical Quantum Computing Architecture, *Quantum* **8**, 1423 (2024)
P. Hilaire *et al.* Enhanced Fault-tolerance in Photonic Quantum Computing... arXiv:2410.07065 (2024)

FBQC – Fusion-based quantum computing



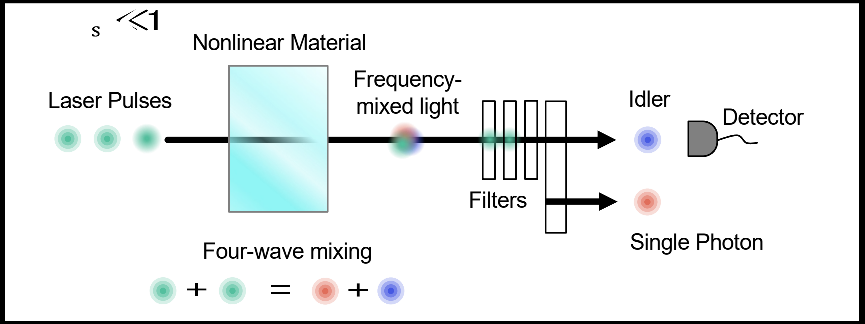


S. Bartolucci *et al.* Fusion-based quantum computation, *Nat. Commun.* **14**, 912 (2023)

Three sources of single photons

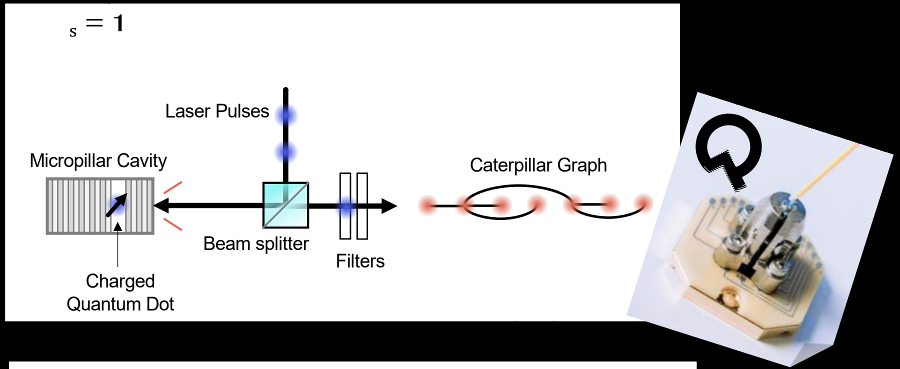
Single photon
Quantum emitter

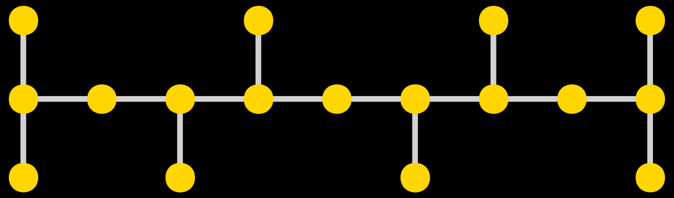
Probabilistic source



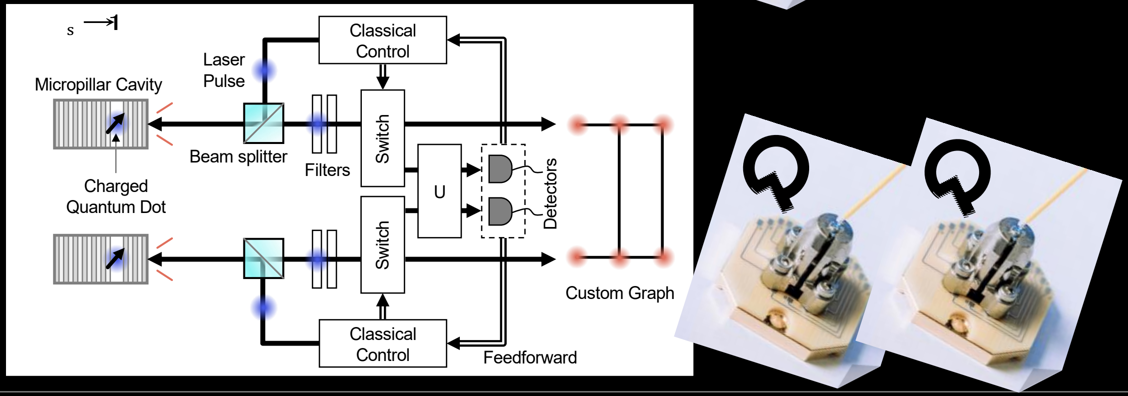
with probability p<1

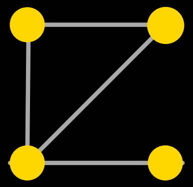
Caterpillar source



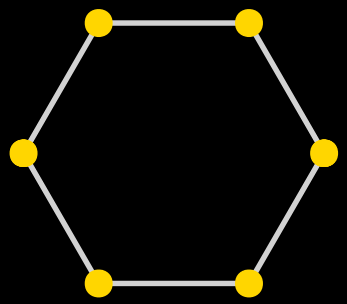


Repeat-until-success module

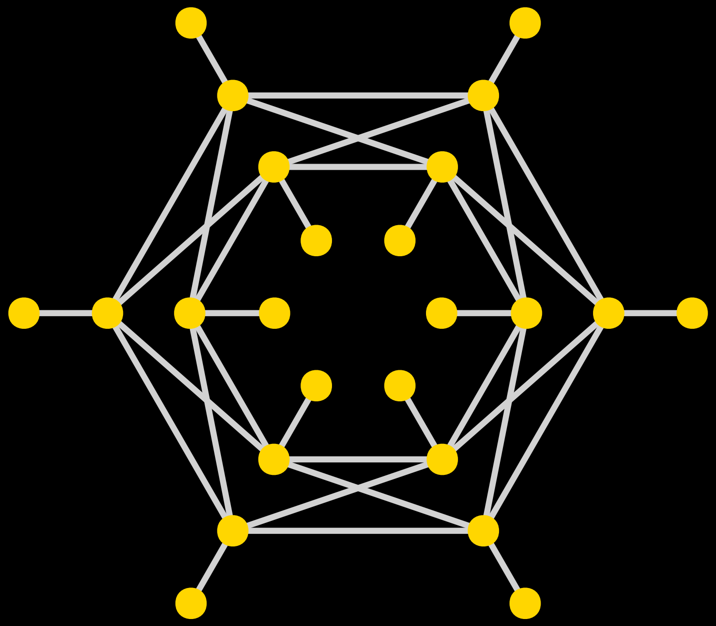




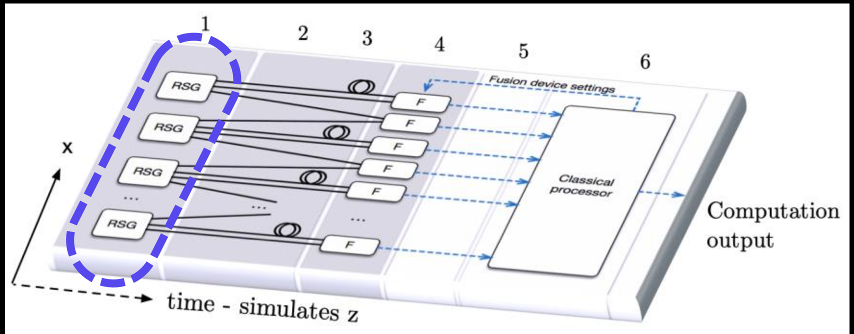
Focus on resource state generation



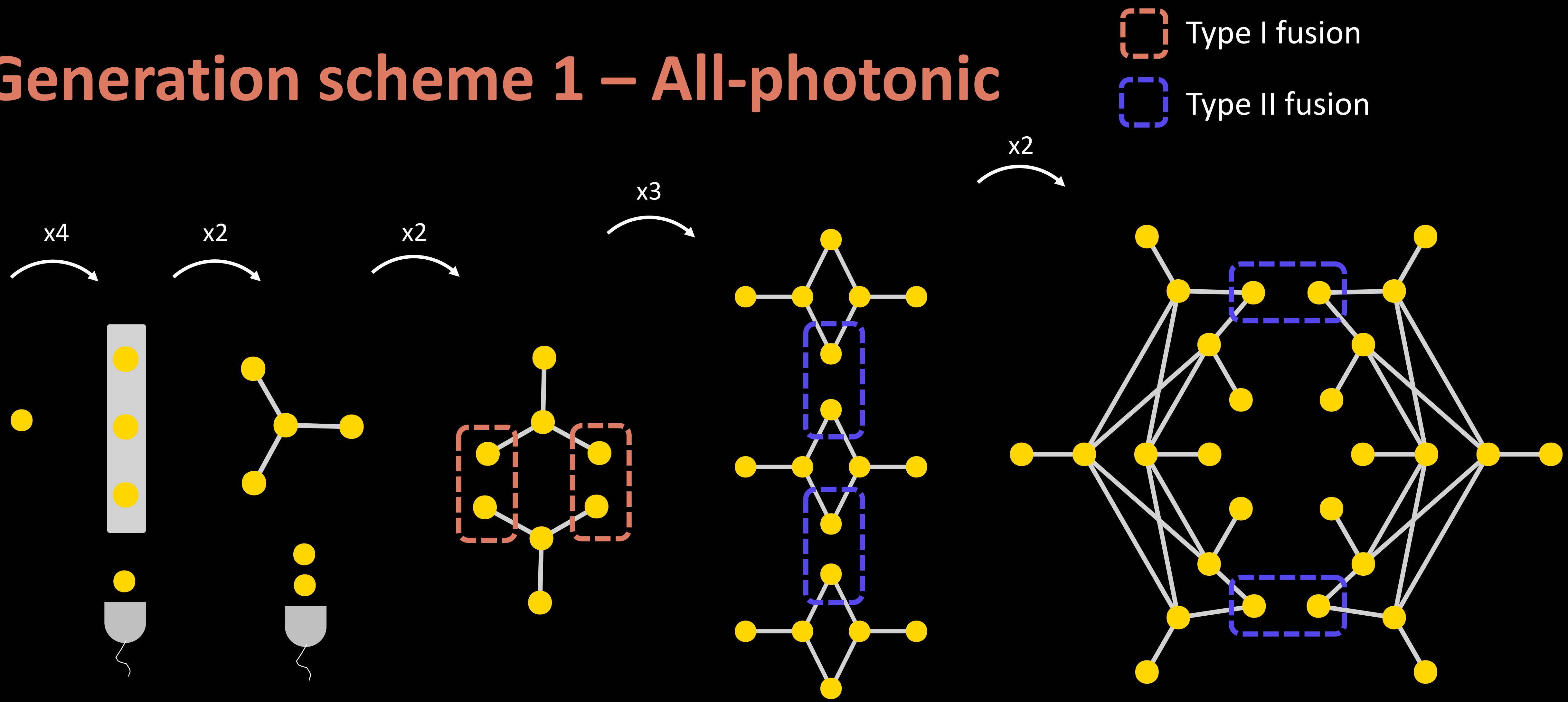
6-ring graph state



QPC(2,2)-encoded
6-ring graph state



Generation scheme 1 – All-photonic



S. Bartolucci *et al.* Creation of Entangled Photonic States Using Linear Optics, arXiv:2106.13825 (2021)

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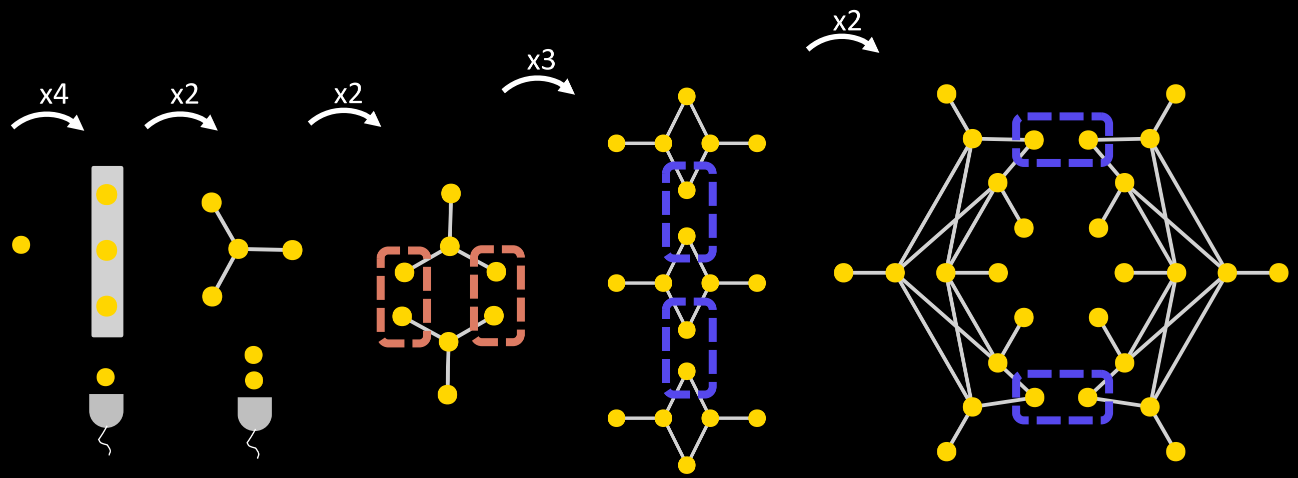
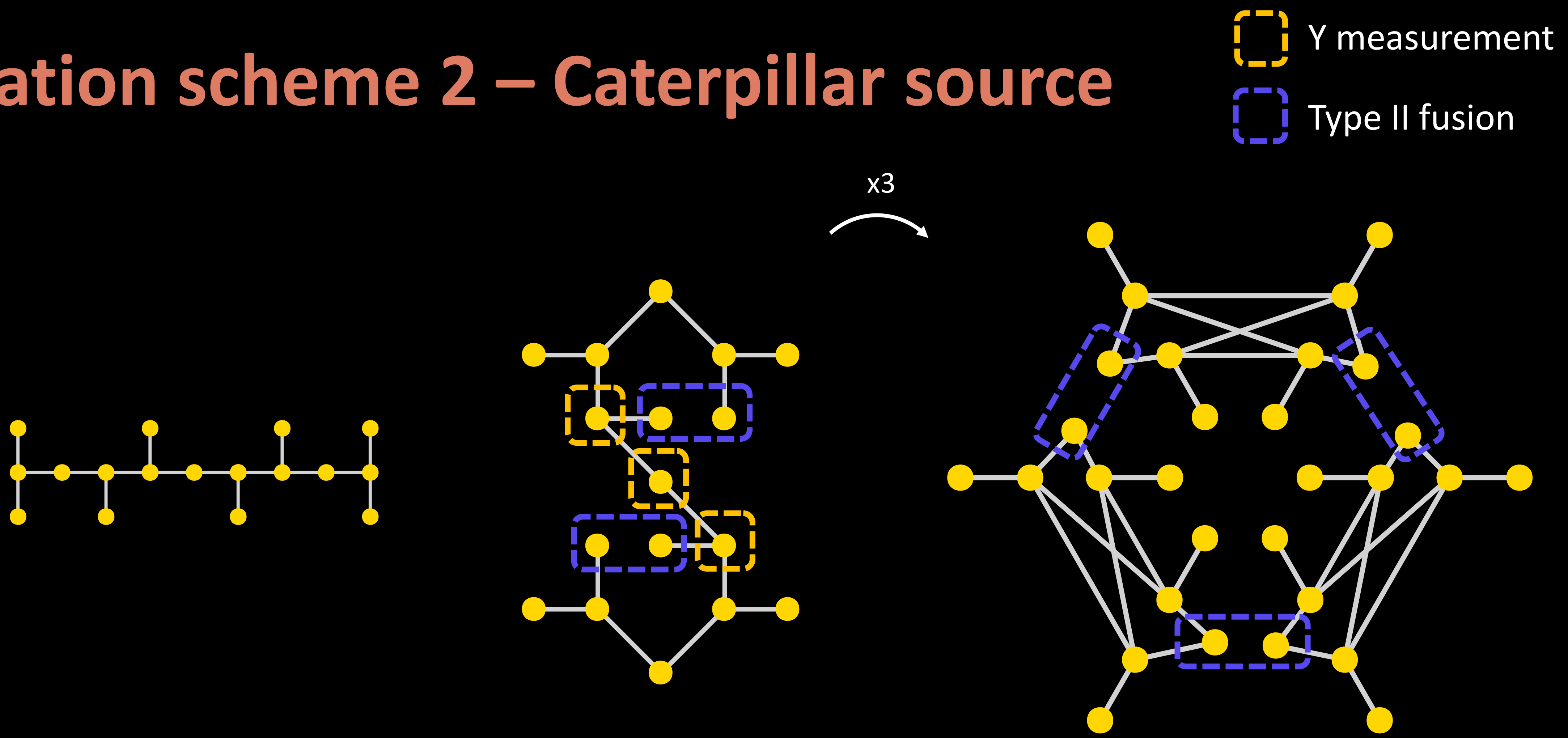


$$N_{\mathrm{avg},i} = c_i \frac{N_{\mathrm{avg},i-1} + a_i}{p_i}$$

Stage, i	1	2	3	4	5	6
Probability, p_i	1	$20\sqrt{2} - 28$	$\frac{3+2\sqrt{2}}{64}$	$\frac{9}{16}$	$\frac{9}{16}$	$\frac{9}{16}$
Copies, c_i	4	2	2	3	2	1
Auxiliary photons, a_i	0	0	0	8	8	8
Detected photons, d_i	1	1	2	10	12	12
Cumulative average photon number, $N_{\mathrm{avg},i}$	4	28	618	3339	11900	21170
Cumulative optical depth, D_i	9	15	21	27	33	36

S. Bartolucci *et al.* Creation of Entangled Photonic States Using Linear Optics, arXiv:2106.13825 (2021)

Generation scheme 2 – Caterpillar source



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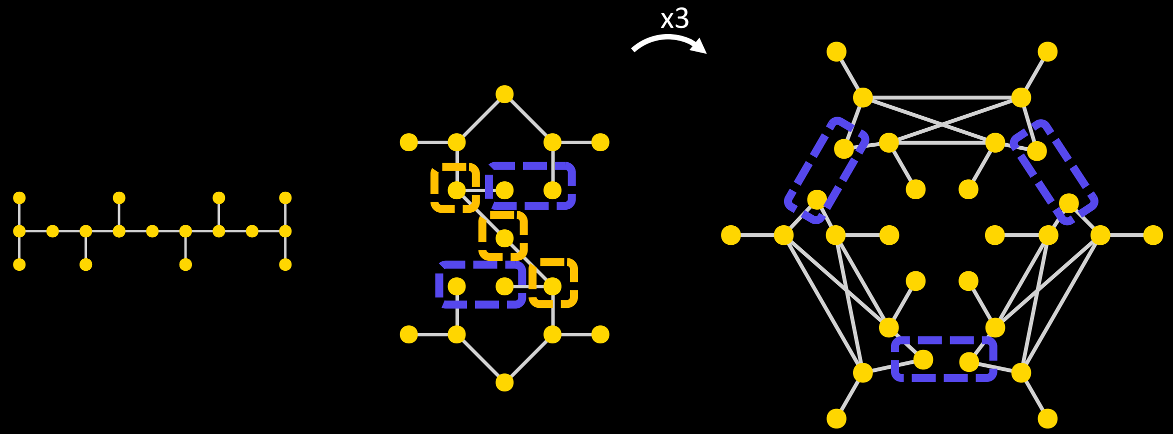
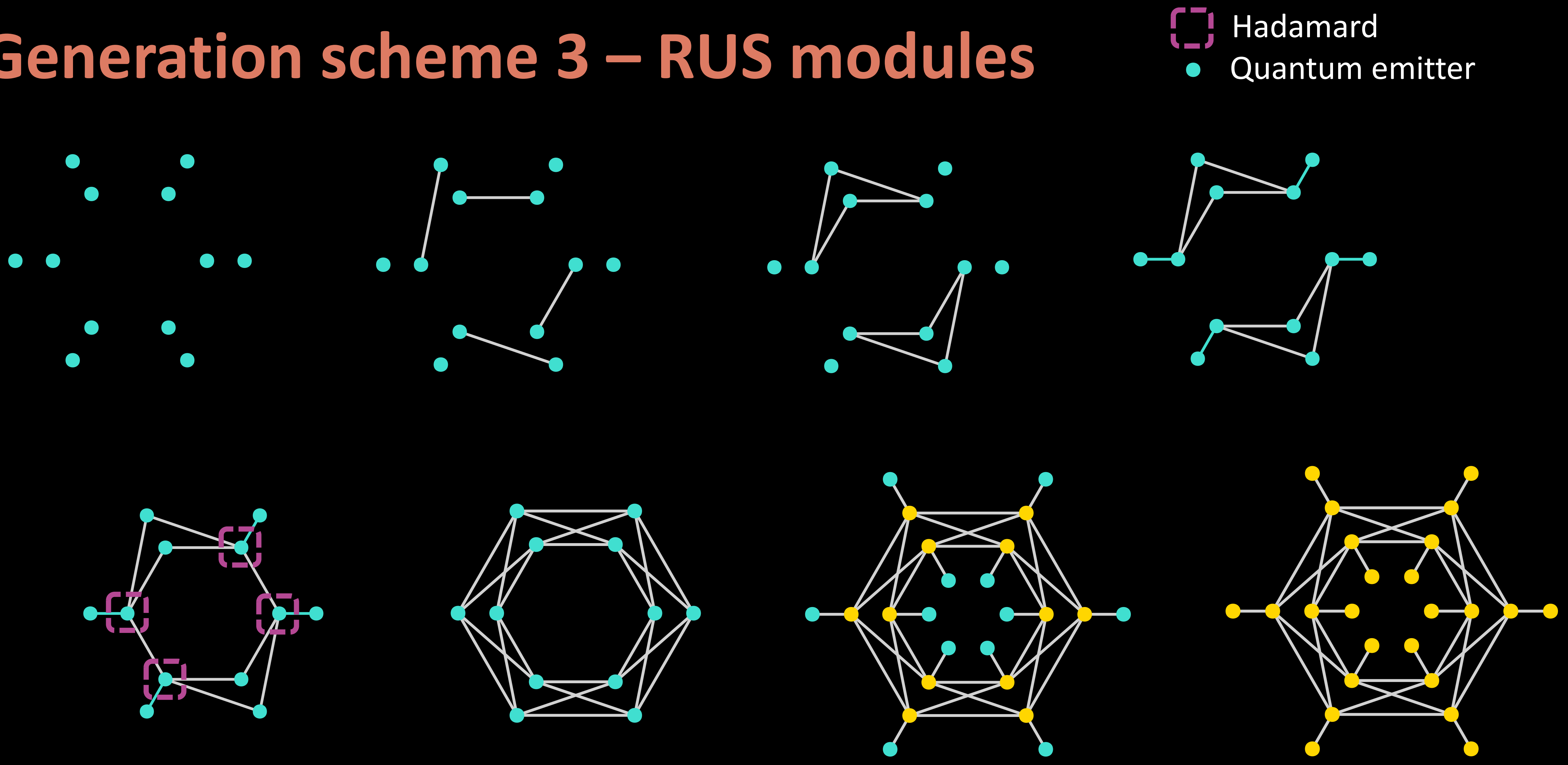


$$N_{\text{avg},i} = c_i \frac{N_{\text{avg},i-1} + a_i}{p_i}$$

Stage, i	1	2	3
Probability, p_i	1	$\frac{9}{16}$	$\frac{27}{64}$
Copies, c_i	1	3	1
Auxiliary photons, a_i	0	4	6
Detected photons, d_i	0	11	12
Cumulative average photon number, $N_{\text{avg},i}$	17	112	280
Cumulative optical depth, D_i	0	9	12

Generation scheme 3 – RUS modules



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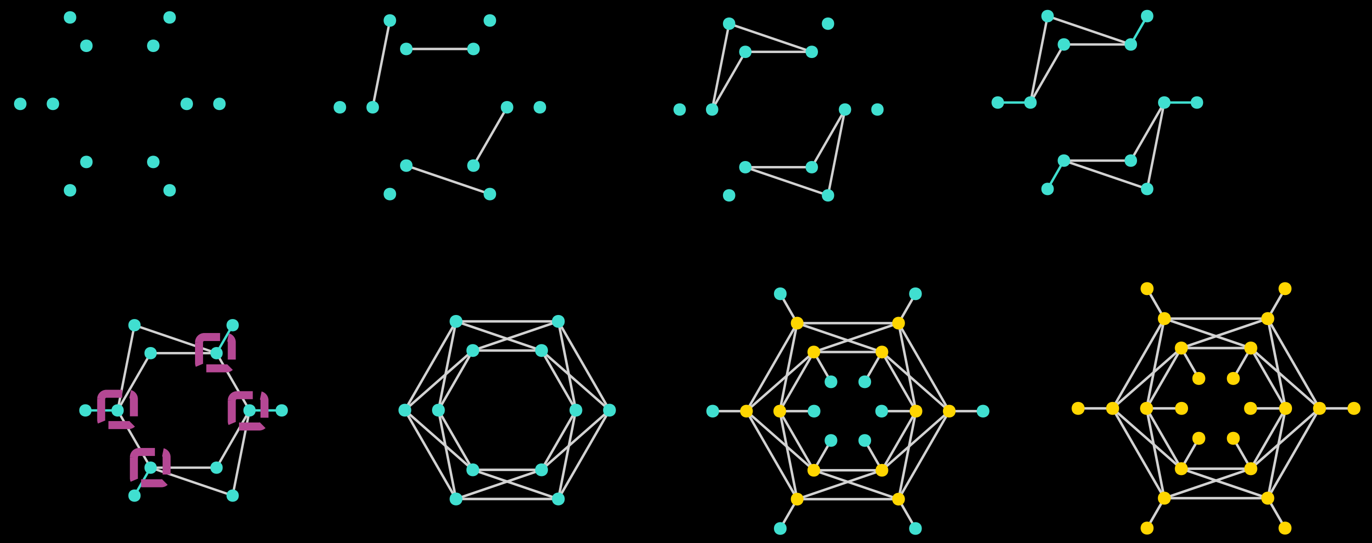


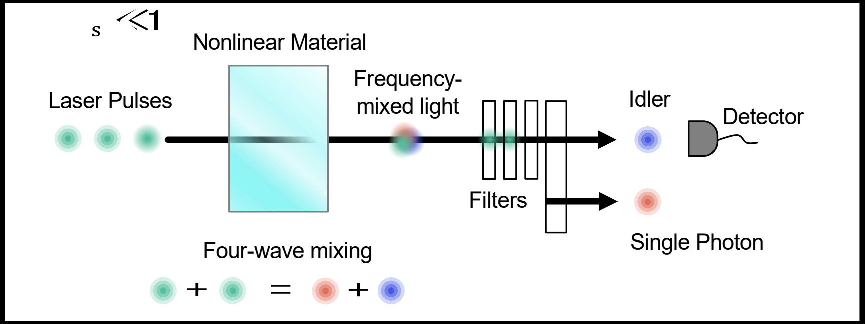
$$N_{\text{avg},i} = c_i \frac{N_{\text{avg},i-1} + a_i}{p_i}$$

Stage, i	1	2	3	4	5	6	7	8
Probability, p_i	1	1	1	1	1	1	1	1
Copies, c_i	1	1	1	1	1	1	1	1
Auxiliary photons, a_i	0	0	0	0	0	0	12	12
Detected photons, d_i	0	16	16	16	8	0	0	0
Cumulative average photon number, $N_{\text{avg},i}$	0	16	32	48	56	56	68	80
Cumulative optical depth, D_i	0	0	0	0	0	0	1	1

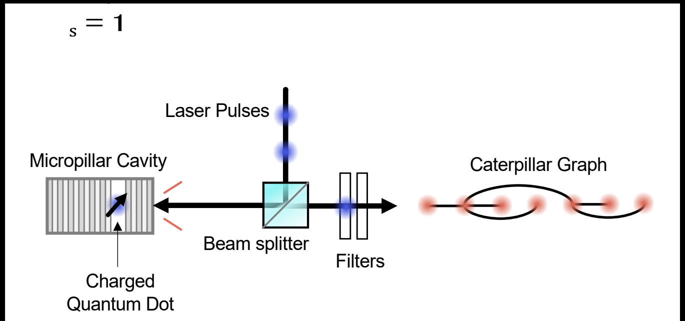
Optimal resource overhead and maximal tolerable loss

Source type	Average photon number	Resource efficiency	Number of sources	Optical depth	Maximal loss per component
Probabilistic source $p_s = 5\%$	**21170**	**0.0057%**	**42340**	**36**	**0.22%**
Probabilistic source $p_s = 25\%$	**21170**	**0.029%**	**8468**	**36**	**0.22%**
Caterpillar source	**280**	**9.9%**	**25**	**12**	**0.65%**
RUS module	**80**	**20%**	**12**	**1**	**7.5%**

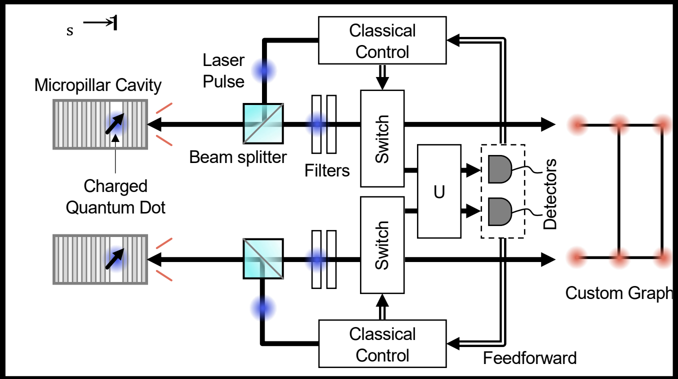
Probabilistic source



Caterpillar source



RUS module



Conclusion

What we showed

- ➢ Hybrid spin-photon devices enable deterministic entangling operations and easy long-range connectivity
- ➢ They drastically reduce the resource overhead of resource state generation for fusion-based quantum computing
- ➢ The generation scheme based on RUS modules is the most efficient approach

Future work

- ➢ We focused on loss $\Longrightarrow$ We'll investigate other sources of errors
- ➢ We focused on FBQC $\Longrightarrow$ We'll compare SPOQC and FBQC

AND THANK YOU FOR YOUR ATTENTION!

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arxiv:2412.08611
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