All-photonic two-way quantum repeaters with multiplexing based on concatenated bosonic and discrete-variable quantum codes

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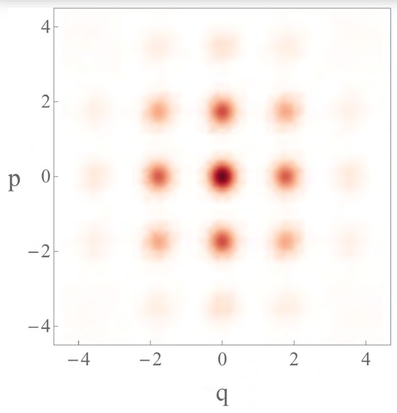
Introduction

We propose a **two-way all-photonic repeater** architecture[1] based on the **bosonic Gottesman-Kitaev-Preskill (GKP) qubit code**[2]. The architecture achieves high **entanglement / secret key rates per transmitted mode** thanks to a novel form of **multiplexing**, which is enabled by two salient features of the GKP qubits: i) They admit a **deterministic two-qubit gate**. ii) The GKP qubit code syndrome measurements provide additional **analog information** quantifying the reliability of each GKP correction round. The architecture relies on entangled resource states that can be near deterministically prepared from on-demand **GKP qubit** sources at the repeater nodes.

GKP qubit code



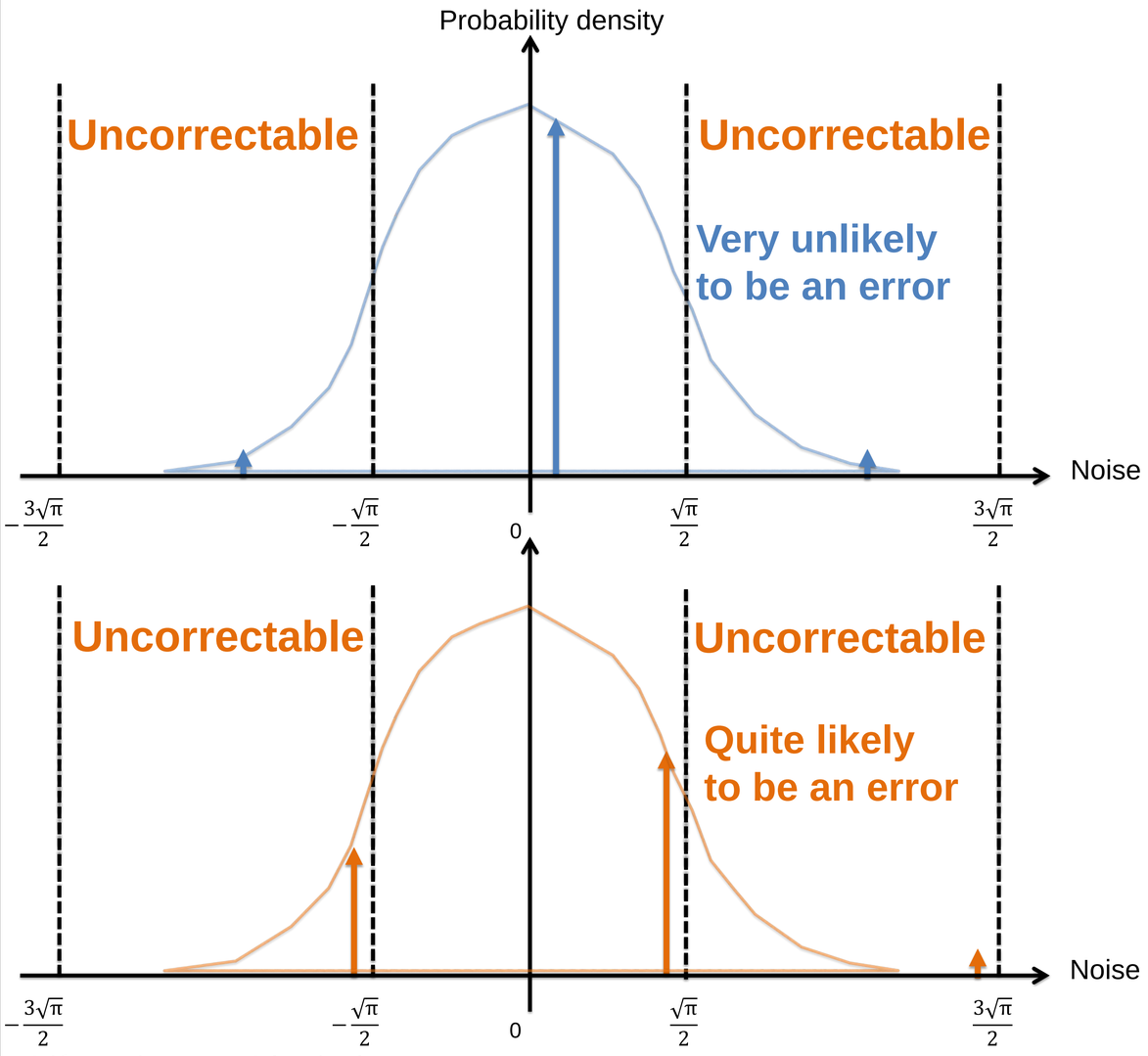
$$\hat{S}_q = e^{i2\sqrt{\pi}\hat{q}} \text{ and } \hat{S}_p = e^{-i2\sqrt{\pi}\hat{p}}$$

$$|0_{gkp}\rangle \propto \sum_{n\in\mathbb{Z}} |\hat{q} = \sqrt{\pi}(2n)\rangle$$

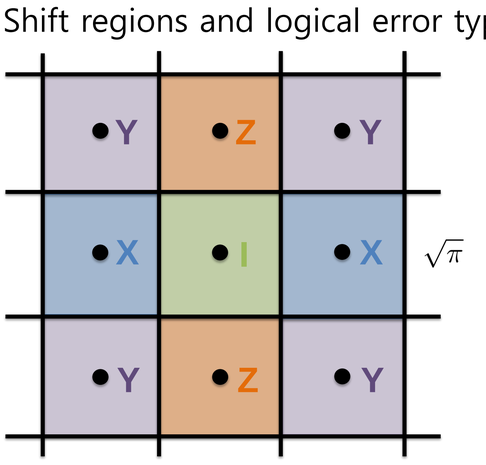
$$|1_{gkp}\rangle \propto \sum_{n\in\mathbb{Z}} |\hat{q} = \sqrt{\pi}(2n+1)\rangle$$

$\hat{q} = \hat{p} = 0 \; mod\sqrt{\pi}$: Can correct **shift errors** in phase space

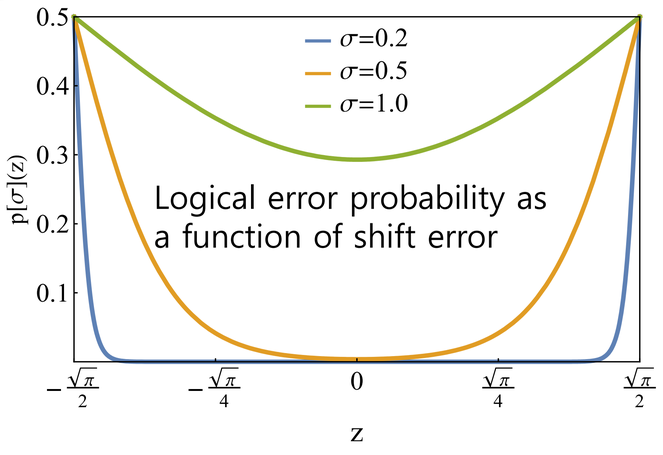
Logical Pauli errors under the action of a Gaussian random displacement channel with standard deviation σ:



Shift regions and logical error types

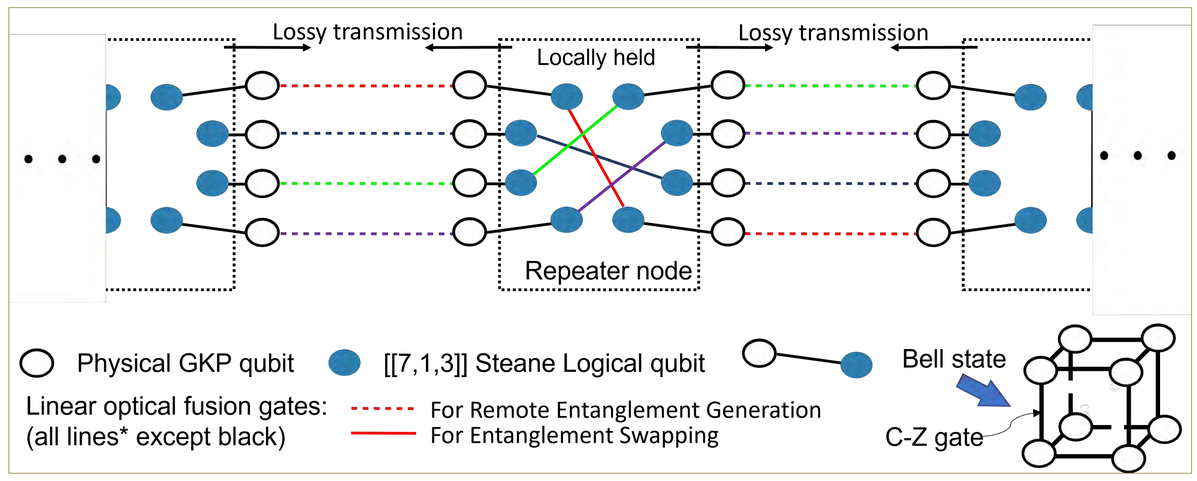


Y error quadratically suppressed



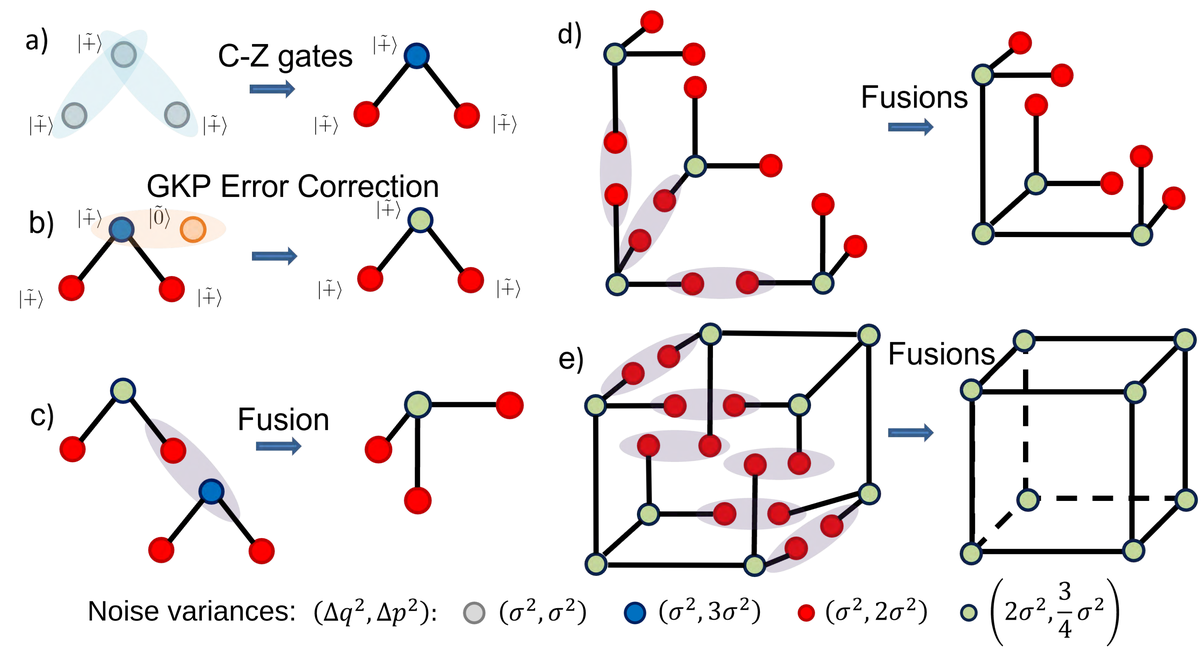
Quantum repeaters

- Previous works on GKP repeaters[3,4]
- Our proposed new architecture:

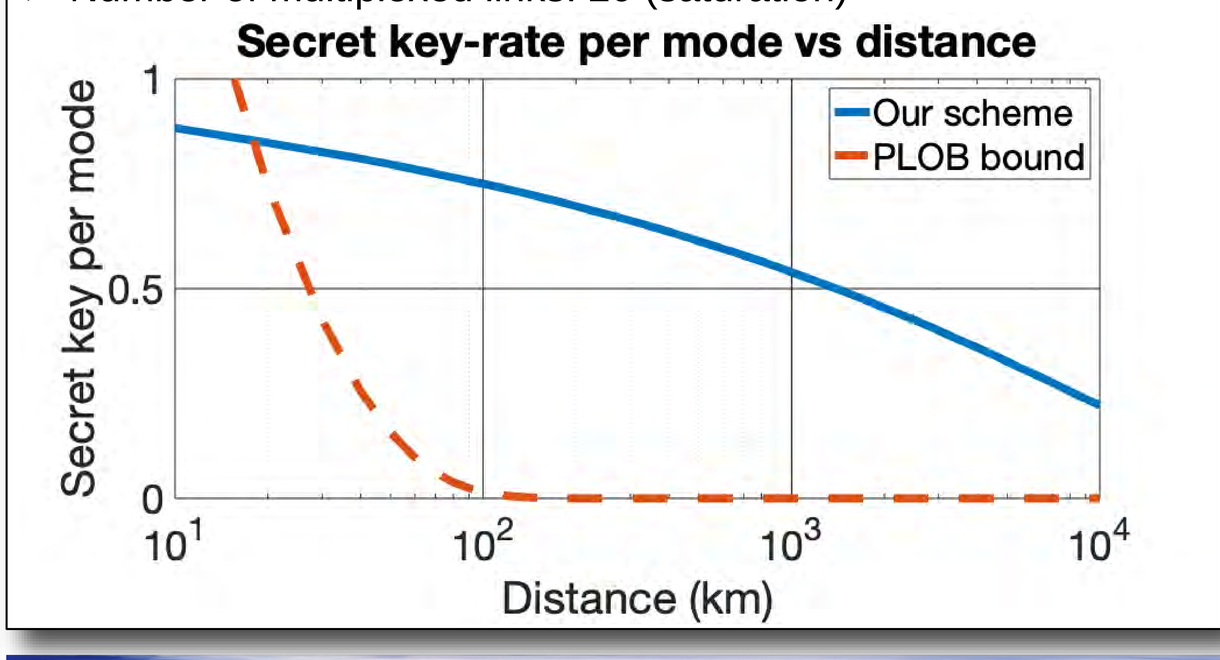


- ➢ Novel Multiplexing: *Different colors indicate a ranking of the elementary links based on their entanglement quality.
- ➢ Links on the left and right of each repeater matched by rank, before entanglement swapping is performed.

- Resource state preparation[5]:



- End-to-end state: Bell diagonal with X and Z type errors that depend on initial GKP squeezing, inter-repeater spacing, GKP error correction frequency, and multiplexing.
- Simulation Parameters:
- ➢ Initial finite GKP squeezing (peak width), $s_{gkp} = 14.7$ dB
- ➢ Repeater separation: 2 km
- ➢ Number of multiplexed links: 20 (saturation)



References

1. Pant, M., et al., Phys. Rev. A **95**, 012304 (2017)
2. Gottesman, D., Kitaev, A., and Preskill, J., *Phys. Rev. A*, 64(1):012310, (2001)
3. Fukui, K., Alexander, R., van Loock, P., Phys. Rev. Research 3, 033118 (2021)
4. Rozpedek, F., et al., npj Quantum Information 7, 102 (2021)
5. Fukui, K., et al. Phys. Rev. X 8, 021054 (2018)