To advance quantum information technologies, many quantum devices and protocols are being developed based on a variety of physical systems, including photons, atoms, mechanical oscillators, solidstate or superconducting devices. Implementations do not only choose between the vast landscape of platforms but also between favoured degrees of freedom and the advantages they can provide [1]. The capability to convert between different encodings is key to linking separate devices in a future heterogeneous quantum network [2]. Such a process is challenging as it requires one to preserve fragile quantum superpositions during the transcoding while functioning as a black box with propagating input and output qubits, a requisite that demands the process to be heralded and free of post-selection. Here we report the experimental realization of such a converter in the optical domain [3,4], schematically shown in Fig. 1a.

Photons are ideally suited to transmit information and are available in the two most distinct encodings that represent the particle- and wave-like qubit. A first link between the two was established by entangling an optical discrete single-photon qubit with an optical continuous cat-state qubit [5] followed by advanced hybrid protocols [6,7,8]. Using the required high-purity resources and the subsequent operations we demonstrate the conversion of optical discrete- to continuous-qubits (DV and CV, respectively). The input qubit is created via the use of an optical parametric oscillator creating high-fidelity single photons. An additional displacement beam on its heralding path enables us to perform rotations on the Bloch sphere, heralding DV qubits in the Fock-state basis |0⟩|cat⟩ + eiθ|1⟩|cat⟩. Quantum teleportation with the aforementioned hybrid entanglement of the form κ0|0⟩ + eθκ1|1⟩ enables a mapping of the discrete Fock-basis input qubits to their continuous cat-basis output counterparts. The Bell-state measurement needed for the teleportation process is applied on the DV qubit that is brought to interfere with the DV mode of the hybrid entangled state. By detecting one and only one photon in one beam splitter output port we are able to detect one of the four Bell states. Introducing homodyne conditioning on top of the usual bucket detection permits us to detect a two-photon event as an error and therefore boost the fidelity of this measurement. Upon four successful events, i.e., heralding of the qubit, entanglement creation, Bell-state measurement click and homodyne conditioning, the initial DV qubit is teleported onto a CV qubit of the form κ0|cat⟩ + eθκ1|cat⟩, therefore completing the computational basis conversion.

To evaluate the performance of the converter, the fidelity between the input qubit projected onto the DV basis and the output qubit projected onto the CV basis is calculated. The successful teleportation of all input states is shown in Fig. 1b. Our realization functions as a black box, being heralded and post-selection free, with an output freely-propagating cat-qubit ready for subsequent operations. This work represents a significant advance towards connecting quantum hardware and processing schemes, a grand challenge to scale up quantum infrastructures.