# Irreversibility in unitary quantum homogenization: Theory and Experiment

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## OBJECTIVE

Is it possible to reconcile irreversibility and a time-reversal symmetric unitary theory such as quantum mechanics?

- We present a *constructor-based irreversibility*, that allows generalizing classical irreversibility based on the second law of thermodynamics.
- We test this constructor-based irreversibility in a proof-of-principle experiment, with a multi-photon realization of a quantum *homogenizer*.

## CONSTRUCTOR-BASED IRREVERSIBILITY

*Task T*: specification of a physical transformation on qubits: $T = \{\rho \rightarrow \sigma\}$

*Transpose task*: $T\sim = \{\sigma \rightarrow \rho\}$.

*Substrate:* qubit $Q$ undergoing the task $T$

***Constructor*** *for T on Q*: subsystem with $N$ rest ($R$) qubits that can perform a task $T$ on $Q$ while retaining the ability to do it again.

***Constructor-based irreversibility***: task $T$ possible, transpose task $T\sim$ impossible.

Task possible if:

1. The rest $R$ can perform the task $T$ to arbitrarily high accuracy, once.
2. The rest $R$ is resilient: $\lim_{\epsilon \rightarrow 0} \lim_{n \rightarrow \infty} P_T(n) = 0$

($P_T(n) = {}^{\epsilon}/_{\delta_T(n)}$: rest *relative deterioration)*

$\epsilon = 1 - F(\rho_{final}, \rho_{goal})$: *error* on the task output state $\rho_{final}$ with respect to the goal state $\rho_{goal}$. $\quad (F(A,B) = Tr\left(\sqrt{\sqrt{A}B\sqrt{A}}\right))$

$\delta_T(n) = Sup_{\rho_R \in V_\epsilon[T]}\left[F\left(\rho_R^{(0)}, \rho_R^{(n)}\right)\right]$: $R$ deterioration. $\rho_R^{(n)}$: $R$ state after $n$ tasks, each performed on a new (identically initialized) $Q$. $V_\epsilon[T]$: set of quantum states of $R$ that can perform $T$ with error $\epsilon$.

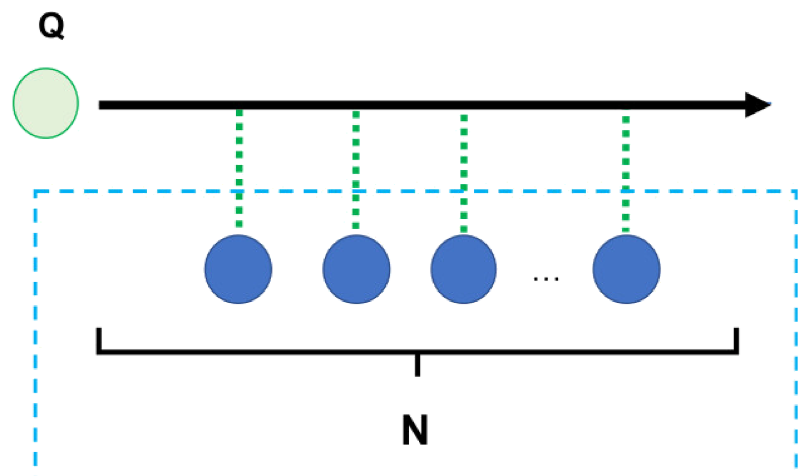
## HOMOGENIZER

Task $T = \{\rho \rightarrow \sigma\}$: a qubit ($Q$) in a pure state $\rho$ undergoes a series of $N$ partial swaps with the $N$ rest qubits in the mixed state $\sigma$.

Reverse task $T\sim = \{\sigma \rightarrow \rho\}$: a qubit ($Q$) in a mixed state $\sigma$ undergoes a series of $N$ partial swaps with $N$ rest qubits in the pure state $\rho$.

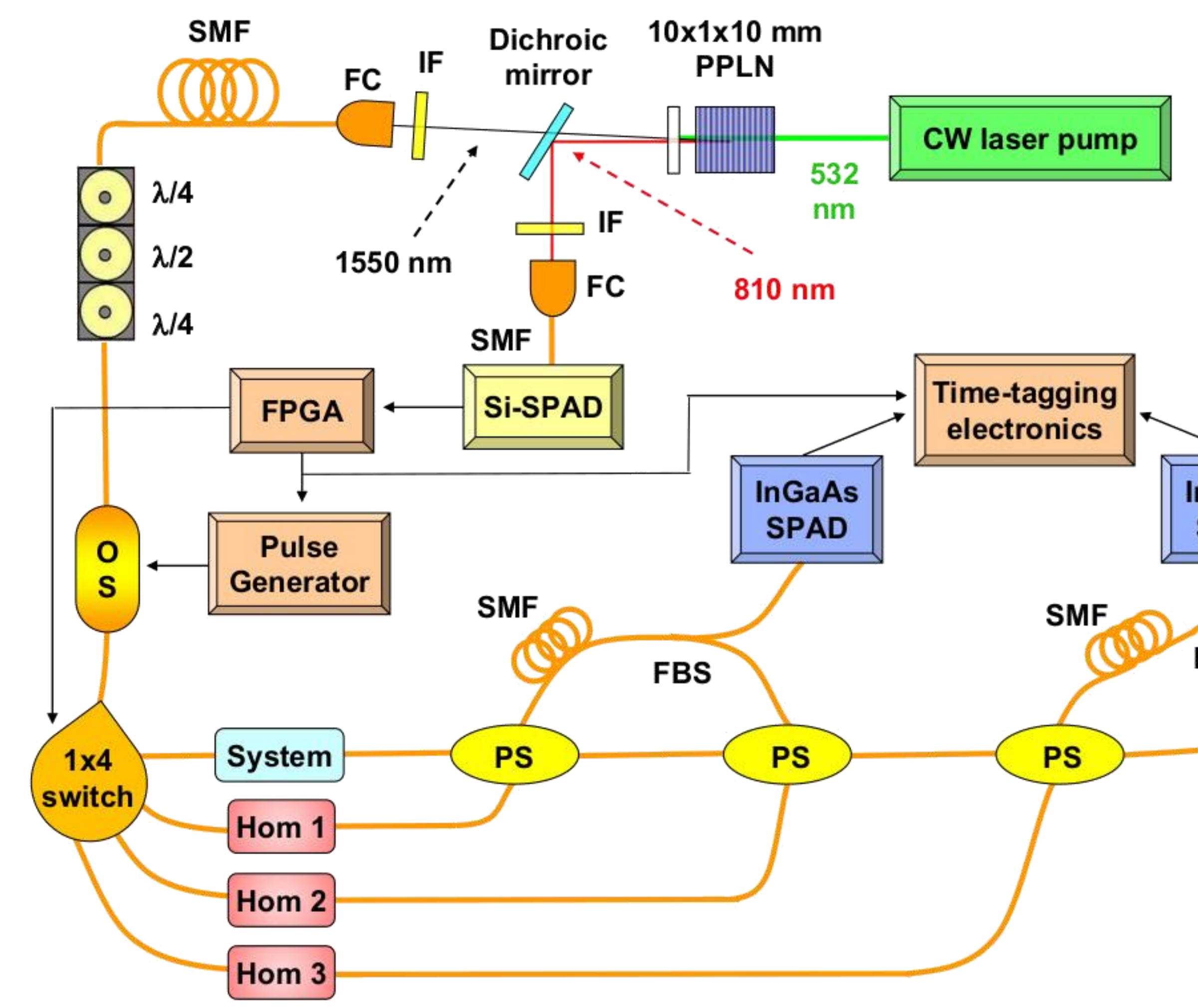
Partial swap: $\quad U = \cos\eta\, I + i \sin\eta\, \Sigma_{12}$

$$\Sigma_{12}|\psi\rangle_1|\phi\rangle_2 = |\phi\rangle_1|\psi\rangle_2$$



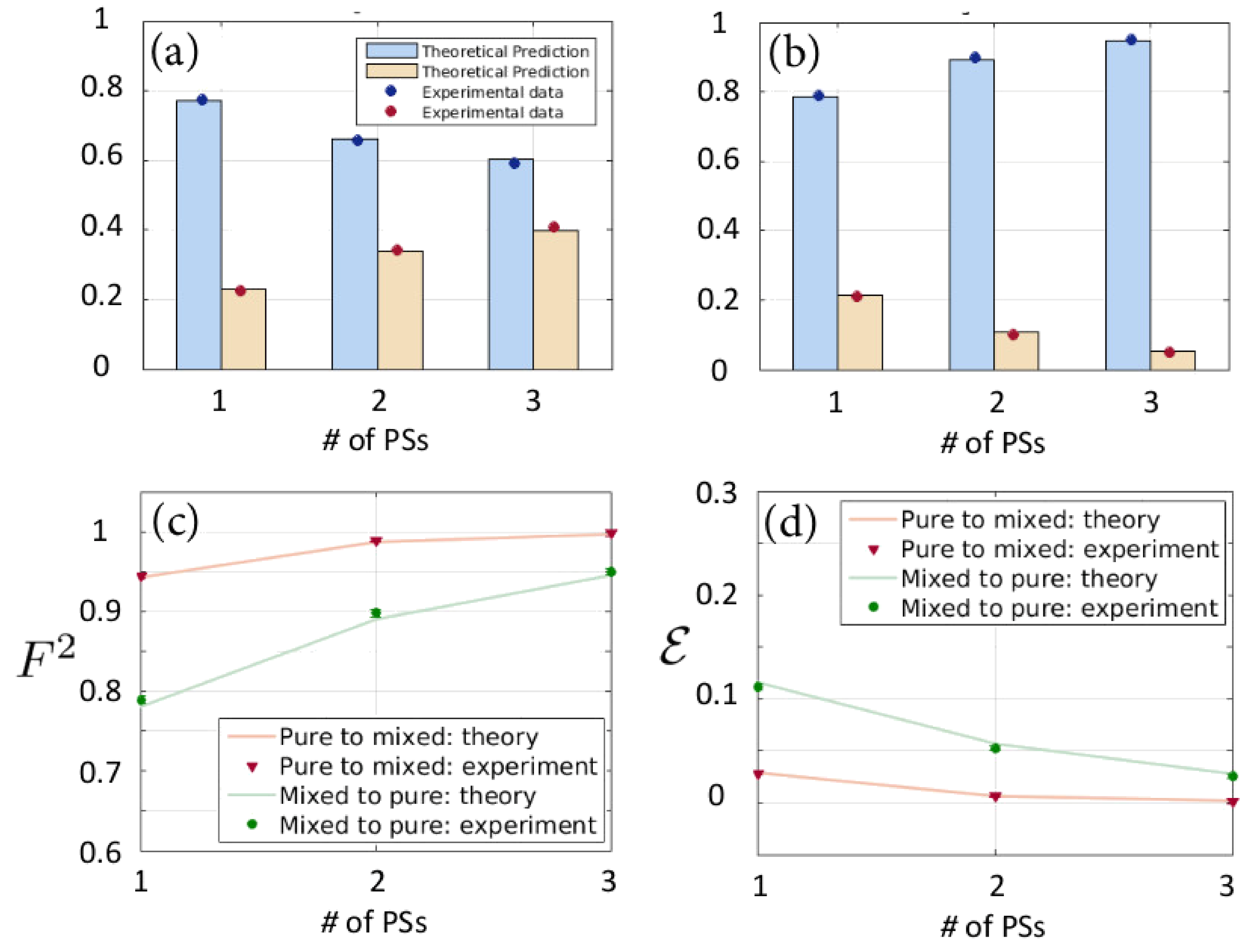

Both $T$ and $T\sim$ fulfill condition (1), but only $T$ fulfills condition (2) . → ***Constructor-based irreversibility***

## SETUP




- Heralded single photons are produced by parametric down-conversion.
- The heralding triggers a field-programmable gate array (FPGA) operating a fast electro-optical shutter (OS), sending the signal photon to a 1x4 fiber optical switch.
- The 1x4 switch addresses the photon either to the substrate path (system) or to one of the homogenizer paths (hom1-3).
- Pure states: $\rho = |0\rangle\langle 0|$ $\quad$ mixed states: $\sigma = 0{,}55|0\rangle\langle 0| + 0{,}45|1\rangle\langle 1|$
- The photon meets a cascade of $N = 3$ partial swaps (PS) realized by several sets of fiber beam splitters (splitting ratios 50:50, 76:24, 90:10).
- Photon detection is performed by two free-running indium/gallium-arsenide SPADs (InGaAs SPADs), whose output is sent to the time-tagging electronics together with the FPGA-validated heralding counts.
- IF: interference filter. FC: fiber coupler. SMF: single-mode fiber. $\lambda/4$: quarter-wave fiber paddle. $\lambda/2$ : half-wave fiber paddle. FBS: 50:50 fiber beam splitter.

## RESULTS FOR $\eta = 0{,}78$ (50:50 BS)




*(Preliminary results)*

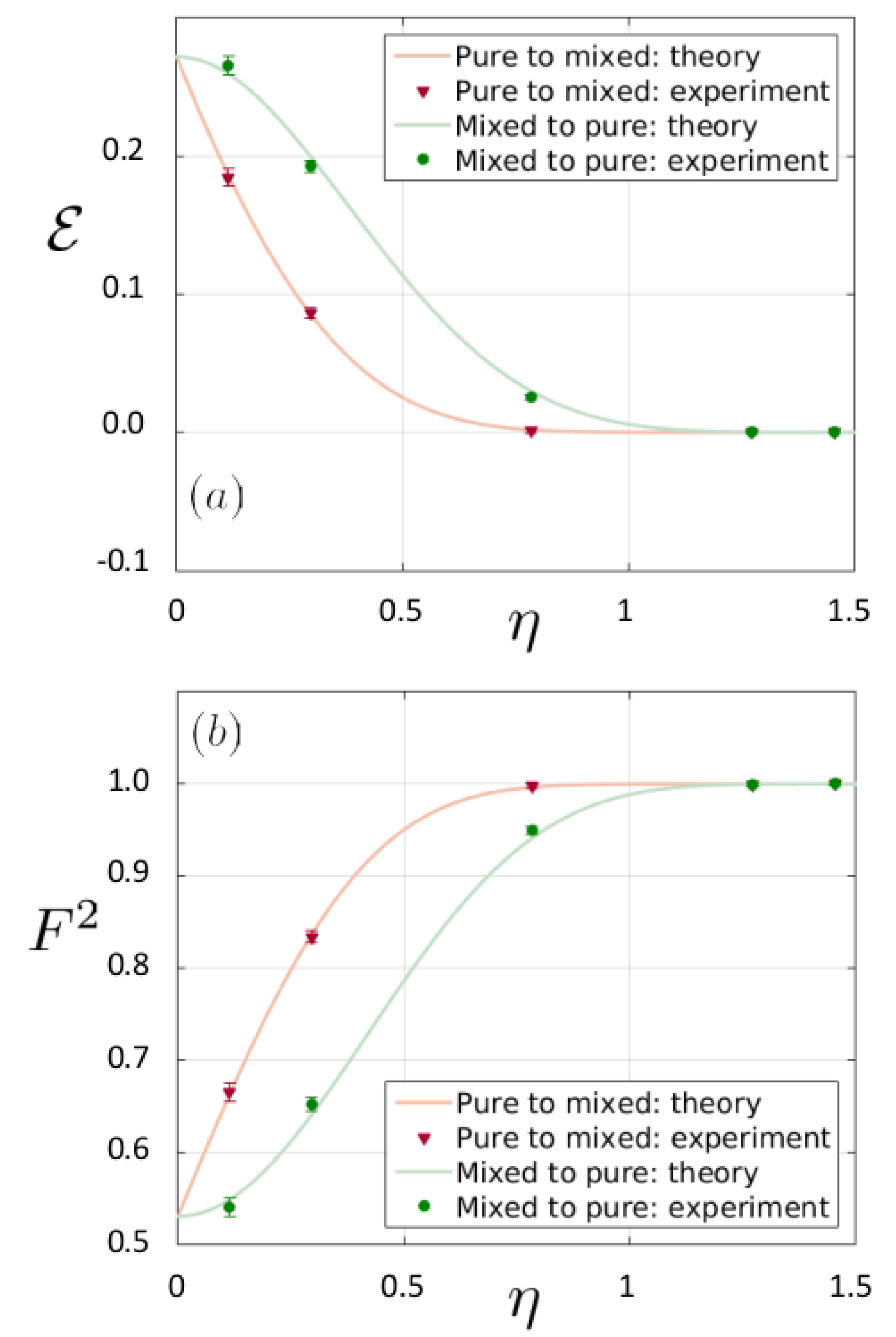
Upper row: $\rho_{00}$ (blue) and $\rho_{11}$ (orange) elements of the density matrix of the substrate $Q$ at each stage of the task; (a) pure to mixed (task $T$), (b) mixed to pure (task $T\sim$).

Lower row: square fidelity $F^2$ (c) and error $\epsilon = 1 - F$ (d) between the task goal state and the substrate state.

## CONCLUSIONS

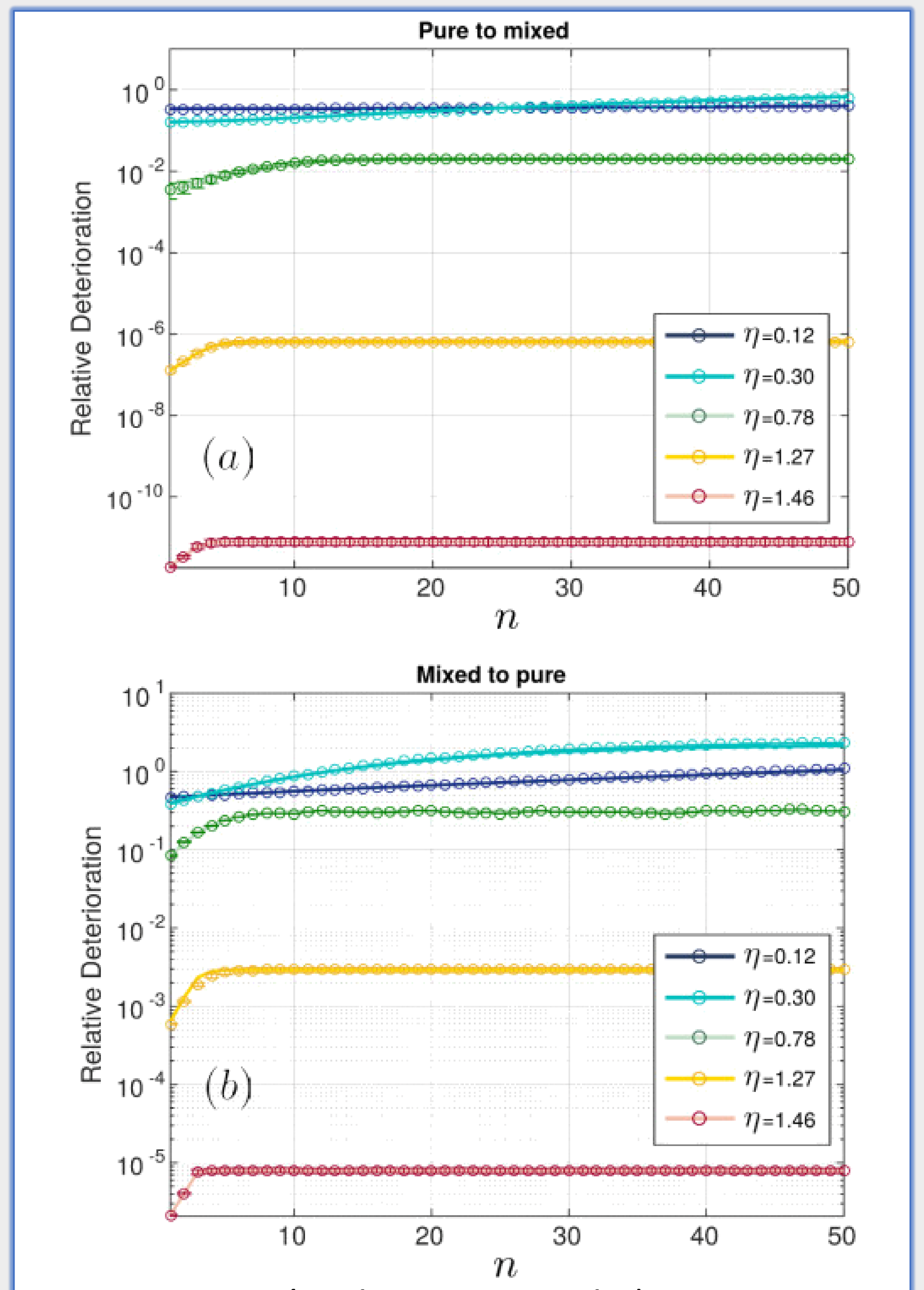
- We proposed a way to reconcile irreversibility and unitary evolution in quantum mechanics.
- Our results show that the homogenizer realizing $T$ always outperforms the one implementing $T\sim$, that even suffers higher degradation than its counterpart.
- This is proof of the compatibility of classical (constructor-based) irreversibility with quantum mechanics.

## PERFORMANCE




Performances of the 3-qubits homogenizer (as a function of $\eta$) for the pure-to-mixed task T and its reverse $T\sim$ (mixed-to-pure). *(Preliminary results)*

## RELATIVE DETERIORATION




*(Preliminary results)*

Relative deterioration of our 3-qubit homogenizer for tasks $T$ (a) and $T\sim$ (b), as a function of the number of usages $n$.

Solid lines: theoretical predictions; circles: experimental reconstructions.