Remote state preparation based on optical hybrid entanglement

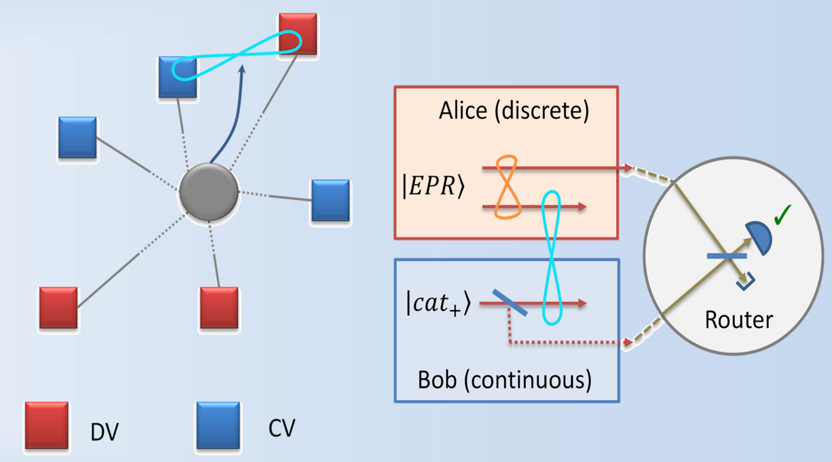
Adrien Cavaillès, Hanna LeJeannic, Jérémy Raskop, Kun Huang, Olivier Morin and Julien Laurat
Laboratoire Kastler Brossel, UPMC-Sorbonne Universités, CNRS, ENS-PSL Research University, Collège de France, 4 Place Jussieu, 75005 Paris, France

Introduction

The wave-particle duality of light has led to two different encodings for optical quantum information processing. Several approaches have emerged based either on particle-like discrete-variable states, e.g. finite-dimensional quantum systems, or on wave-like continuous-variable states, e.g. infinite-dimensional systems.

Aiming at connecting the two worlds in order to build quantum heterogeneous networks [1], where a discrete qubit can be converted in a continuous encoding, we demonstrate the first measurement-induced generation of hybrid entanglement between optical quantum bits of these different types [2], located at distant places and connected by a lossy channel.

Using this hybrid resource, we can engineer remotely any coherent state superposition or qu-mode by conditioning on the results of quadrature measurements performed on the discrete part of this hybrid state

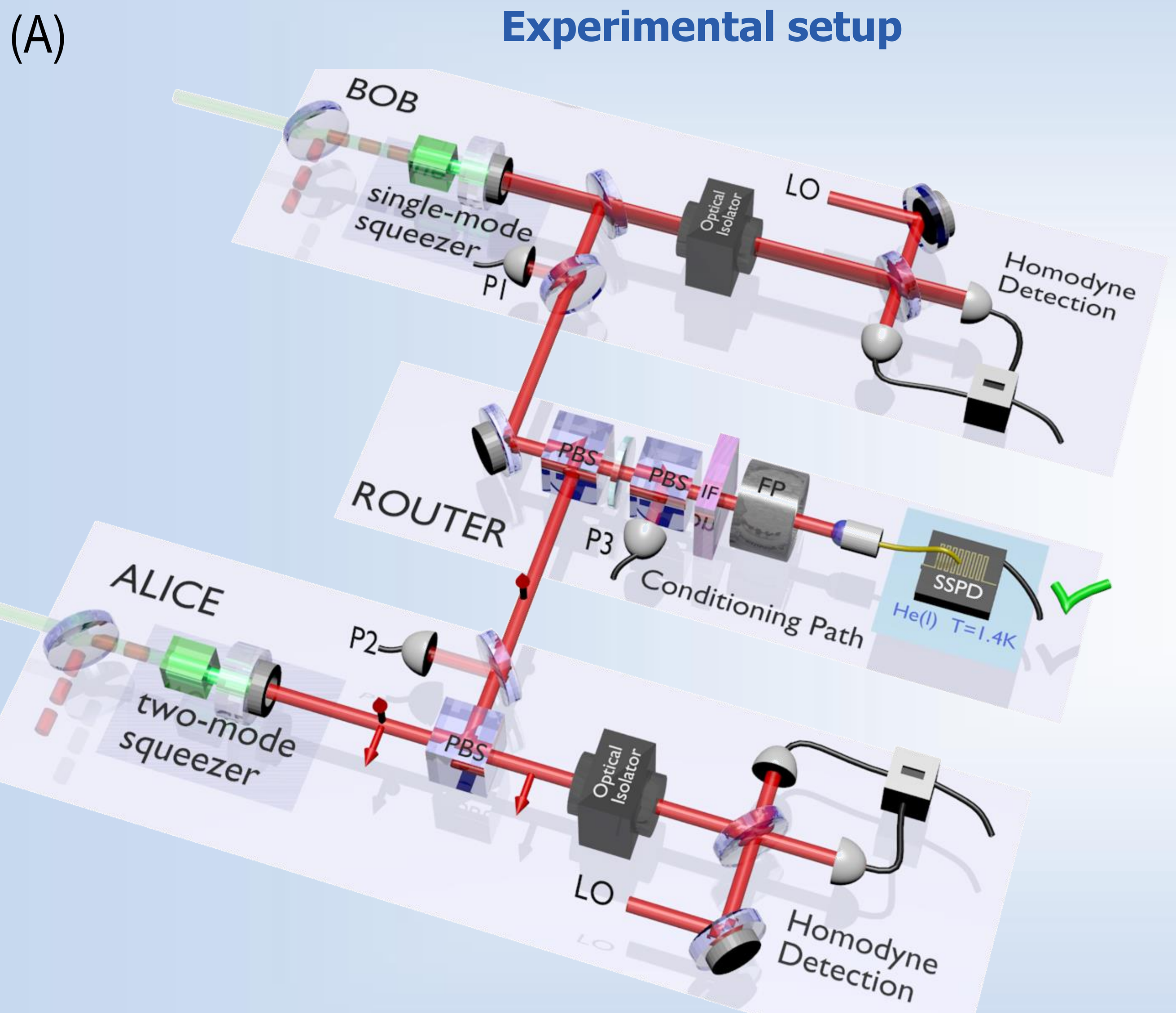


Heterogeneous network

Measurement-induced generation of hybrid entanglement

(A)

Experimental setup

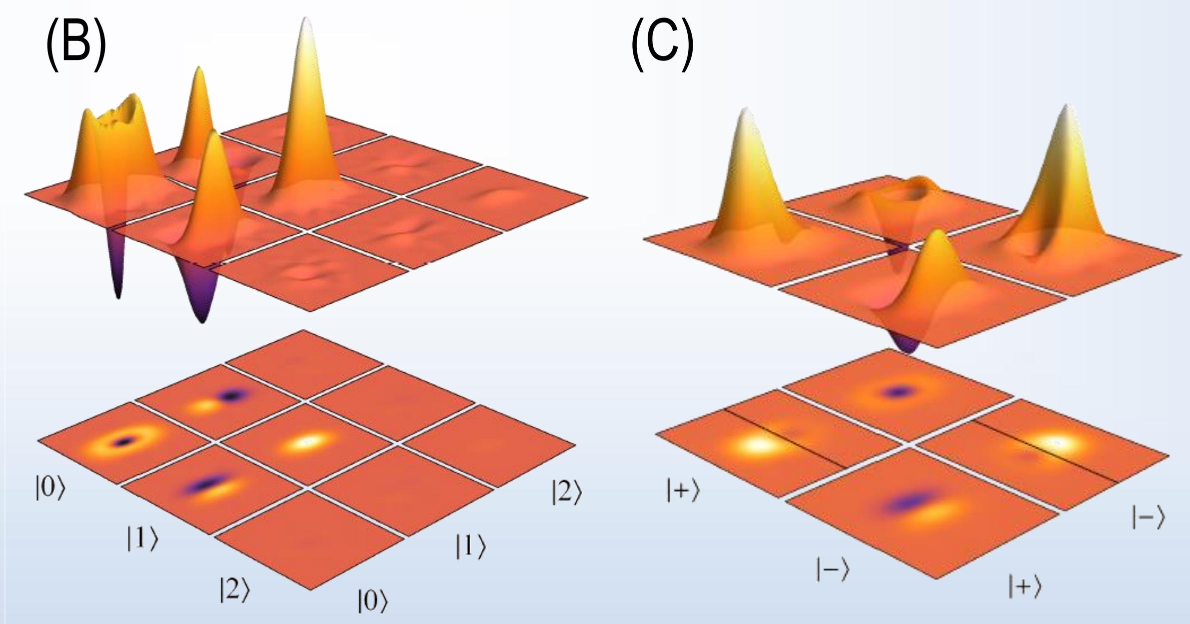


$|1\rangle_{DV}|\text{cat}_+\rangle_{CV} + e^{i\phi}|0\rangle_{DV}|\text{cat}_-\rangle_{CV}$

(A) Alice and Bob locally generate the required resources by using continuous-wave optical parametric oscillators (OPOs) operated below threshold [3][4]. A two-mode squeezer and a single-mode squeezer are used respectively on Alice's and Bob's node. A small fraction of Bob's squeezed vacuum is tapped (3%) and mixed at a central station to the idler beam generated by Alice. The resulting beam is then frequency filtered and detected by a superconducting single photon detector (SNSPD). Given a detection event, which heralds the generation of entanglement between an even and an odd cat state and the presence or absence of a single photon, the entangled state is characterized by two high-efficiency homodyne detections in the optimal temporal modes [5].

Two-mode quantum state tomography

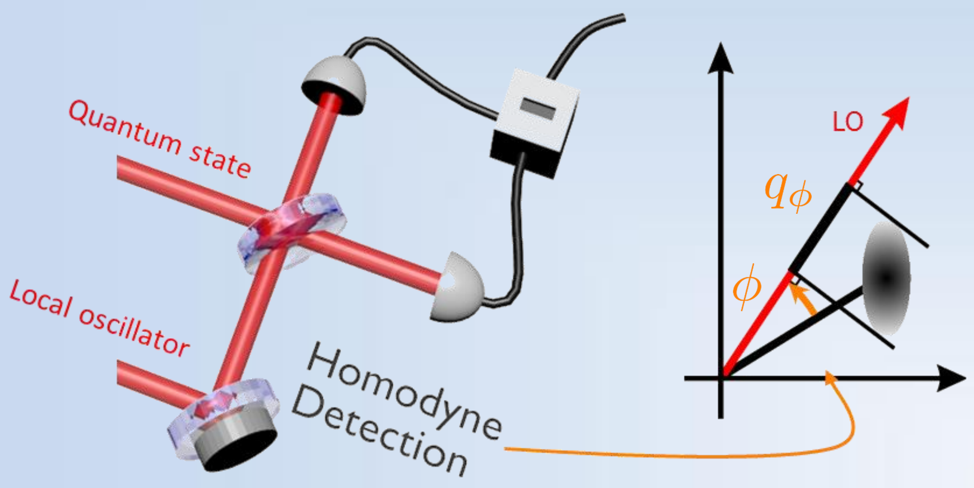
(B) (C)



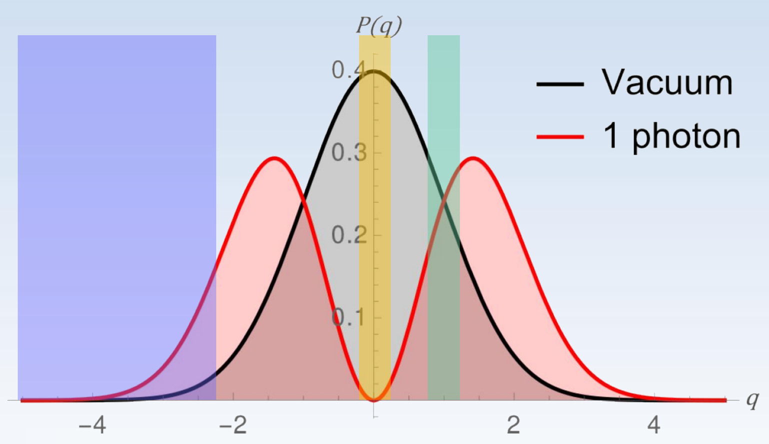
$|0\rangle_{DV}|\text{cat}_-\rangle_{CV} - |1\rangle_{DV}|\text{cat}_+\rangle_{CV}$ $\quad |-\rangle_{DV}|\alpha\rangle_{CV} - |+\rangle_{DV}|-\alpha\rangle_{CV}$

(B) The beam splitter ratio in the central station is adjusted to generate a maximally entangled state. The figure gives Wigner functions associated with the reduced density matrices $\langle k|\hat{\rho}|l\rangle$ with $k,l \in \{0,1,2\}$ after correction for detection losses ($\eta = 85\%$). For components with $k \neq l$, the plots give the real part of $\langle k|\hat{\rho}|l\rangle$ (back corner) and the imaginary part of $\langle l|\hat{\rho}|k\rangle$ (front corner). **(C)** Wigner functions associated with the reduced density matrices $\langle k|\hat{\rho}|l\rangle$ with $k,l \in \{+,-\}$, where $|\pm\rangle = (|0\rangle \pm |1\rangle)/\sqrt{2}$. A fidelity $77 \pm 3\%$ is obtained with the target state with $|\alpha| = 0.9$.

Remote state preparation: Generation of arbitrary continuous variable qu-modes



$$\frac{1}{\sqrt{2}}(|cat+\rangle_{CV}\,|1\rangle_{DV} + |cat-\rangle_{CV}\,|0\rangle_{DV})$$

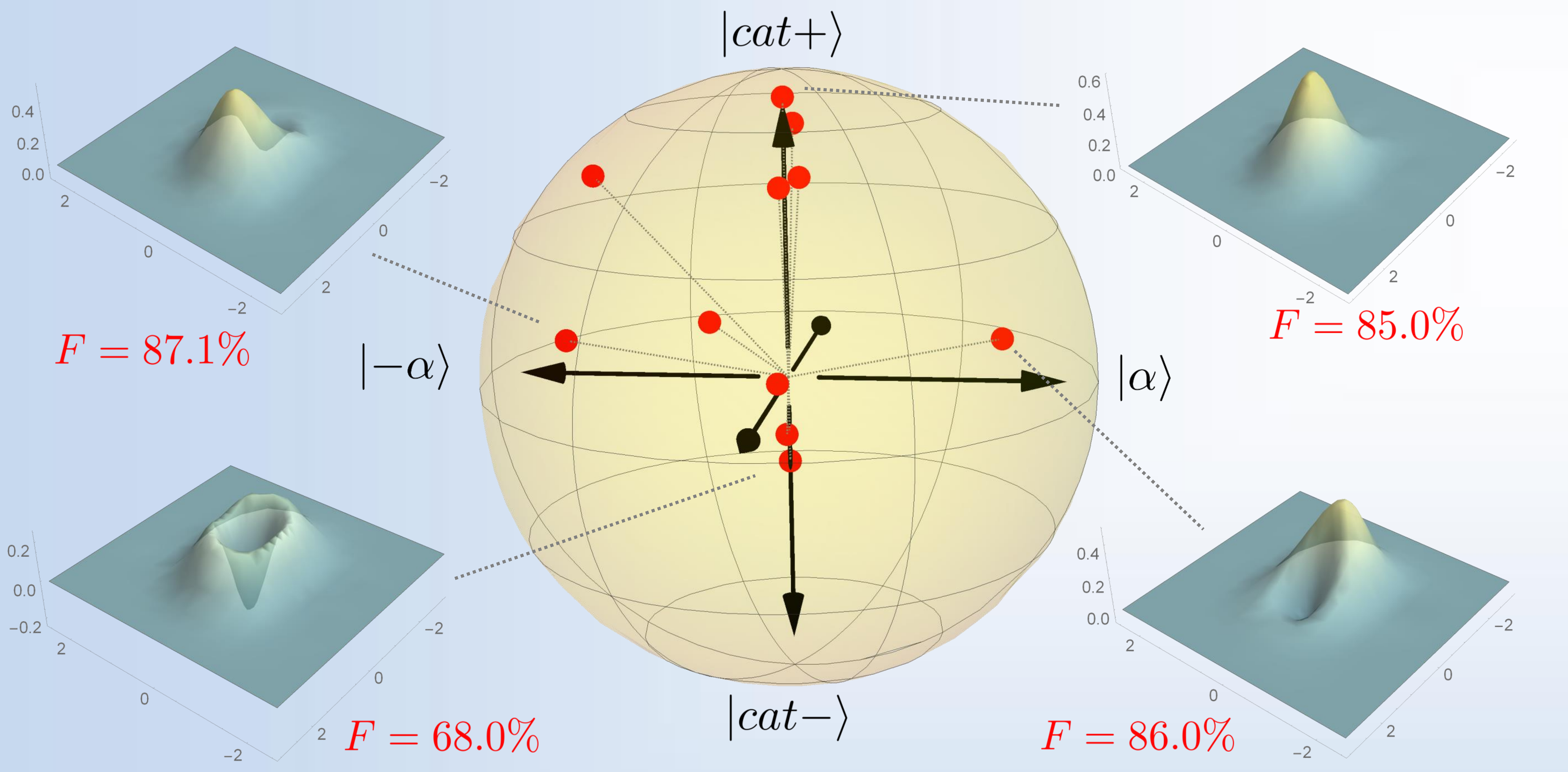


Conditioning on the result of the homodyne measurement on the DV side, it is possible to choose the state created on the CV side.

Any qu-mode is accessible by choosing ϕ and q_ϕ.

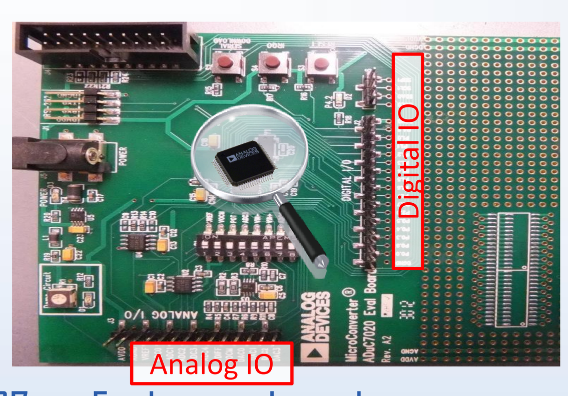
$$\langle q_\phi|\Psi\rangle_{DV} = \frac{1}{\sqrt{N_q}}(|cat-\rangle_{CV} + q_\phi e^{i\phi}\,|cat+\rangle_{CV})$$

Bloch sphere representation

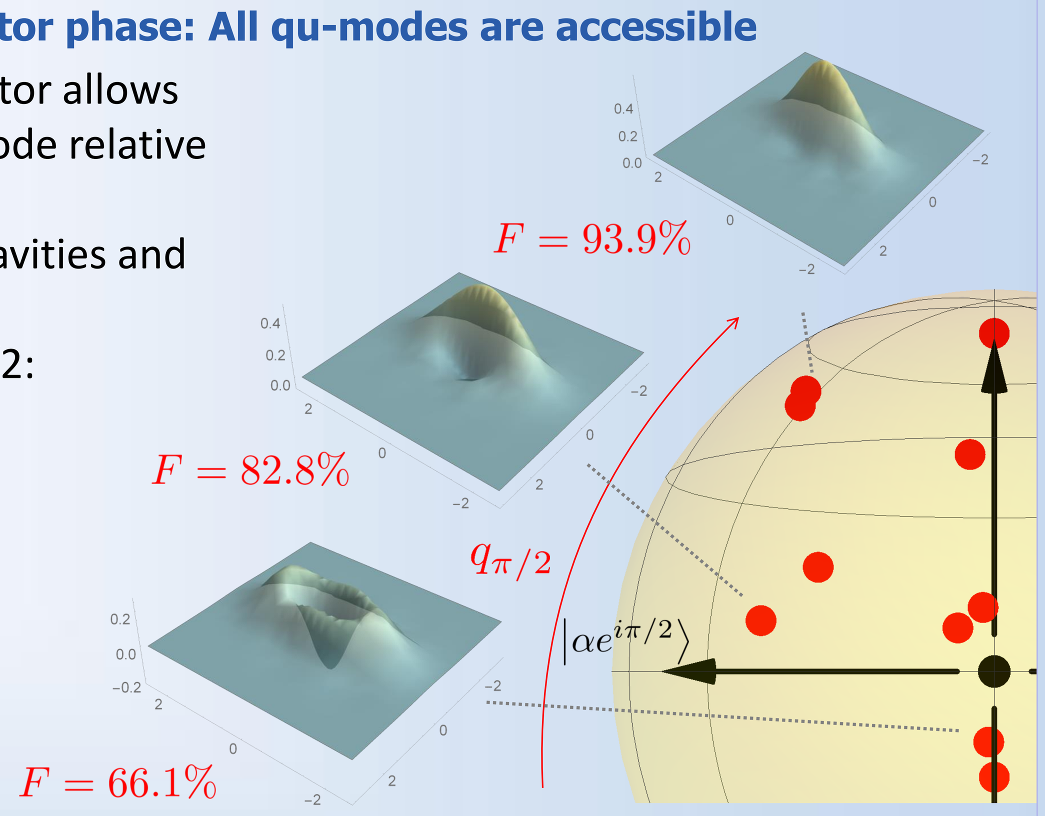


Locking the Local oscillator phase: All qu-modes are accessible

Control of the phase of the local oscillator allows the selection of the phase of the qu-mode relative to the squeezing direction.
We use microcontrollers to lock both cavities and local oscillator phase. [6]
Experimental results when locked at π/2:

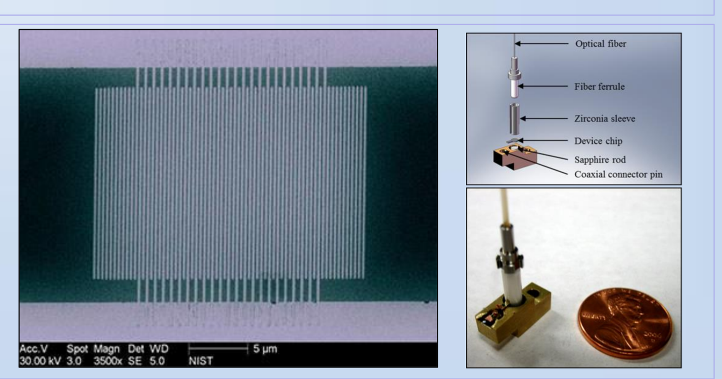


ADuC7xxx Evaluation board



Superconducting Nanowire Single-photon detector (SNSPD)

To herald our state generation, we use SNSPDs based on WSi from a collaboration with the National Institute of Standards and Technology (NIST) and the Jet Propulsion Laboratory (JPL) [7]. Those detectors reach 93% of detection efficiency at 1064 nm [8] instead of 1% for an avalanche photodiode, with low dark counts (<10Hz). Using them we characterise our single photon source as a 1 MHz generation rate and above 90% heralding efficiency.



References:

1. U.L. Andersen, J.S. Neergaard-Nielsen, P. van Loock, and A. Furusawa, "Hybrid-discrete- and continuous-variable quantum information ", Nat. Phys. **11**, 713-719 (2015)
2. O. Morin et al., "Remote creation of hybrid entanglement between particle-like and wave-like optical qubits", Nat. Photon. **8**, 570 (2014)
3. O. Morin et al., "A high-fidelity single-photon source based on a type-II optical parametric oscillator", Opt. Lett. **37**, 3738 (2012)
4. O.Morin et al., "Quantum state engineering of light with continuous-wave optical parametric oscillators", J. Vis. Exp. **87**, e51224 (2014)
5. O. Morin, C. Fabre, and J. Laurat, "Experimentally accessing the optimal temporal mode of traveling quantum light states", PRL **111**, 213602 (2013)
6. K. Huang et al., "Microcontroller-based locking in optics experiments", Rev . Sci. Instrum. **85**, 123112 (2014)
7. F. Marsili et al., "Detecting single infrared photons with 93% system efficiency", Nat. Photon. **7**, 210 (2013)
8. H. Le Jeannic et al. «High-efficiency WSI superconducting nanowire single-photon detectors for quantum state engineering in the near infrared», **TBP**, arXiv:1607,07459

QScale
chist-era
erc HybridNet