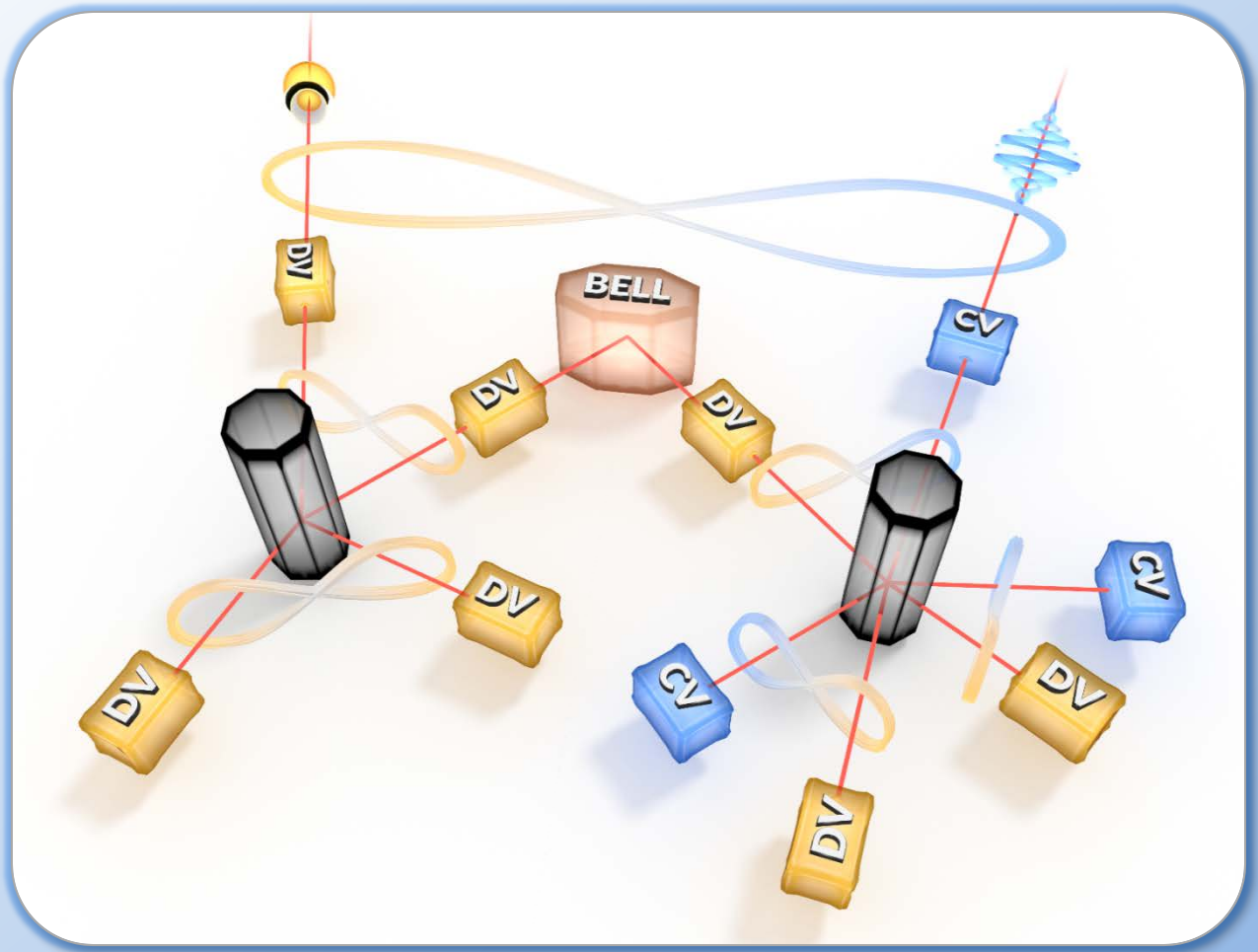
Hybrid Entanglement for Heterogeneous Quantum Networks



Tom Darras, Giovanni Guccione, Adrien Cavaillès and Julien Laurat
Laboratoire Kastler Brossel, Quantum Networks Team

Paris, April 2021, 22th

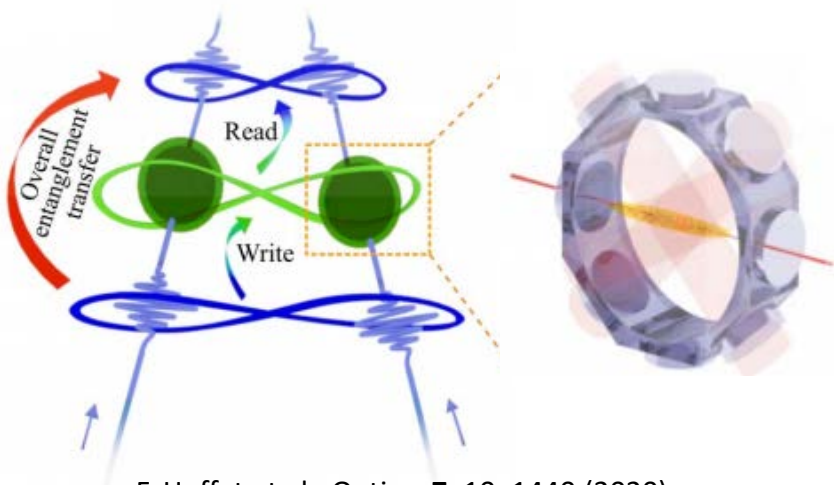
Hybrid Entanglement for Heterogeneous Quantum Networks

Gouraud et al., *PRL*, 114, 180503 (2015).

Quantum Networks

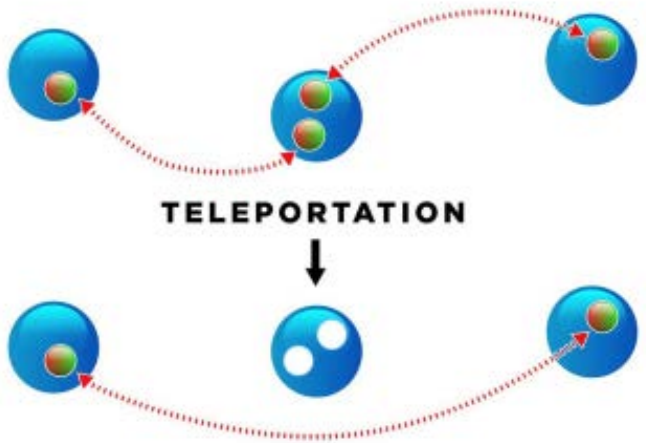
- ✓ Outperforms classical information processing
- ✓ Require two key ingredients

Storage of quantum states in the nodes



F. Hoffet et al., Optica, **7**, 10, 1440 (2020).

Distribution of entanglement in the channels



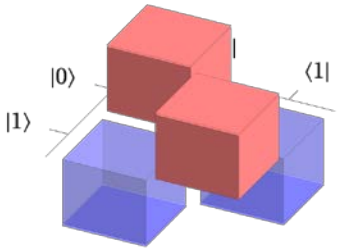
Wehner et al., *Science,* **362**, 303 (2018).

Hybrid Entanglement for Heterogeneous Quantum Networks

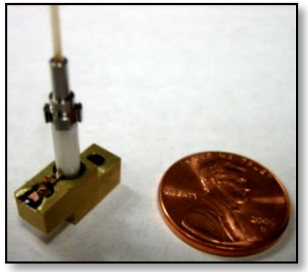
Encoding Quantum Information

Discrete-variable encoding

$$|\psi\rangle = c_0|0\rangle + c_1|1\rangle$$



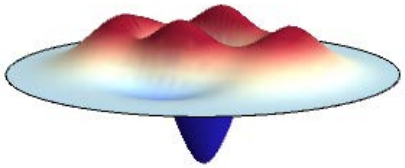
Density matrix



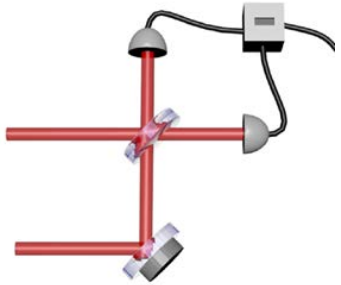
Single-photon detectors

Continuous-variable encoding

$$|\psi\rangle = c_\alpha|\alpha\rangle + c_{-\alpha}|-\alpha\rangle$$

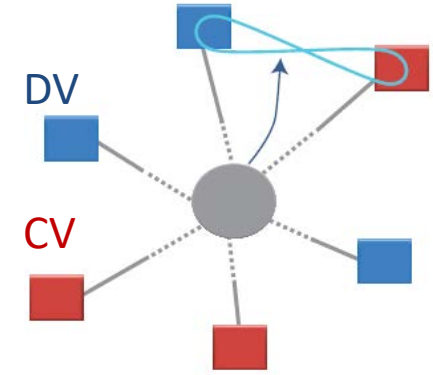


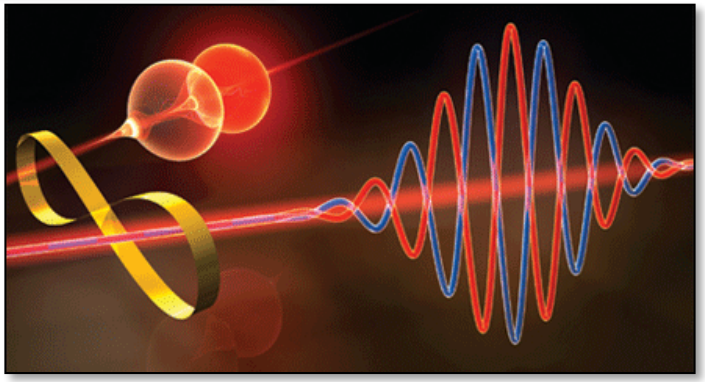
Wigner function



Homodyne detection

Going hybrid using entanglement

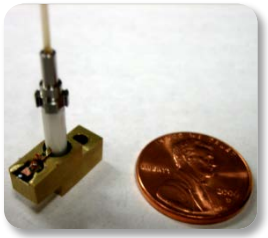


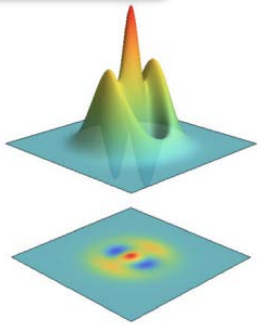


How do we generate this hybrid entanglement ?

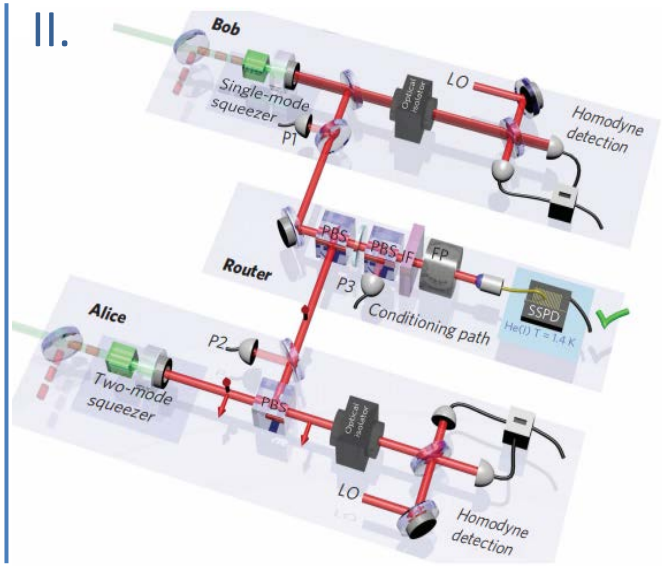
Hybrid Entanglement for Heterogeneous Quantum Networks

I.

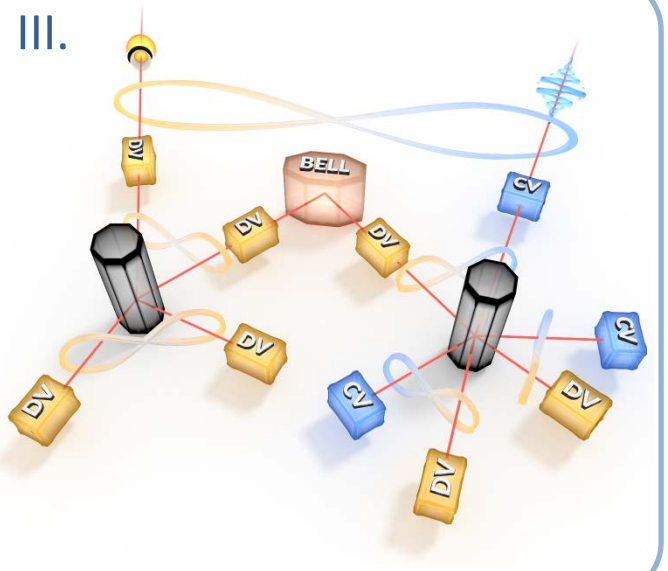




II.



III.



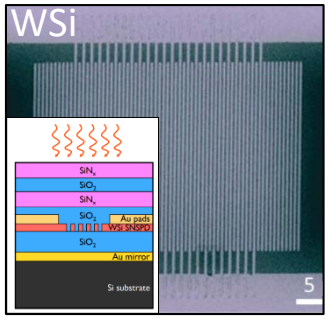
I. Optical Quantum State Engineering.

II. Remote creation of hybrid entanglement of light.

III. Entanglement swapping using optical hybrid entanglement.

Remote creation of hybrid discrete- and continuous- variable entanglement of light

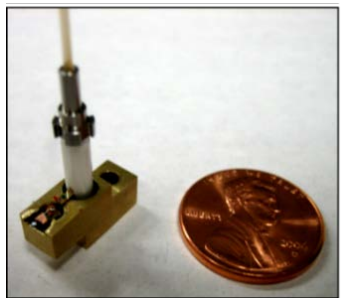
DV State Generation: Experimental Setup

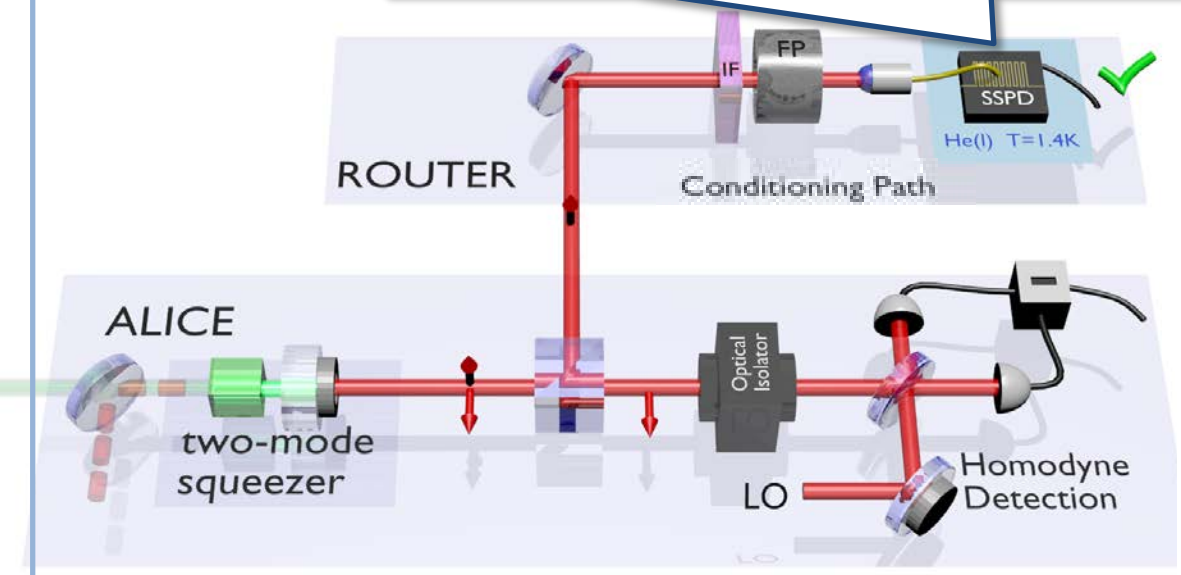


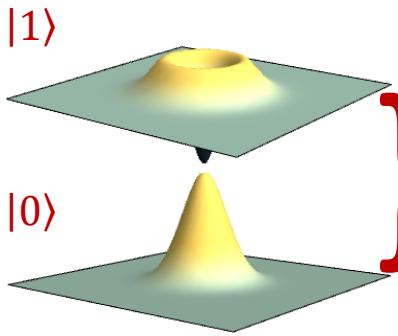
Superconducting Nanowire Single-Photon Detectors

- Quantum efficiency > 90% at 1064 nm
- Dark count rate below Hz level
- Collaboration with NIST and NASA JPL

Le Jeannic et al., *Optics Letters,* **41**, 5341 (2016).



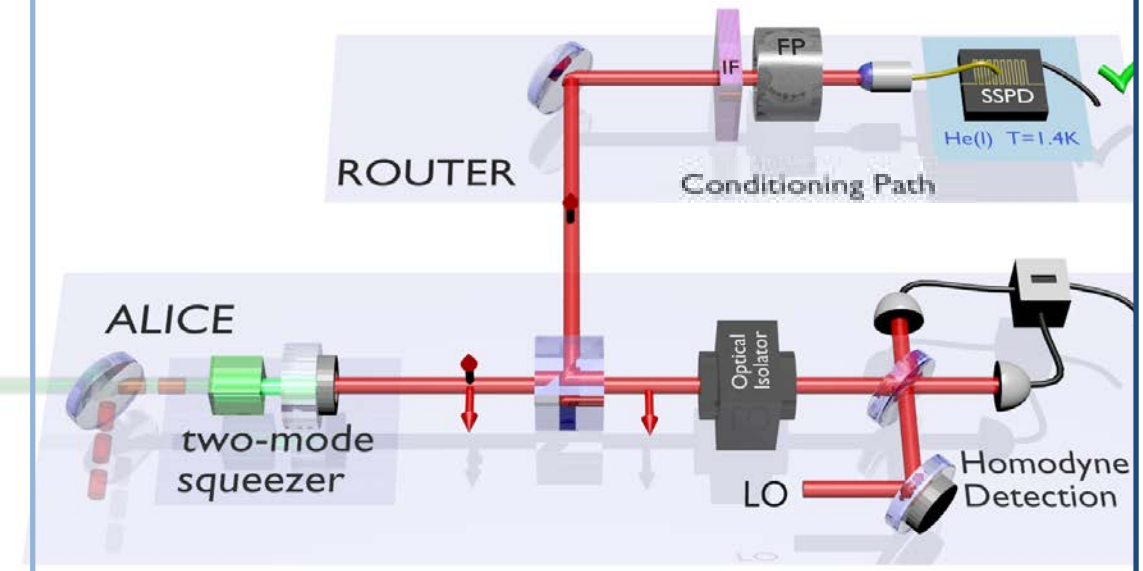




DV states

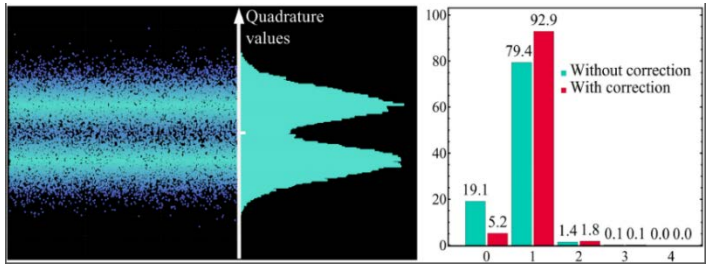
Remote creation of hybrid discrete- and continuous- variable entanglement of light

DV State Generation: Experimental Setup

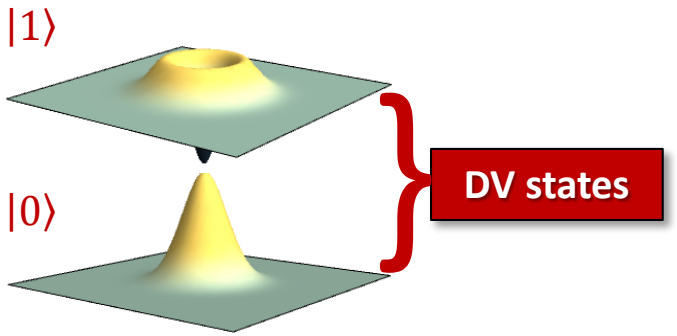


High-purity Single-Photon

Zapletal et al., *arXiv:2012,08544* (2021).

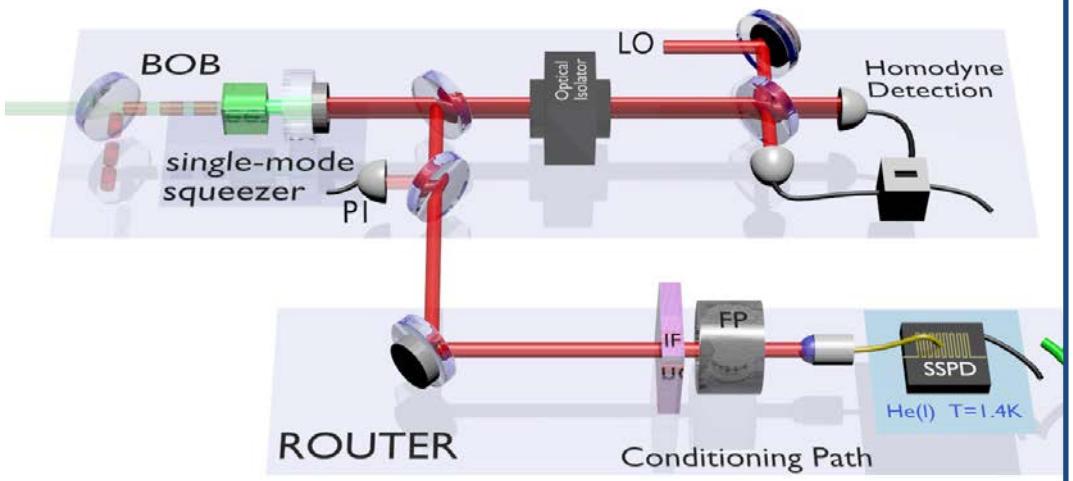


Le Jeannic et al., *Optics Letters,* **41**, 5341 (2016).



Remote creation of hybrid discrete- and continuous- variable entanglement of light

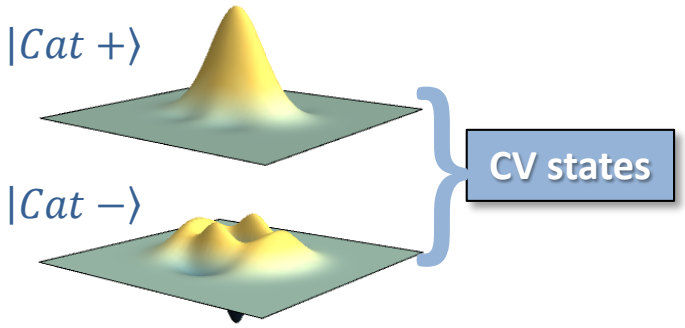
CV State Generation: Experimental Setup



High-purity odd kitten states

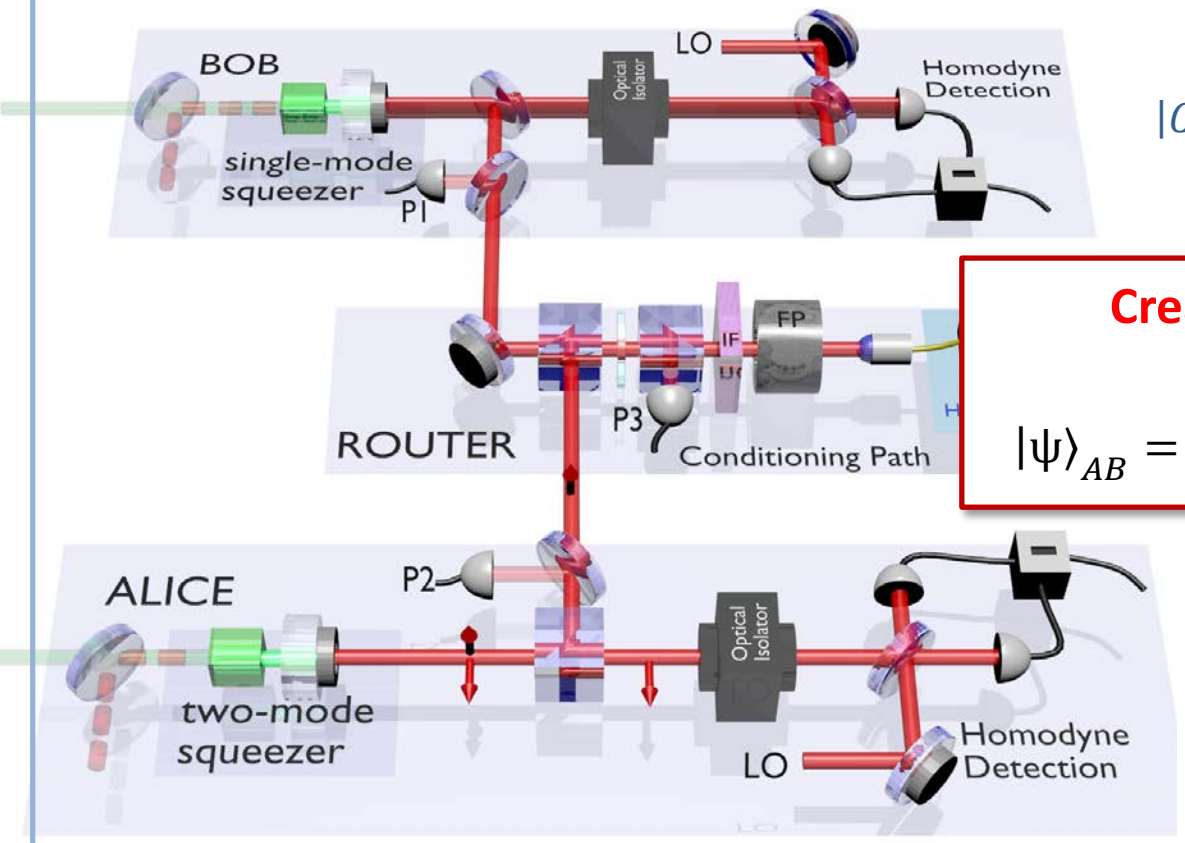
- $|\alpha|^2 \sim 1$
- 500 kHz heralding rate

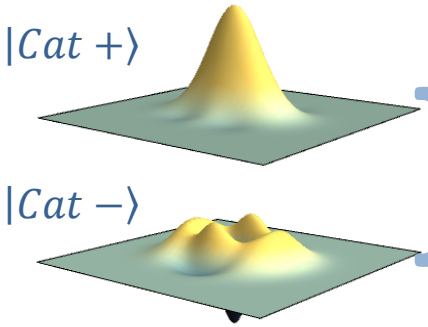
Morin et al., *J. Vis. Exp.*, **87**, e51224 (2014).



Remote creation of hybrid discrete- and continuous- variable entanglement of light

Entanglement Generation: Experimental Setup

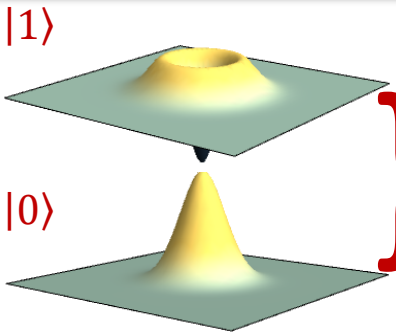




CV states

Creates an entangled state of the form:

$$|\psi\rangle_{AB} = |0\rangle_A |Cat-\rangle_B + |1\rangle_A |Cat+\rangle_B$$

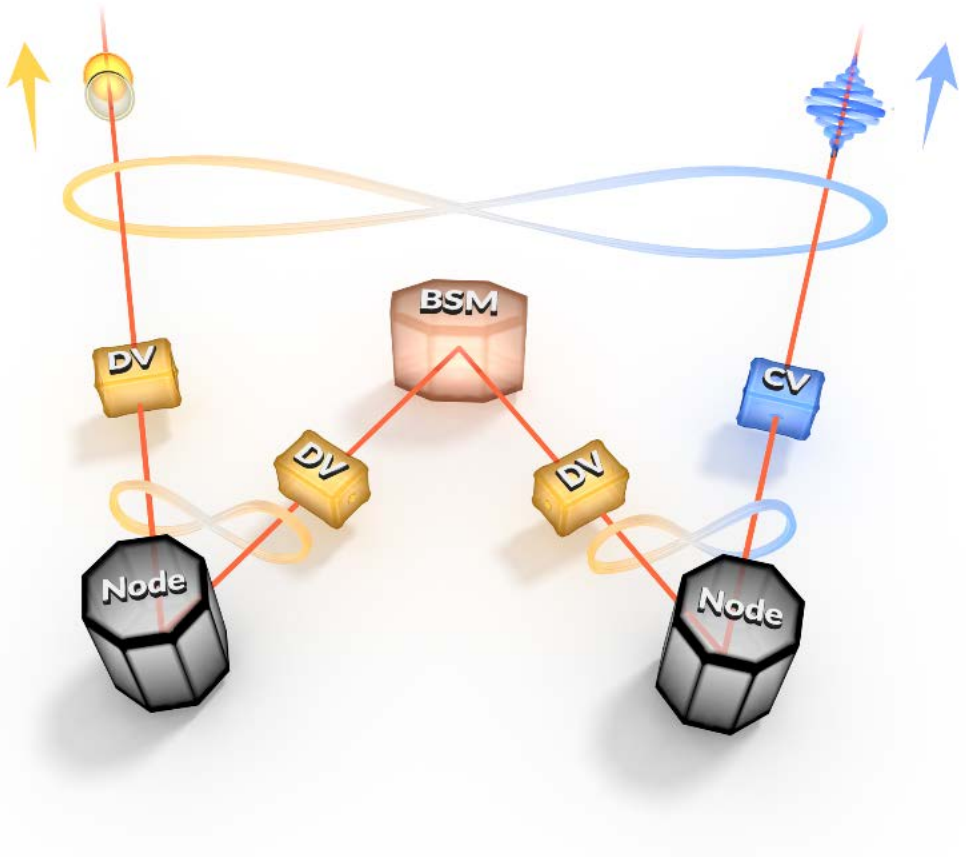


DV states

O. Morin et al., *Nat. Phot.*, **8**, 570 (2014).

Hybrid Entanglement Swapping for Connecting Heterogeneous Quantum Networks

Hybrid entanglement swapping: motivations



Entanglement swapping

- Start with two independent entangled states.
- When Bell measurement is successful, a new entangled state is created between modes that have never interacted.
- Enable the distribution of hybrid entanglement in the quantum network.
- At the basis of quantum repeaters.

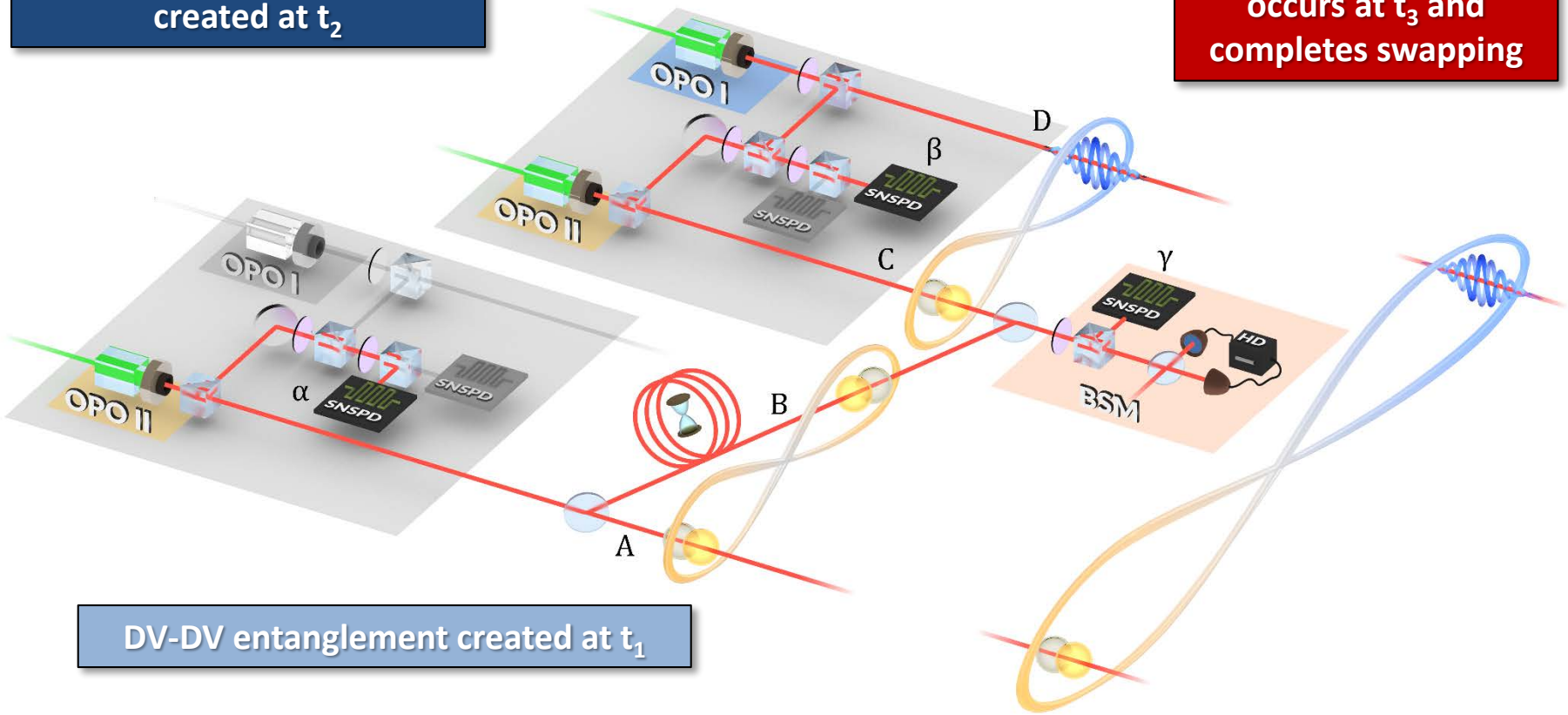
G. Guccione, T. Darras et al., *Science Advances,* **6**, 22, eaba4508 (2020).

Hybrid Entanglement Swapping for Connecting Heterogeneous Quantum Networks

Experimental setup:

DV-CV hybrid entanglement created at t_2

Bell measurement occurs at t_3 and completes swapping



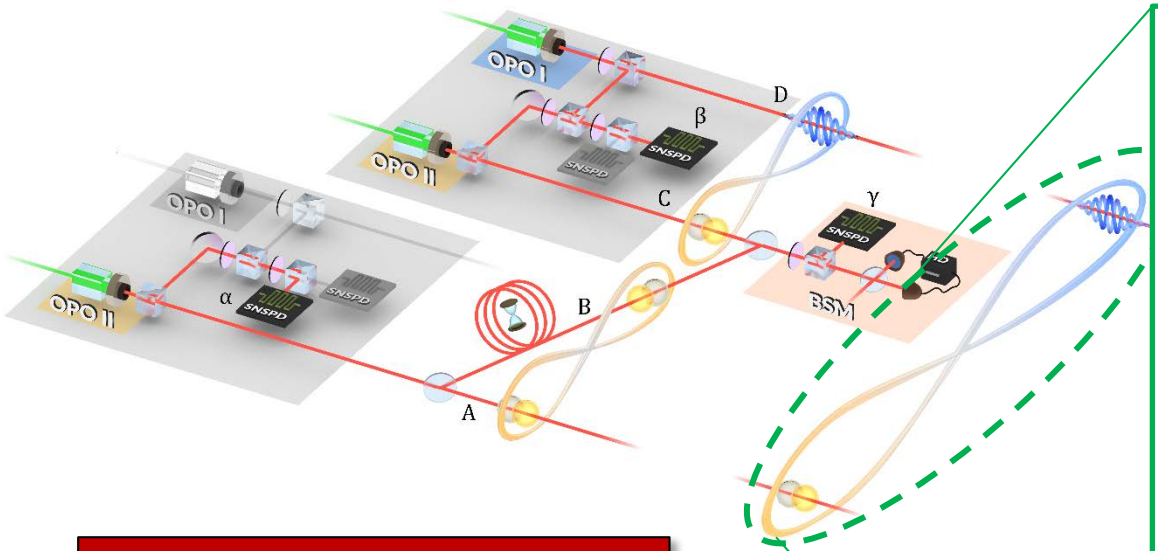
DV-DV entanglement created at t_1

G. Guccione, T. Darras et al., *Science Advances,* **6**, 22, eaba4508 (2020).

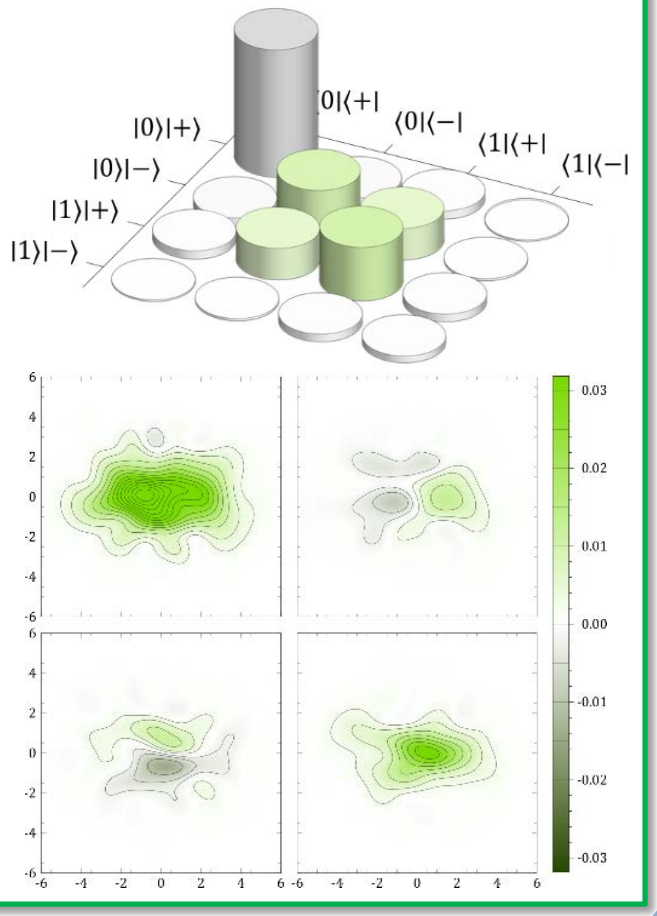
Hybrid Entanglement Swapping for Connecting Heterogeneous Quantum Networks

State characterization:

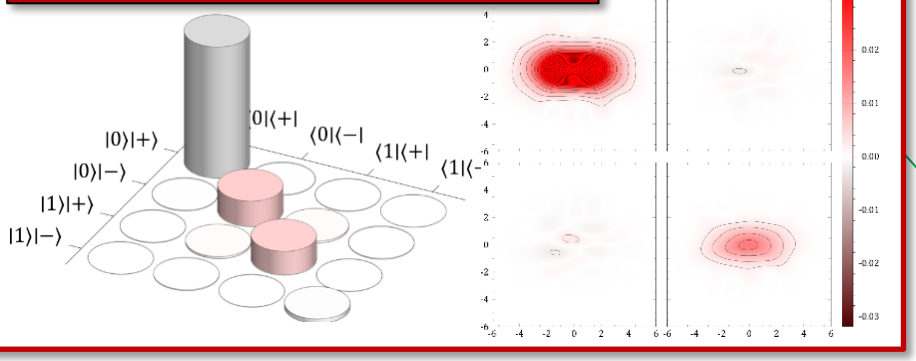
G. Guccione, T. Darras et al., *Science Advances,* **6**, 22, eaba4508 (2020).



Output DV-CV entanglement:

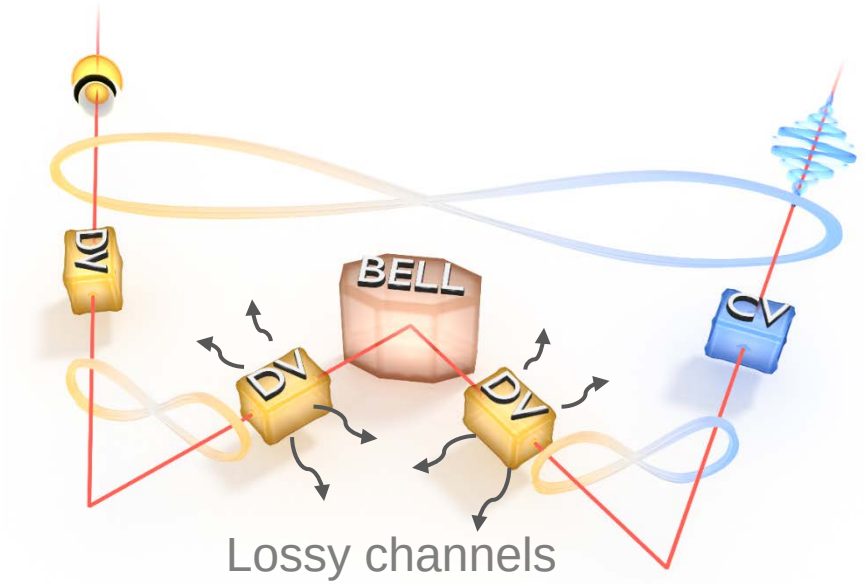


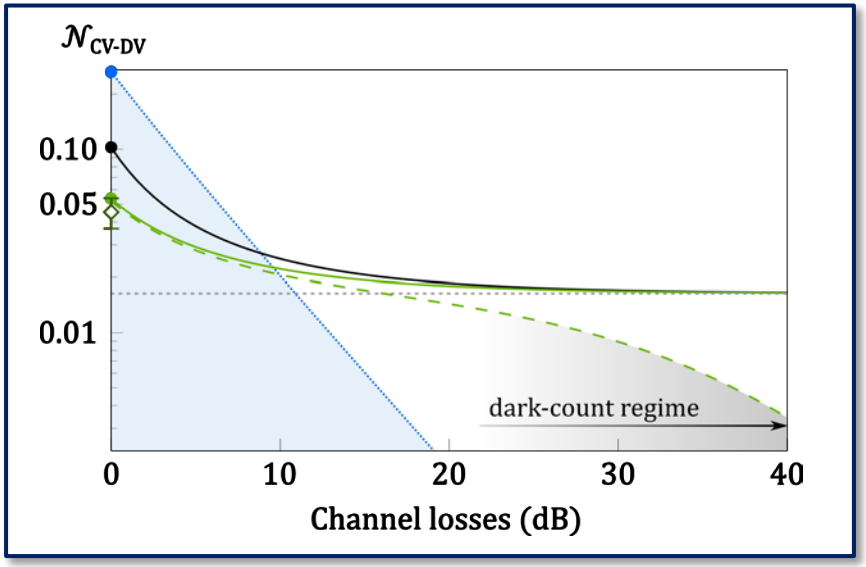
Without Bell measurement



Hybrid Entanglement Swapping for Connecting Heterogeneous Quantum Networks

Propagating hybrid entanglement in lossy channels:





Enables better propagation in lossy channels for applications in quantum repeaters

But still requires entanglement to be purified!

G. Guccione, T. Darras et al., *Science Advances,* **6**, 22, eaba4508 (2020).

Hybrid Entanglement for Heterogeneous Quantum Networks

Summary:

I. Optical quantum state engineering

II. Remote creation of hybrid DV-CV entanglement

III. Entanglement swapping with hybrid entanglement