Université Paris Cité

MPQ

Workshop « Synchronisation de précision et réseaux »

Entanglement distribution in a fibered network with an AlGaAs chip

Othmane Meskine

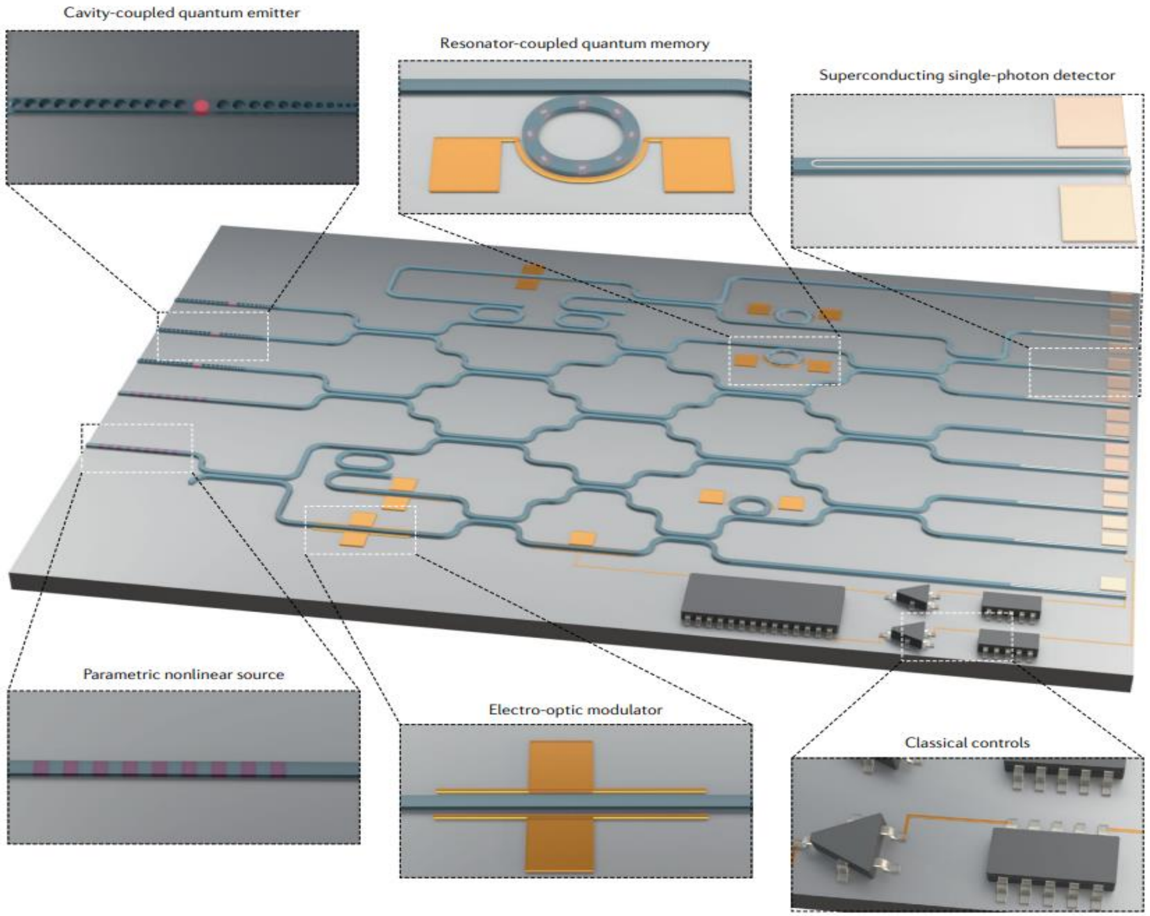
02/10/24

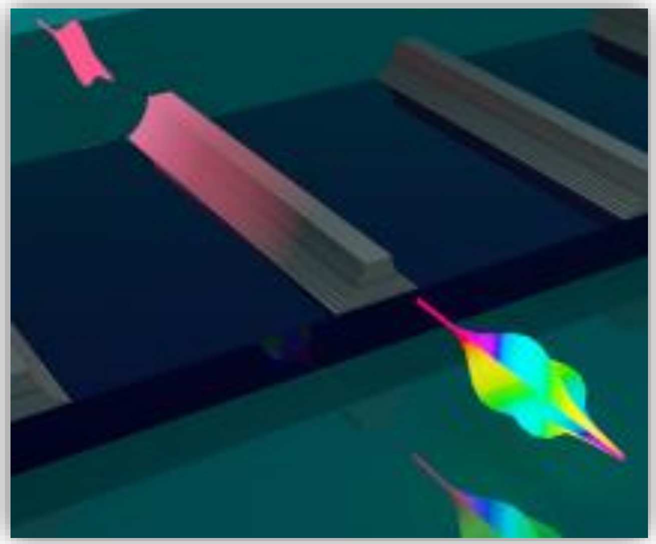
FIRST TF

Refimeve+
Réseau fibré métrologique à vocation européenne

Integrated quantum photonics

Emission, manipulation, and detection of photons in the quantum regime





Photon-pair sources

- Design
- Fabrication
- Experiments/theory
- Quantum Information protocols

Nat Rev Phys **4**, 194–208 (2022)

Outline

I. **AlGaAs-waveguide photon-pair source: working principle**

II. **Quantum communications: entanglement distribution**

III. **Open questions: clock synchronization**

Outline

I. **AlGaAs-waveguide photon-pair source: working principle**

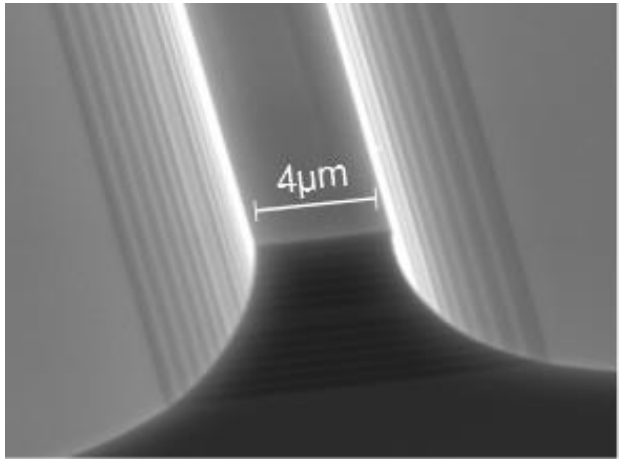
II. Quantum communications: entanglement distribution

III. Open questions: clock synchronization

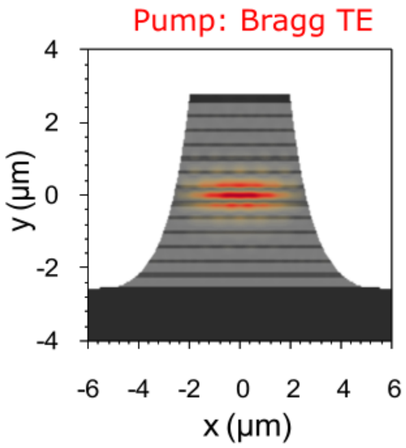
AlGaAs platform

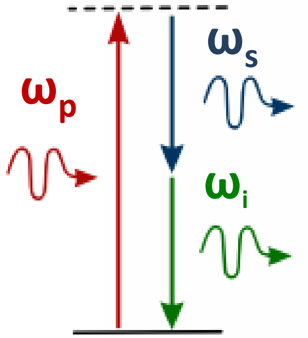
- ✓ Single emitters/ Parametric sources (SPDC, SFWM)
- ✓ Direct band-gap
- ✓ Strong electro-optics effect
- ✓ Possible integration with other material platforms (SOI, superconductors)

AlGaAs Bragg reflector waveguides



Spontaneous Parametric Down Conversion (SPDC)





- ✓ Strong second order nonlinearity
- ✓ Room temperature
- ✓ Telecom wavelength

Energy conservation

$\omega_p = \omega_i + \omega_s$

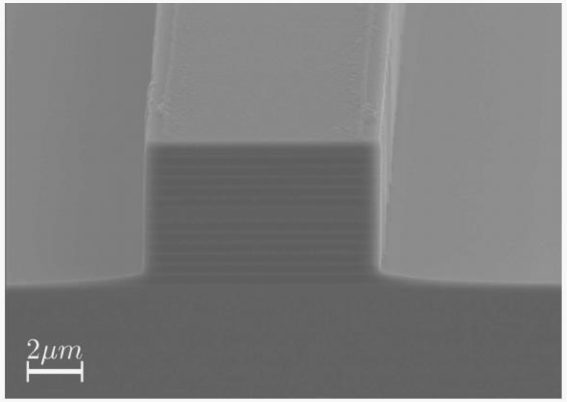
Momentum conservation (Phase-matching)

$\mathbf{k}_p = \mathbf{k}_i + \mathbf{k}_s$

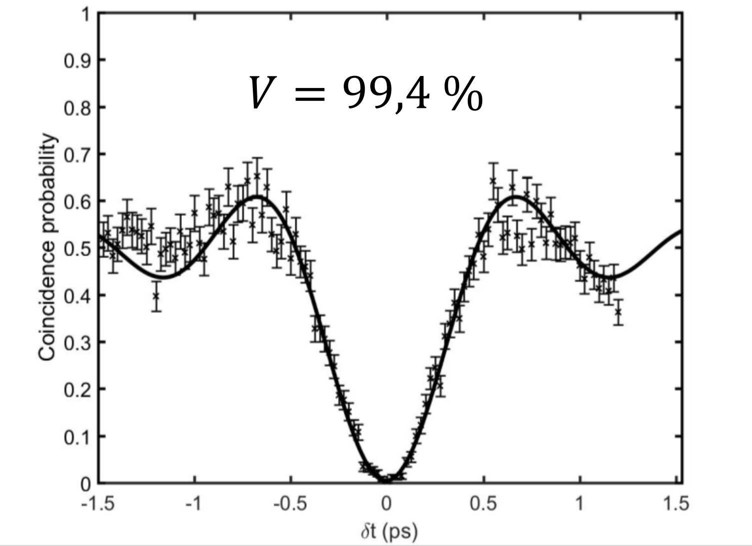
Metrics

Typical length: 2mm

On chip optical losses : 0.4-0.5 dB/cm

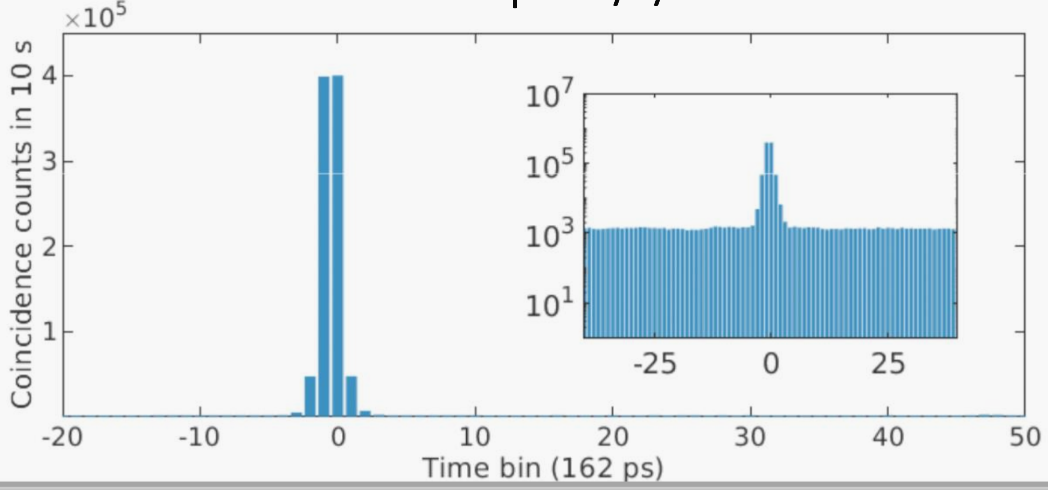


Indistinguishability

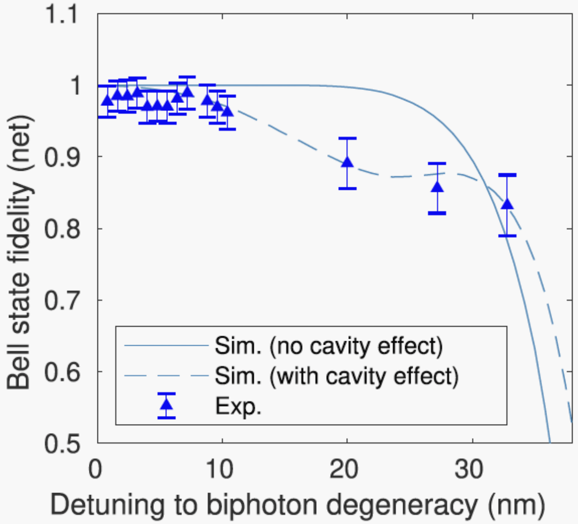


Pair Generation Rate on chip (CW pump)

~ 10^6 -10^7 pairs/s/mW



Polarization entanglement at the chip output



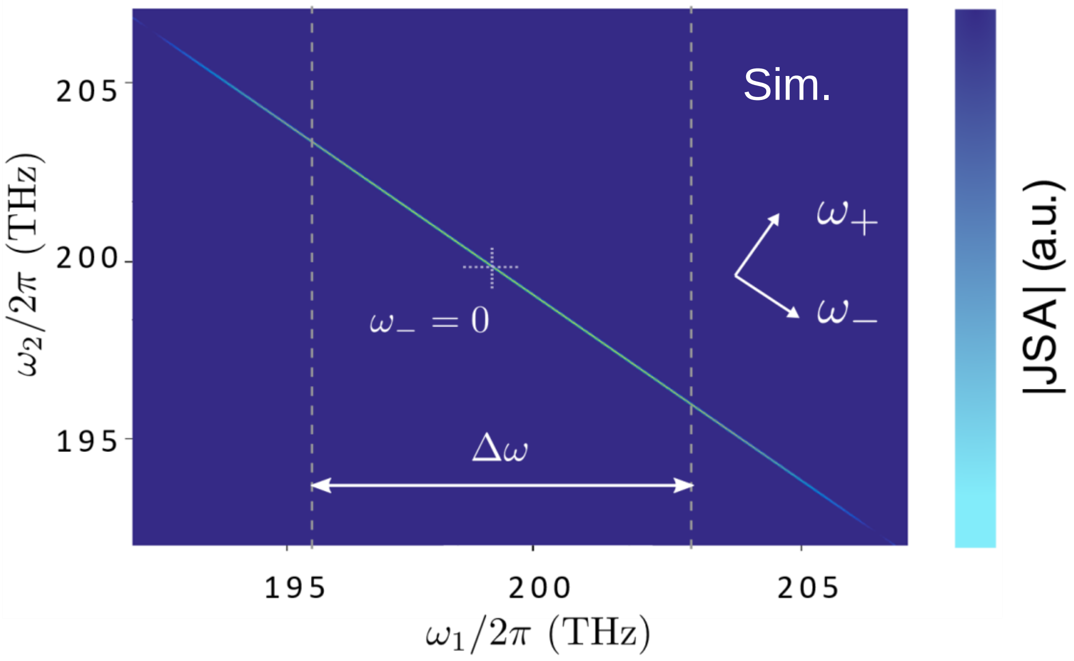
Quantum state

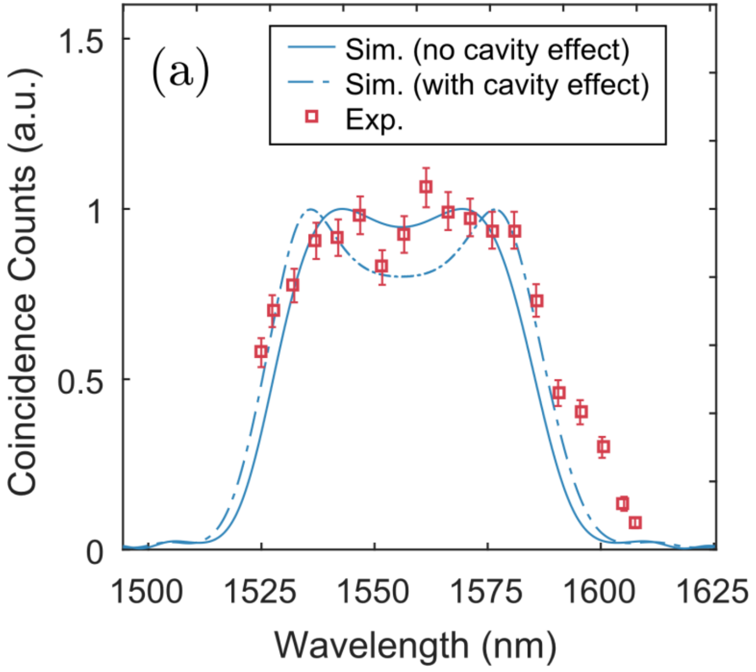
$$|\Psi\rangle = \iint d\omega_1 d\omega_2 \mathcal{C}(\omega_1, \omega_2) \hat{a}_H^\dagger(\omega_1) \hat{a}_V^\dagger(\omega_2) |\text{vac}\rangle$$

Joint Spectral Amplitude (JSA)

→ Broadband (60-80 nm FWHM)

→ Telecom C-Band (1530-1565 nm)





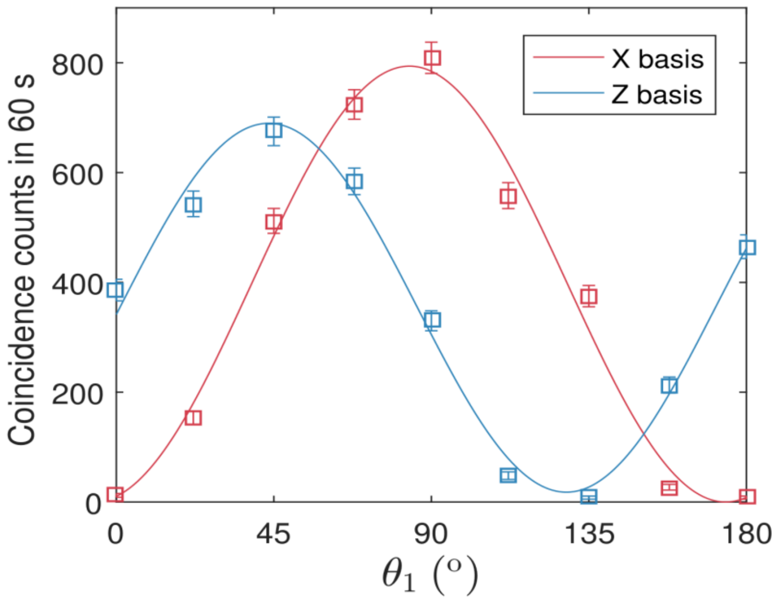
Polarization-entangled state

$$|\psi\rangle = \iint_{\omega_s \geq \omega_i} d\omega_s d\omega_i \left[C(\omega_s, \omega_i) |HV\rangle + C(\omega_i, \omega_s) |VH\rangle \right] |\omega_s\rangle_a |\omega_i\rangle_b$$

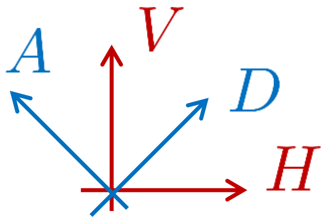
- Anticorrelated JSA
- Low birefringence

→ **Inherent polarization entanglement**

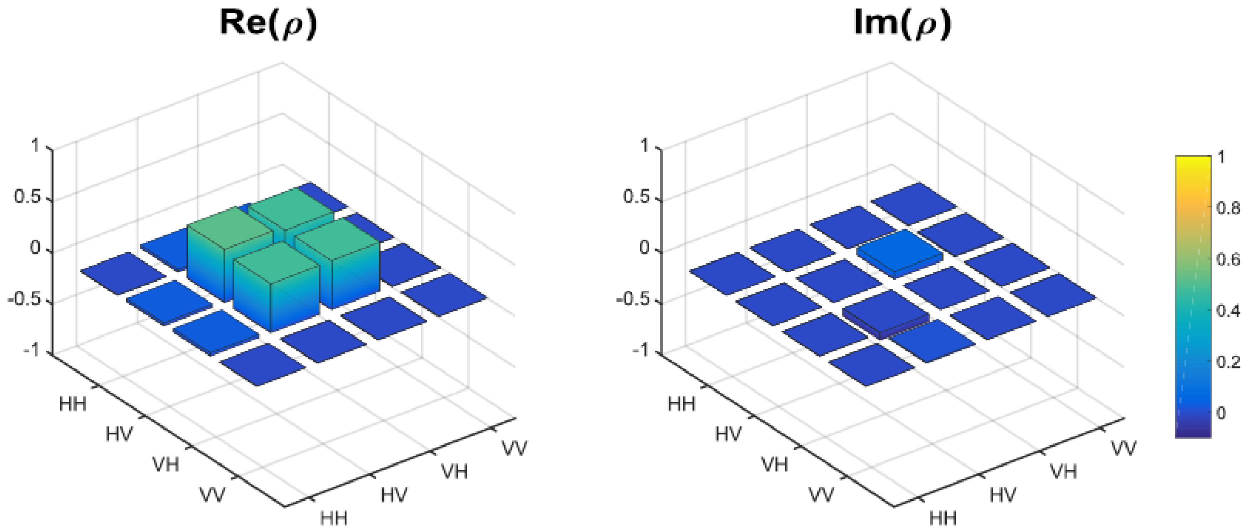
V_X = 98.0 % V_Z = 97.7 %



Bell correlation curves



$\rho = |\psi\rangle\langle\psi|$



Outline

I. AlGaAs-waveguide photon-pair source: working principle

II. Quantum communications: entanglement distribution

III. Open questions: clock synchronization

Entanglement-based quantum communication networks

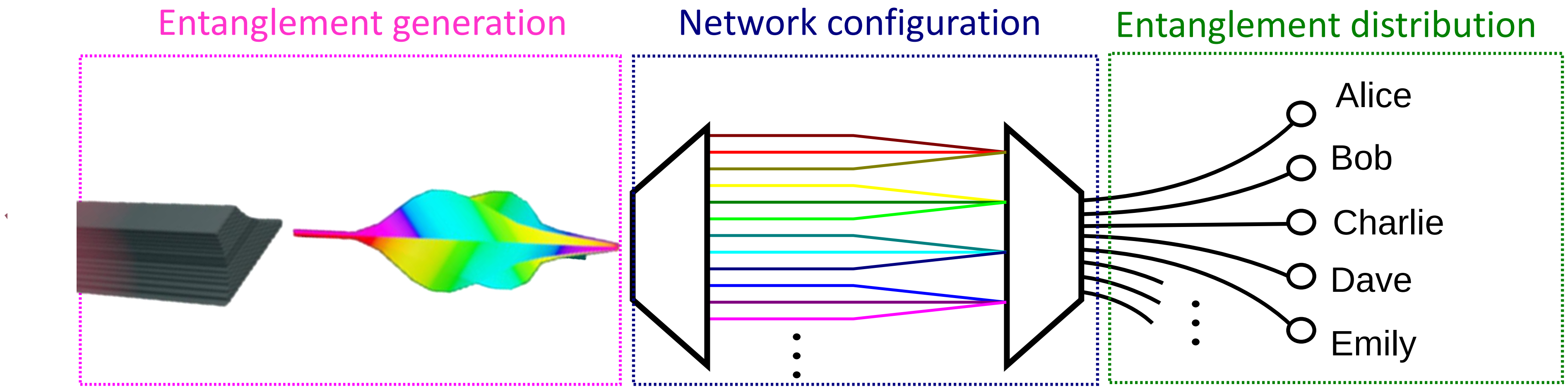
Quantum networks enable the transmission of information in the form of qubits between physically distant nodes

Quantum entanglement → Trusted-node free networks

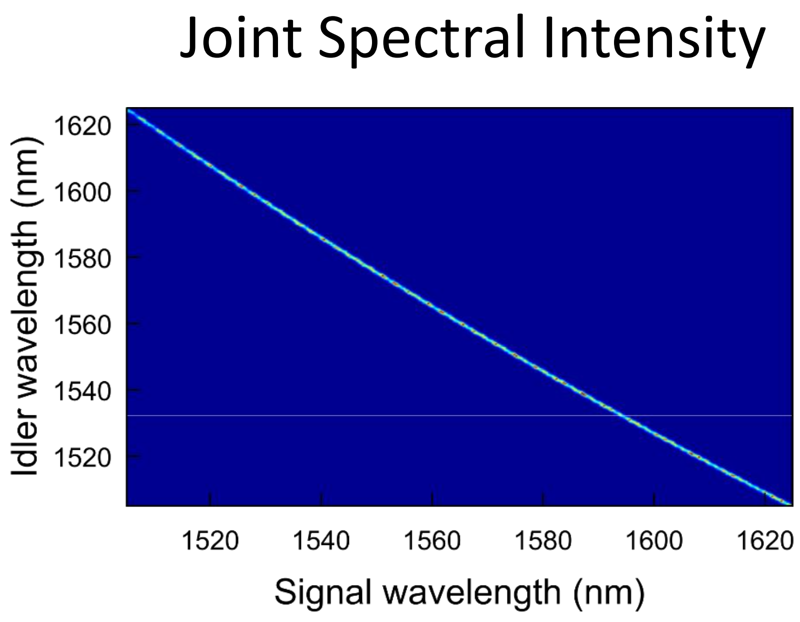
Interesting topology → Polarization + energy time entangled photons

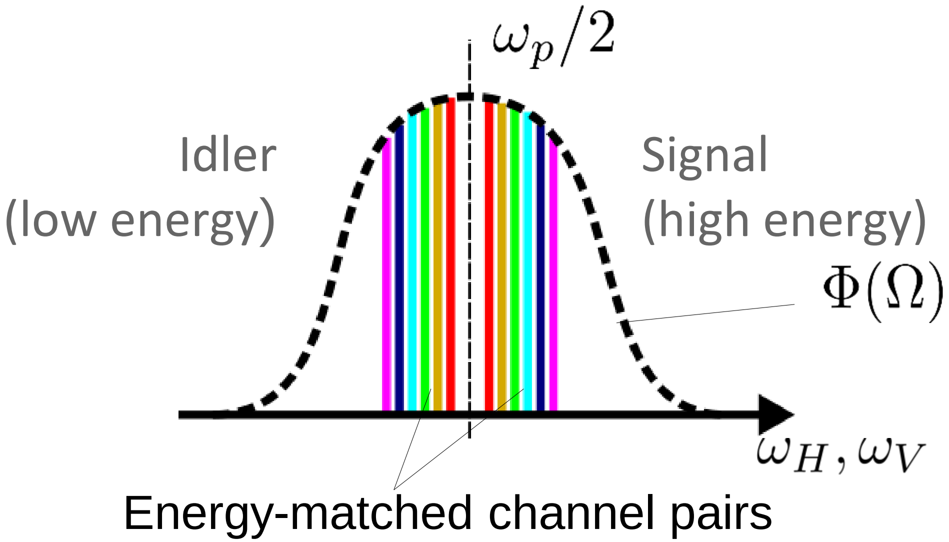
Metropolitan fibered links(R. Ursin/J. Rarity groups, Vienna/Bristol)

Joshi, S. et al, Science Advances, ***6****, aba0959 (2020)*



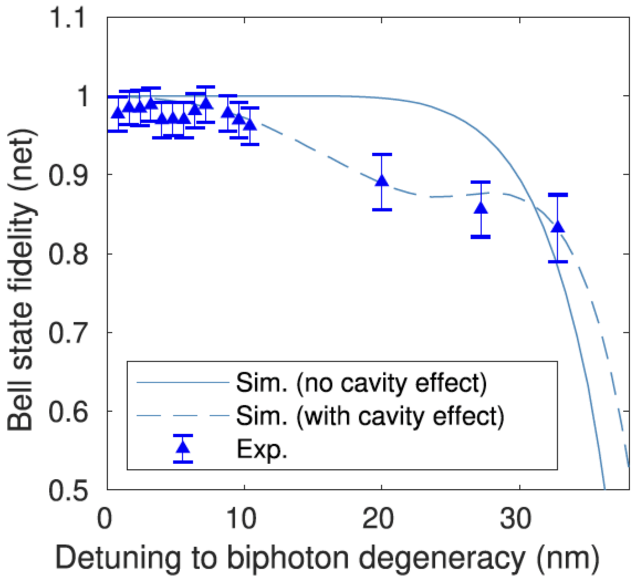
Exploiting broadband polarization entanglement….





- ✓ Large bandwidth
- ✓ Strong frequency anticorrelations
- ✓ Polarization entanglement

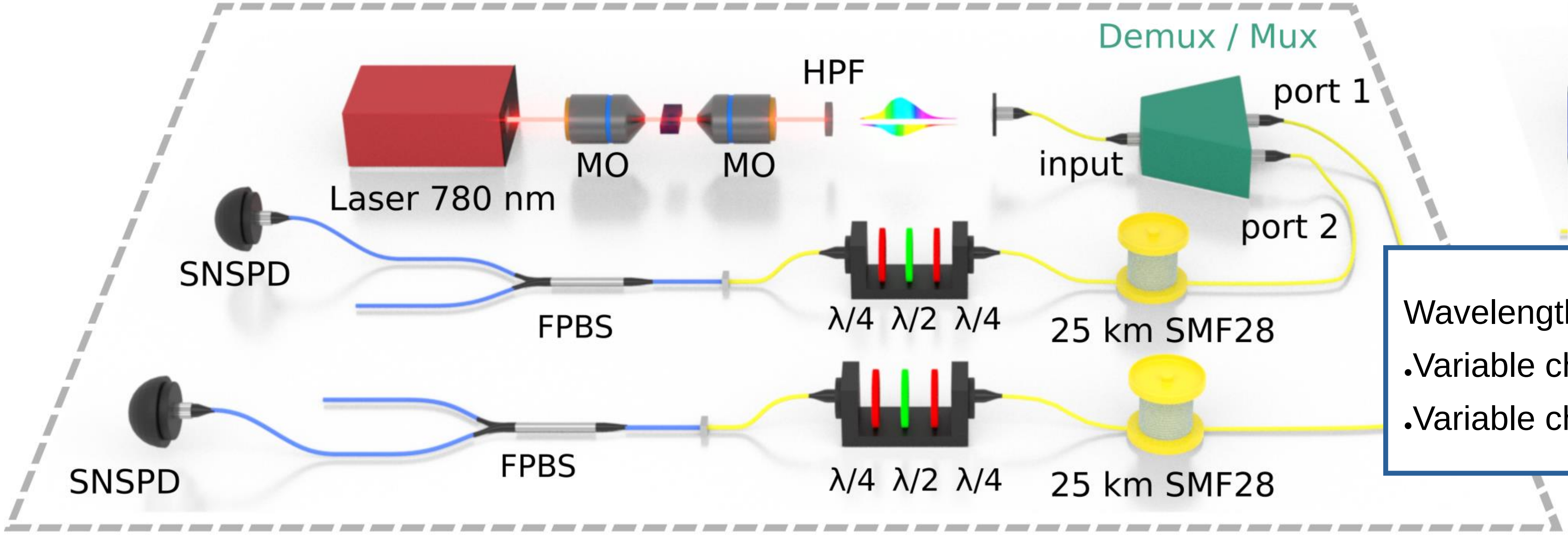
Without off-chip compensation, directly at the output



Entanglement bandwidth
- **26 nm at *F* > 95 %**
- **60 nm at *F* > 85 %**

…to implement a flexible entanglement-distribution network

Collaboration with E. Diamanti (LIP6) and F. Boitier (Nokia Bell-Labs)



Wavelength selective switch

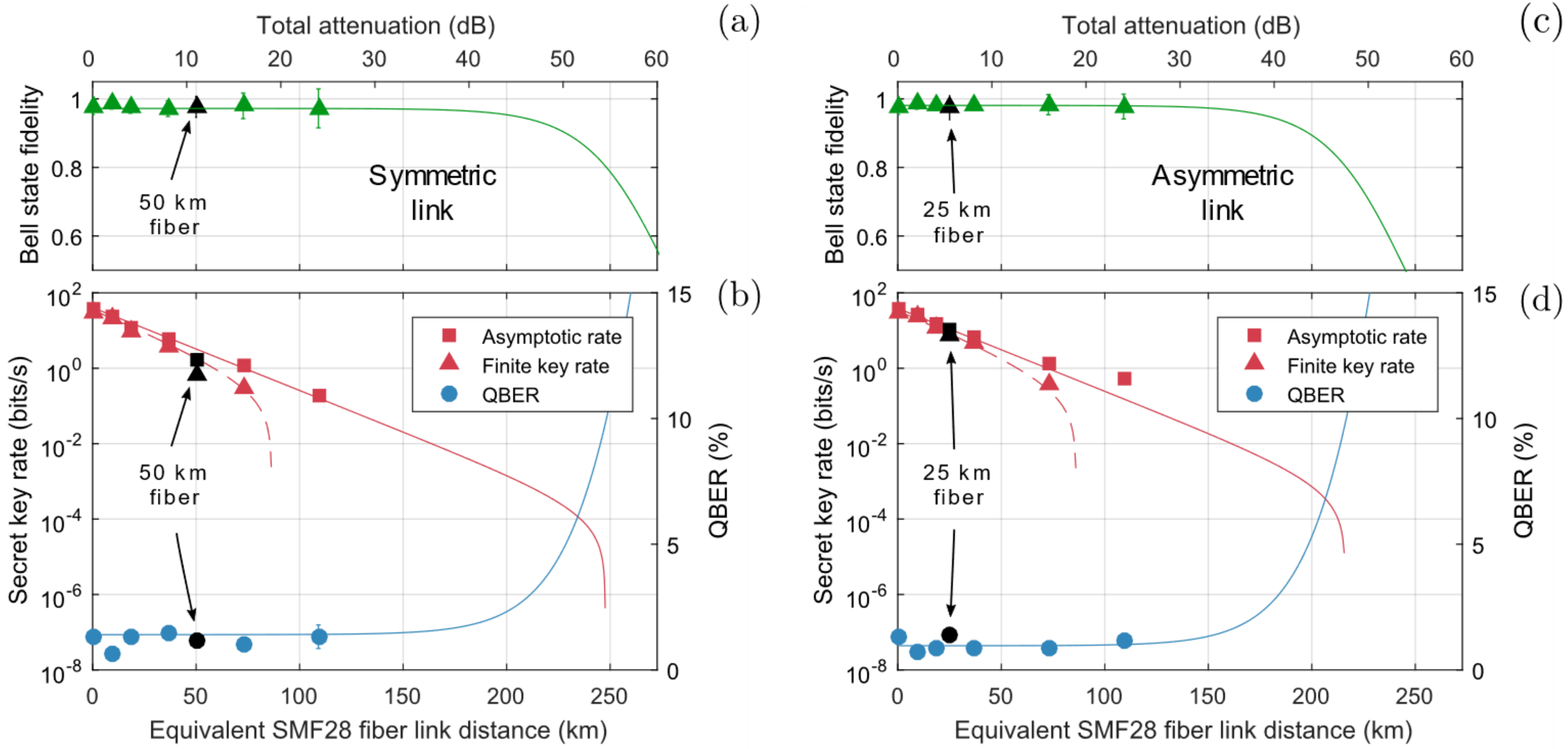
- Variable channel center
- Variable channel width

Detection

Polarization control

F. Appas et al. npj Quantum Information (2021)

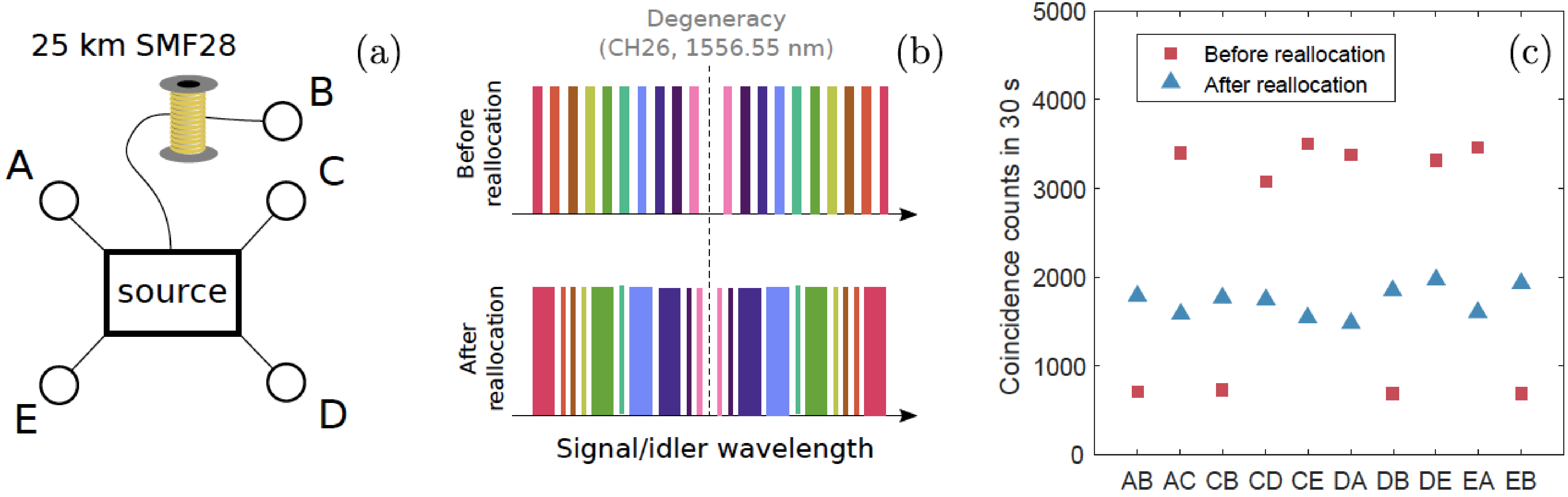
Secret key rate sharing between users pairs (BBM92)



Available bandwidth: 76 ITU 100 GHz channels (36 users pairs simultaneously)

F. Appas et al. npj Quantum Information (2021)

Flexible bandwidth allocation



Optimizing the signal of each link following structural constraints (elastic network)

F. Appas et al. npj Quantum Information (2021)

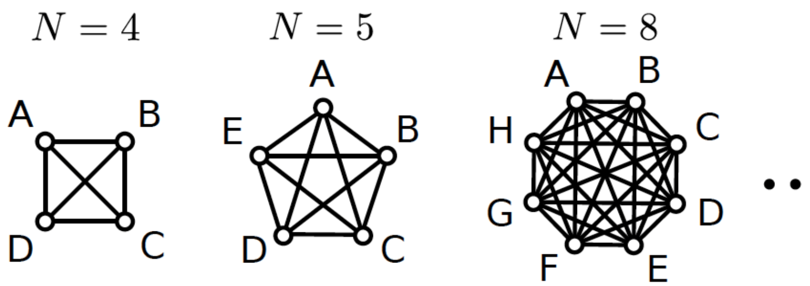
Quantum network performances

- **Secret key sharing between users pairs (BBM92 protocol)**

  Available bandwidth: 76 ITU 100 GHz channels (36 users pairs simultaneously)

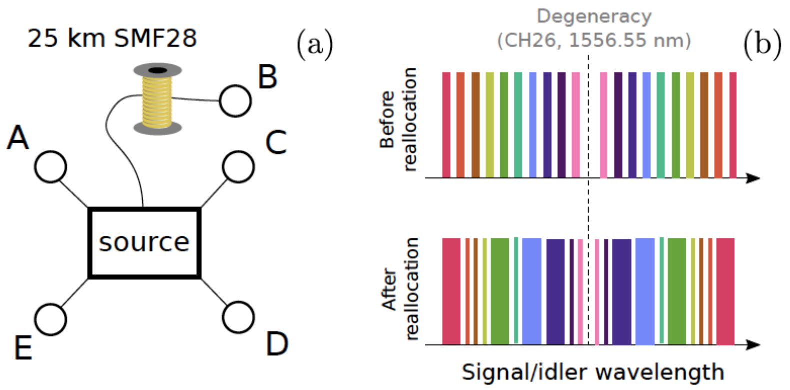
  Distances up to 75 km in fibered optical links (including finite key size effects)

- **Reconfigurable fully connected multiusers entanglement network**

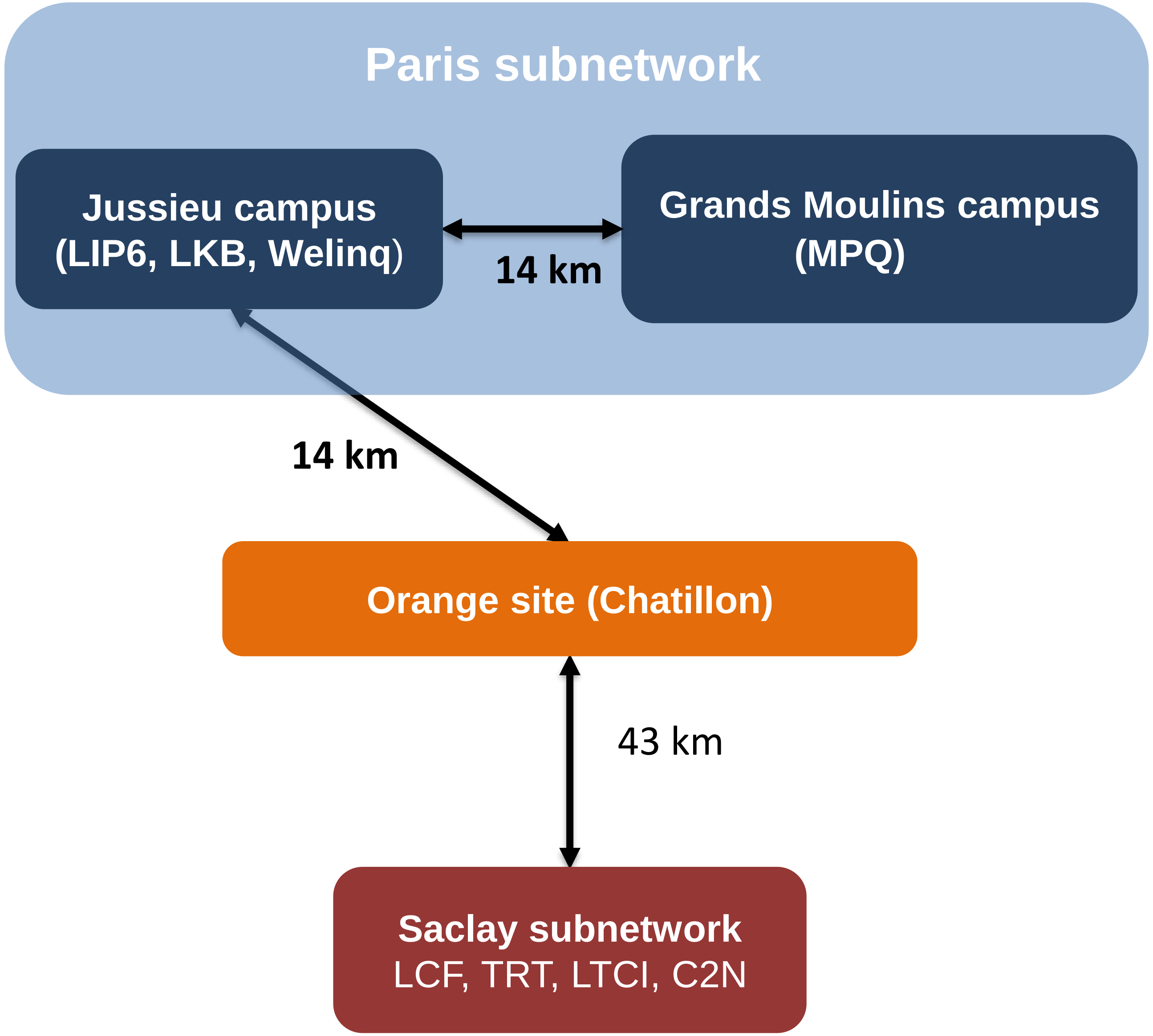


Networks of N users sharing an entangled state with the N-1 remaining users

- **Flexible bandwidth allocation**



Quantum communications testbed in Paris region

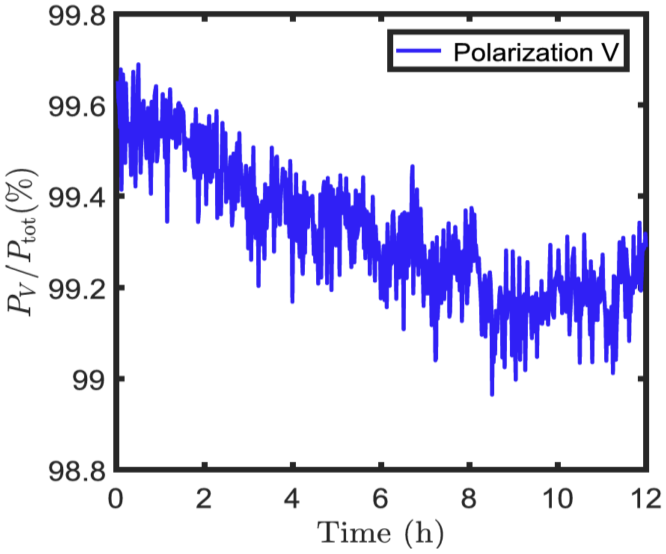


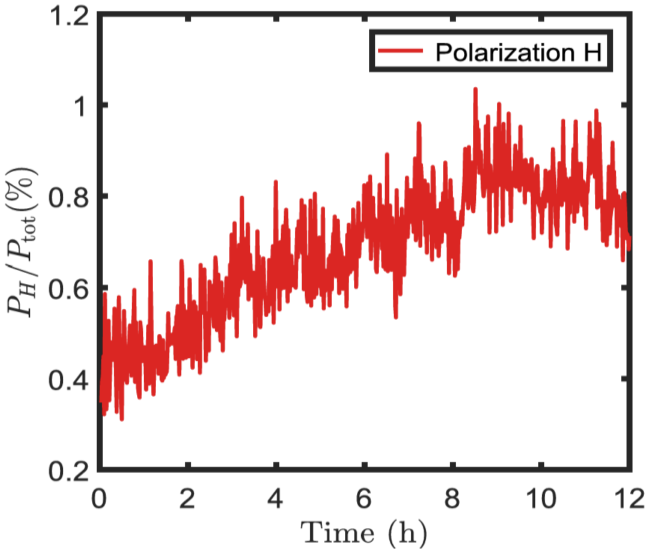
Paris subnetwork MPQ-LIP6

Classical characterization

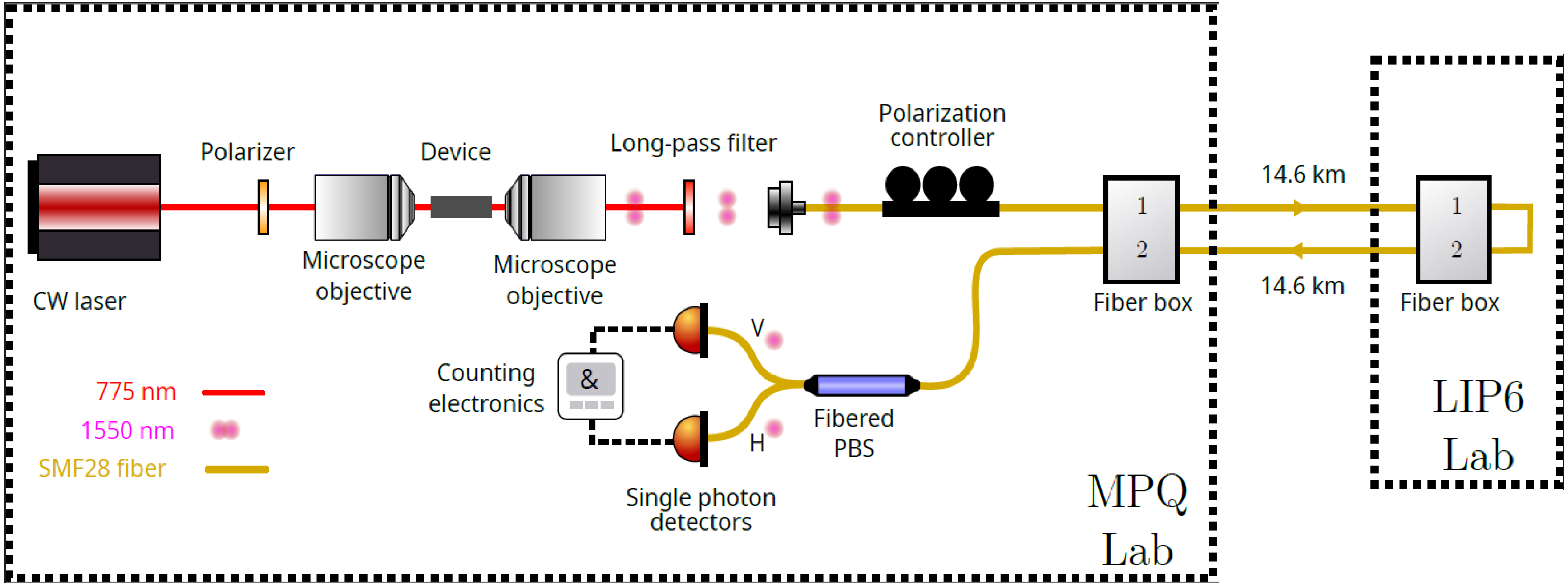
Measured losses: 3 - 3.5 dB (0.2-0.23 dB/km)

Polarization stability: 0.4% fluctuations over 12 hours





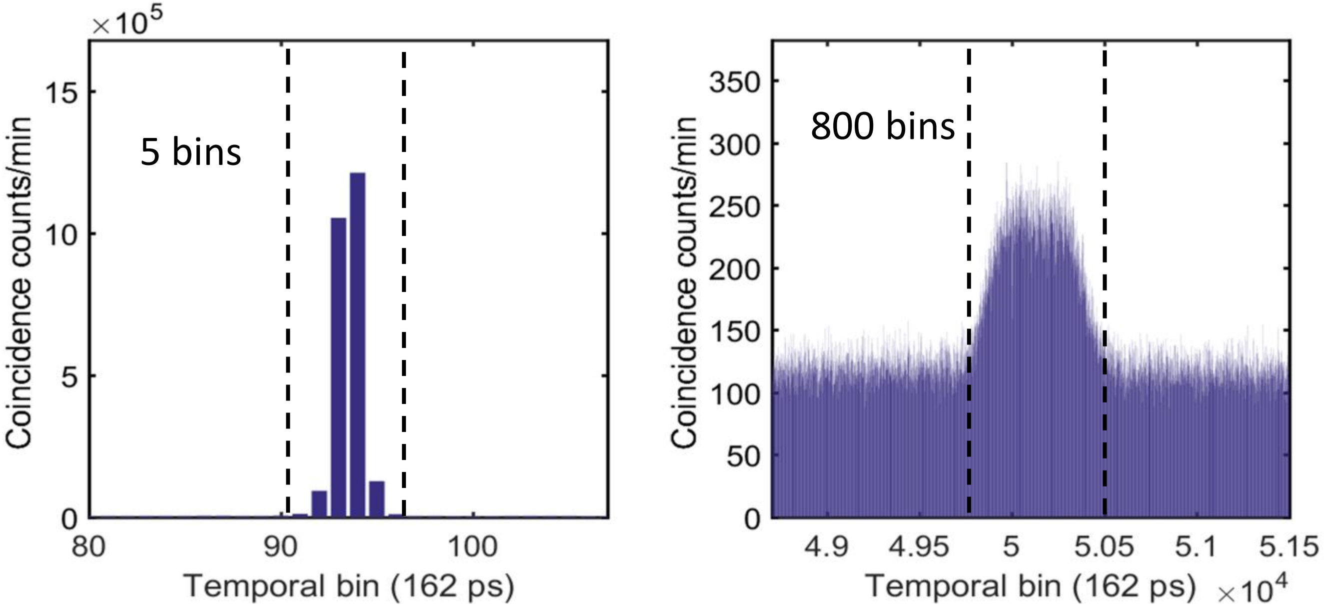
Quantum characterization:



Quantum characterization:

1. Chromatic dispersion: 20 ps²/km

	At the chip output	After propagation
Coinc rate/s	$41\ kHz$	$2.6\ kHz$
CAR	110	1.7
Temporal width (ps)	800	129600



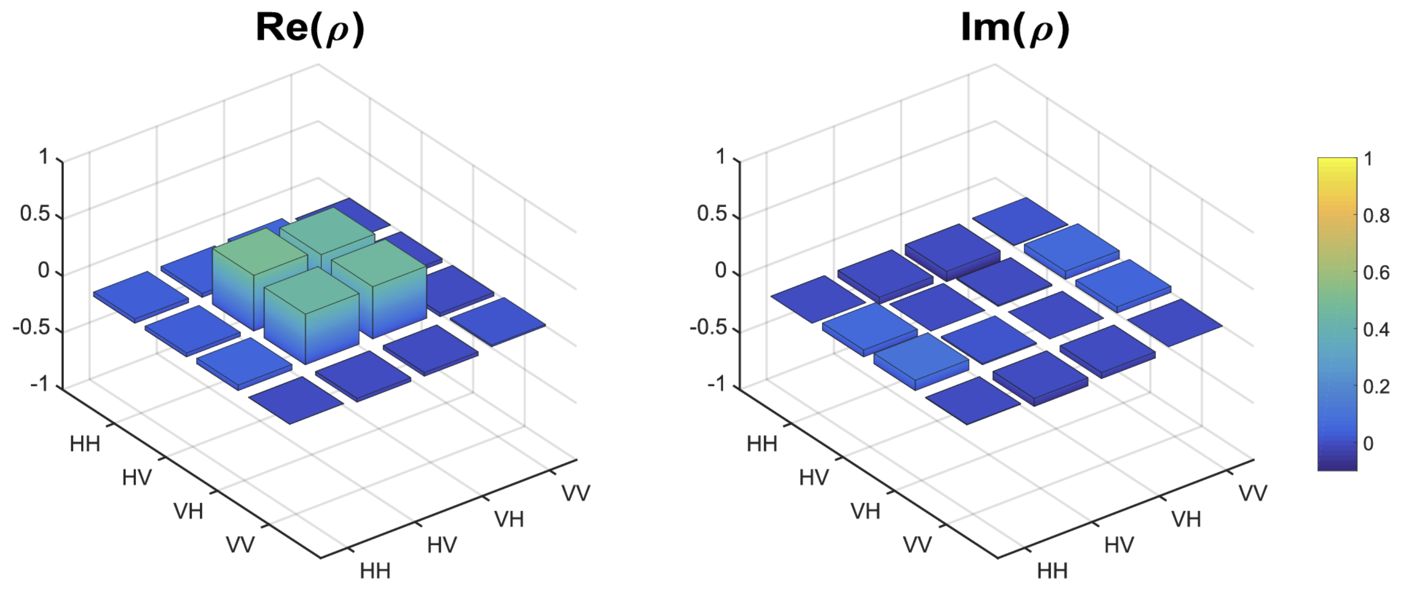
160-fold widening of the coincidence peak

Quantum characterization:

1. Chromatic dispersion: 20 ps²/km

2. Density matrix reconstruction (Quantum tomography)

$$\rho = |\psi\rangle\langle\psi|$$

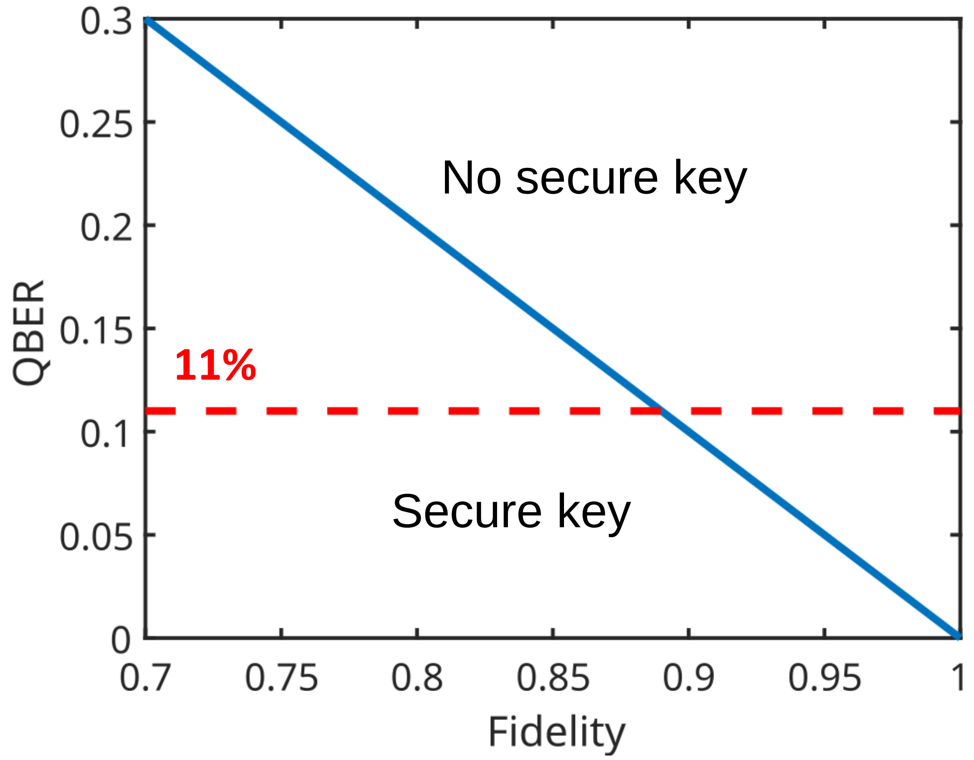


	At the chip output	After propagation
Fidelity	97.5%	91.8%
Purity	96.6%	89.7%

Quantum characterization:

1. Chromatic dispersion: 20 ps²/km
2. Density matrix reconstruction (Quantum tomography)
3. Simulation of QBER as a function of F

$$QBER \geq 1 - F$$



QBER < 11% ↔ F > 89 %

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Next step:

Alice (LIP6)

Synchronization

Bob (MPQ)

- Define a time zero
- Maintain the same clock rate on both systems

Clock synchronization with correlated photons

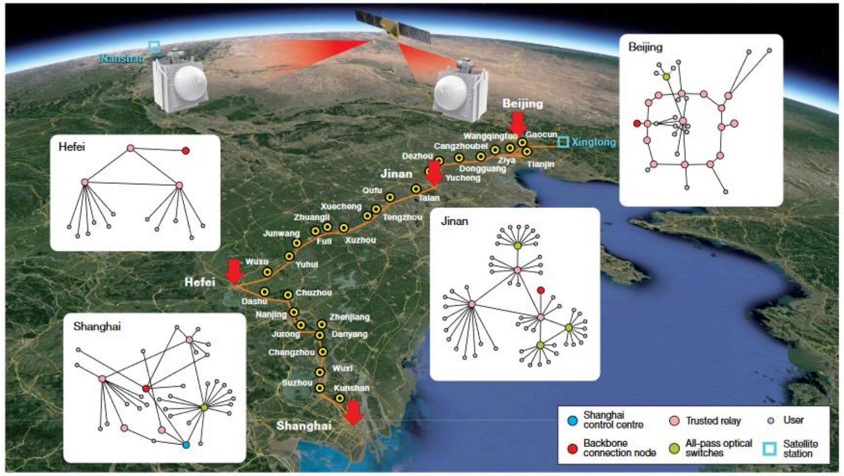
Y. Pelet et al, PRA 20, 044006 (2023)

Active tracking of the central peak

Constraints on processing time:

⟹ limits the SKR (secure key rate)

Clock synchronization with a classical reference



Y. Chen et al, Nature 589, 214-219 (2021)

Use a dedicated channel for the synchronized clock signal between Alice and Bob

⟹ Exploiting the Refimeve fiber linking our lab to Jussieu

Acknowledgments

Permanent staff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QSN PARTNERSHIP

LABEX SEAM

ASTRID

ANR

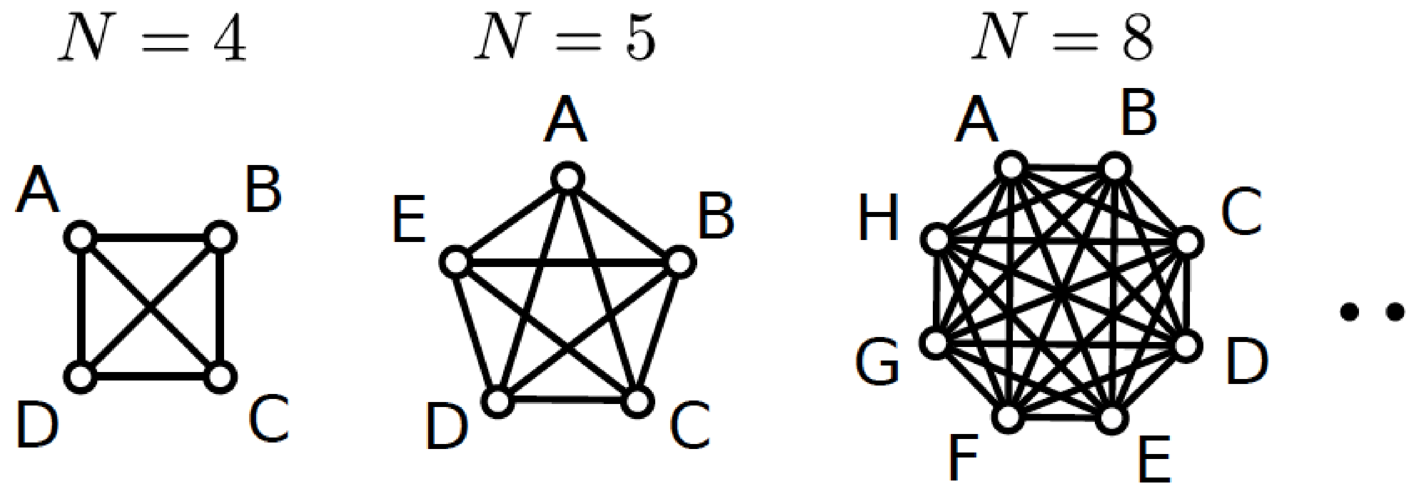
DGA

IDEX UNIVERSITÉ DE PARIS

Reconfigurable fully connected multiusers entanglement network

Networks of N users sharing an entangled state with the N-1 remaining users

→ n° of two-user links needed: N(N - 1)/2



Demultiplexing of the generated signal in N(N -1) frequency channels

Recombine those channels into optical fibers, one for each user

WSS

Entanglement-based quantum key distribution (QKD)

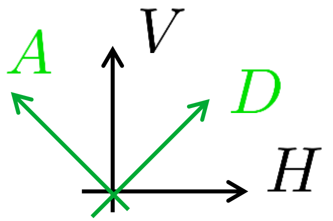
BBM92 protocol

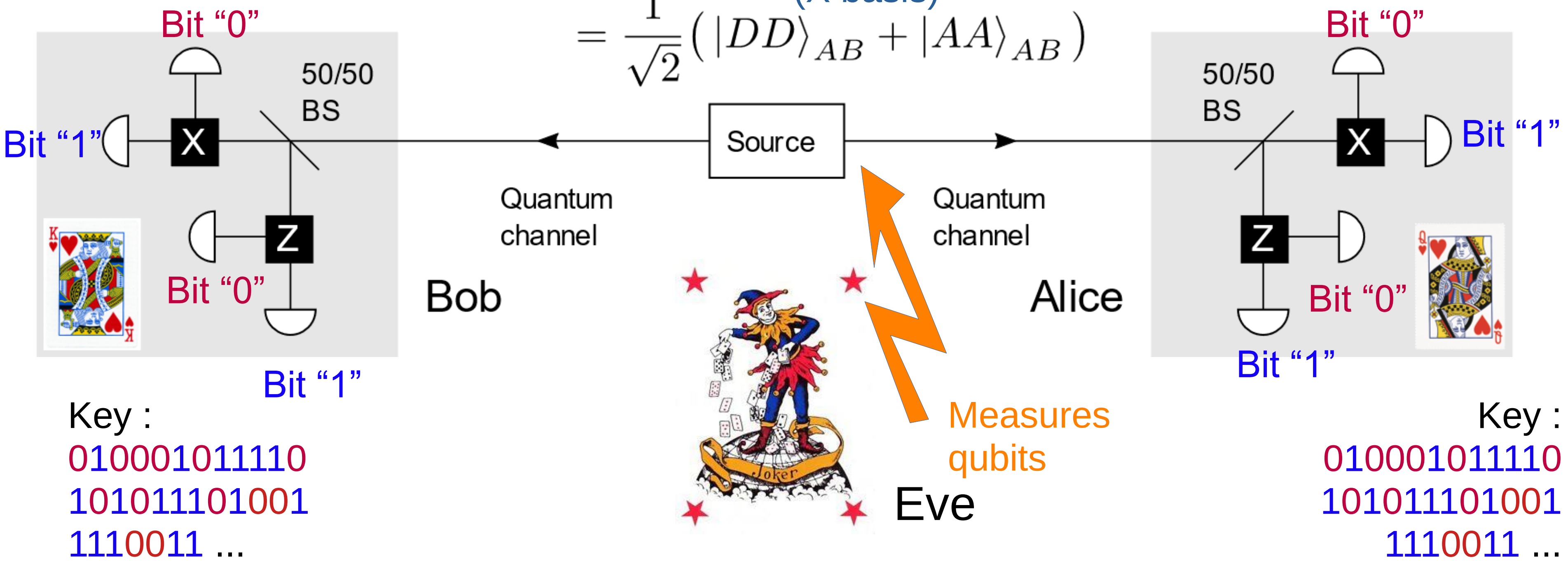
(Z basis)

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}\left(|HV\rangle_{AB} + |VH\rangle_{AB}\right)$$

(X basis)

$$= \frac{1}{\sqrt{2}}\left(|DD\rangle_{AB} + |AA\rangle_{AB}\right)$$





→ **Entanglement guarantees the security of the key**

→ **No need for trusted source or relay nodes**

Bennet, Brassard, Mermin, Phys. Rev. Lett. (1992)

Reconfigurable fully connected multiusers entanglement network