Realizing an entanglement-based multi-user quantum network with integrated photonics

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Outline

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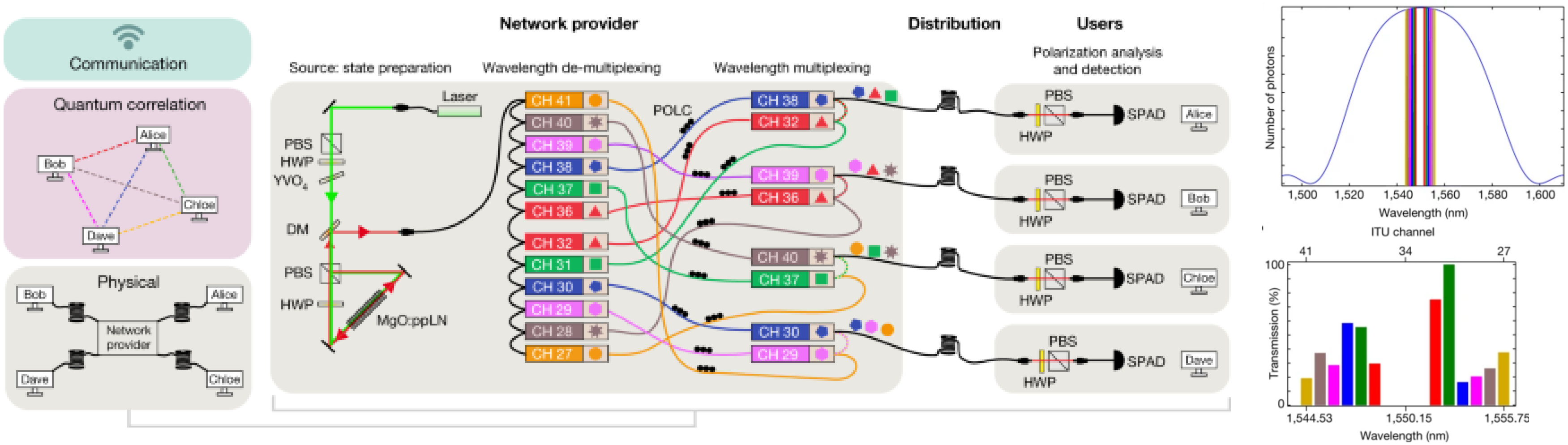
- **Our work**
  - **Photon pair source and its characterization**
  - **Network architecture and wavelength allocation**
  - **Phase coding using energy-time entanglement**

Entanglement-based multi-user quantum network



Fully connected, a promising network architecture.
How can we improve the hardware?

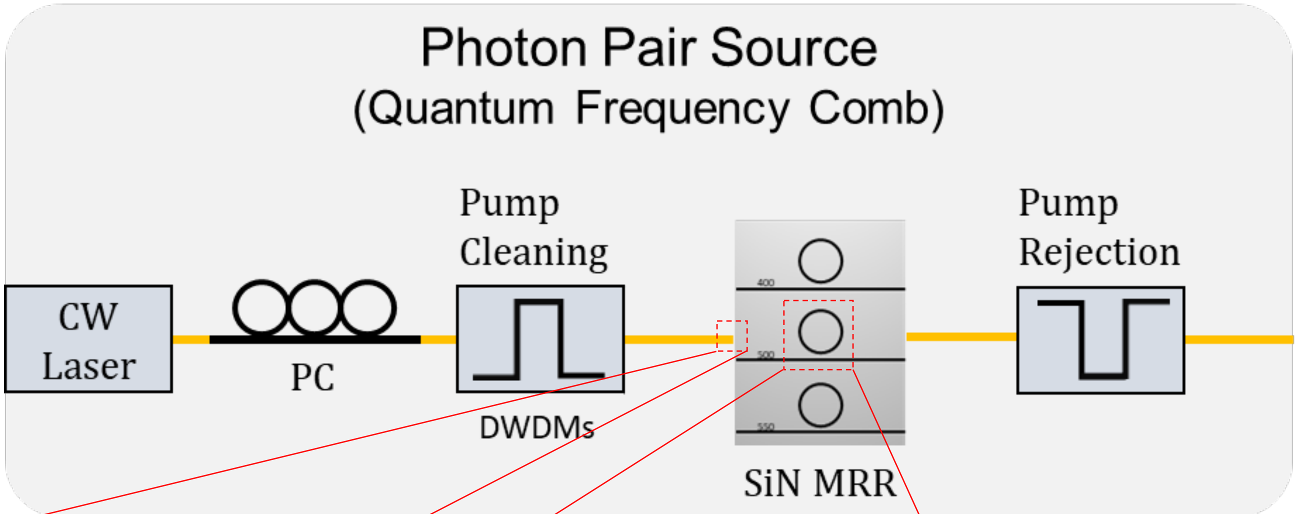
- Broadband phase-matching range with many discrete frequency modes.
- Individual frequency modes with narrow bandwidth, compatible with the quantum memory (hundreds of MHz).
- A stable, alignment-free with scalable production solution.

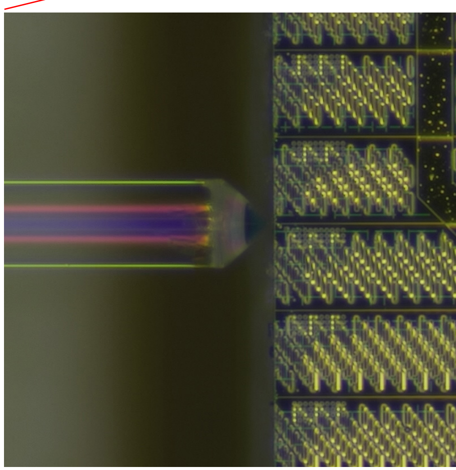
Quantum optical microcombs

Nature 564, 225 (2018)
Sci. Adv. 6, eaba0959 (2020)

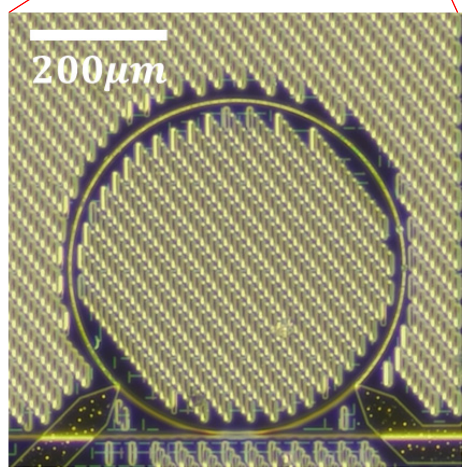
Photon pair source

Generate energy-time entangled optical frequency comb in a resonator.





Lensed Fiber

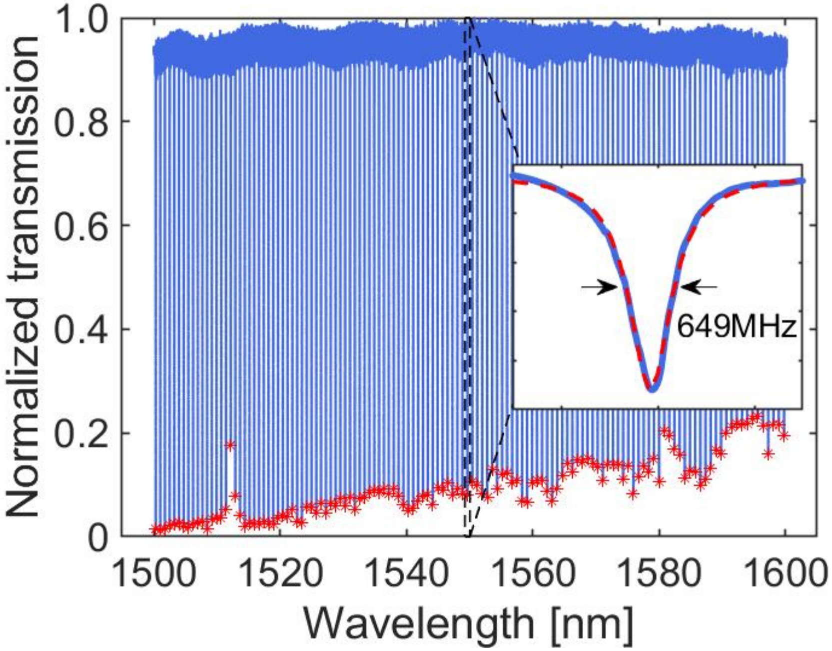


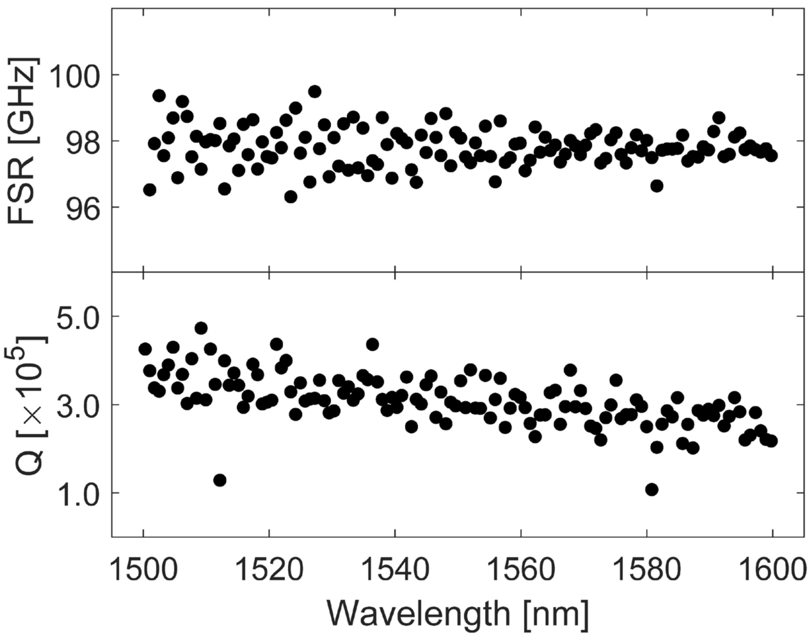
Si_3N_4 Microring Resonator
(Ligentec)

- CW at 1549.32nm (ITU CH35)
- DWDMs: dense wavelength division multiplexers at CH35
- MRR diameter: 460μm
- Waveguide cross-section: 1600nm×800nm
- Total insertion loss: ~5dB

Characterization of the source

Transmission spectrum





CH35:

FWHM: $649MHz$

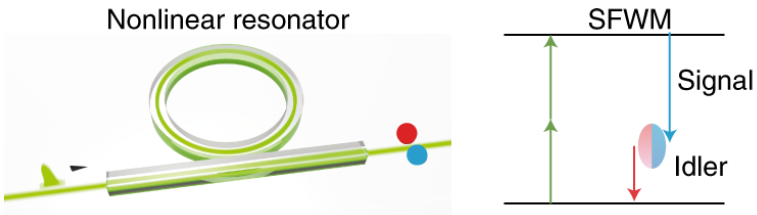
Q factor: 2.98×10^5

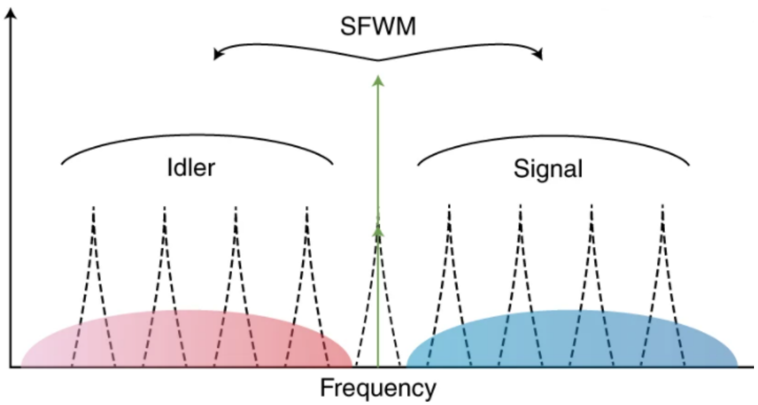
Extinction ratio: $10.75dB$

- 128 modes in 100nm
- $FSR_{ave} = 97.81GHz$

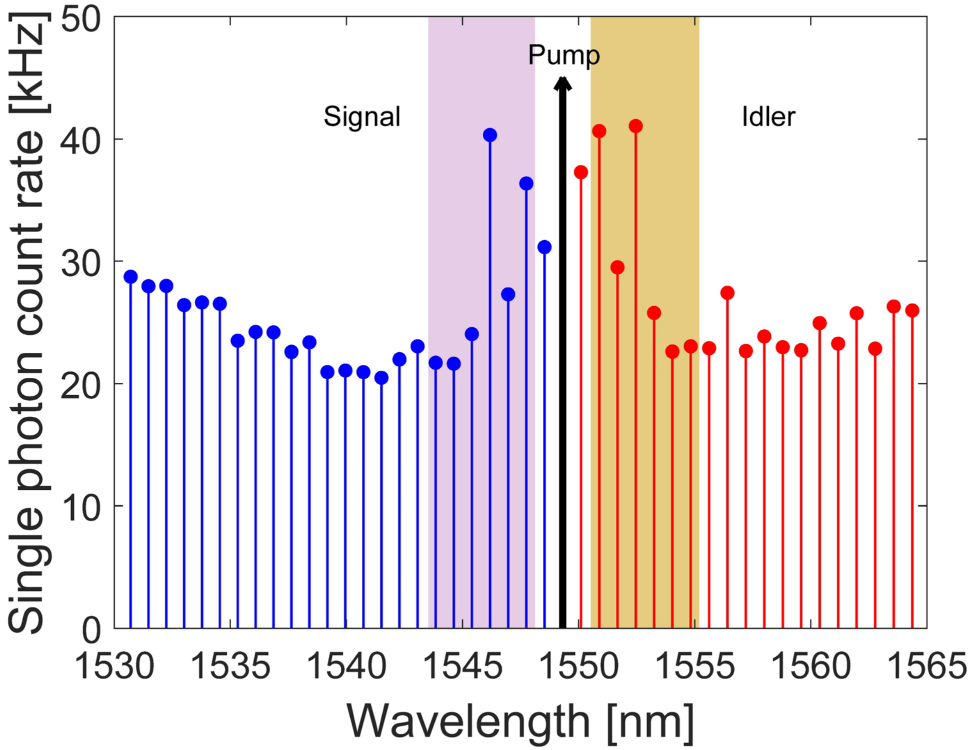
  (close to the standard 100GHz DWDM)
- $Q_{ave} = 3.10 \times 10^5$

Quantum optical microcombs





Broadband phase matching SFWM



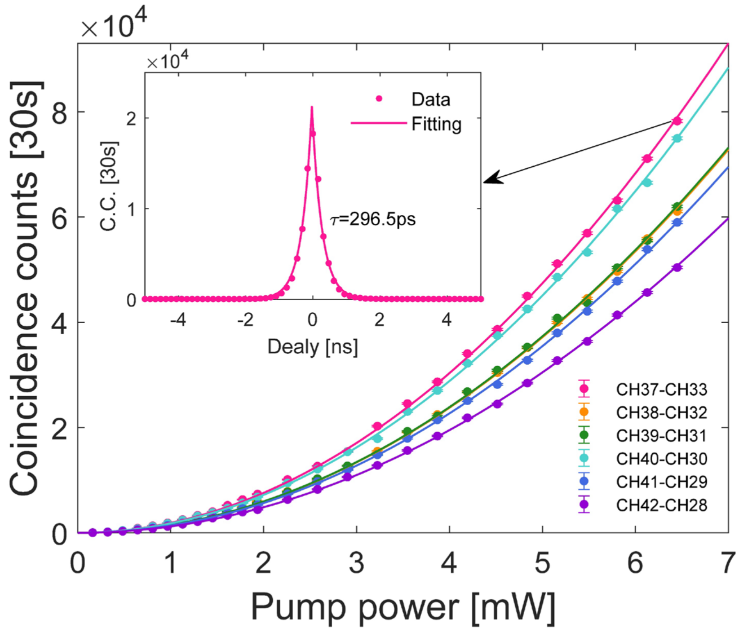
- Broad bandwidth
- Field enhancement offered by the microring resonator
- discrete narrow linewidth spectral modes
- chip-based

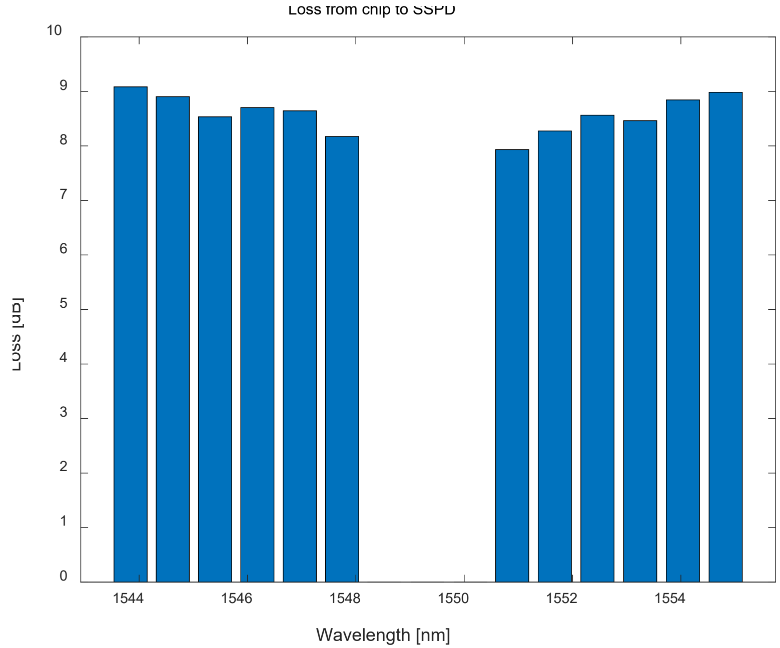
- Our single photon spectrum covering the **entire C-band**, only limited by our spectrometer.
- 12 frequency modes (6 pairs) are selected

related work by the groups of Gisin, Weiner, Morandotti, Kippenberg and so on

See review Nature Photonics 13, 170 (2019)

Characterization of the source



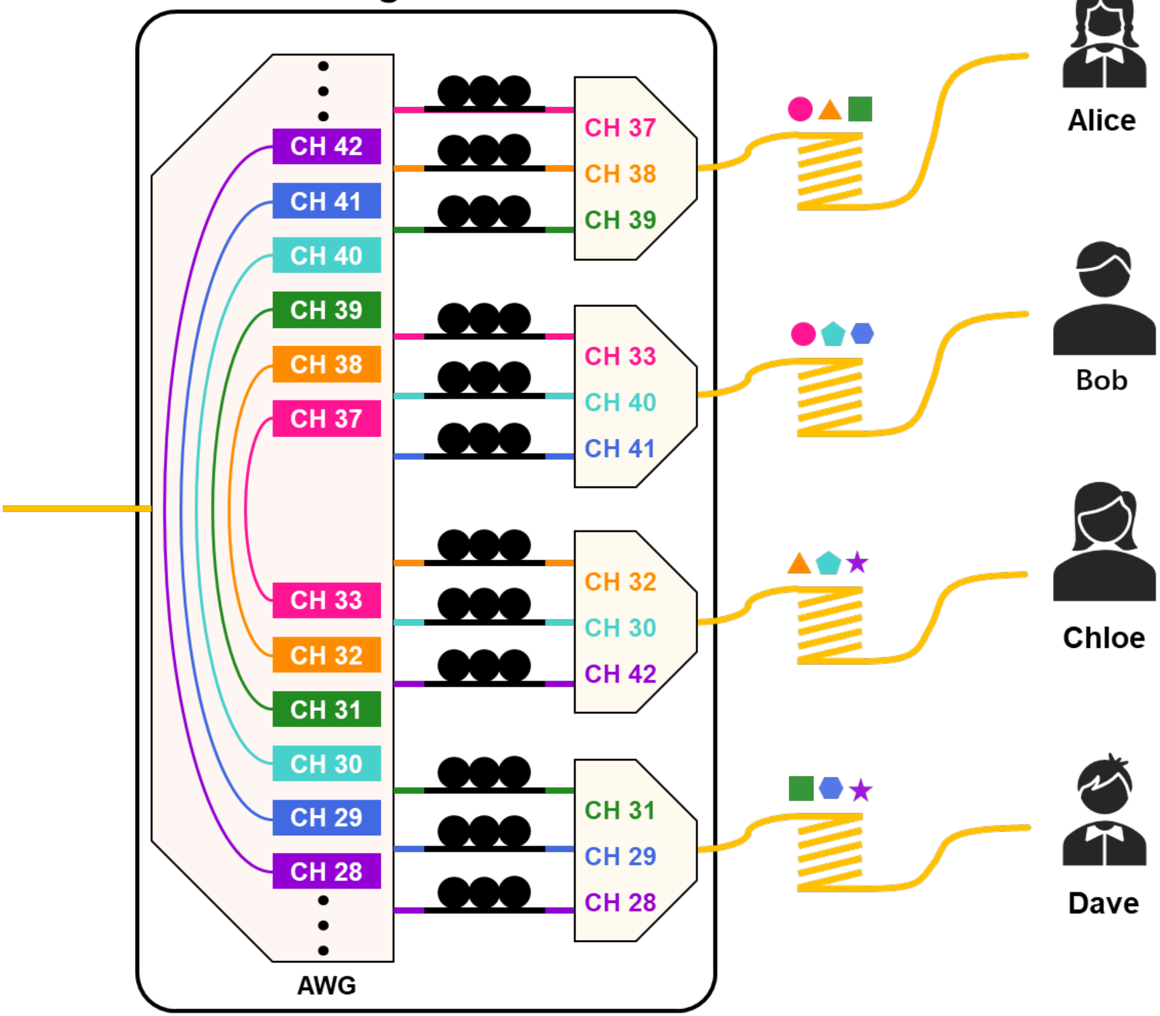


Pairs	Coh. time (ps)	Bandwidth (MHz)	Brightness $(s^{-1}mW^{-2})$	Brightness $(s^{-1}mW^{-2}MHz^{-1})$	Signal Loss (dB)	Idler Loss (dB)
CH37-CH33	296.5	536.8	63.3	0.1179	−8.17	−7.93
CH38-CH32	272.8	583.5	49.6	0.085	−8.64	−8.27
CH39-CH31	288.1	552.5	49.8	0.0901	−8.70	−8.56
CH40-CH30	301.8	527.3	60.1	0.1141	−8.53	−8.46
CH41-CH29	293.5	542.2	47.3	0.0873	−8.90	−8.84
CH42-CH28	279.9	568.7	40.7	0.0715	−9.08	−8.98

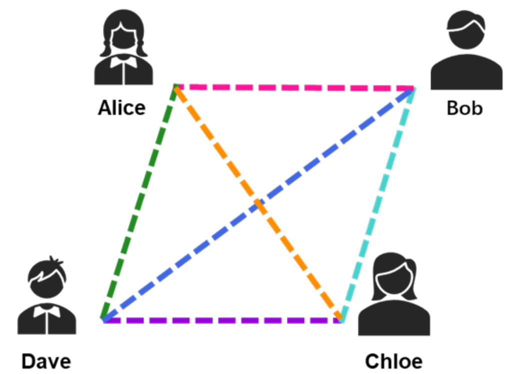
Individual frequency modes with narrow bandwidth

Network architecture and wavelength allocation

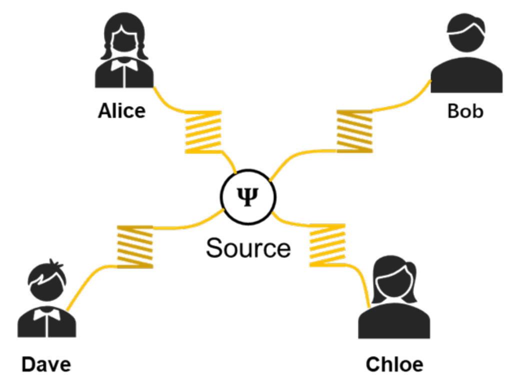
Wavelength allocation



Quantum correlation layer



Physical layer



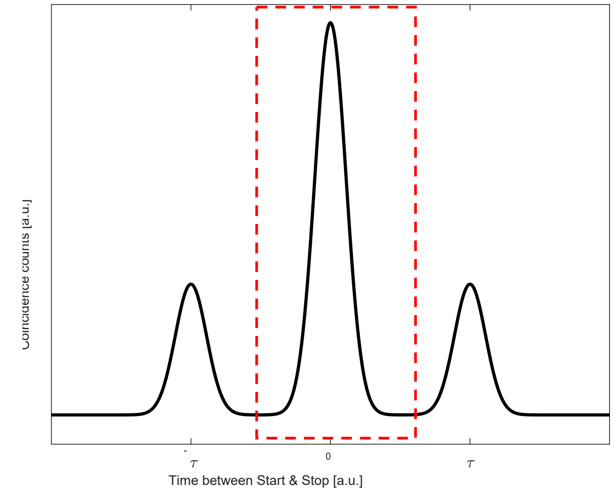
wavelength allocation

Alice	Bob	Chloe	Dave
CH 37	CH 33	CH 32	CH 31
CH 38	CH 40	CH 30	CH 29
CH 39	CH 41	CH 42	CH 28

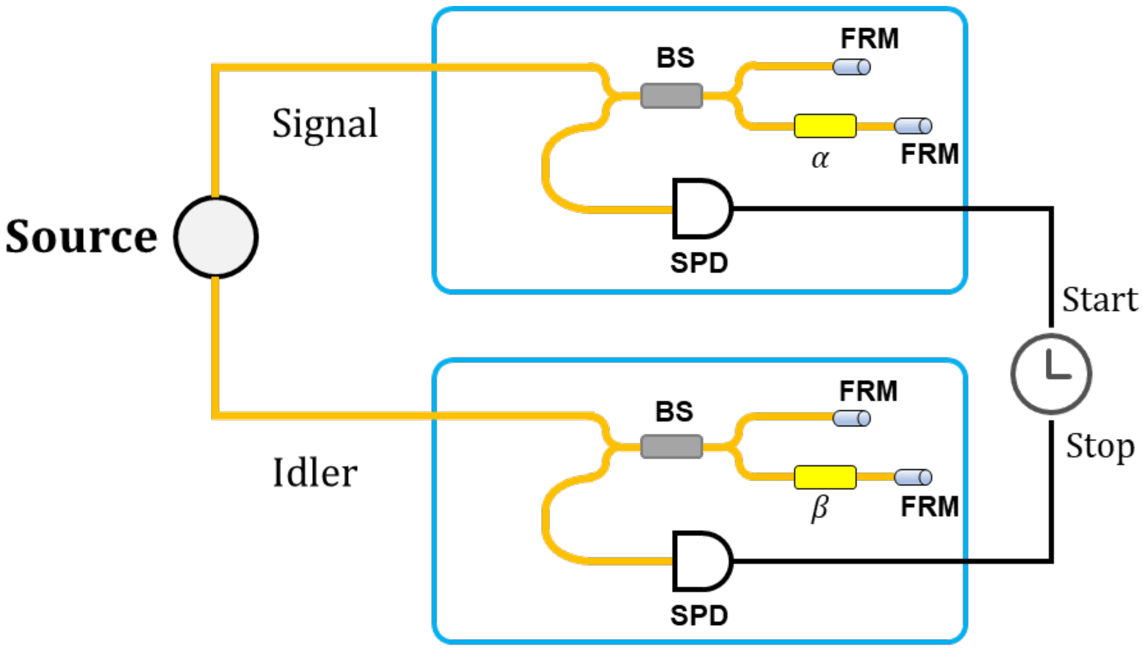
Phase coding using energy-time entanglement

Polarization:
- easy to manipulate
- challenging for fiber transfer

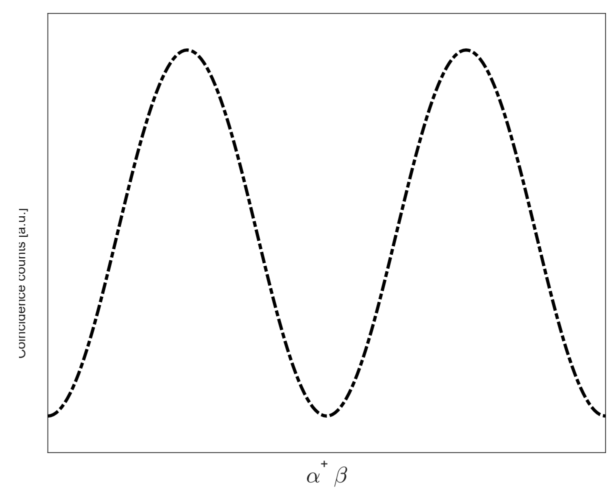
Energy-time:
- ideal for fiber transfer
- high-dimensional states



Franson interferometer

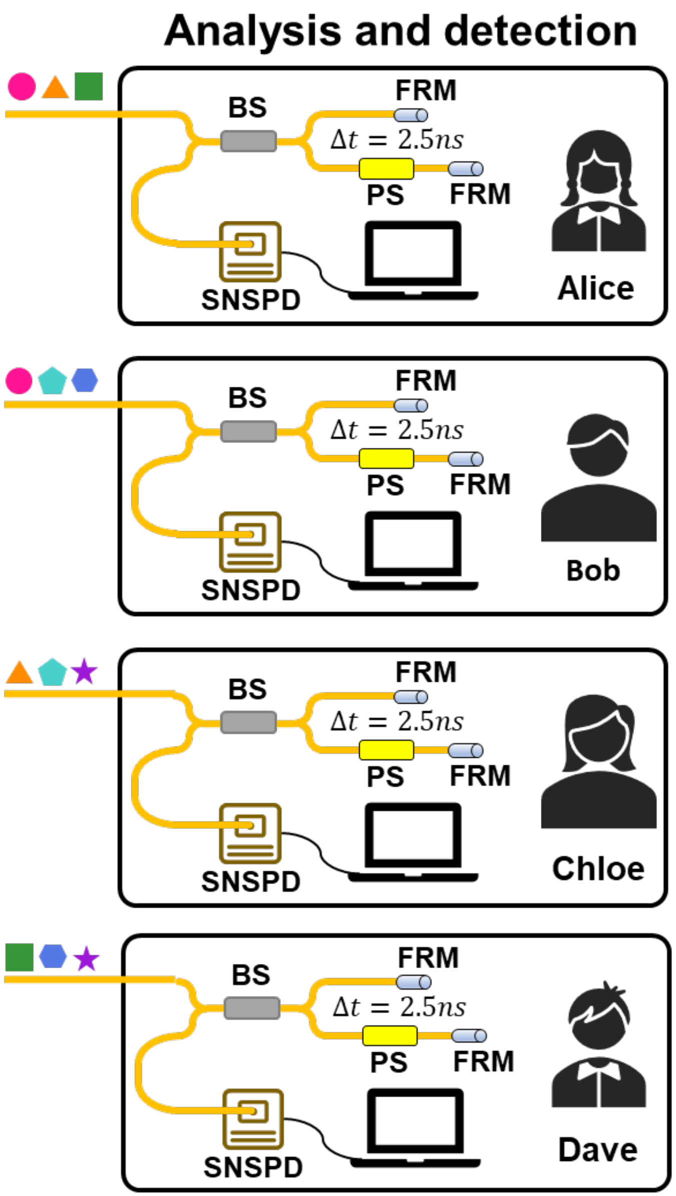


$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|SS\rangle + e^{i(\alpha+\beta)}|LL\rangle\right)$$



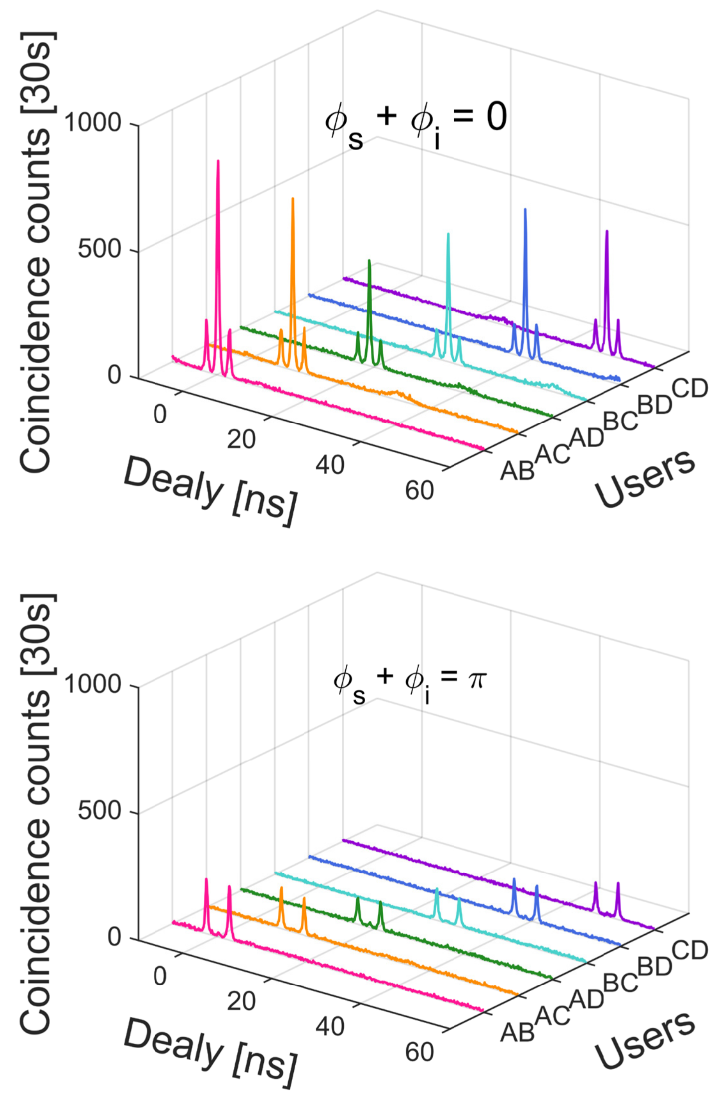
Physical Review Letters 62, 2205-2208 (1989).
Reviews of Modern Physics **74**, 145-195 (2002).

Temporal cross correlation histograms

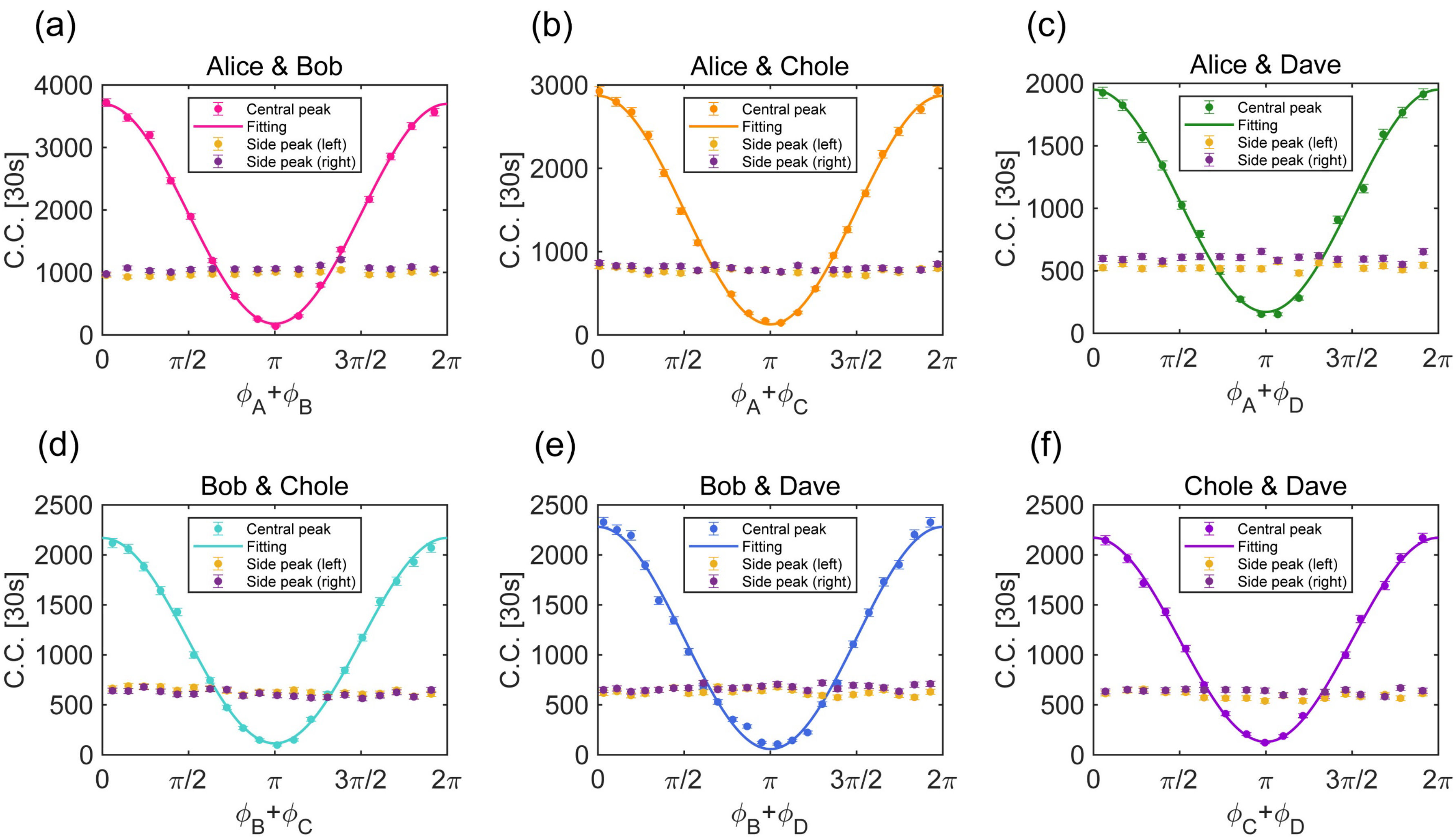


$\tau_c \approx 300ps \ll \Delta t = 2.5ns \ll \tau_p$

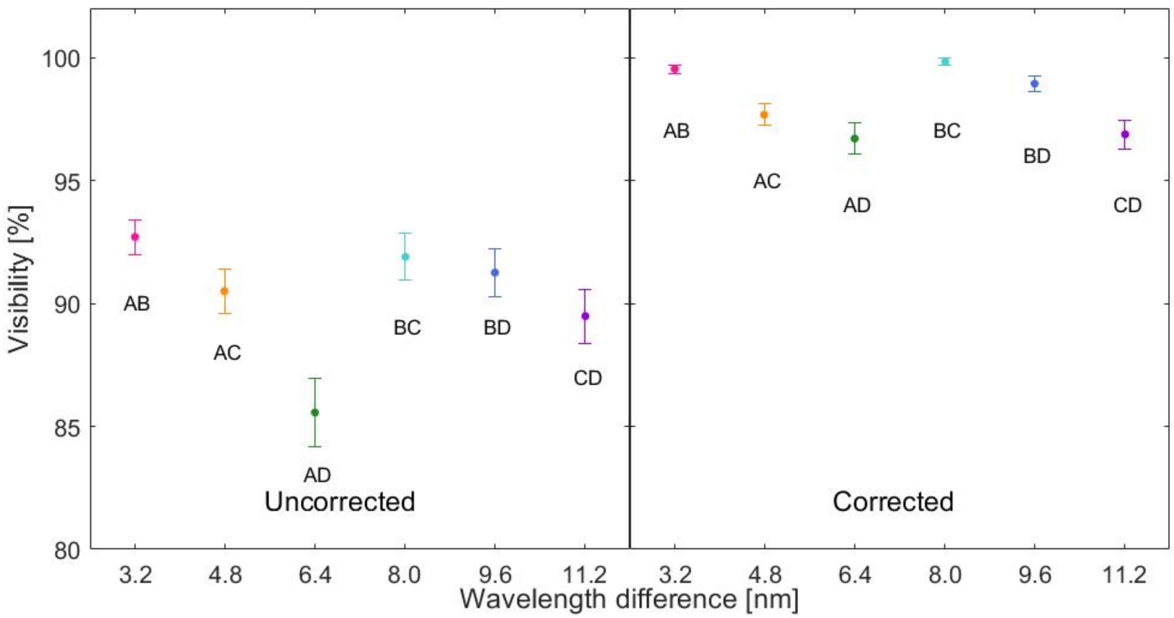
Use time DOF to distinguish between different user pairs. Nature 564, 225 (2018)



Coincidences between all users in the network



Detected brightness and visibility

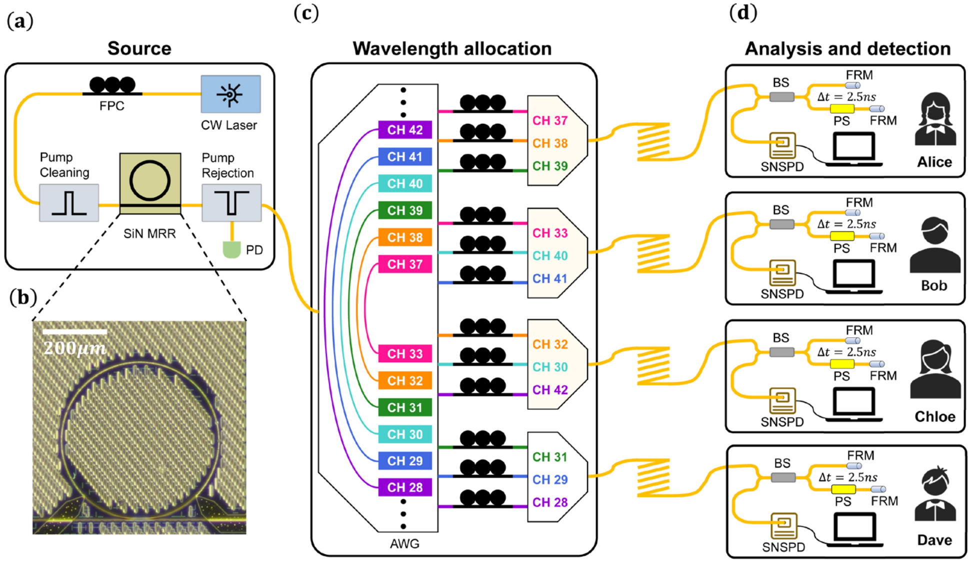


Entanglement in fully connected quantum network.

User	ITU Channels	Detected Brightness ($s^{-1}mW^{-2}MHz^{-1}$)	Total Loss (dB) Signal	Total Loss (dB) Idler	Visibility Raw	Visibility Net
Alice & Bob	CH37 - CH33	0.92×10^{-2}	-14.29	-13.20	92.70±0.70%	99.53±0.17%
Alive & Chole	CH38 - CH32	0.67×10^{-2}	-14.90	-13.12	90.50±0.90%	97.67±0.44%
Alice & Dave	CH39 - CH31	0.47×10^{-2}	-15.27	-15.30	85.56±1.37%	96.70±0.65%
Bob & Chole	CH40 - CH30	0.54×10^{-2}	-14.03	-14.01	91.89±0.94%	99.83±0.13%
Bob & Dave	CH41 - CH29	0.57×10^{-2}	-13.86	-14.67	91.25±0.97%	98.93±0.32%
Chole & Dave	CH42 - CH27	0.51×10^{-2}	-14.29	-14.56	89.48±1.10%	96.87±0.59%

Conclusion

- We developed an energy-time entanglement-based dense wavelength division multiplexed network based on an integrated silicon nitride micro-ring resonator, which offers a wide frequency span ($> 100nm$) and narrow bandwidth modes ($\sim 5pm$).
- Six pairs of photons are selected to form a fully connected four-user quantum network.
- The observed quantum interference visibilities ($> 96.7\%$) are well above the classical limits among all users.
- Our results pave the way for realizing large-scale quantum networks with integrated photonic architecture.



Thanks!