Centre DE Nanosciences & DE Nanotechnologies

- Entangled photonic quDits encoded in 21GHz spaced frequency bins generated on chip using a silicon micro resonator for Quantum Communications with telecom devices
  - George Crisan, Antoine Henry, Dario Fioretto, Carlos Ramos, Eric Cassan, Laurent Vivien, Stéphane Monfray, Frederic Boeuf, Kamel Bencheikh, Isabelle Zaquine, Pascale Senellart-Mardon, Nadia Belabas

cnrs université PARIS-SACLAY TELECOM ParisTech

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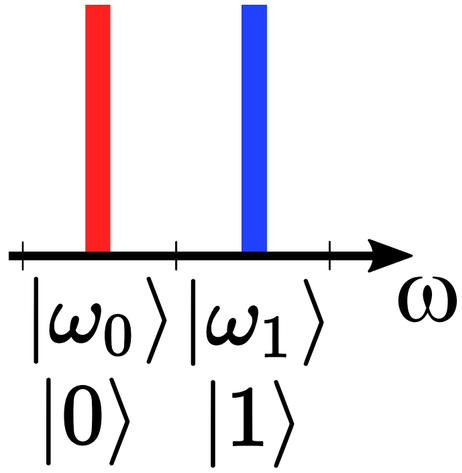
Quantum states encoded in frequency bins

Frequency-bin encoding:



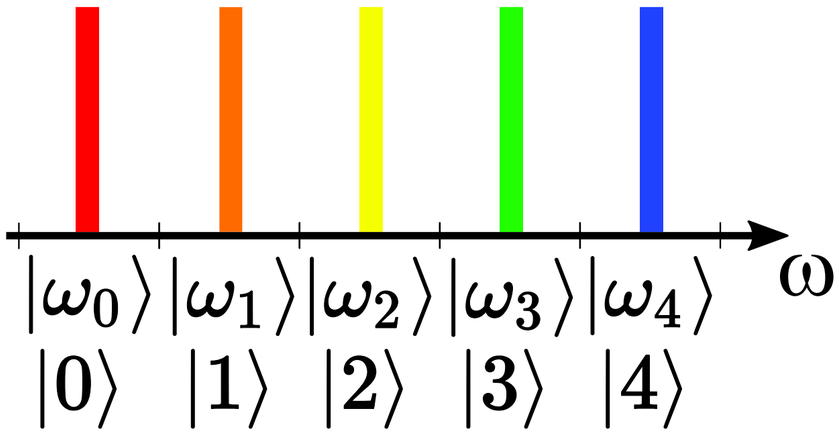
quBit

Frequency-bin encoding

- Dense fiber transmission
- Intrinsic phase stability
- Robustness to polarization instabilities
- Access to High Dimensional Hilbert space, quDits

Quantum states encoded in frequency bins

Frequency-bin encoding:



quDit

Frequency-bin encoding

- Dense fiber transmission
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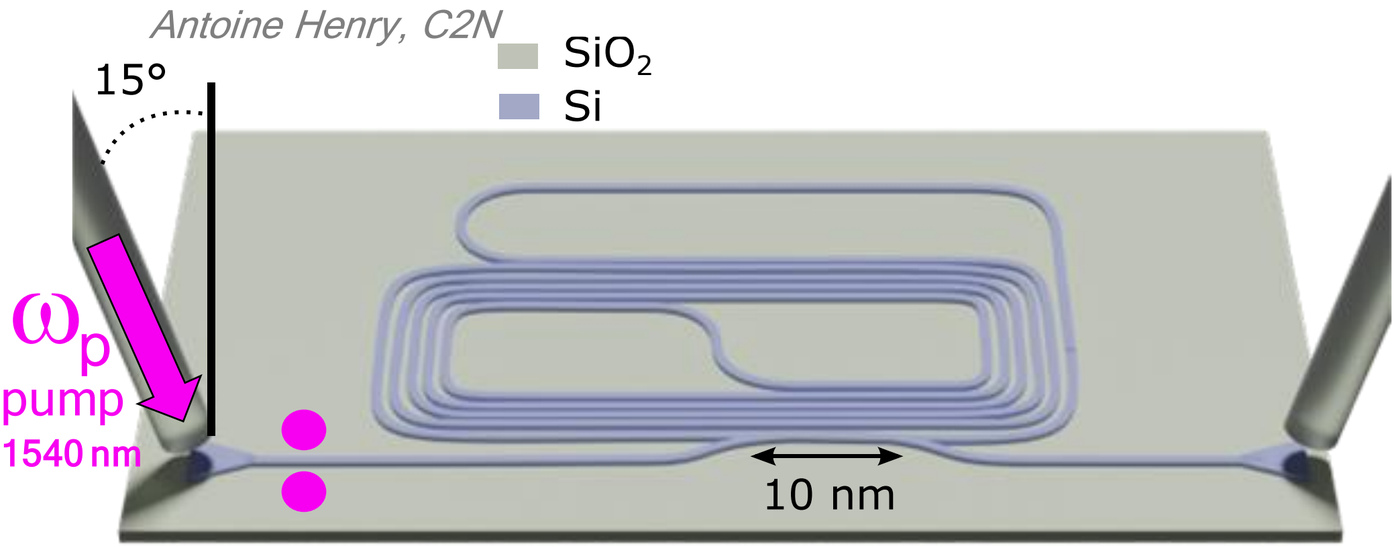
Silicon-on-Insulator micro resonator




L.Vivien


C.Ramos


E.Cassan


S.Monfray


F. Boeuf

Telecom frequency

- Low fiber losses
- Already existing telecom networks
- Off-the-shelf telecom devices

*[C.Harris, PRX ,**4** 041047 (2014)]*

*[C.Reimer, Opt.Express **22** 6535-6546 (2014)]*

Silicon technology

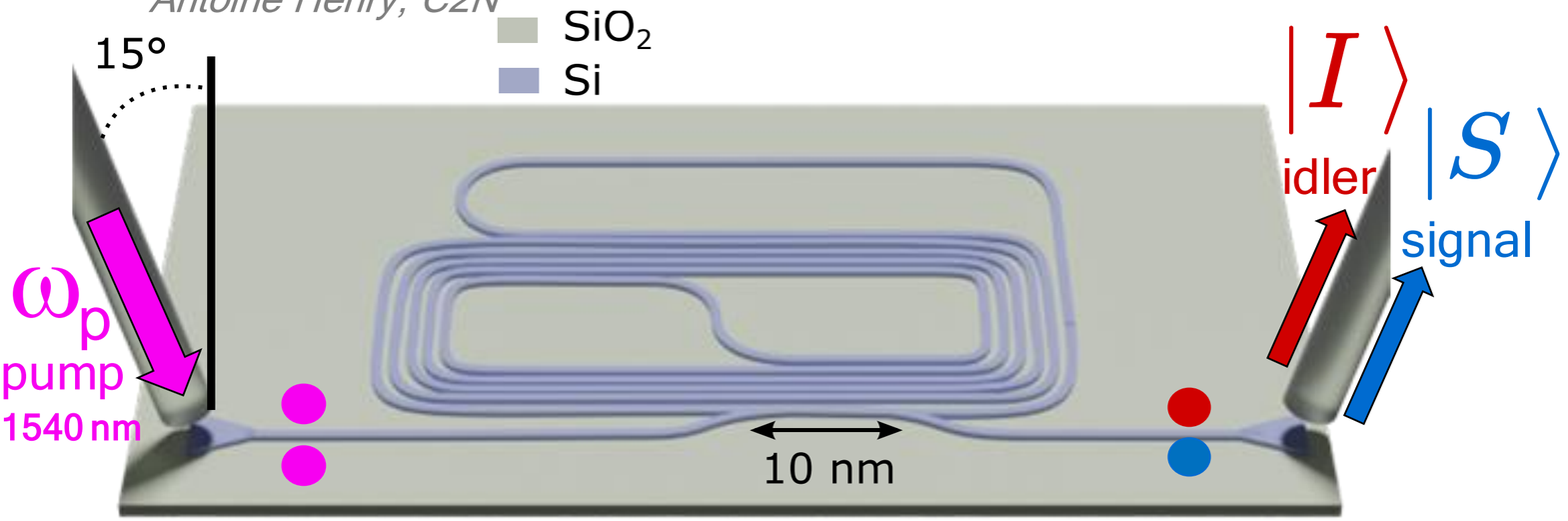
- Widely used micro-electronics know-how
- Easy to integrate, CMOS compatible, scalable
- $\chi^{(3)}$ NL component ($5.10^{-18} m^{-2}W^{-1}$) > SiN

*[Guo, Yuan, Optics letters,**39 8** 2526-9 (2014)]*

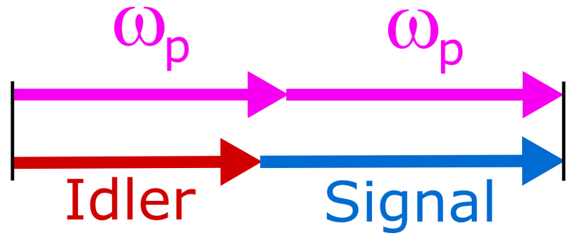
*[X.Shi, PRA,**12.3** 034053 (2019)]*

Silicon-on-Insulator micro resonator

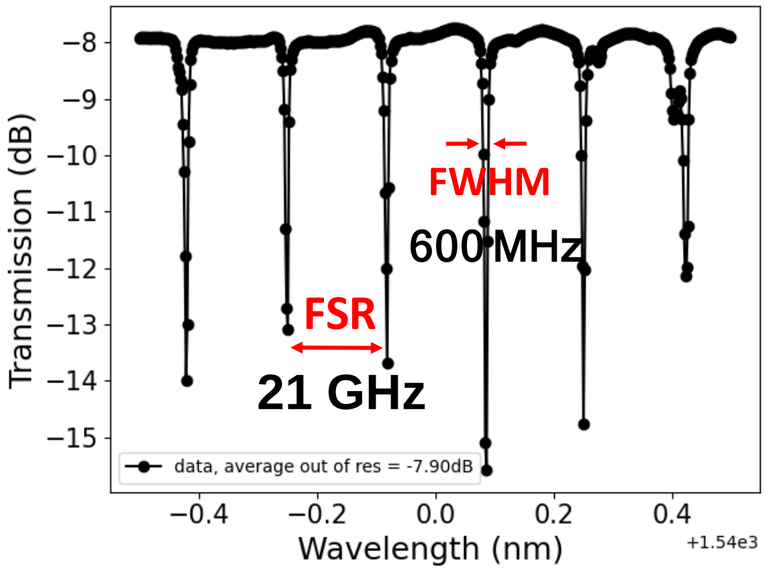
Antoine Henry, C2N



Four Wave Mixing

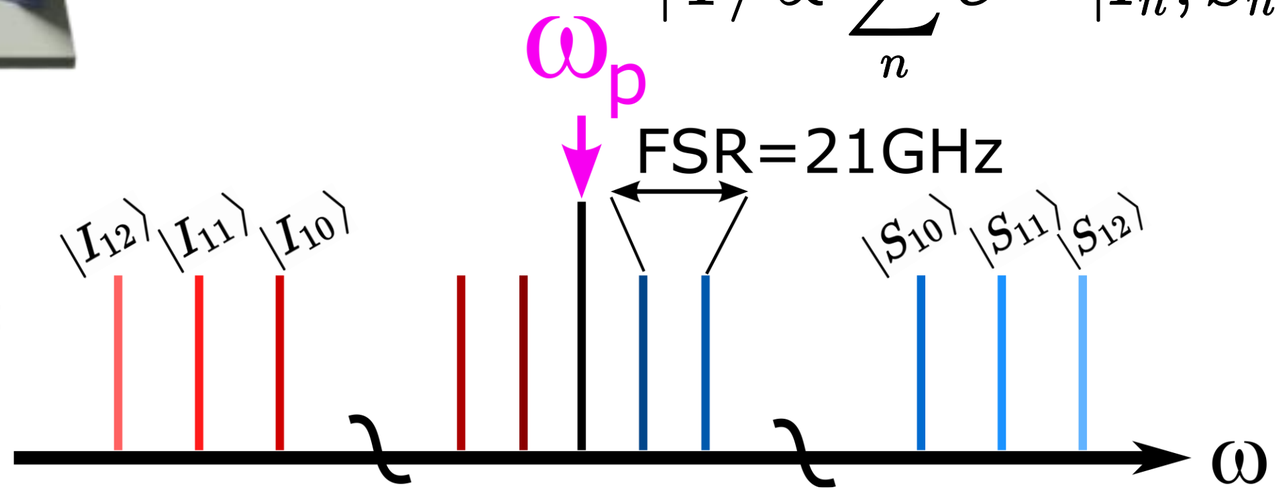


$$|\Psi\rangle \propto \sum_n e^{i\alpha_n} |I_n, S_n\rangle$$



Quality factor:
Q = 3x10^5

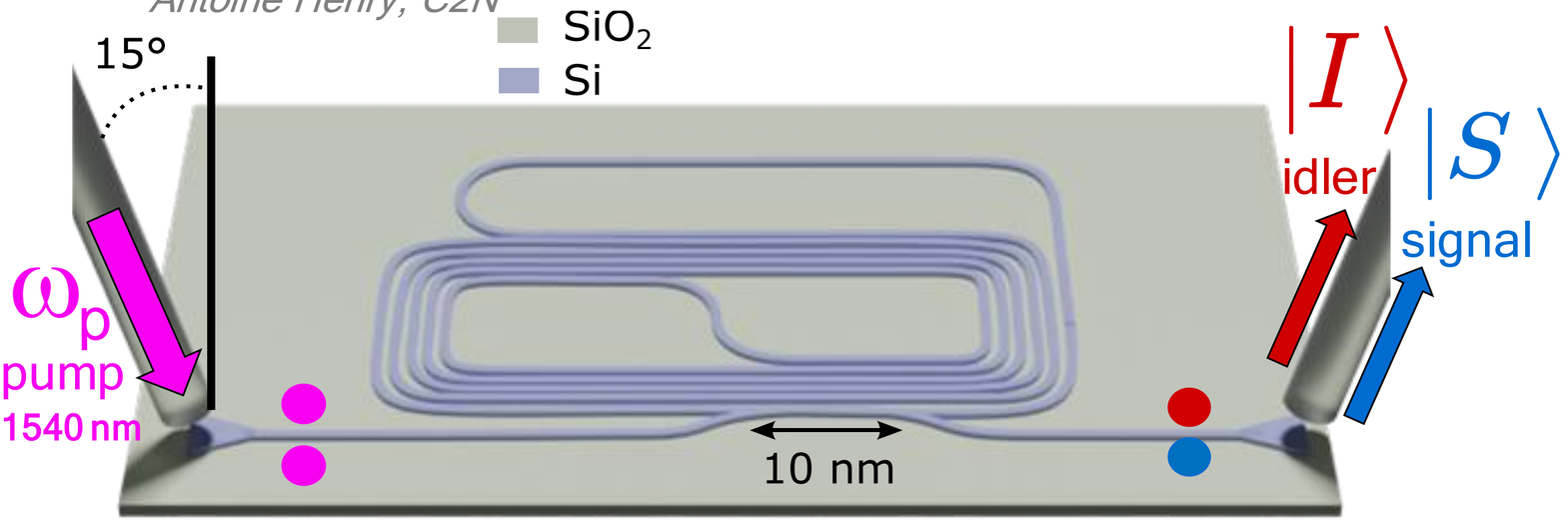
Fiber-to-fiber losses:
7.9 dB

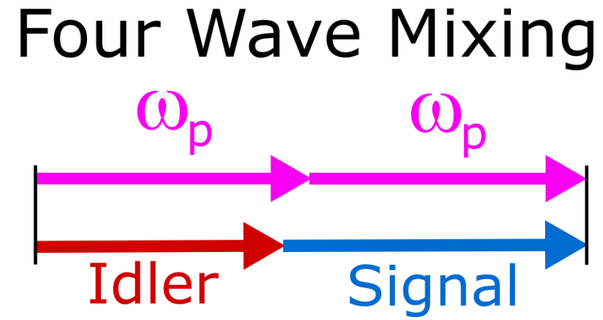


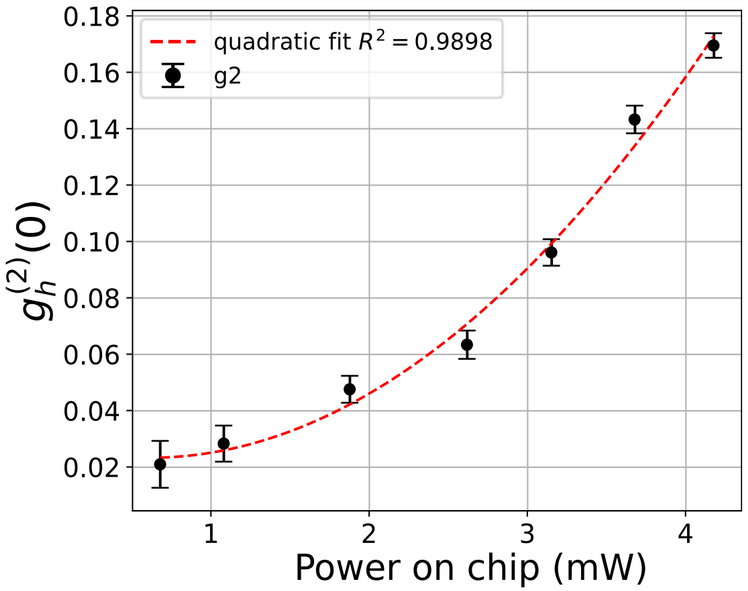
[Kues, Nature (2017)] 200 GHz FSR
[Imany, Opt.Express (2018)] 50GHZ FSR
*[M.Borghi, Phys. Rev. Applied **19** 064026 (2023)] 20 GHz FSR with multiple 100 GHz rings*

Silicon-on-Insulator micro resonator

Antoine Henry, C2N

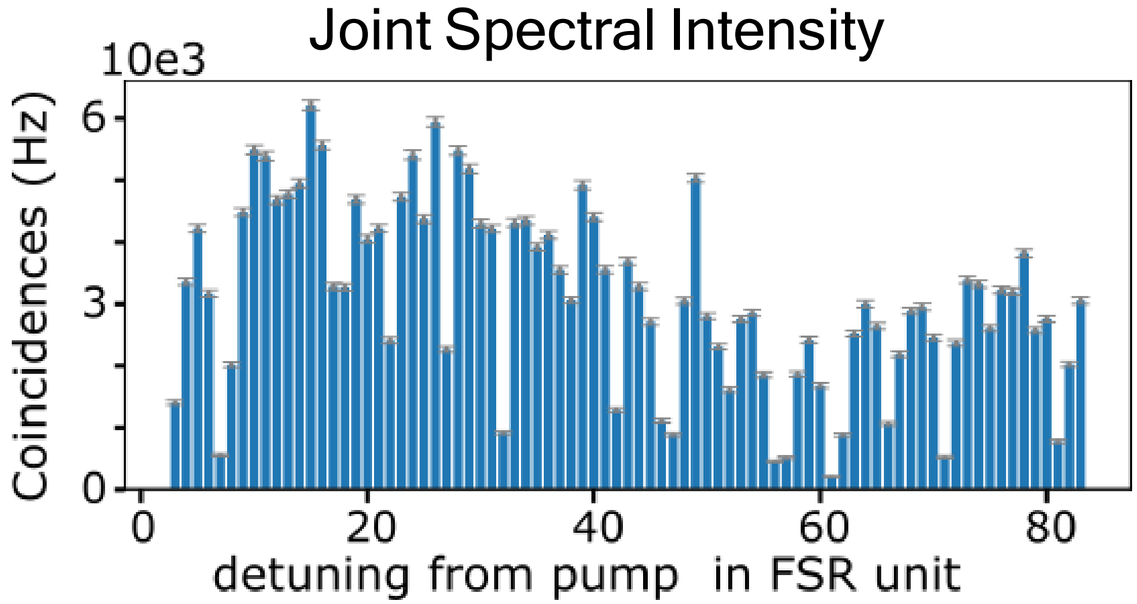






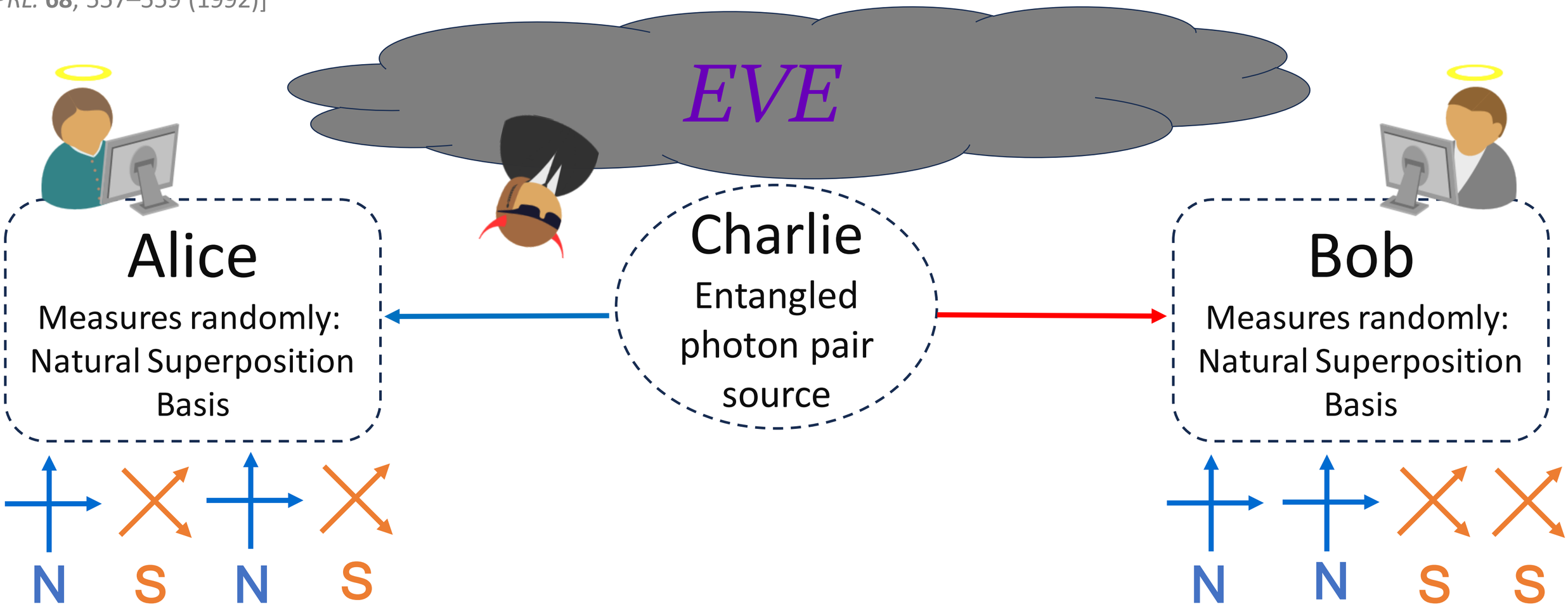
$g^{(2)}_h(0)$ of 6% at
2.4 mW on chip power

Brightness:
48M pairs.s^{-1}.GHz^{-1}.mW^{-2}



BBM92 Quantum Key Distribution protocol

[PRL. **68**, 557–559 (1992)]



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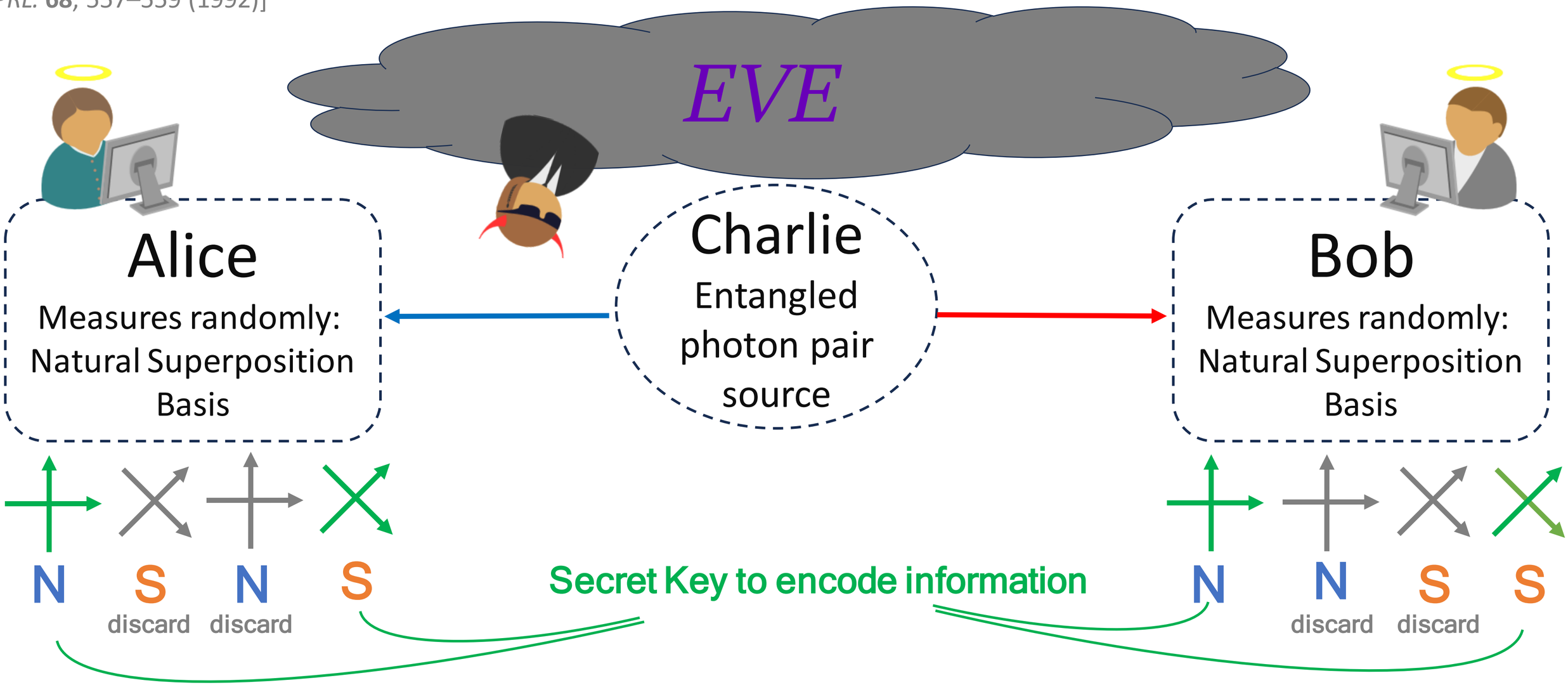
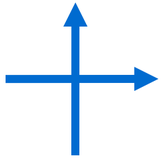


Natural and Superposition Basis : Polarization Vs. Frequency encoding

- Polarization



N Natural Basis

S Superposition Basis

[F.Appas, npj Quantum Inf 7, 118 (2021)]

[R. Winik, Phys. Rev. B 95 235435 (2017)]

$$|H\rangle \qquad |D\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle + |V\rangle\right)$$

$$|V\rangle \qquad |A\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle - |V\rangle\right)$$

Natural and Superposition Basis : Polarization Vs. Frequency encoding

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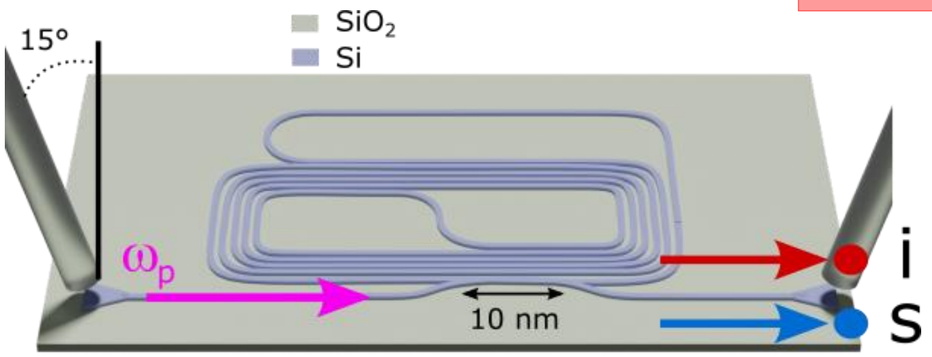
- Frequency bins

D = 2



$$|n_0\rangle = |\omega_0\rangle \qquad |s_0\rangle = \frac{1}{\sqrt{2}}\left(|\omega_0\rangle + |\omega_1\rangle\right)$$

$$|n_1\rangle = |\omega_1\rangle \qquad |s_1\rangle = \frac{1}{\sqrt{2}}\left(|\omega_0\rangle + e^{i\pi}|\omega_1\rangle\right)$$

Natural and Superposition Basis : Polarization Vs. Frequency encoding

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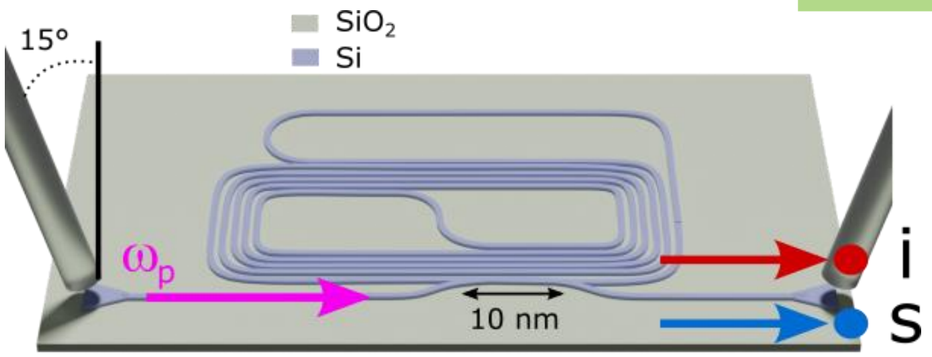
- Frequency bins

D = 3



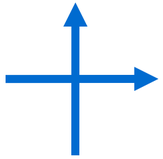
$$|n_0\rangle = |\omega_0\rangle \qquad |s_0\rangle = \frac{1}{\sqrt{3}}\left(|\omega_0\rangle + |\omega_1\rangle + |\omega_2\rangle\right)$$

$$|n_1\rangle = |\omega_1\rangle \qquad |s_1\rangle = \frac{1}{\sqrt{3}}\left(|\omega_0\rangle + e^{2i\pi/3}|\omega_1\rangle + e^{4i\pi/3}|\omega_2\rangle\right)$$

$$|n_2\rangle = |\omega_2\rangle \qquad |s_2\rangle = \frac{1}{\sqrt{3}}\left(|\omega_0\rangle + e^{4i\pi/3}|\omega_1\rangle + e^{8i\pi/3}|\omega_2\rangle\right)$$

Natural and Superposition Basis : Polarization Vs. Frequency encoding

- Polarization



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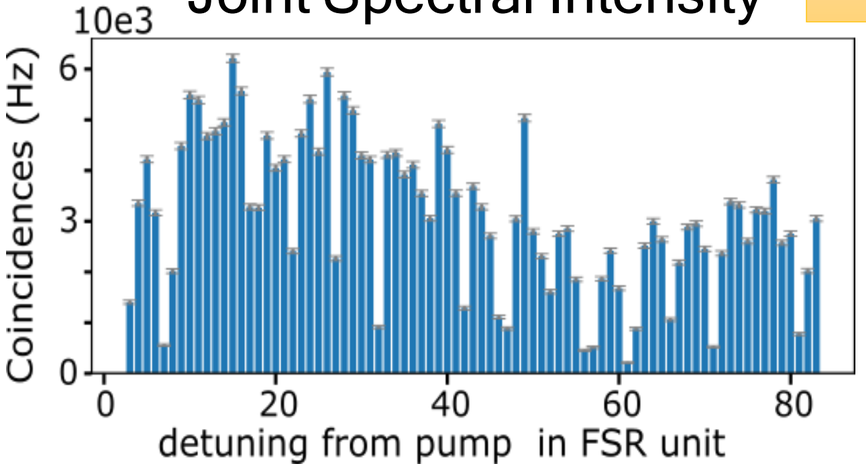
- Frequency bins

Joint Spectral Intensity



D = 4

etc...

$$|n_0\rangle = |\omega_0\rangle \qquad |s_0\rangle = \frac{1}{\sqrt{4}}\left(|\omega_0\rangle + |\omega_1\rangle + |\omega_2\rangle + |\omega_3\rangle\right)$$

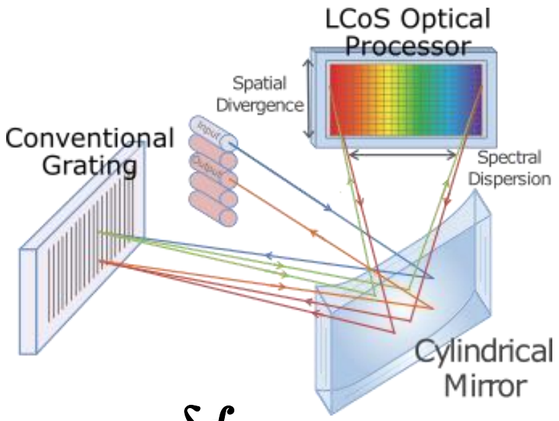
$$|n_1\rangle = |\omega_1\rangle \qquad |s_1\rangle = \frac{1}{\sqrt{4}}\left(|\omega_0\rangle + e^{2i\pi/4}|\omega_1\rangle + e^{4i\pi/4}|\omega_2\rangle + e^{6i\pi/4}|\omega_3\rangle\right)$$

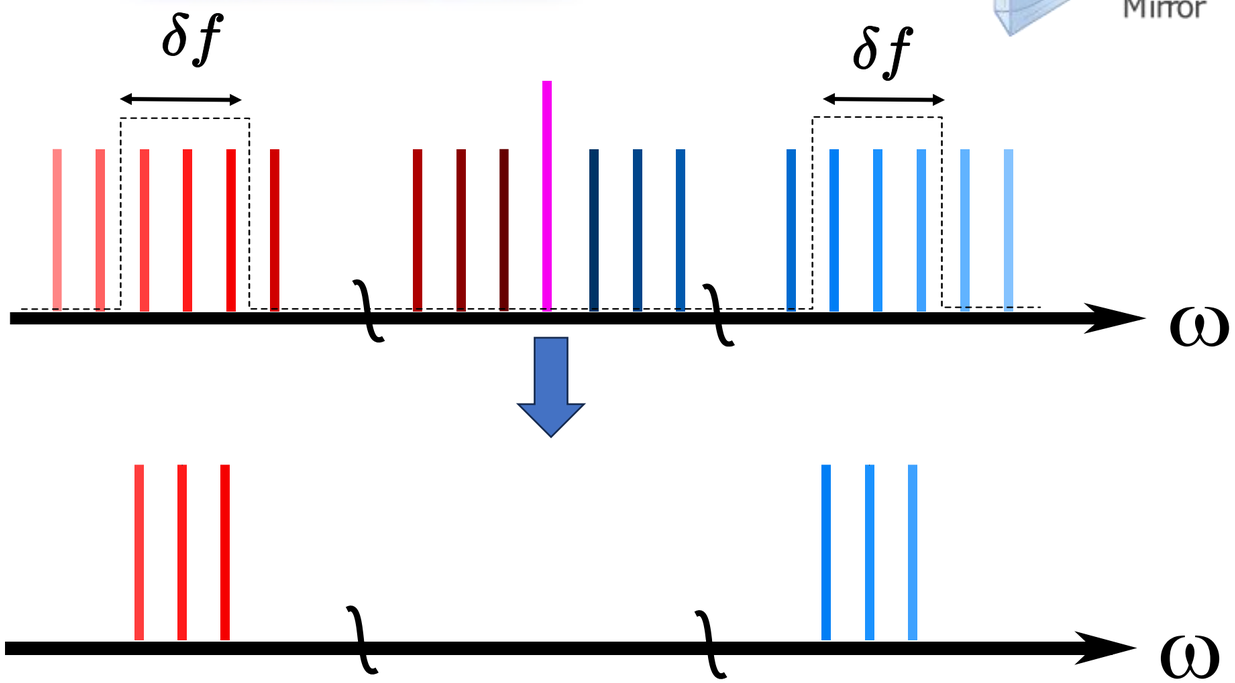
$$|n_2\rangle = |\omega_2\rangle \qquad |s_2\rangle = \frac{1}{\sqrt{4}}\left(|\omega_0\rangle + e^{4i\pi/4}|\omega_1\rangle + e^{8i\pi/4}|\omega_2\rangle + e^{12i\pi/4}|\omega_3\rangle\right)$$

$$|n_3\rangle = |\omega_3\rangle \qquad |s_3\rangle = \frac{1}{\sqrt{4}}\left(|\omega_0\rangle + e^{6i\pi/4}|\omega_1\rangle + e^{12i\pi/4}|\omega_2\rangle + e^{18i\pi/4}|\omega_3\rangle\right)$$

Manipulation of Frequency-bins with telecom devices

Programable Filter (PF)





[Kues, Nature 546, 622-626 (2017)] *[HH.Lu, Nat Commun **13**, 4338 (2022)]*

Manipulation of Frequency-bins with telecom devices

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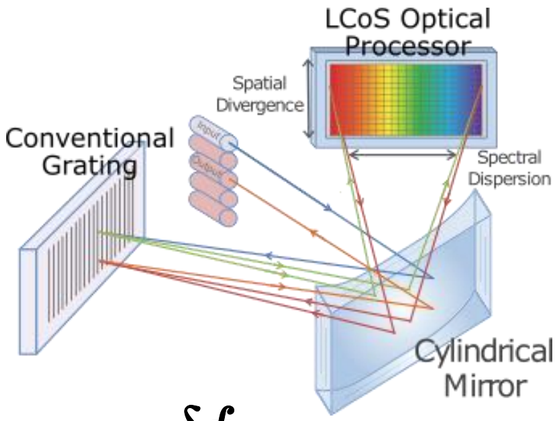
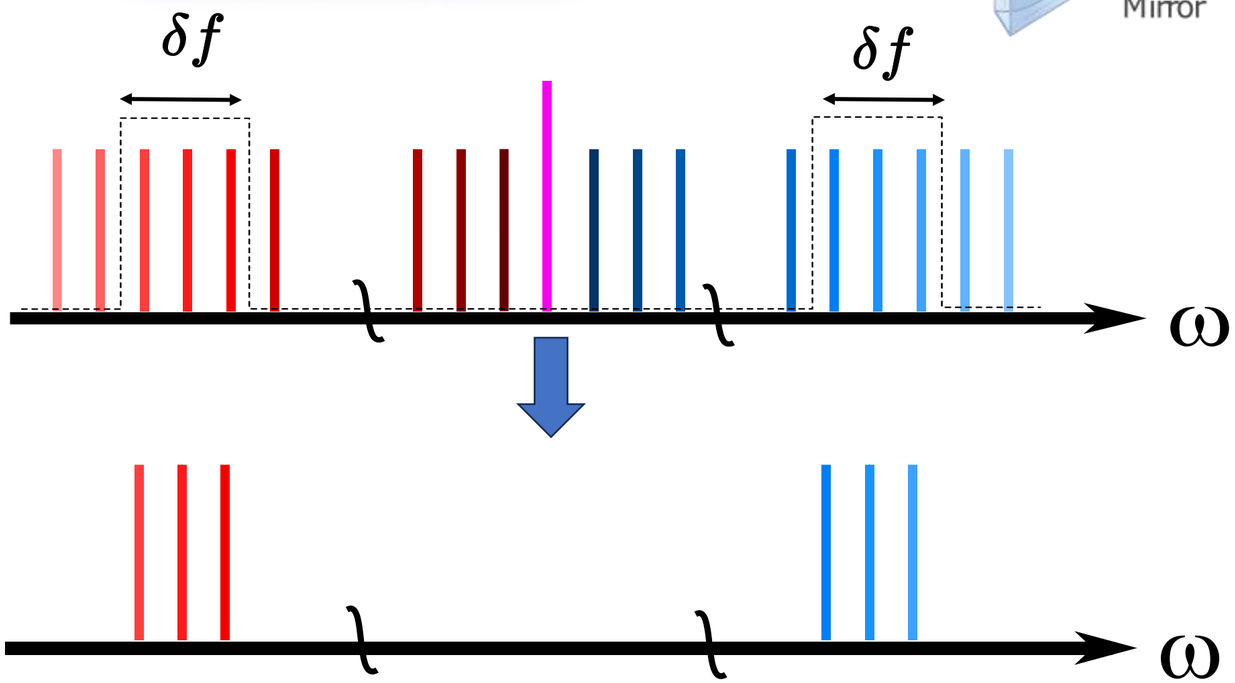
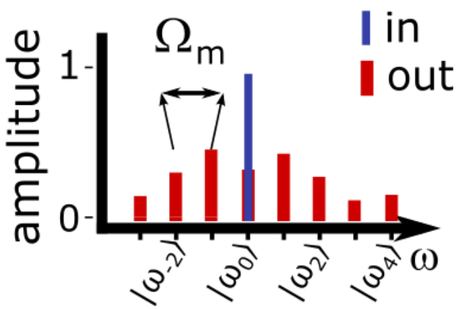
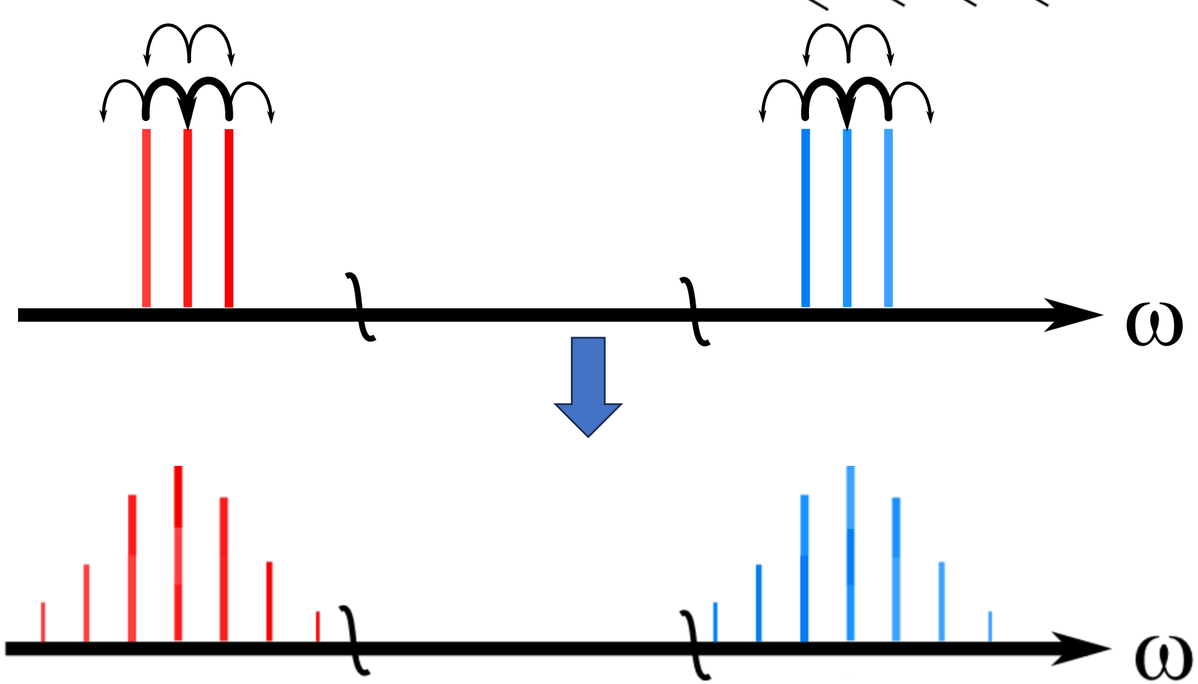




Electro-Optic Modulator (EOM)

Electro-Optics phase modulators
superposition of frequencies





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Manipulation of Frequency-bins with telecom devices

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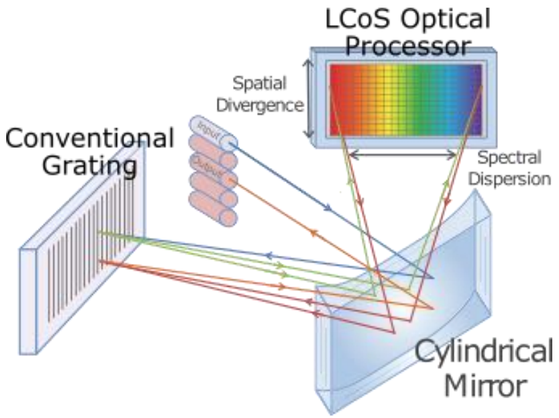

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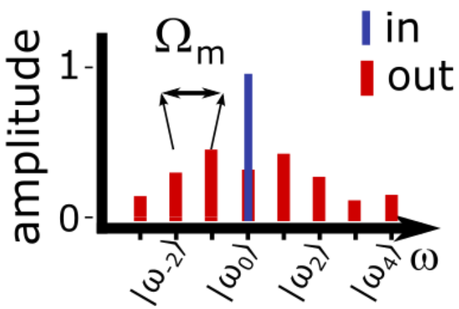
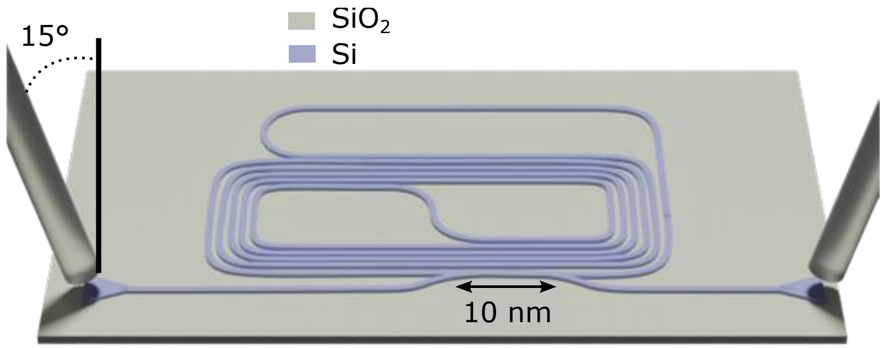
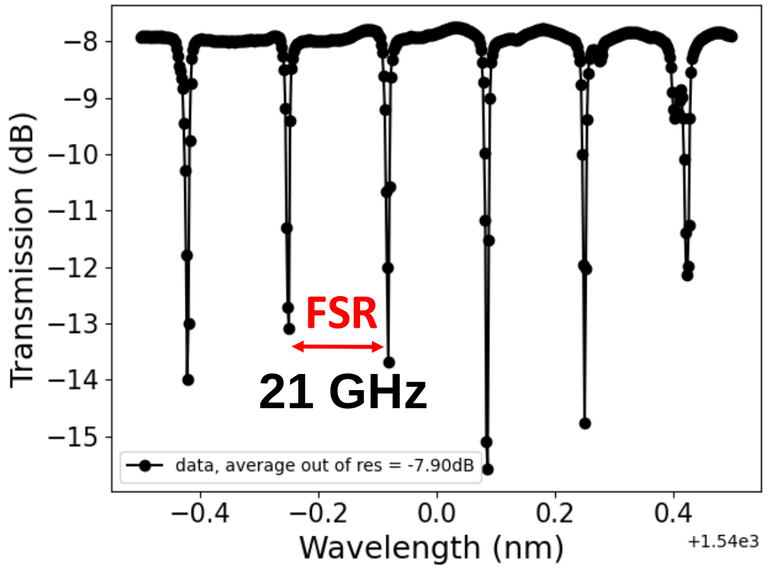


Limitations: $\delta f > 10$ GHz

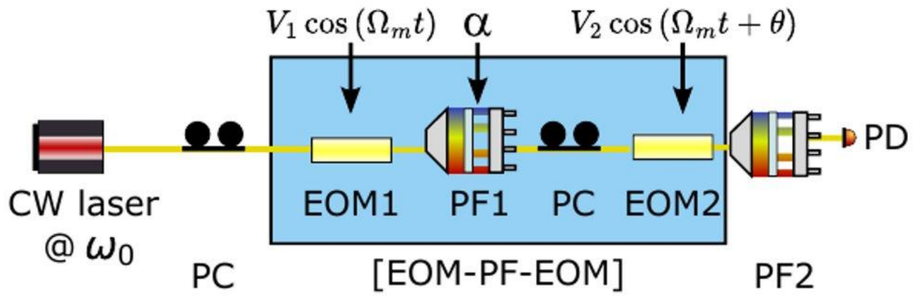
$\Omega_m < 33$ GHz

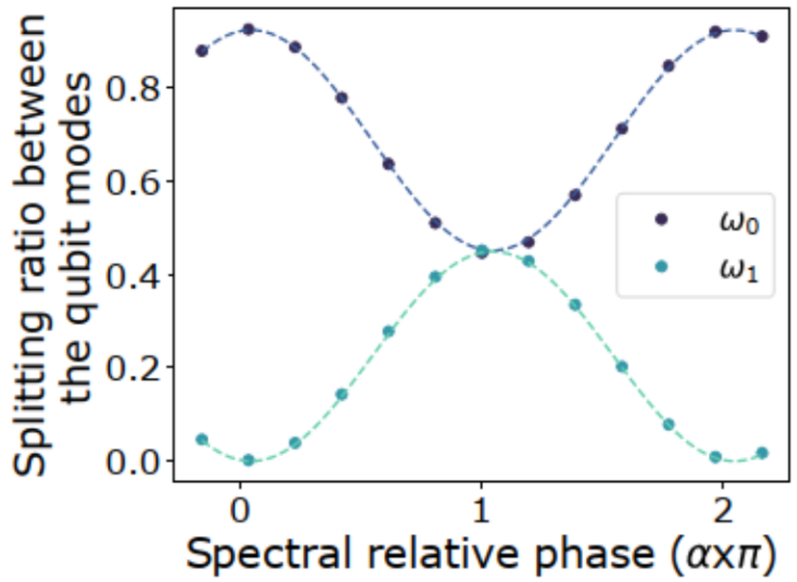


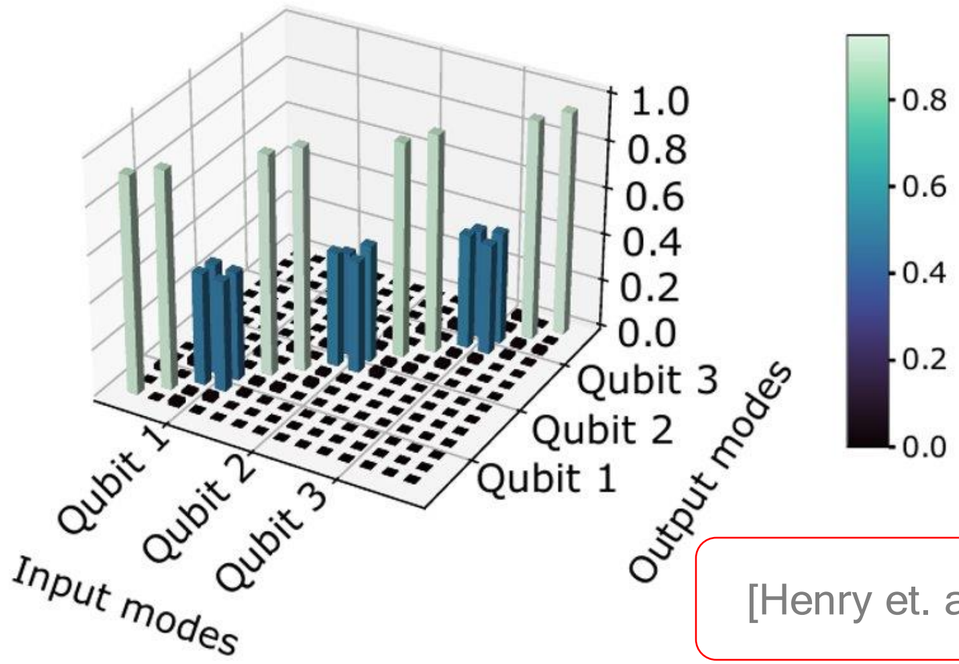


[Kues, Nature 546, 622-626 (2017)] *[HH.Lu, Nat Commun **13**, 4338 (2022)]*

Manipulating Frequency bins with telecom devices: Tunable Rotation for independent Qubits







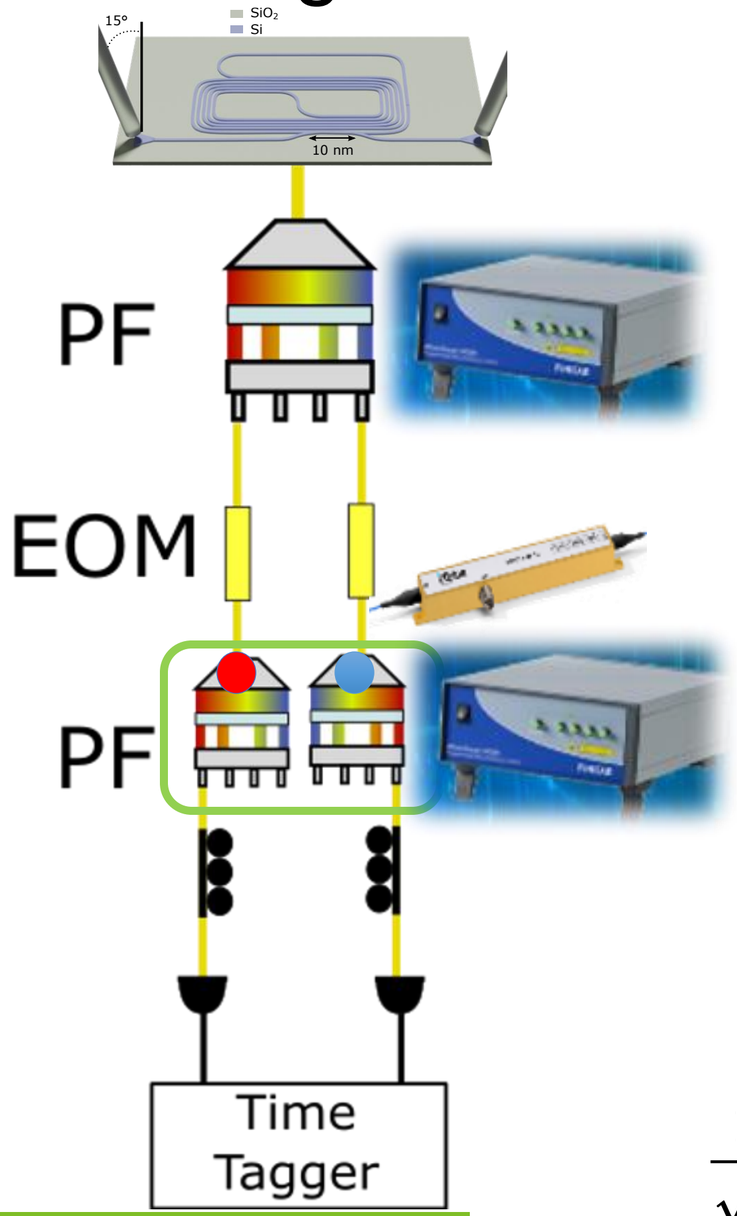
Antoine Henry

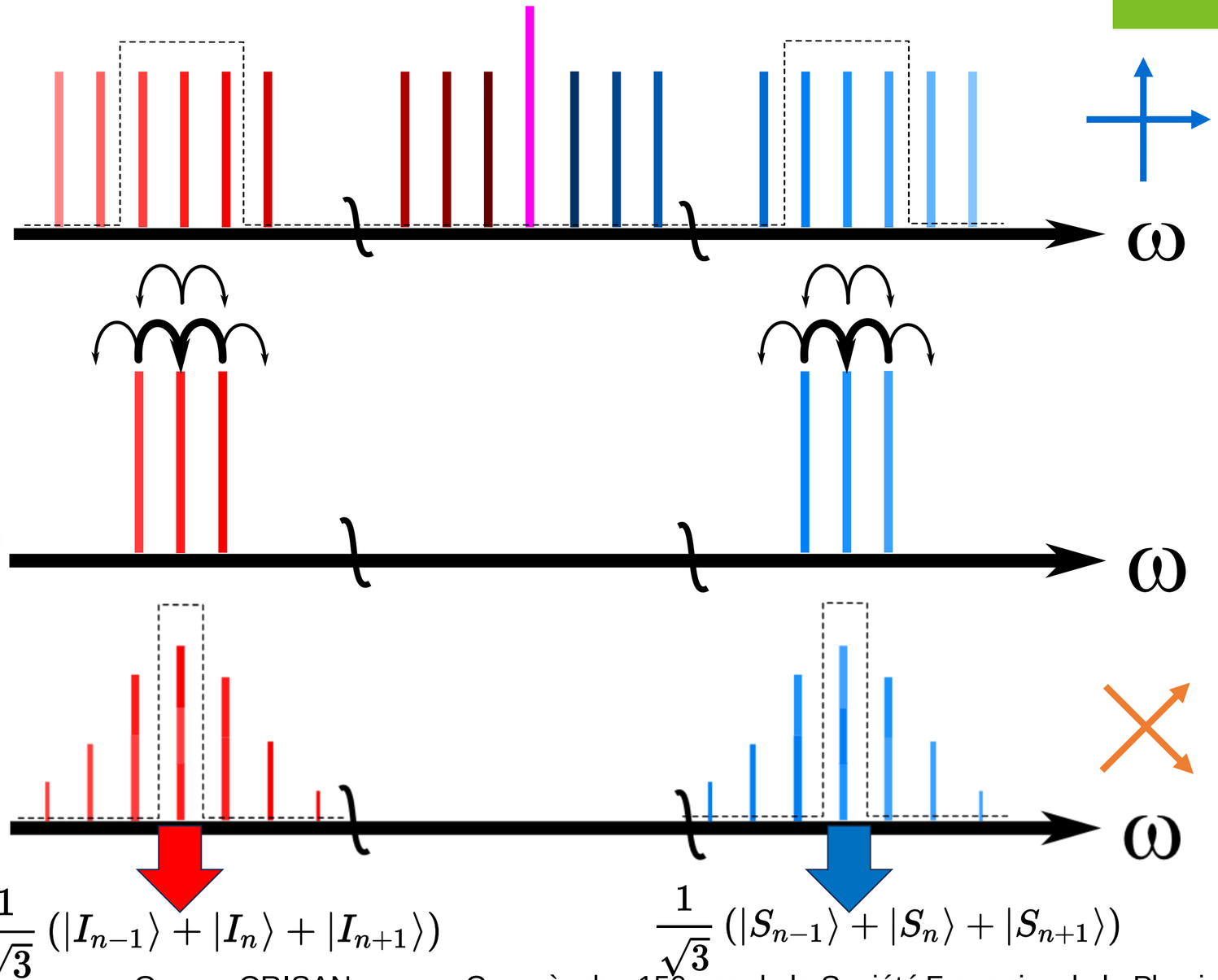
[Henry et. al, arXiv:2305.0345]

[Lukens et al. Vol. **4**, Issue 1(2017)]

[Lu et. al, Phys. Rev. Lett. **125**, 120503]

Change of base in the frequency domain





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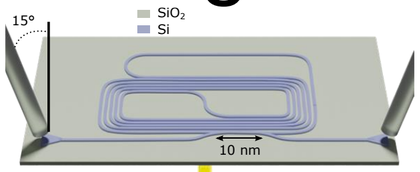
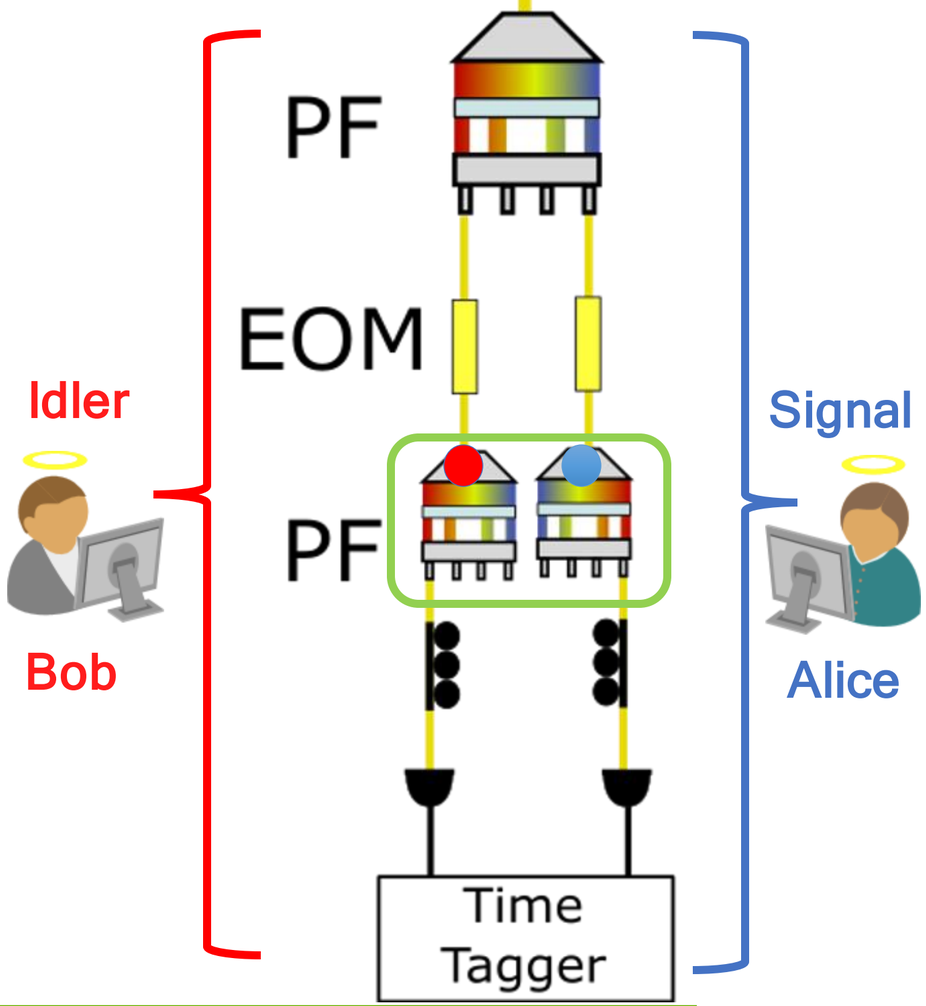
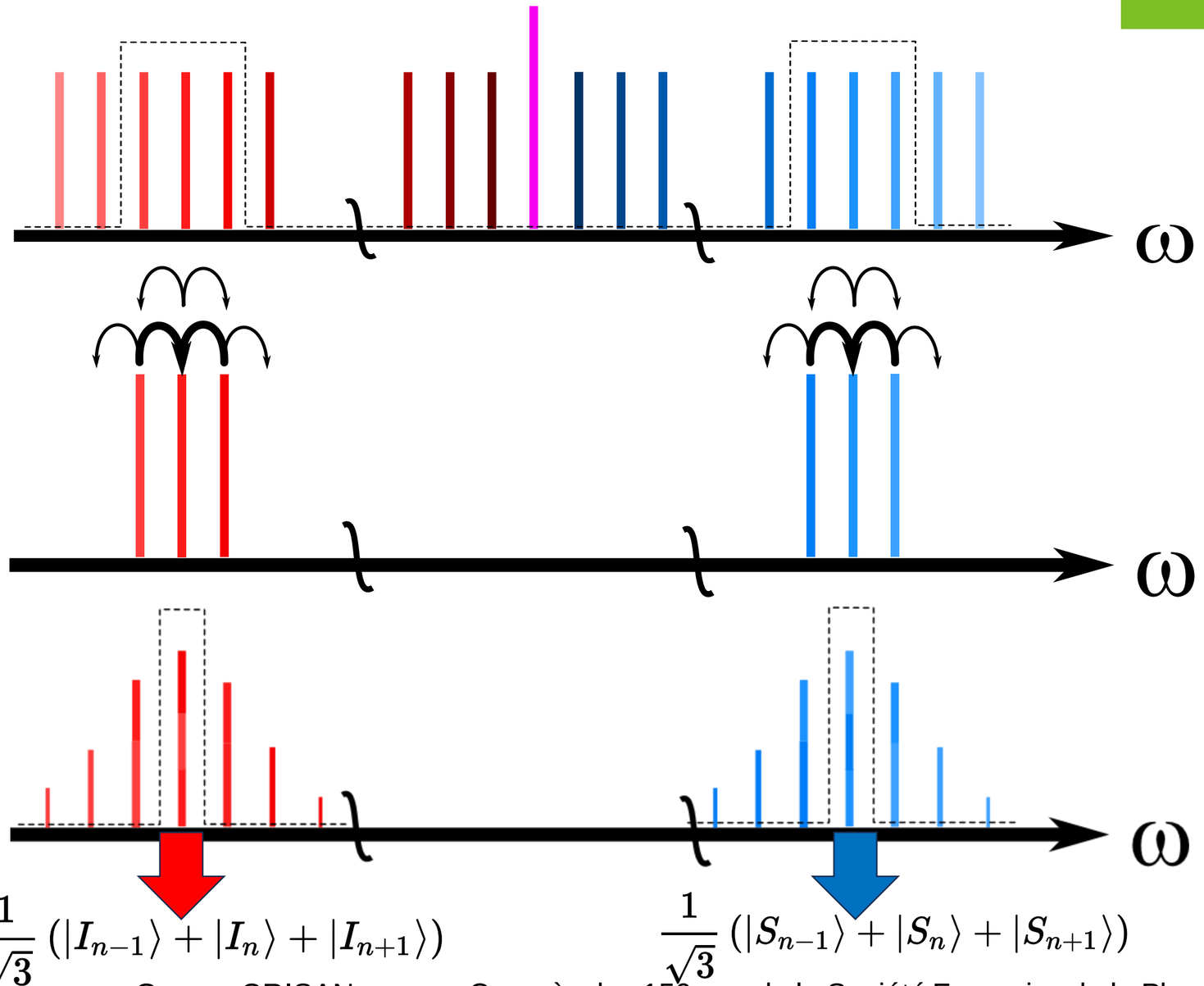


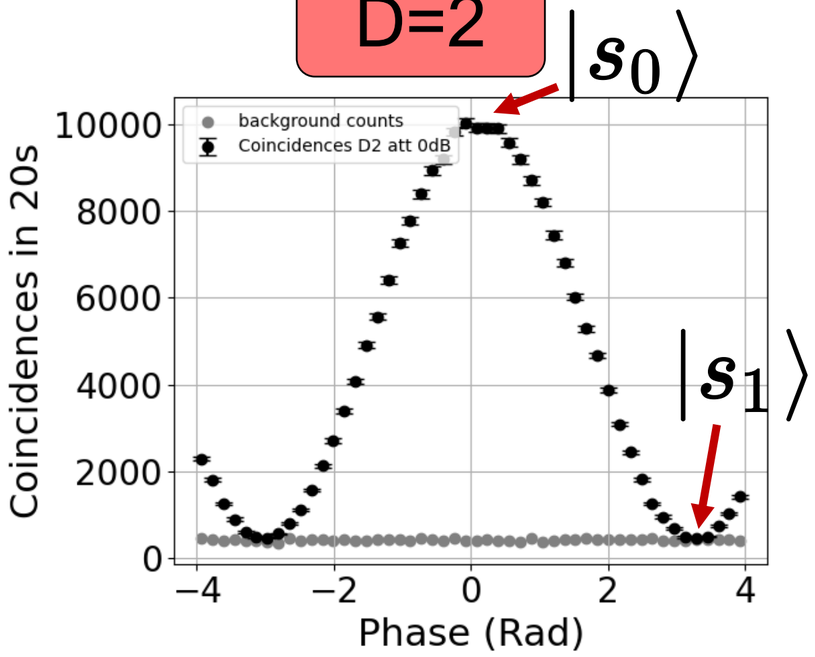




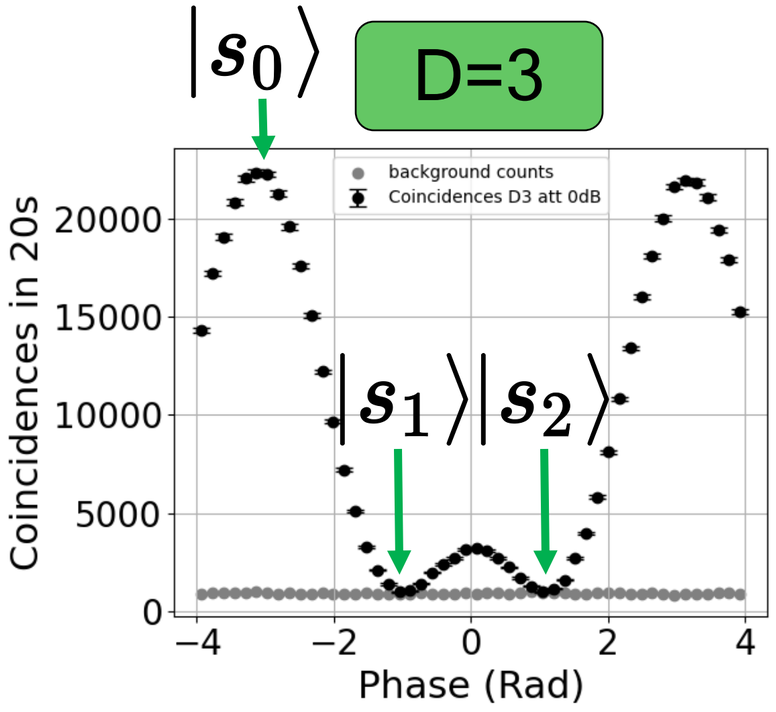
Scan the states in the Superposition basis: quDits interferences

$$|\Psi\rangle = \frac{1}{\sqrt{D}}\left(|I_{\omega 0}, S_{\omega 0}\rangle + e^{\phi i\pi}|I_{\omega 1}, S_{\omega 1}\rangle + e^{2\phi i\pi}|I_{\omega 2}, S_{\omega 2}\rangle + \ldots\right)$$

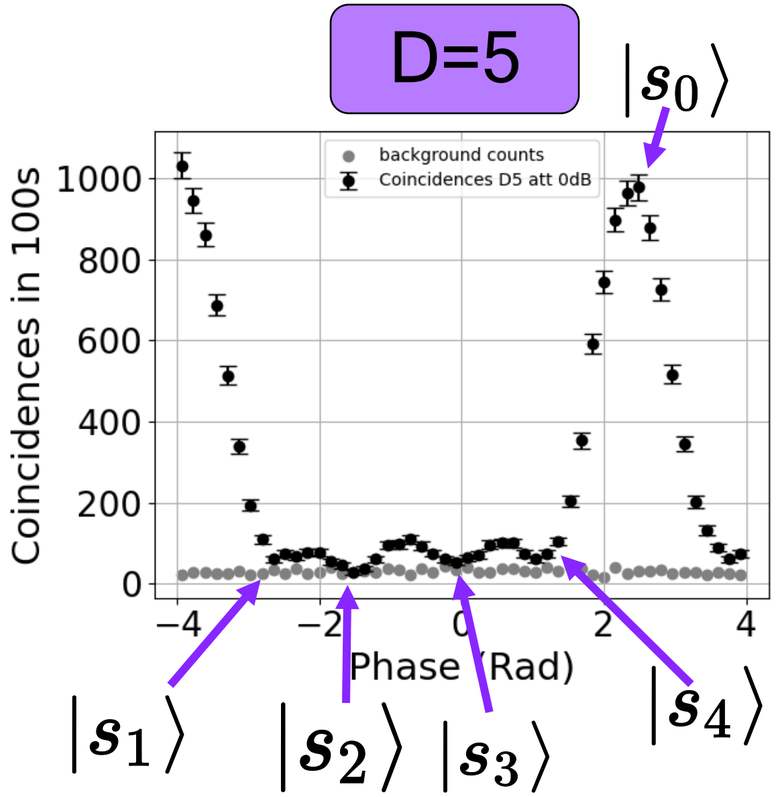
D=2



D=3



D=5



$$|s_0\rangle = \frac{1}{\sqrt{3}}\left(|\omega_0\rangle + |\omega_1\rangle + |\omega_2\rangle\right)$$

$$|s_2\rangle = \frac{1}{\sqrt{3}}\left(|\omega_0\rangle + e^{4i\pi/3}|\omega_1\rangle + e^{8i\pi/3}|\omega_2\rangle\right)$$

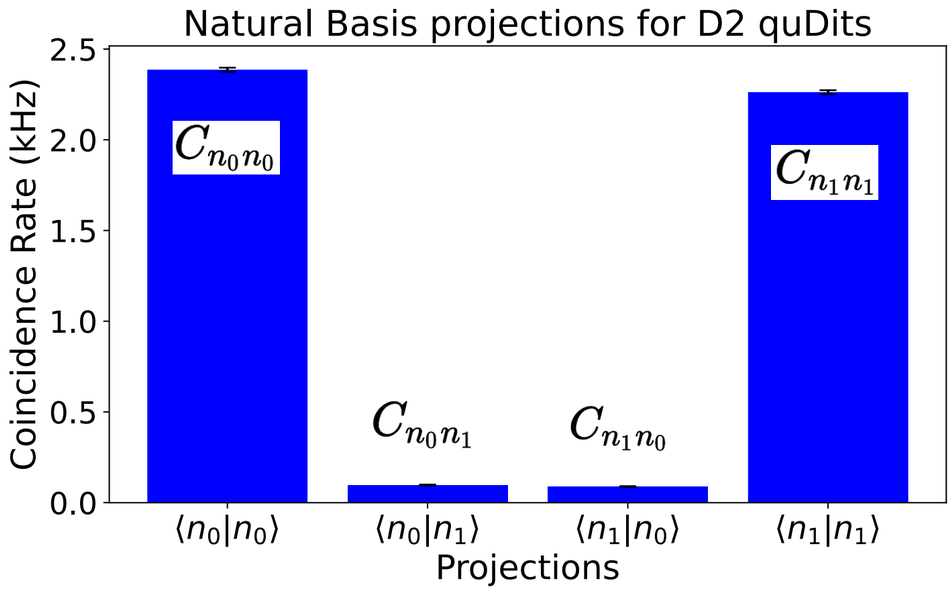
Quantum Key Distribution performances quDit D=2

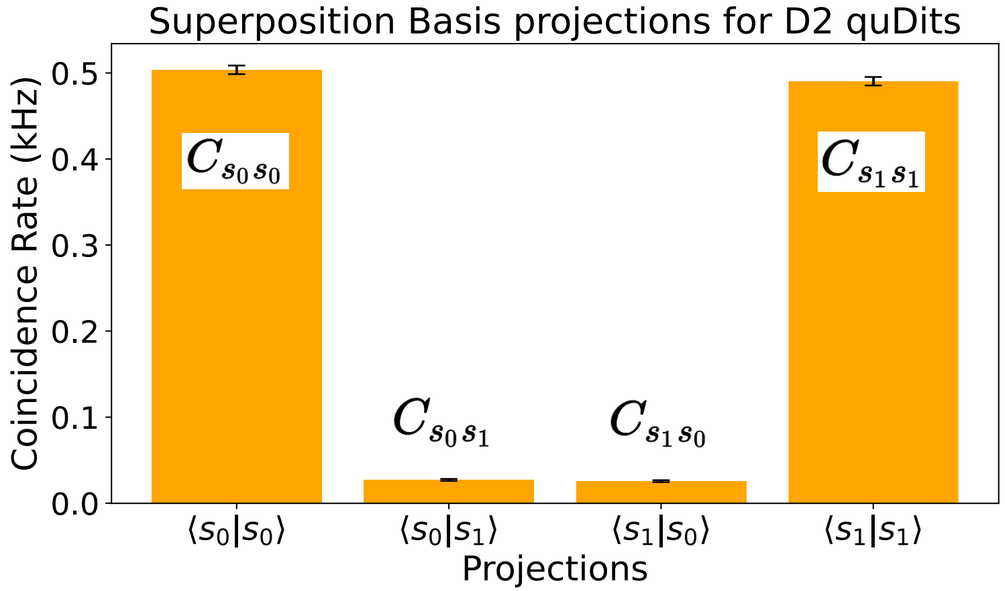
$$C^{\text{raw}}_{N,pol} = C_{HH} + C_{HV} + C_{VH} + C_{VV}$$

$$C^{\text{raw}}_{N} = C_{n_0 n_0} + C_{n_1 n_0} + C_{n_0 n_1} + C_{n_1 n_1}$$

$$C^{\text{raw}}_{S,pol} = C_{DD} + C_{DA} + C_{AD} + C_{AA}$$

$$C^{\text{raw}}_{S} = C_{s_0 s_0} + C_{s_1 s_0} + C_{s_0 s_1} + C_{s_1 s_1}$$



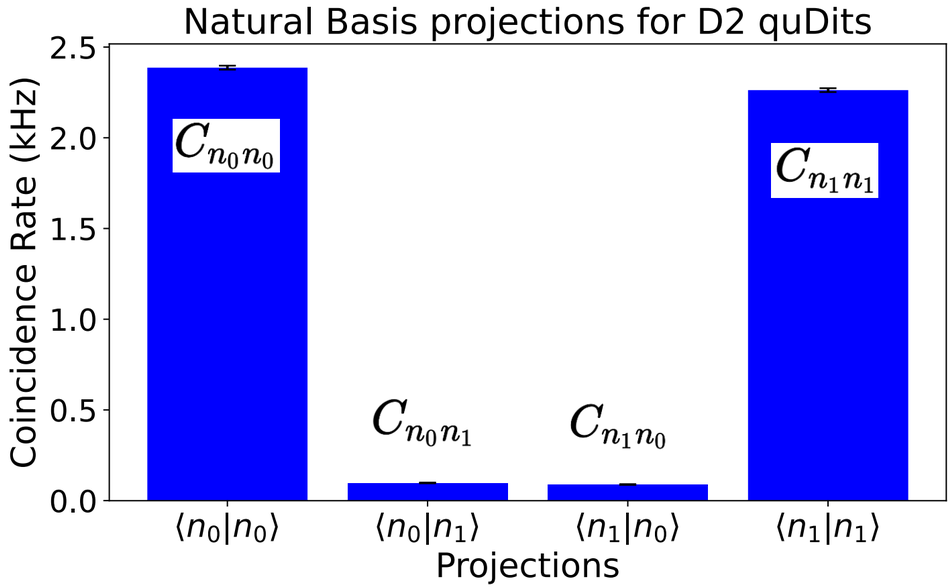


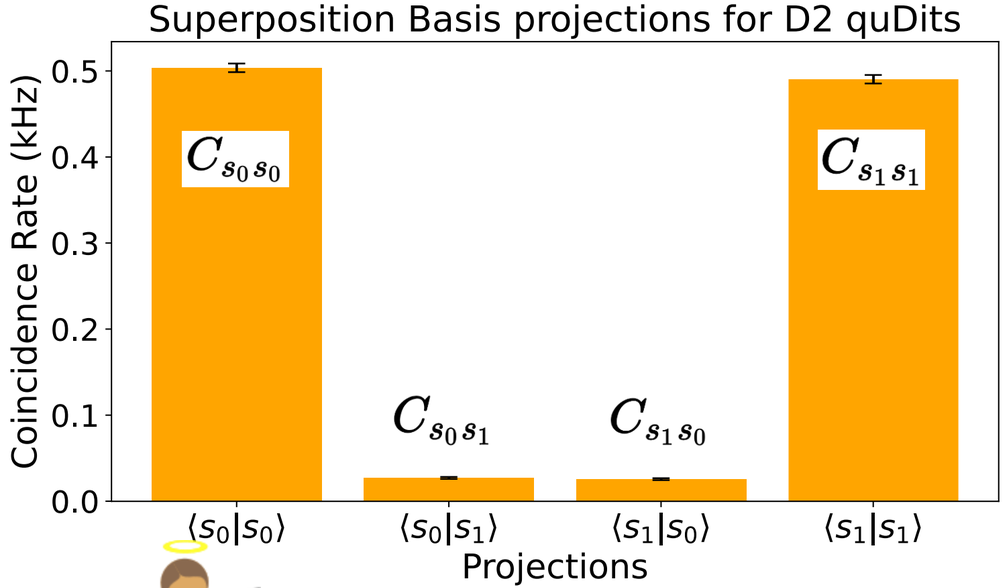
[F.Appas, npj Quantum Inf 7, 118 (2021)]

Quantum Key Distribution performances quDit D=2

$$C^{\text{raw}}_{N,pol} = C_{HH} + C_{HV} + C_{VH} + C_{VV}$$
$$C^{\text{raw}}_{N} = C_{n_0 n_0} + C_{n_1 n_0} + C_{n_0 n_1} + C_{n_1 n_1}$$

$$C^{\text{raw}}_{S,pol} = C_{DD} + C_{DA} + C_{AD} + C_{AA}$$
$$C^{\text{raw}}_{S} = C_{s_0 s_0} + C_{s_1 s_0} + C_{s_0 s_1} + C_{s_1 s_1}$$





$$QBER = \frac{C_{n_1 n_0} + C_{n_0 n_1} + C_{s_0 s_1} + C_{s_1 s_0}}{C^{\text{raw}}_N + C^{\text{raw}}_S} = \frac{C_{\text{accidentals}}}{C_{\text{Total}}}$$

6%

$$R_{\text{raw}} = \frac{1}{2}\frac{C^{\text{raw}}_N + C^{\text{raw}}_S}{\tau_{\text{integration time}}}$$

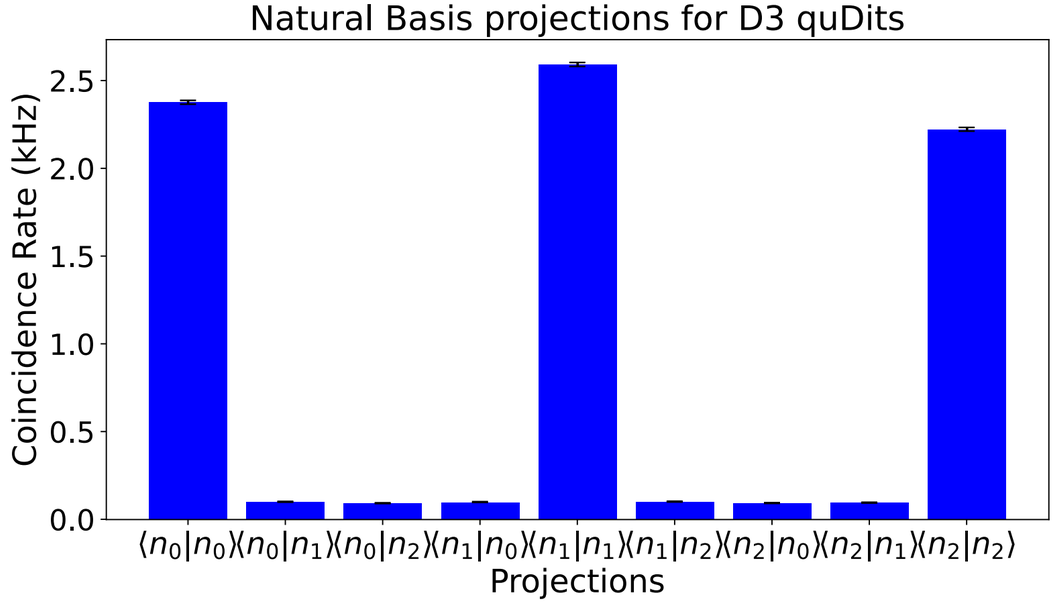
600 Hz

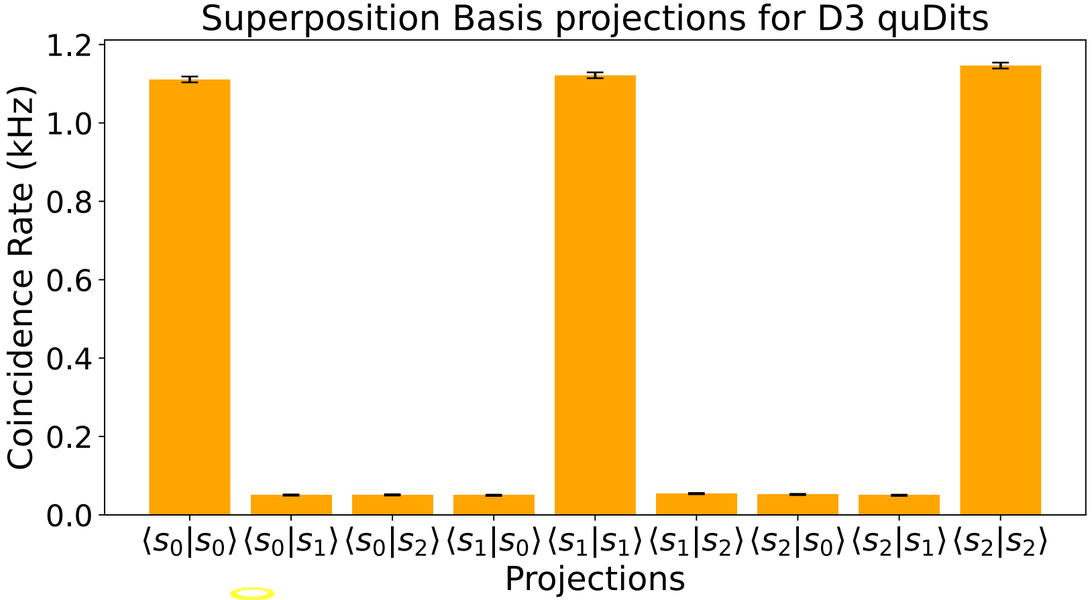
[F.Appas, npj Quantum Inf 7, 118 (2021)]

Quantum Key Distribution performances quDit D=3

$C_N^{\text{raw}} = \text{total coincidences in } N \text{ basis}$

$C_S^{\text{raw}} = \text{total coincidences in } S \text{ basis}$





$$QBER = \frac{C_{\text{accidentals}}}{C_{\text{Total}}}$$

10%

2 KHz

$$R_{\text{raw}} = \frac{1}{2}\frac{C_N^{\text{raw}} + C_S^{\text{raw}}}{\tau_{\text{integration time}}}$$

[F.Appas, npj Quantum Inf 7, 118 (2021)]

Quantum Key Distribution performances estimation

Secret Key Rate

$$SKR \geq \frac{1}{2} R_{\text{raw}} \times [log_2(d) - H_d(e) - f_d(e) H(e)]$$

$$R_{\text{raw}} = \frac{1}{2} \frac{C_N^{\text{raw}} + C_S^{\text{raw}}}{\tau_{\text{integration time}}}$$

$$e = QBER = \frac{C_{accidentals}}{C_{\mathbb{Z}}^{(\text{raw})} + C_{\mathbb{X}}^{(\text{raw})}}$$

Binary Entropy Function

$$H(e) = -e \log_2(\frac{e}{d-1}) - (1-e) \log_2(1-e)$$

Post Processing efficiency $f_d(e) = 1.2$

*[Bouchard,Quantum. **2**, 111 (2018)]*

*[Appas, npj Quantum Inf **7**, 118 (2021)]*

Quantum Key Distribution performances estimation

Secret Key Rate

$$SKR \geq \frac{1}{2} R_{\text{raw}} \times [log_2(d) - H_d(e) - f_d(e) H(e)]$$

Dimension

$$R_{\text{raw}} = \frac{1}{2} \frac{C_N^{\text{raw}} + C_S^{\text{raw}}}{\tau_{\text{integration time}}}$$

$$e = QBER = \frac{C_{accidentals}}{C_{\mathbb{Z}}^{(\text{raw})} + C_{\mathbb{X}}^{(\text{raw})}}$$

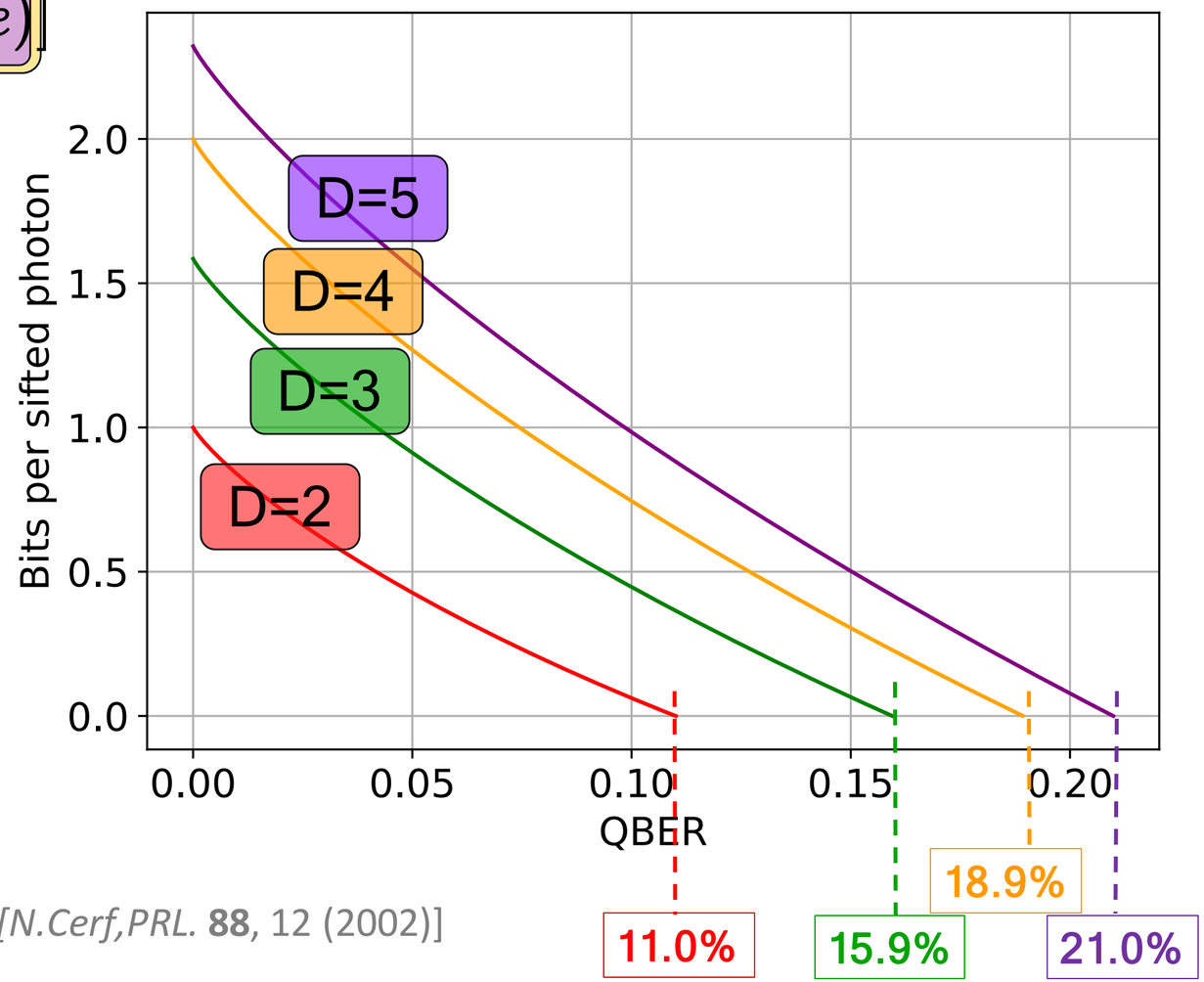
Binary Entropy Function

$$H(e) = -e \log_2(\frac{e}{d-1}) - (1-e) \log_2(1-e)$$

Post Processing efficiency $f_d(e)$ =1.2

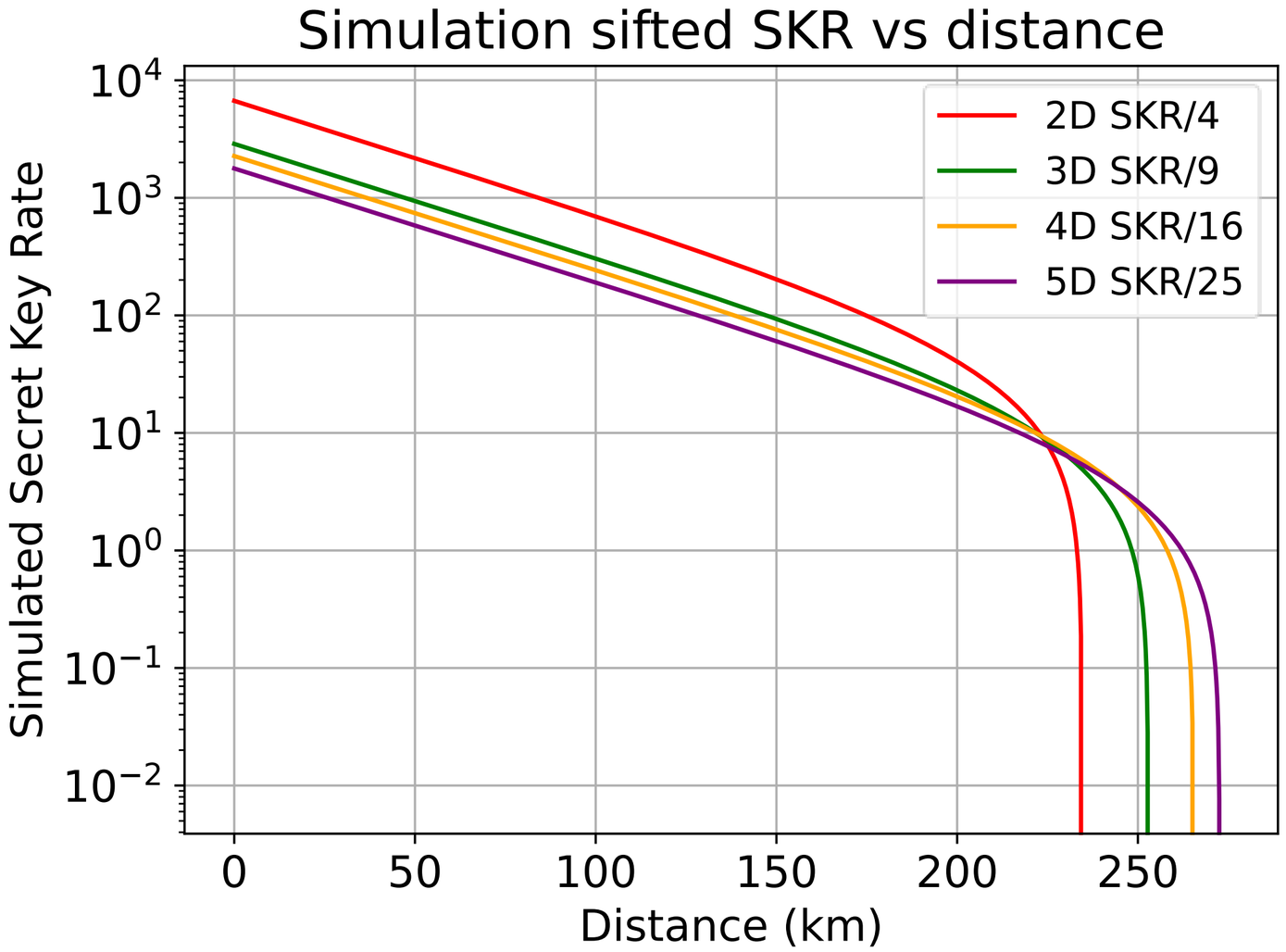
[Bouchard,Quantum. **2**, 111 (2018)]

[Appas, npj Quantum Inf **7**, *118 (2021)]*

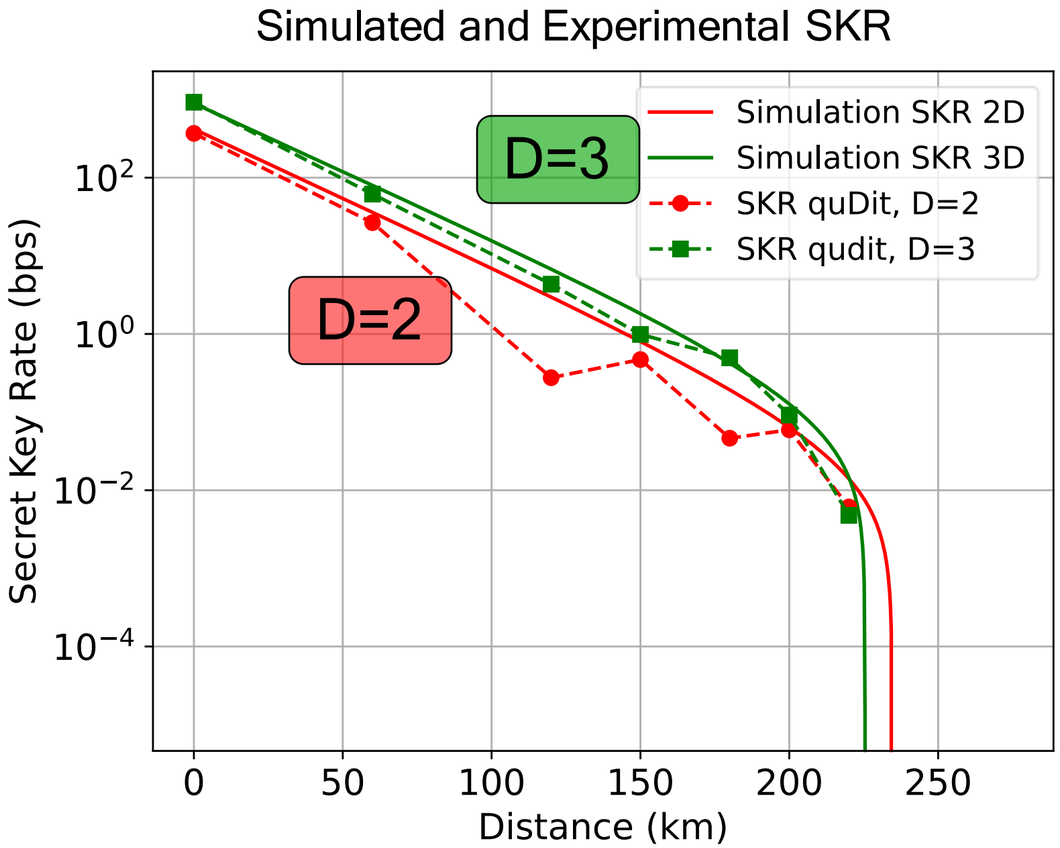


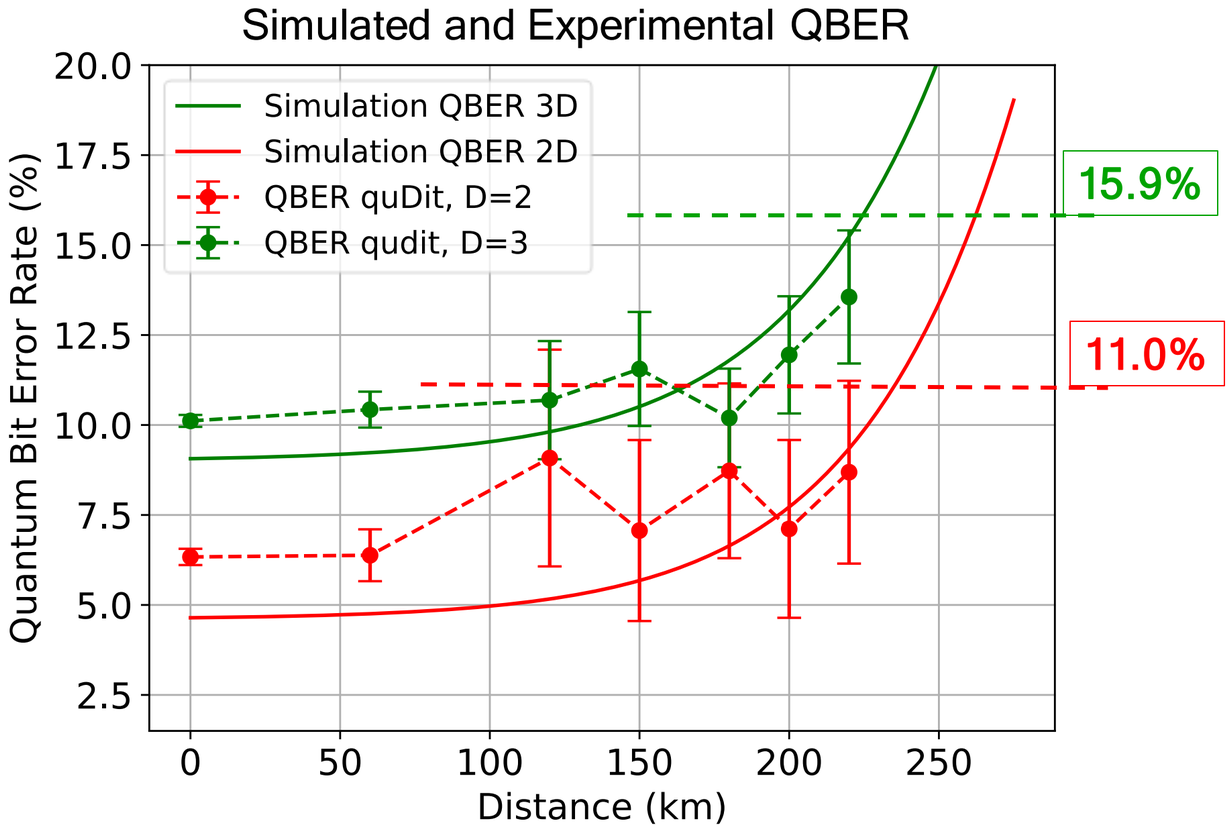
[N.Cerf,PRL. **88**, 12 (2002)]

Secret Key Rate Vs quDit dimension: Theory



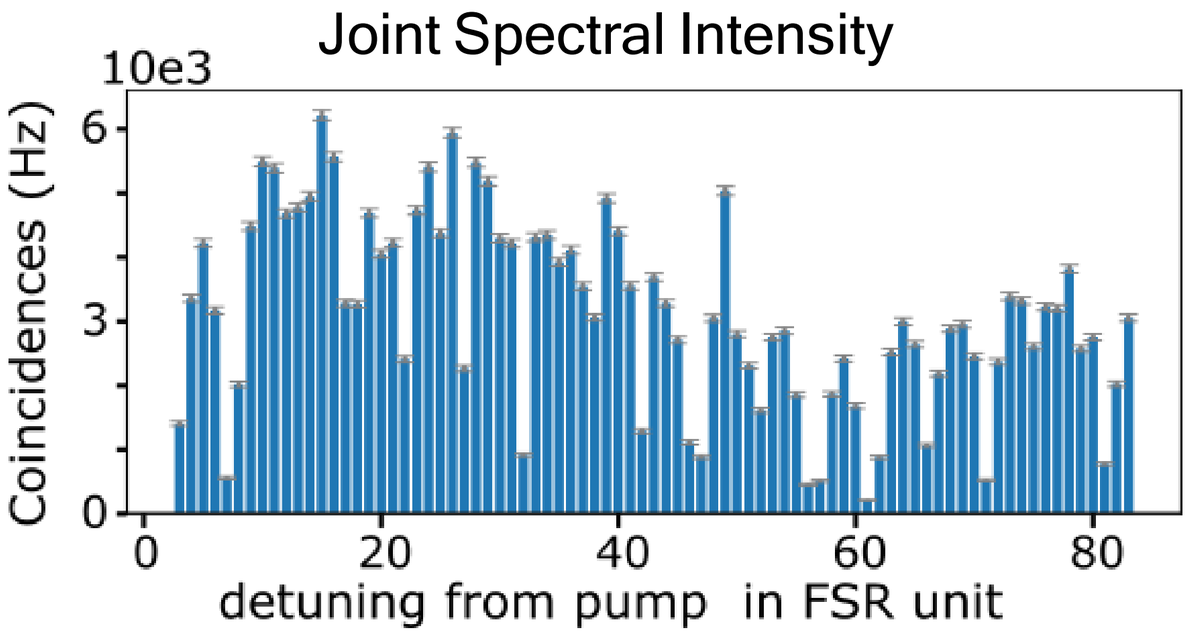
Experimental SKR and QBER: Qubit vs Qutrit

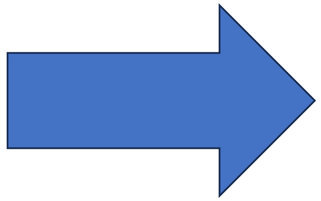


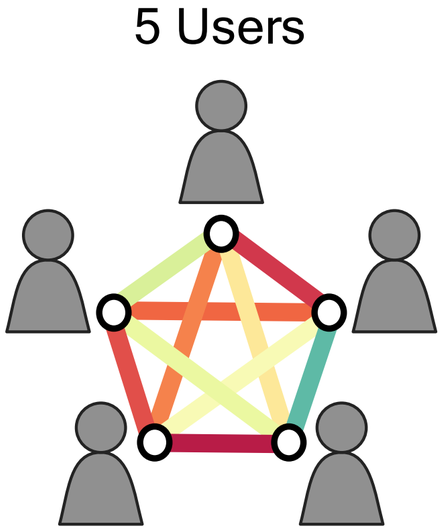


Work in progress → **Make both start with the same QBER**

Perspectives: Demultiplexing Qudits for a Fully Connected HDQKD Network



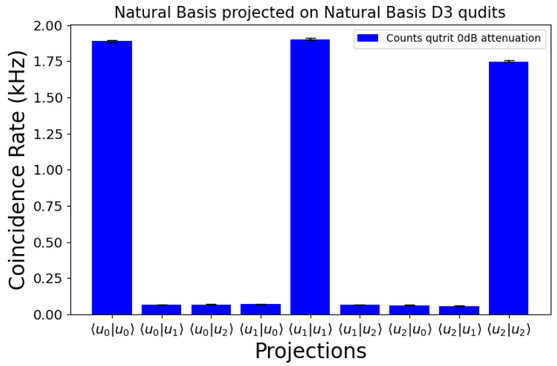


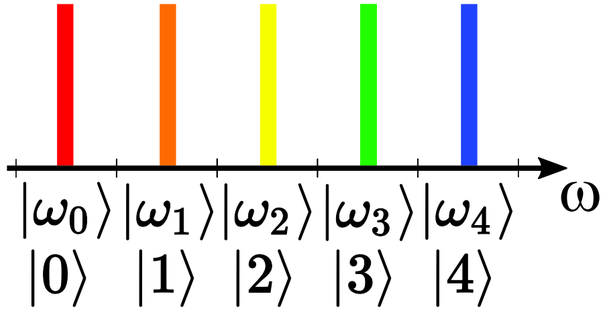


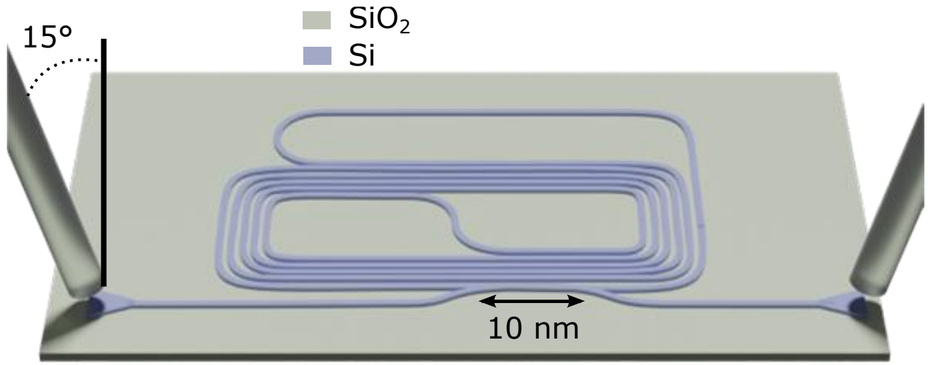
Fully Connected Quantum Key Distribution Network

[F.Appas, npj Quantum Inf 7, 118 (2021)] Polarization domain

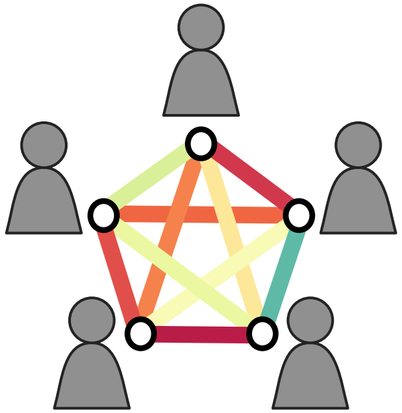
Conclusion

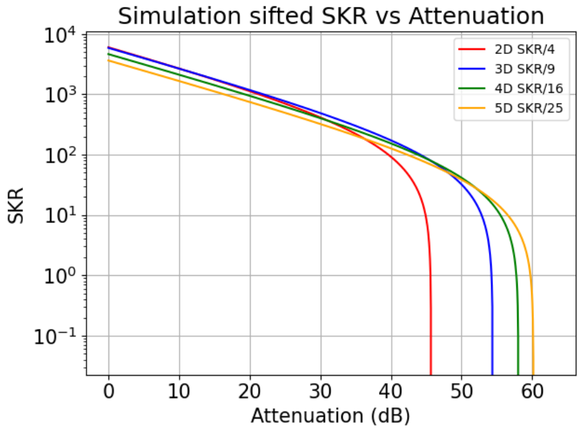






Entangled photonic quDits encoded in 21GHz spaced frequency bins generated on chip using a silicon micro resonator for Quantum Communications with telecom devices





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