Stockholm University

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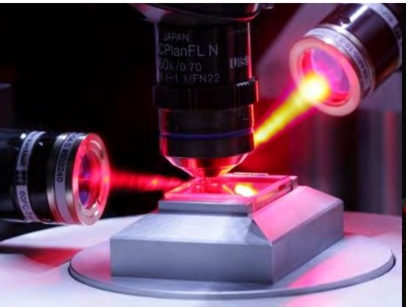
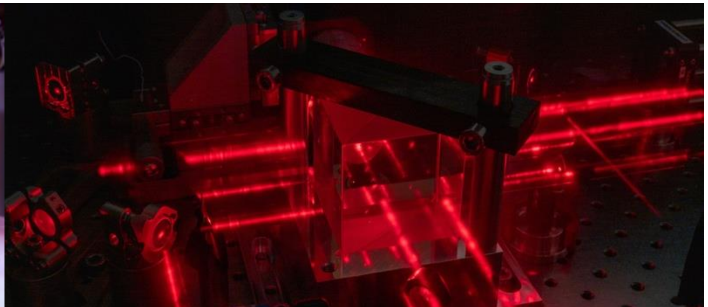
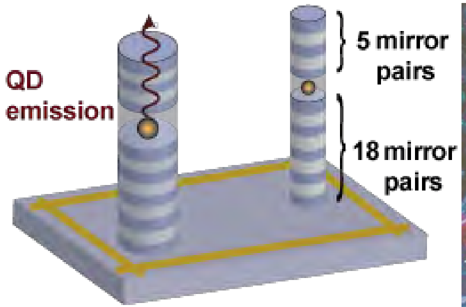
Carl Tryggers Stiftelse för Vetenskaplig Forskning

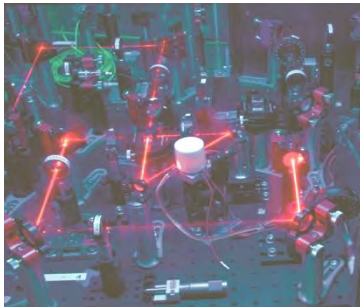
Vetenskapsrådet

Quantum light from quantum emitters: efficiency, characterization, and entanglement generation

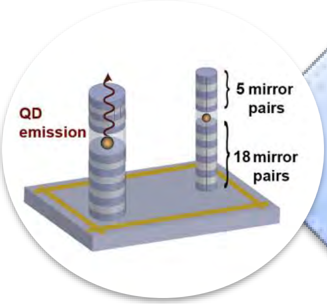
Ana Predojević

Stockholm University

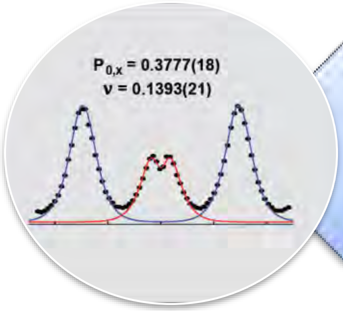


Quantum sources: efficiency, characterization, and entanglement generation



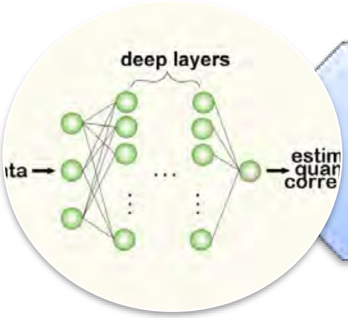
Novel sources of quantum light

Entanglement generation and efficiency engineering



Intrinsic correlations

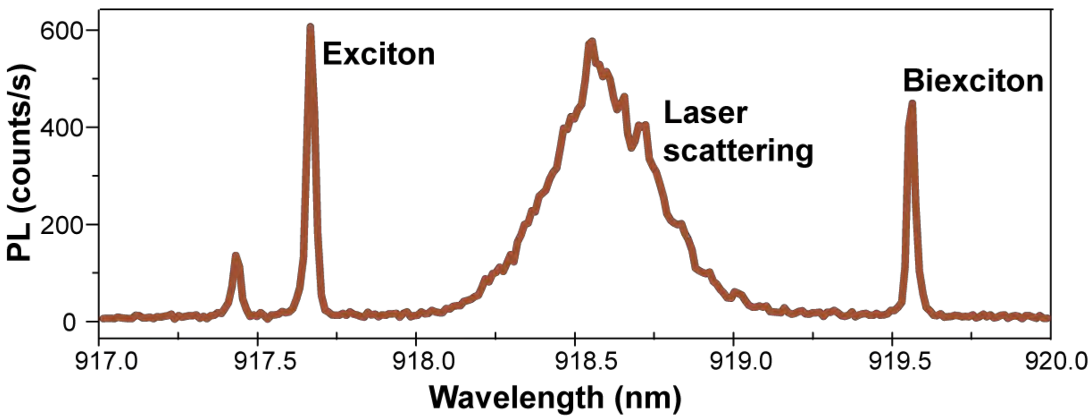
and two-photon interference and non-Gaussianity



Machine learning for quantum technologies

Entanglement quantification

Increasing the extraction efficiency



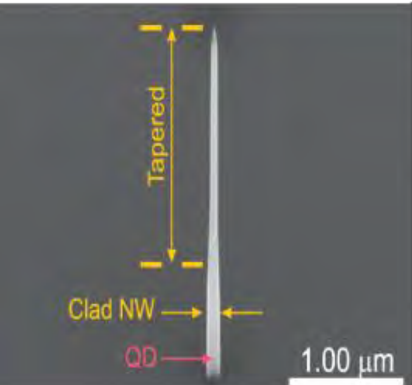
T. Huber et al. *Nano Letters* **14**, 7107 (2014).

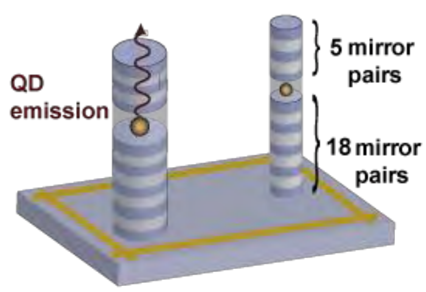
M. Khoshnegar et al. *Nature Comm.* **8**, 15716 (2017).

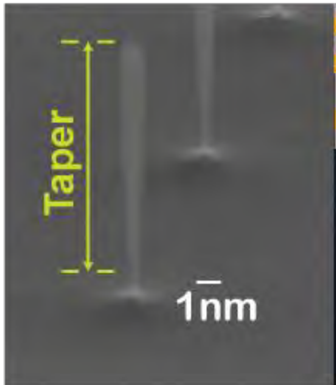
L. Ginés, et al. *Opt. Express* **29**, 4174 (2021).

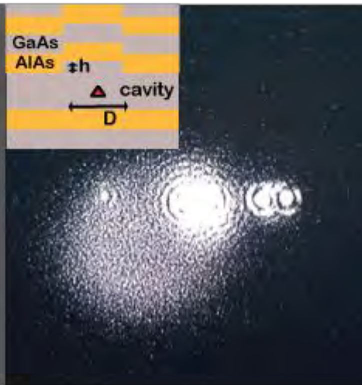
J. Jurkat et al. *Phys. Rev. Materials* **5**, 064603 (2021).

L. Ginés, et al. *Phys. Rev. Lett.* **129**, 033601 (2022).

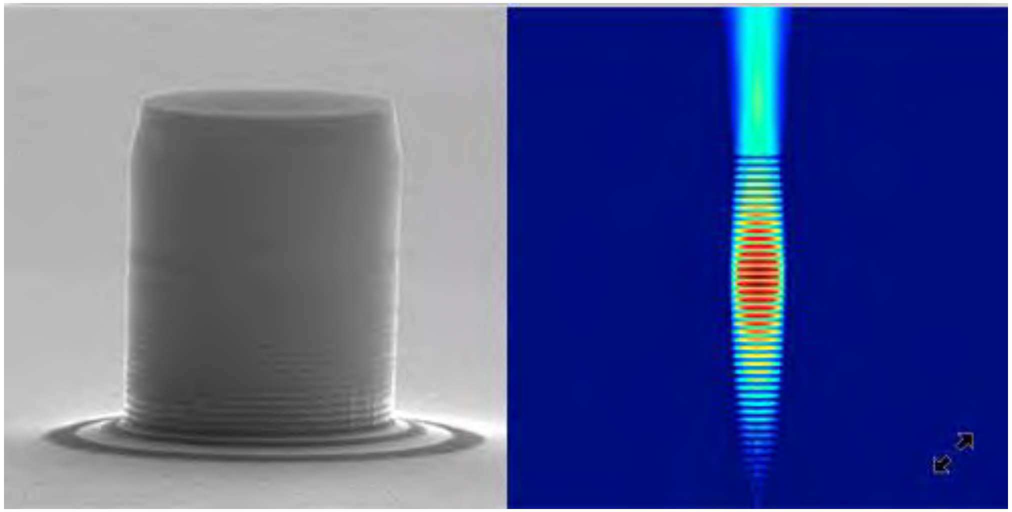








Increasing the extraction efficiency: low Q-factor cavity



Phys. Rev. Lett.116, 020401(2016)

moderate to Q-factor: 1000 – 10000

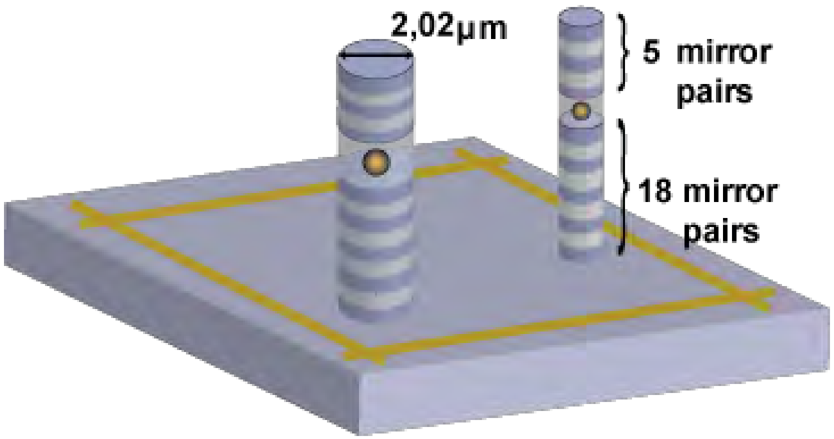
linewidth < 0.5nm

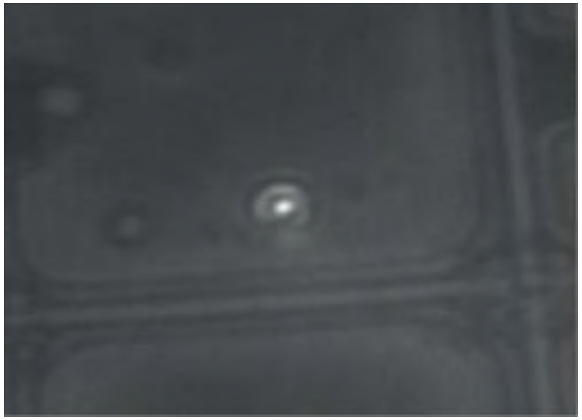
Purcell factor up to 7

N. Somaschi, et al. Nature Photonics10, 340–345 (2016)
X. Ding, et al. Phys. Rev. Lett.116, 020401(2016)
S. Gerhardt, et al. Phys. Rev. B100, 115305 (2019)

Increasing the extraction efficiency: low Q-factor cavity

$$\beta = \frac{F_p}{F_p + \Gamma_{supp}/\Gamma_{bulk}}$$





accuracy <30nm

Low Q-factor design: 200-300

on average linewidth of 4.5nm FWHM

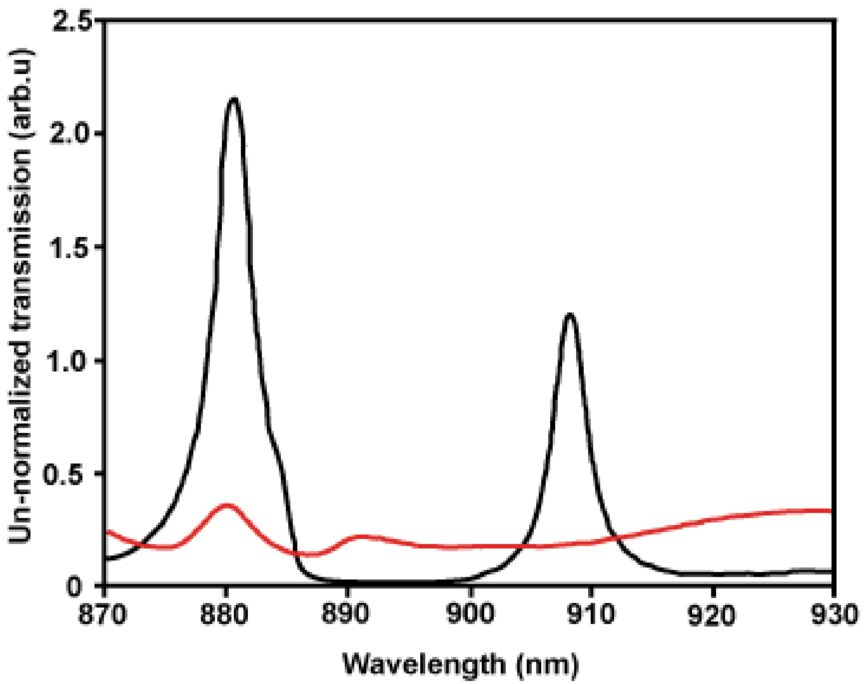
pillar diameter 1.6 – 8μm

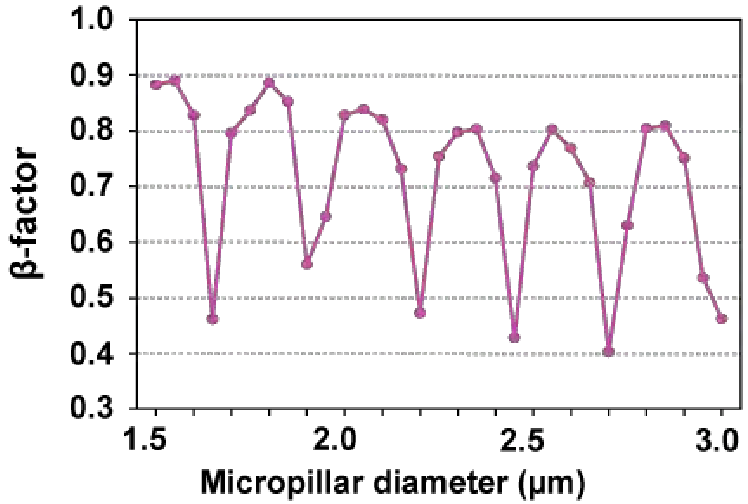
L. Ginés, et al. *Phys. Rev. Lett.* **129**, 033601 (2022).

Increasing the extraction efficiency: low Q-factor cavity

$$\beta = \frac{F_p}{F_p + \Gamma_{supp}/\Gamma_{bulk}}$$

1.50μm Pillar Diameter





Low Q-factor design: 200-300

on average linewidth of 4.5nm FWHM

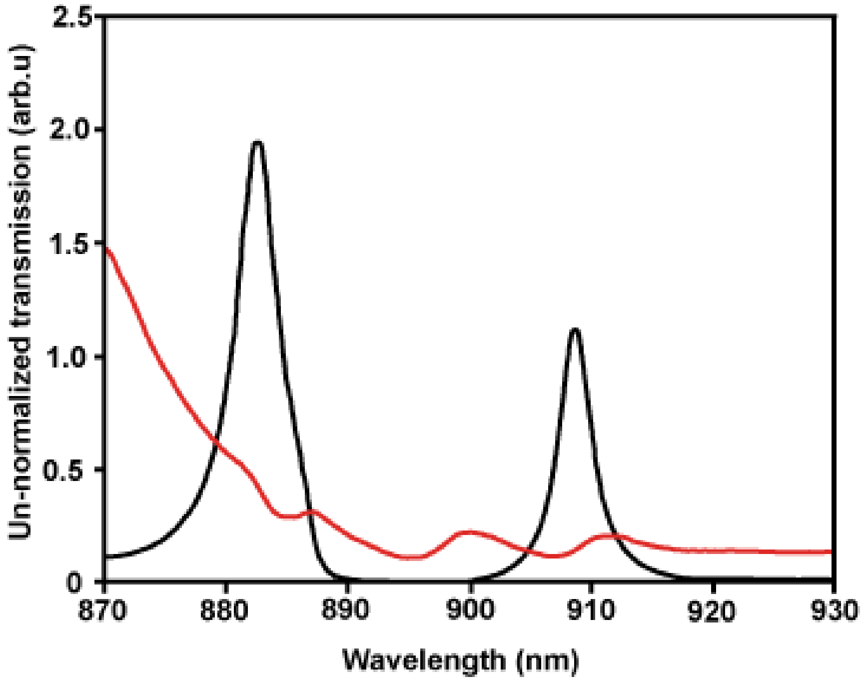
pillar diameter 1.6 – 8μm

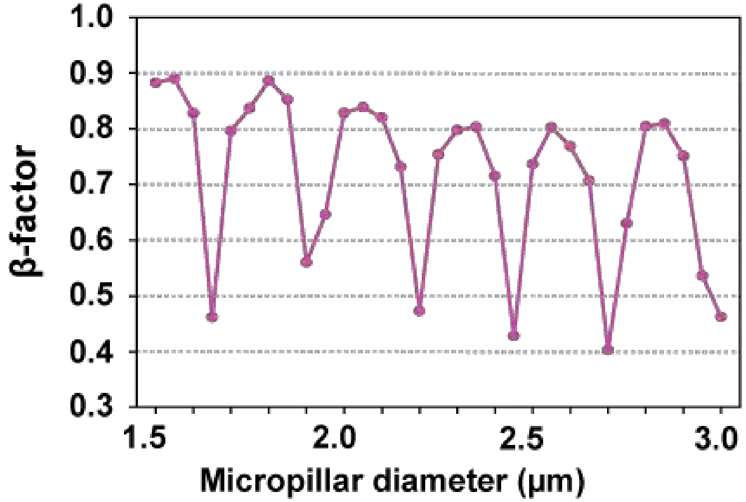
L. Ginés, et al. *Phys. Rev. Lett.* **129**, 033601 (2022).

Increasing the extraction efficiency: low Q-factor cavity

$$\beta = \frac{F_p}{F_p + \Gamma_{supp}/\Gamma_{bulk}}$$

1.55μm Pillar Diameter





Low Q-factor design: 200-300

on average linewidth of 4.5nm FWHM

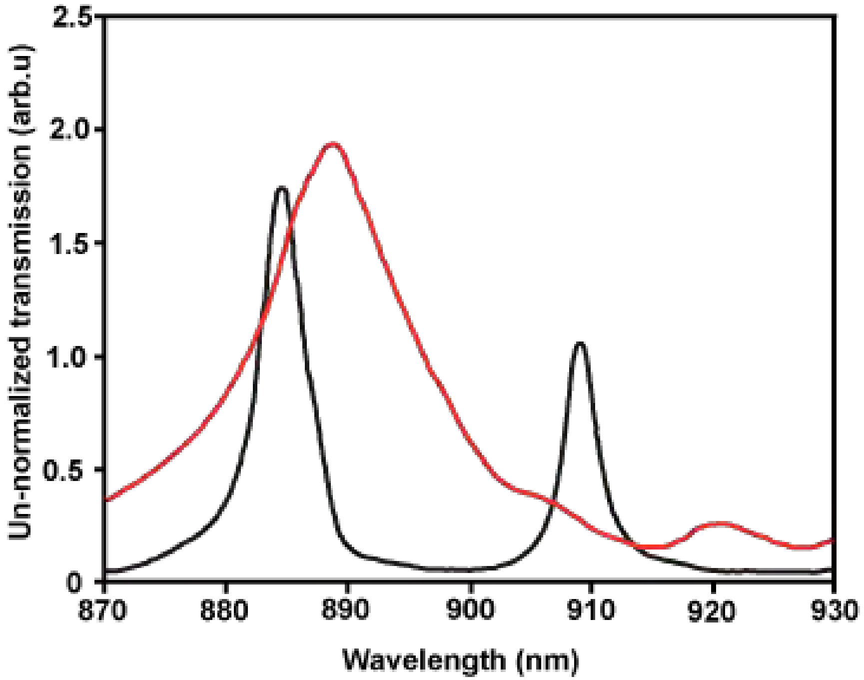
pillar diameter 1.6 – 8μm

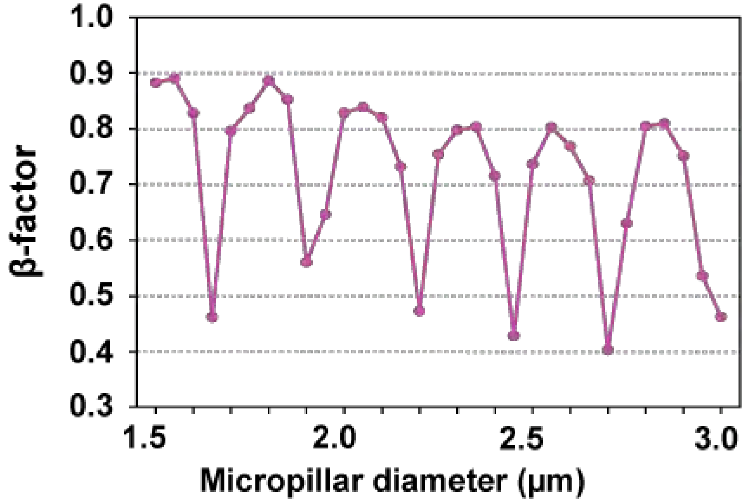
L. Ginés, et al. *Phys. Rev. Lett.* **129**, 033601 (2022).

Increasing the extraction efficiency: low Q-factor cavity

$$\beta = \frac{F_p}{F_p + \Gamma_{supp}/\Gamma_{bulk}}$$

1.60μm Pillar Diameter





Low Q-factor design: 200-300

on average linewidth of 4.5nm FWHM

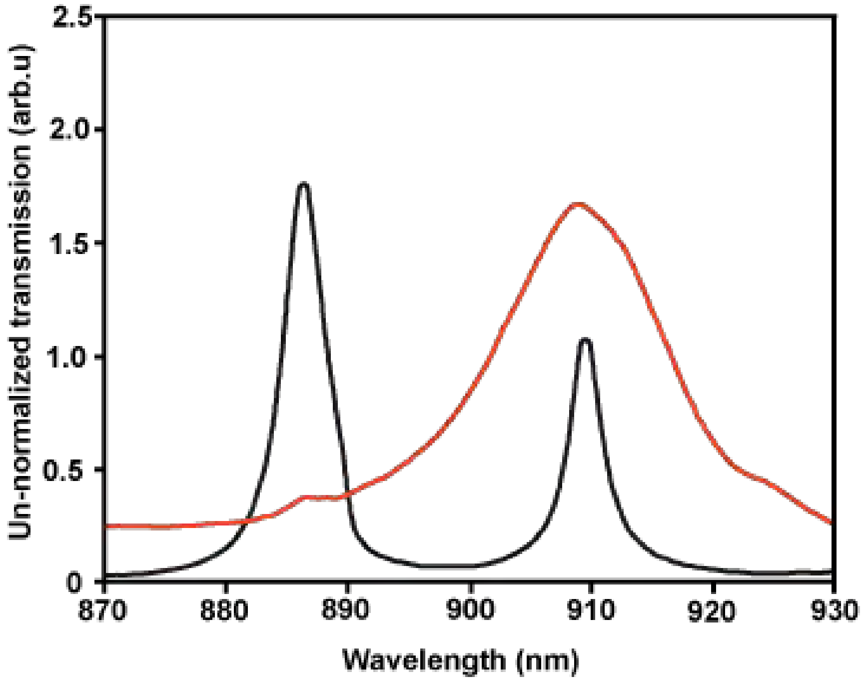
pillar diameter 1.6 – 8μm

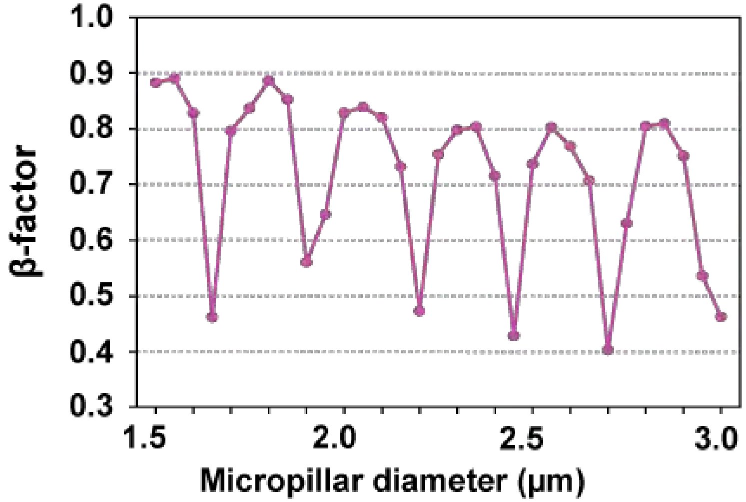
L. Ginés, et al. *Phys. Rev. Lett.* **129**, 033601 (2022).

Increasing the extraction efficiency: low Q-factor cavity

$$\beta = \frac{F_p}{F_p + \Gamma_{supp}/\Gamma_{bulk}}$$

1.65μm Pillar Diameter





Low Q-factor design: 200-300

on average linewidth of 4.5nm FWHM

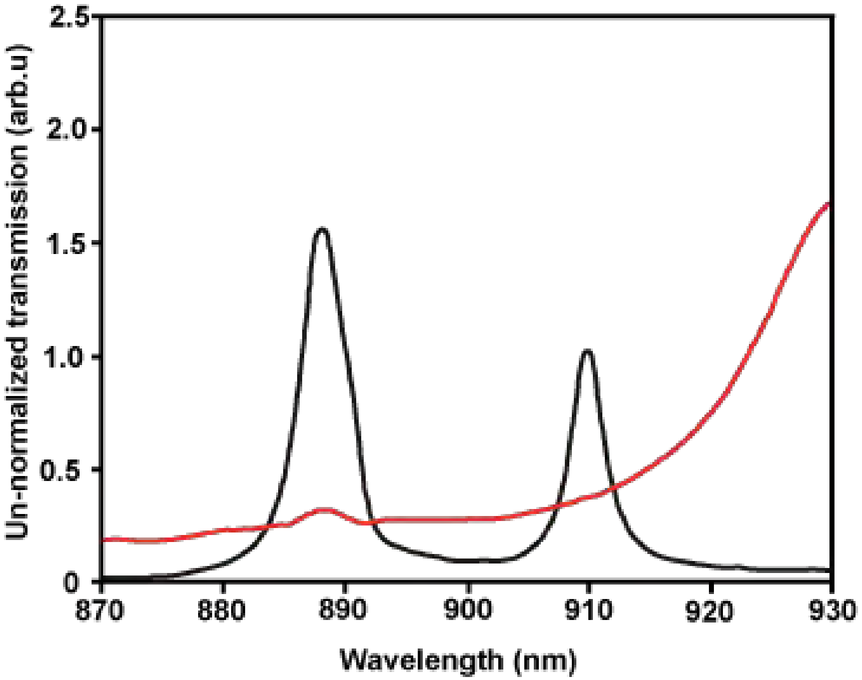
pillar diameter 1.6 – 8μm

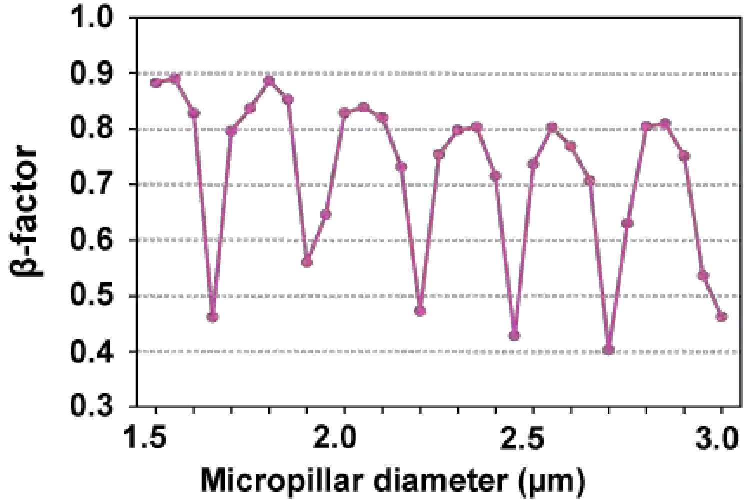
L. Ginés, et al. *Phys. Rev. Lett.* **129**, 033601 (2022).

Increasing the extraction efficiency: low Q-factor cavity

$$\beta = \frac{F_p}{F_p + \Gamma_{supp}/\Gamma_{bulk}}$$

1.70μm Pillar Diameter





Low Q-factor design: 200-300

on average linewidth of 4.5nm FWHM

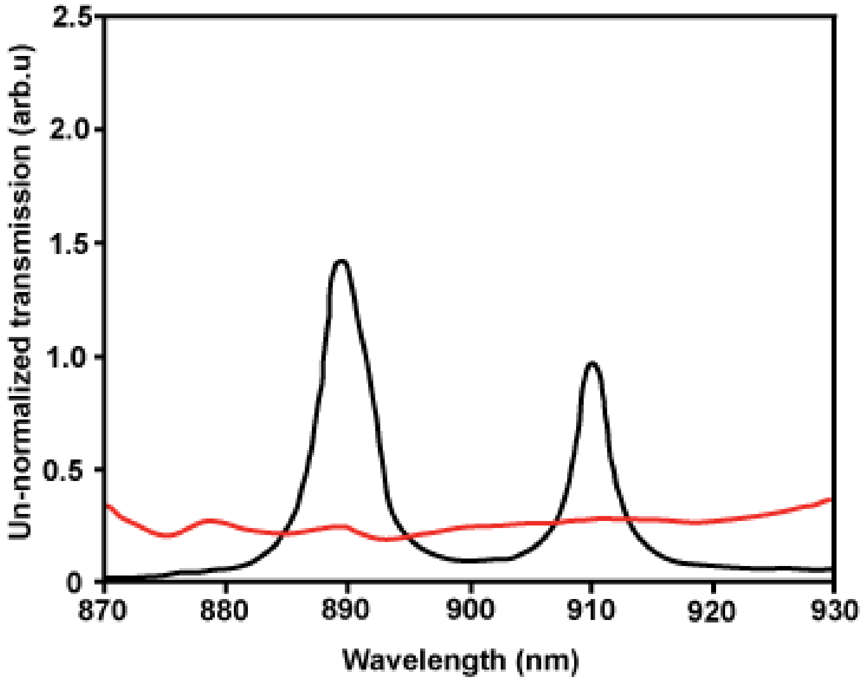
pillar diameter 1.6 – 8μm

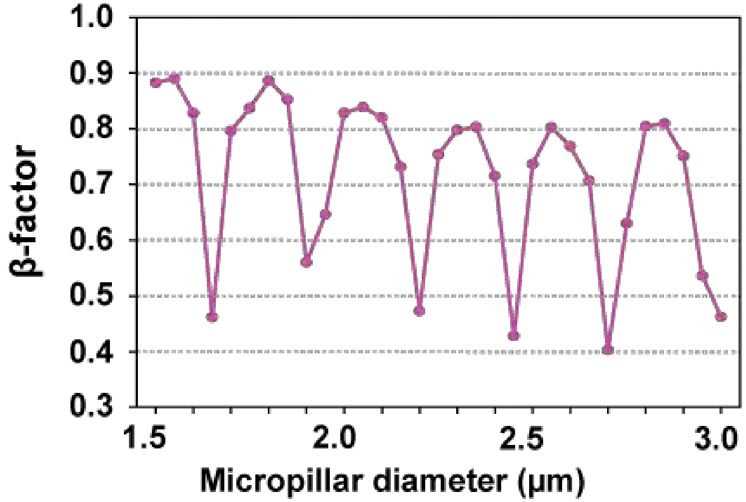
L. Ginés, et al. *Phys. Rev. Lett.* **129**, 033601 (2022).

Increasing the extraction efficiency: low Q-factor cavity

$$\beta = \frac{F_p}{F_p + \Gamma_{supp}/\Gamma_{bulk}}$$

1.75μm Pillar Diameter





Low Q-factor design: 200-300

on average linewidth of 4.5nm FWHM

pillar diameter 1.6 – 8μm

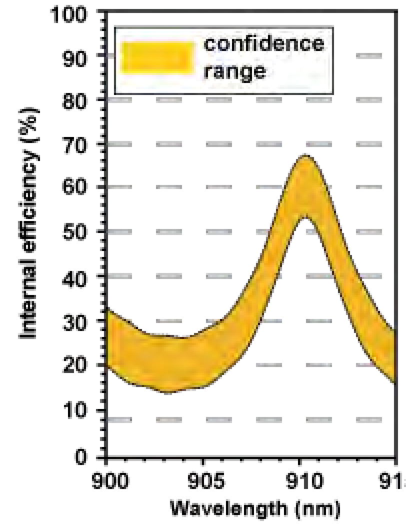
L. Ginés, et al. *Phys. Rev. Lett.* **129**, 033601 (2022).

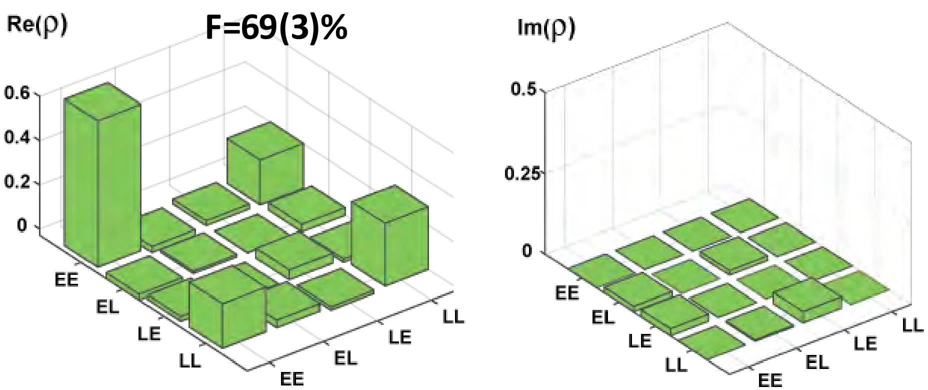
Increasing the extraction efficiency: low Q-factor cavity

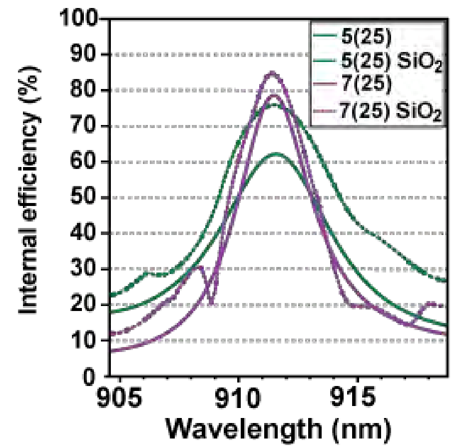
collection efficiency 69.4(10)% (0.68NA)

$$\frac{\text{counts}}{\eta_{det} \times \eta_{fc} \times \eta_{opt} \times rr}$$

counts = 400(1)kHz; η_{det} = 0.40; η_{fc} = 0.29(1); η_{opt} = 0.06(1); rr = 80MHz

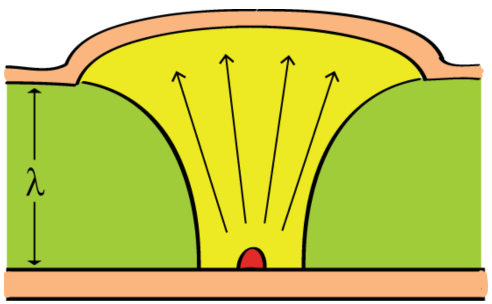


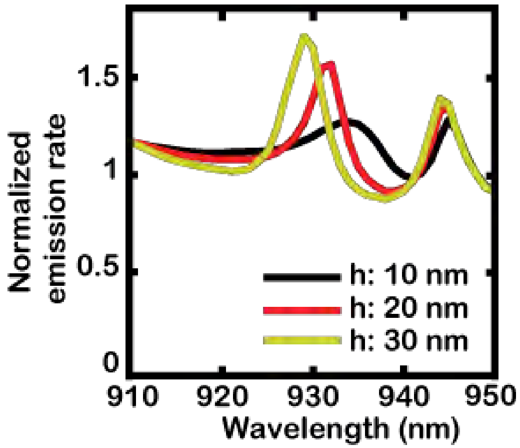


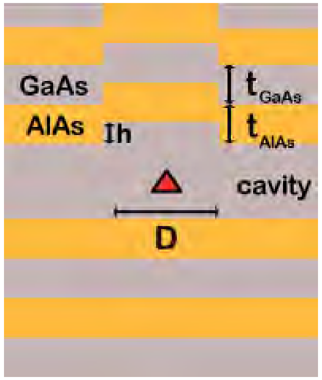


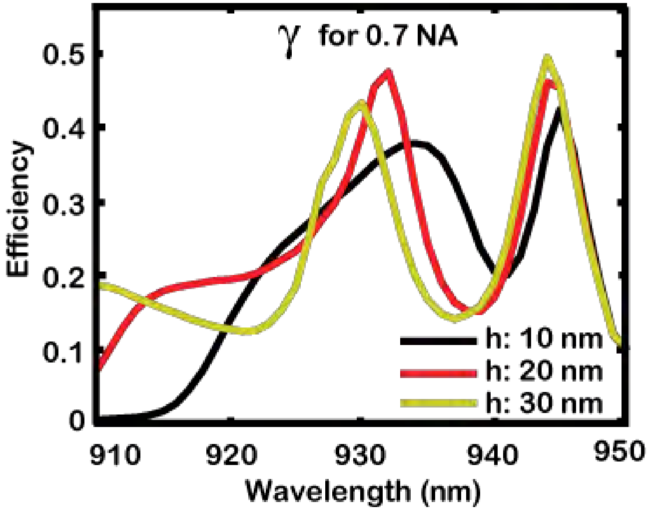
L. Ginés, et al. *Phys. Rev. Lett.* **129**, 033601 (2022).

Increasing the extraction efficiency: self-aligned cavity



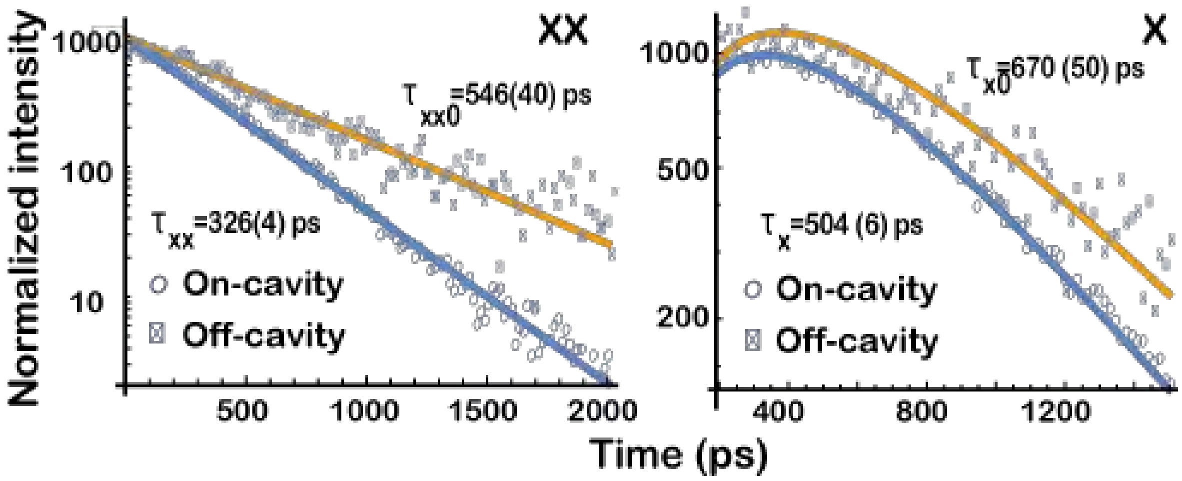






L. Ginés, et al. *Opt. Express* **29**, 4174 (2021).

Increasing the extraction efficiency: self-aligned cavity

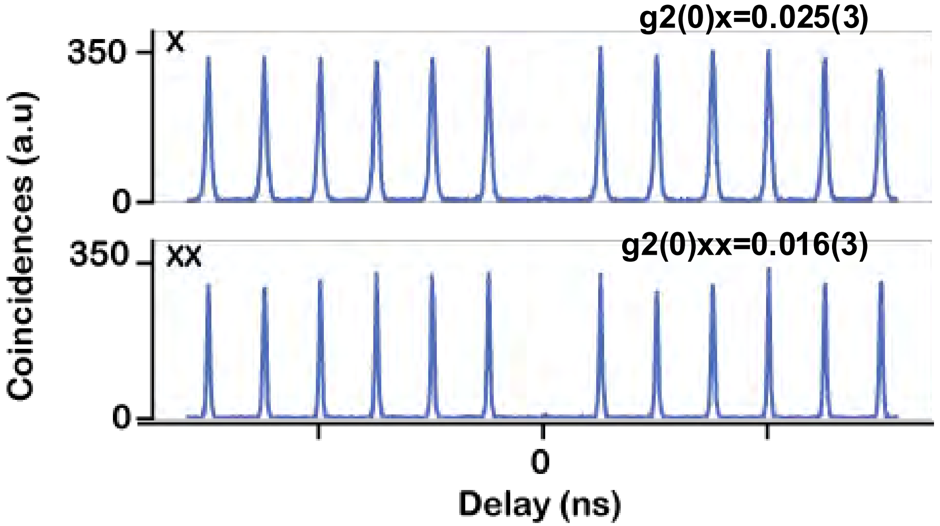


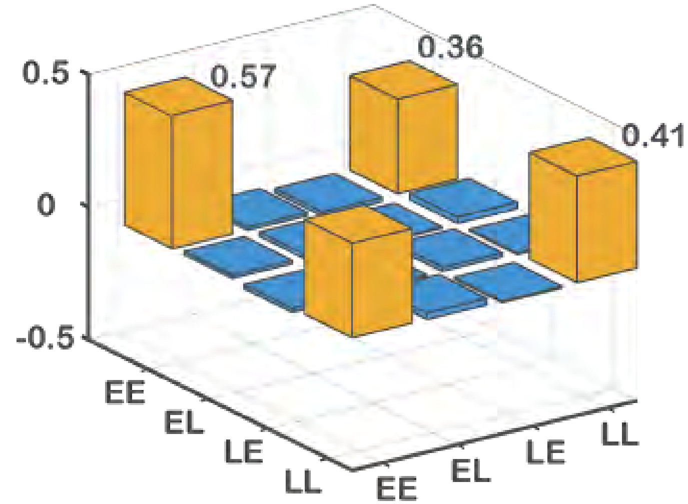
Purcell enhancement
(ranging from 1.2 to 1.7)

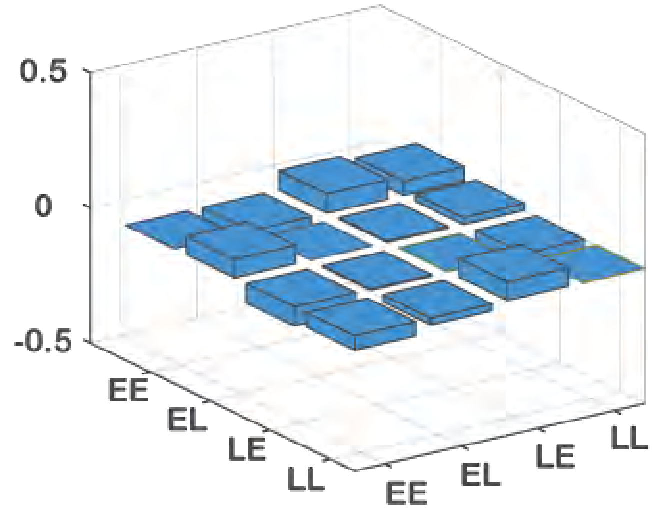
collection efficiency 17.1(10)% (0.62NA)

L. Ginés, et al. *Opt. Express* **29**, 4174 (2021).

Increasing the extraction efficiency: self-aligned cavity



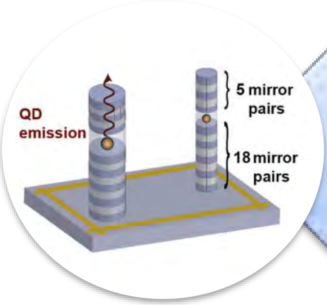




	time bin
concurrence	**0.70 (10)**
fidelity	**0.84(4)**

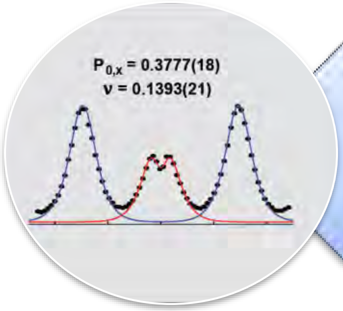
L. Ginés, et al. *Opt. Express* **29**, 4174 (2021).

Quantum sources: efficiency, characterization, and entanglement generation



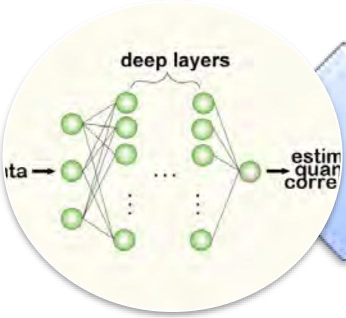
Novel sources of quantum light

Entanglement generation and efficiency engineering



Intrinsic correlations

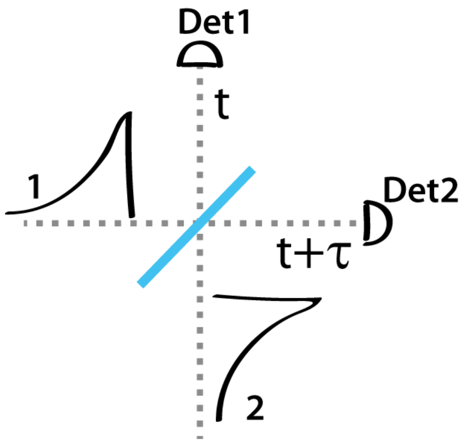
and two-photon interference and non-Gaussianity

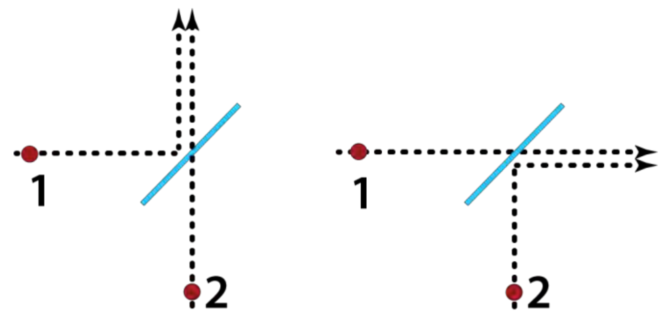


Machine learning for quantum technologies

Entanglement quantification

Two – photon interference





$$G^{(2)}(t,\tau) = \frac{1}{4}\big[I_1(t)\, I_2(t+\tau) + I_2(t) I_1(t+\tau) - G_1^{(1)}(t,\tau)(G_2^{(1)}(t,\tau))^* - (G_1^{(1)}(t,\tau))^* G_2^{(1)}(t,\tau) \big]$$

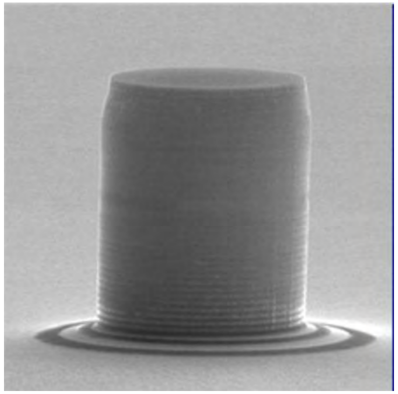
- in the case the photon 1 and photon 2 are identical

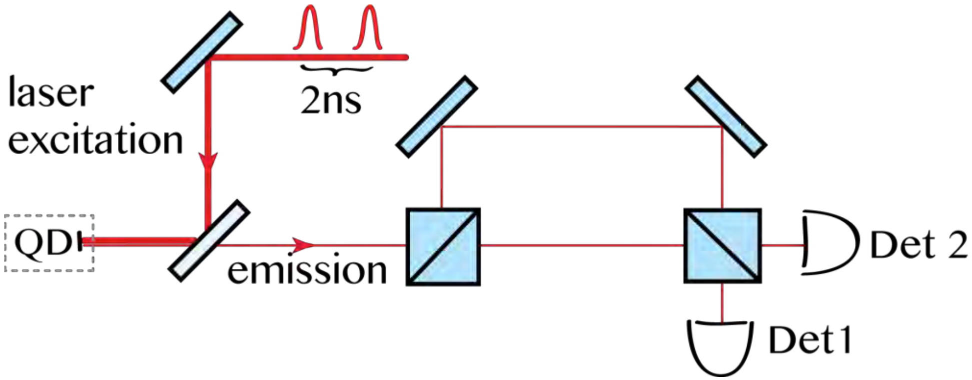
$$G^{(2)}(t,\tau) = \frac{1}{4}\big[2I(t)I(t+\tau) - 2|G^{(1)}(t,\tau)|^2 \big]$$

- importance of two-photon interference:

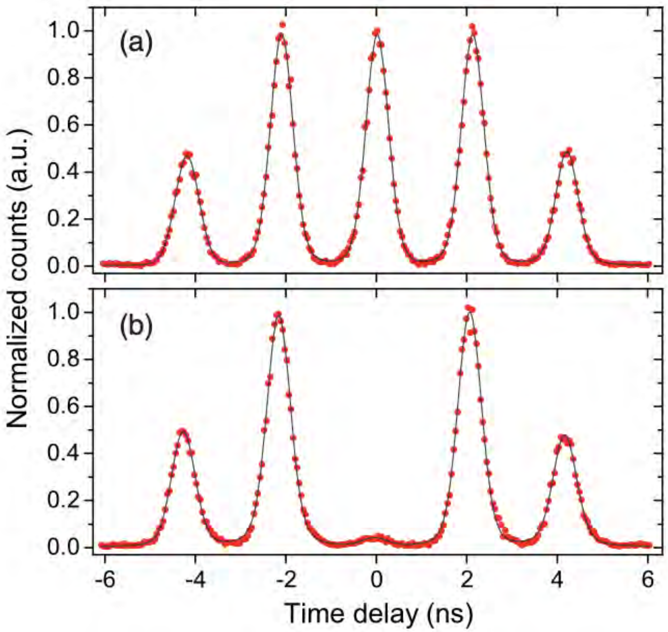
- **quantum teleportation and entanglement swapping**
- **quantum photonic processors**

Two – photon interference without cascade correlations





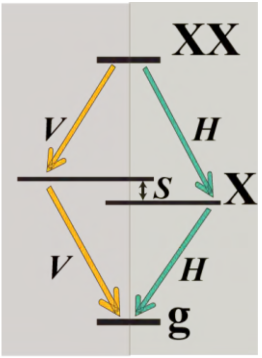
Phys. Rev. Lett.116, 020401(2016)



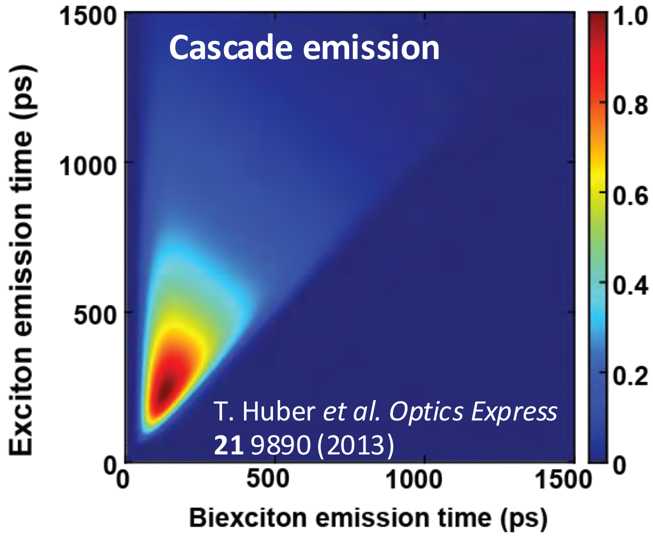
opposite polarizations
visibility= (max-min)/(max+min)= 1

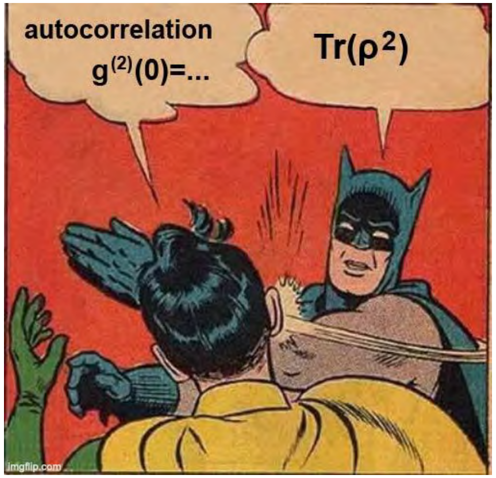
equal polarizations

Cascade correlations



XX – Biexciton
X – Exciton
g – ground state





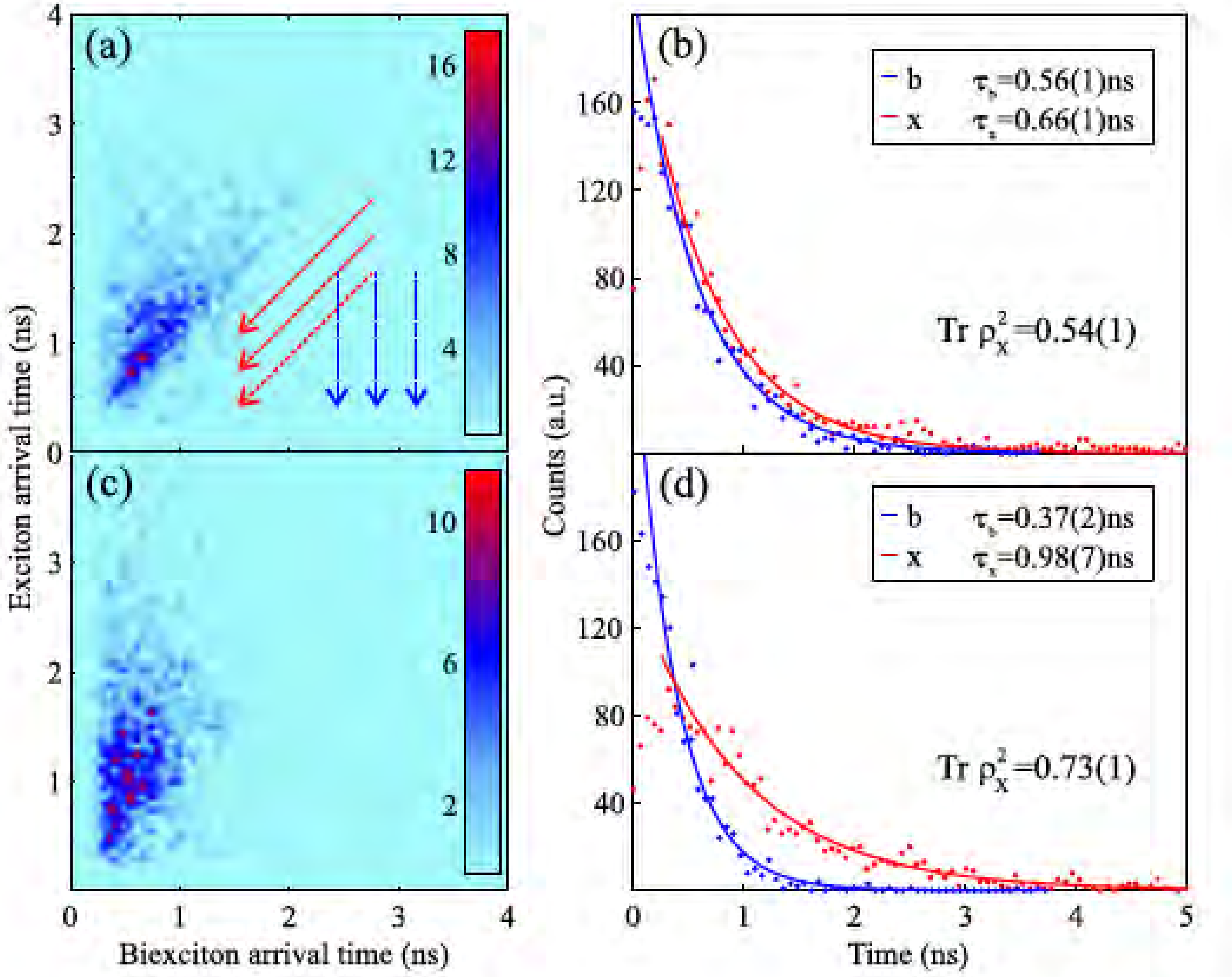
$$\psi(t_b, t_x) = 2\sqrt{\Gamma_b \Gamma_x} \mathrm{e}^{-\Gamma_b t_b} \Theta(t_b) \mathrm{e}^{-\Gamma_x (t_x - t_b)} \Theta(t_x - t_b)$$

$$\rho_x = \mathrm{Tr}_b(\psi^* \psi)$$

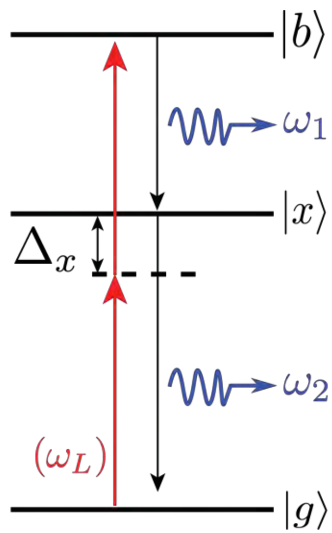
$$\mathrm{Tr}(\rho_x^2) = \frac{\Gamma_b}{\Gamma_b + \Gamma_x}$$

*F. Redivo Cardoso, et al. Phys. Rev. Research **7**, 013190 (2025)*

Cascade correlations



Two – photon interference and cascade decay

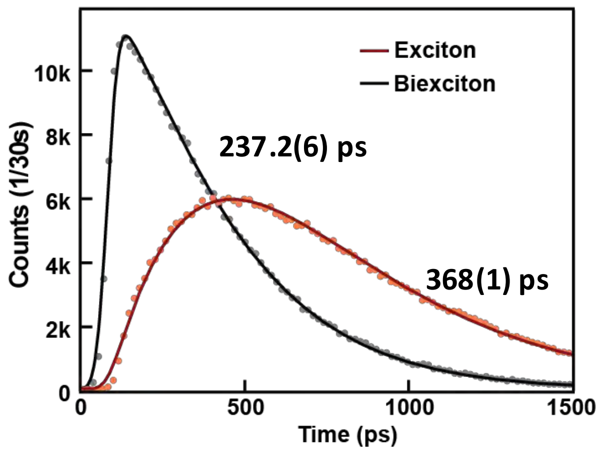


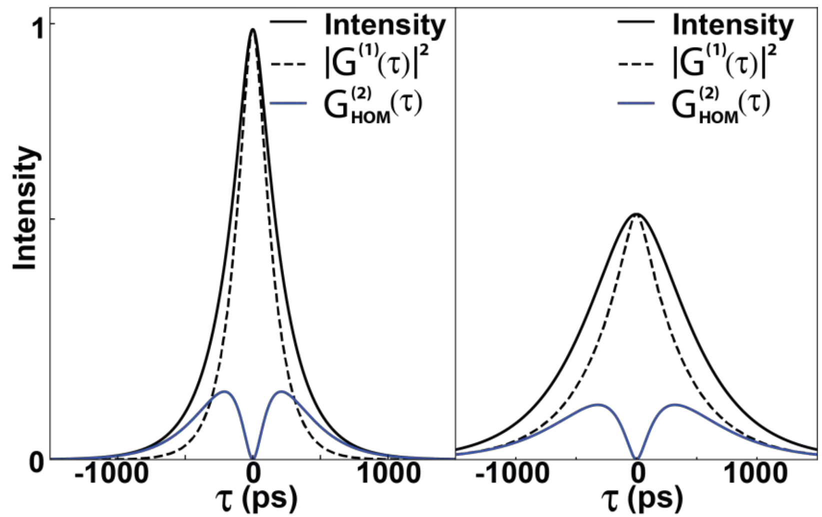
$$H_s = \sum_{j=1}^{2} \left\{ \omega_j \xi_j^\dagger \xi_j + g \left[(\sigma_{xb} + \sigma_{gx}) \xi_j^\dagger + \text{h.c.} \right] \right\}$$

sensor method

$$\mathcal{L}_j \rho = \frac{\kappa_j}{2} \left(2\xi_j \rho \xi_j^\dagger - \xi_j^\dagger \xi_j \rho - \rho \xi_j^\dagger \xi_j \right)$$

additional Lindblad terms



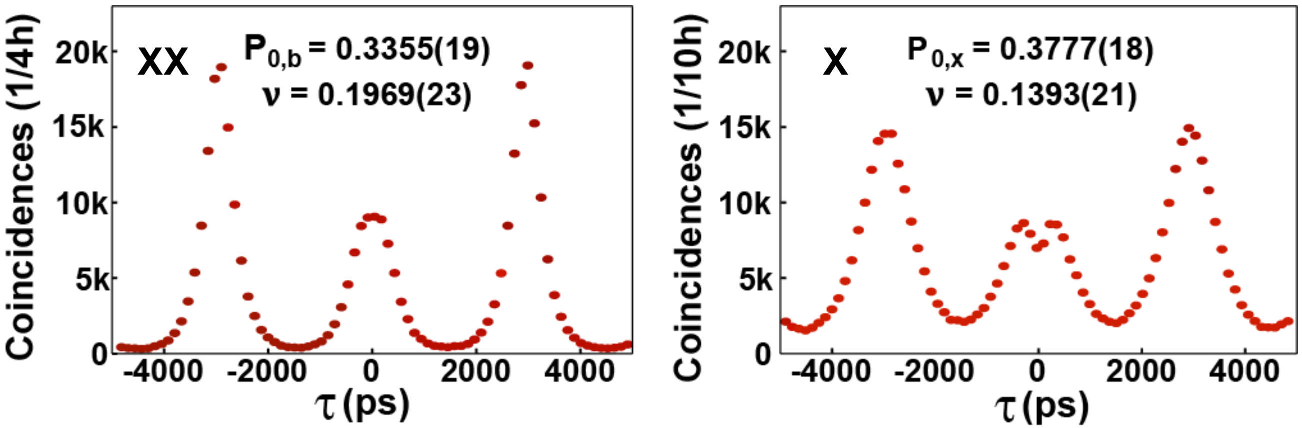


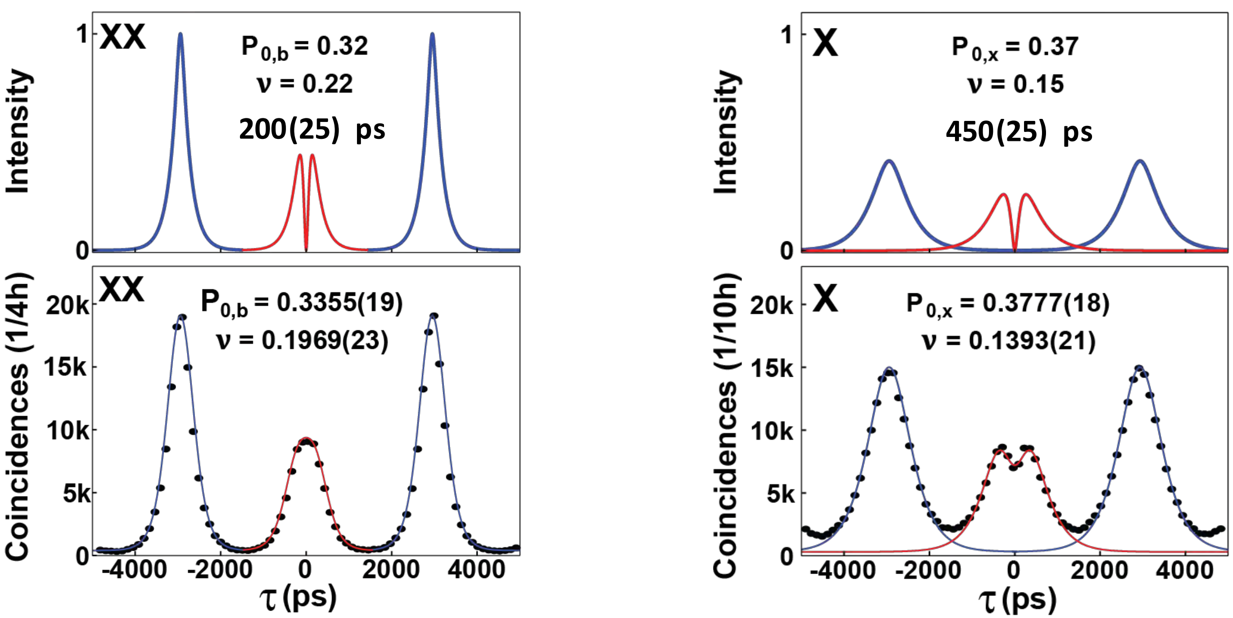
P_0 = 0.15

visibility=v=0.54

F. Redivo Cardoso, et al. Phys. Rev. Research ***7****, 013190 (2025)*

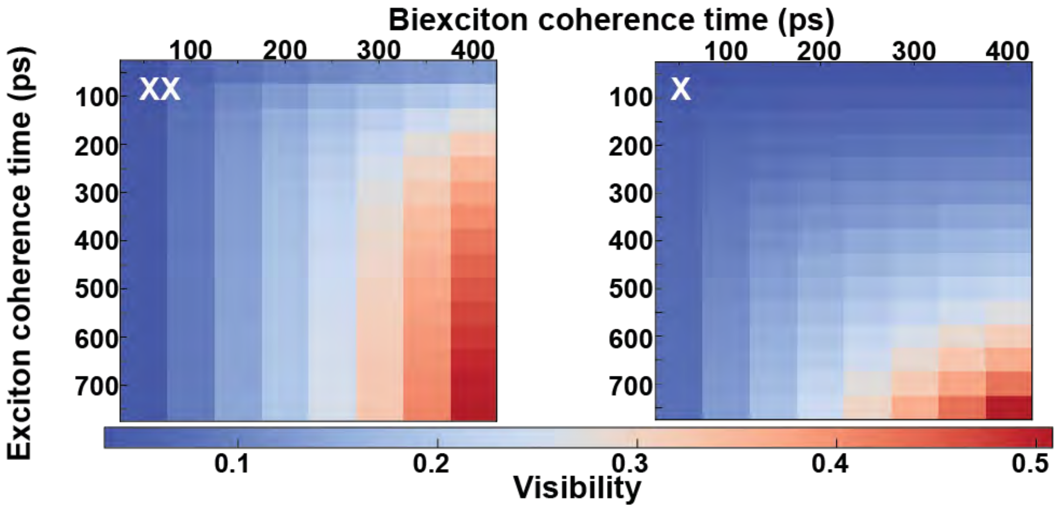
Two – photon interference and cascade decay





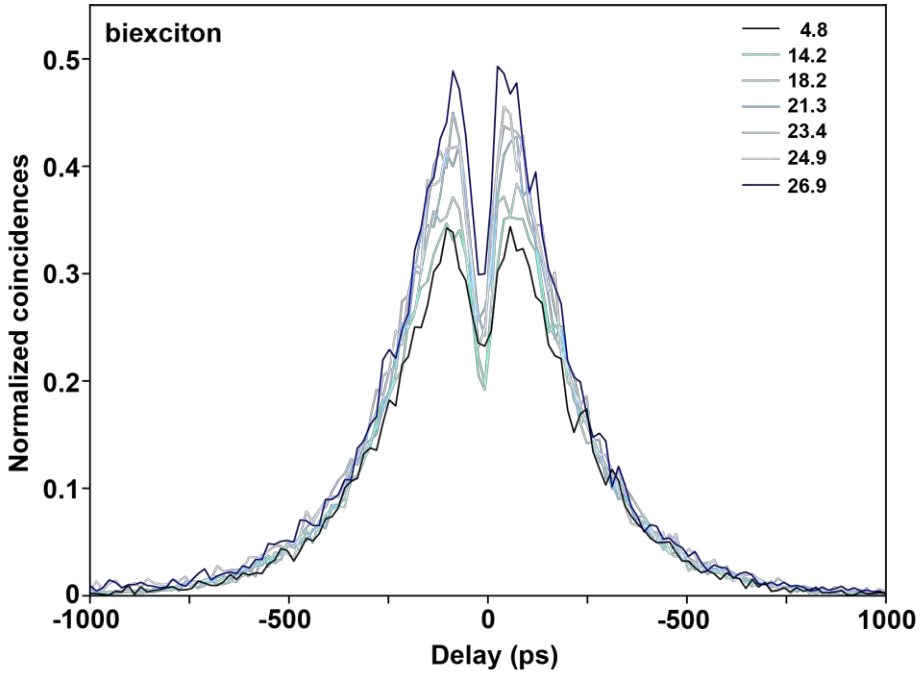
F. Redivo Cardoso, et al. Phys. Rev. Research ***7****, 013190 (2025)*

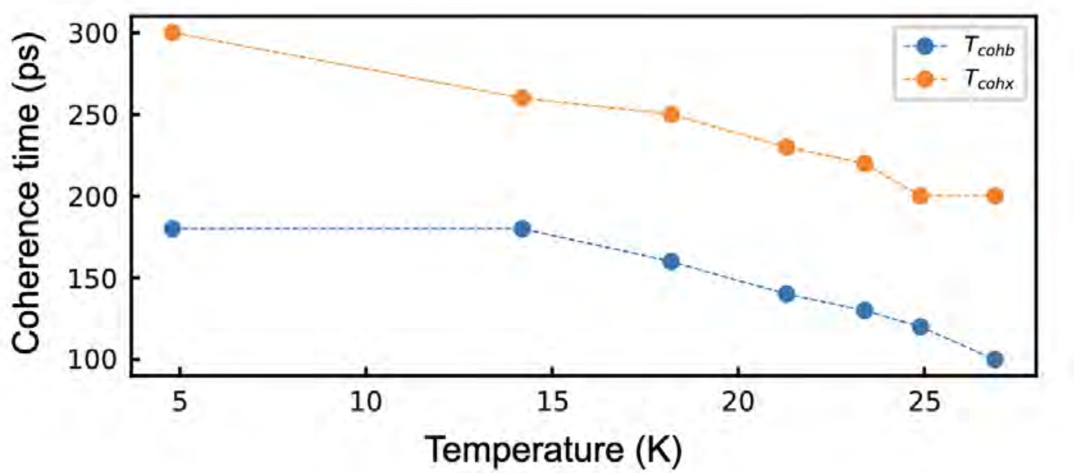
Two – photon interference and cascade decay



*F. Redivo Cardoso, et al. Phys. Rev. Research **7**, 013190 (2025)*

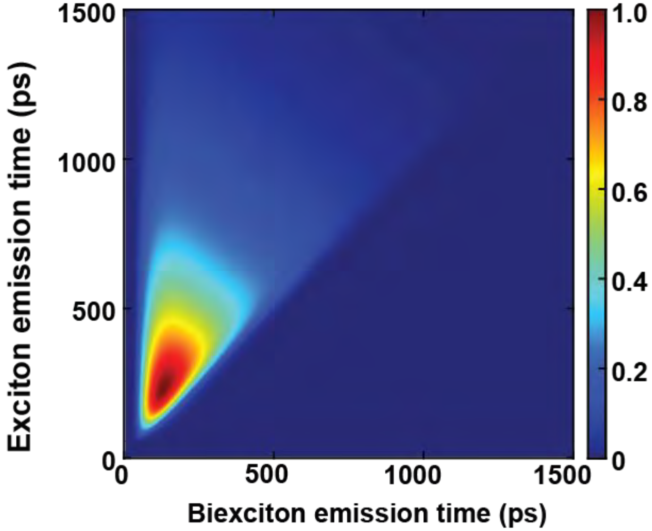
Two – photon interference and cascade decay



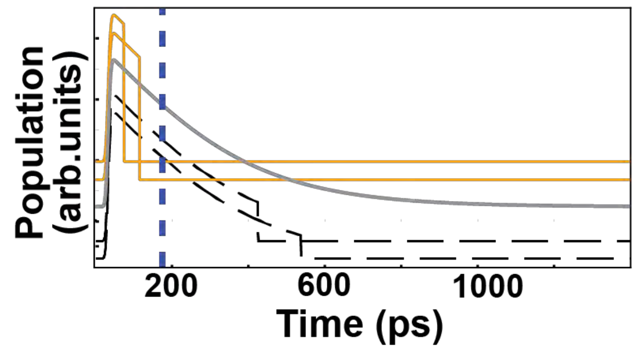


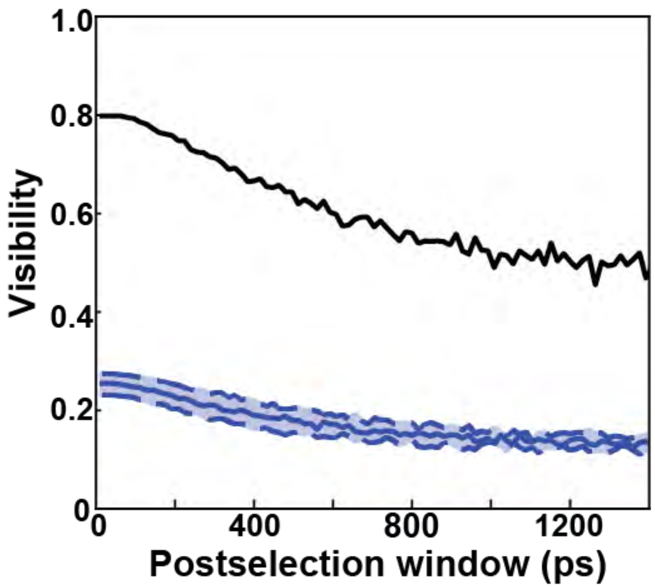
J. Lee, et al. https://arxiv.org/abs/2505.16848 (2025)

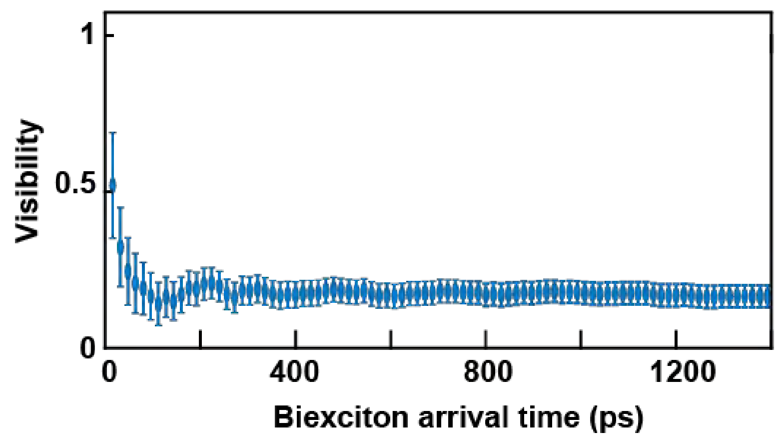
Two – photon interference and postselection



$$H' = H_I - \frac{i\hbar}{2}\sum_k C_k^\dagger C_k$$

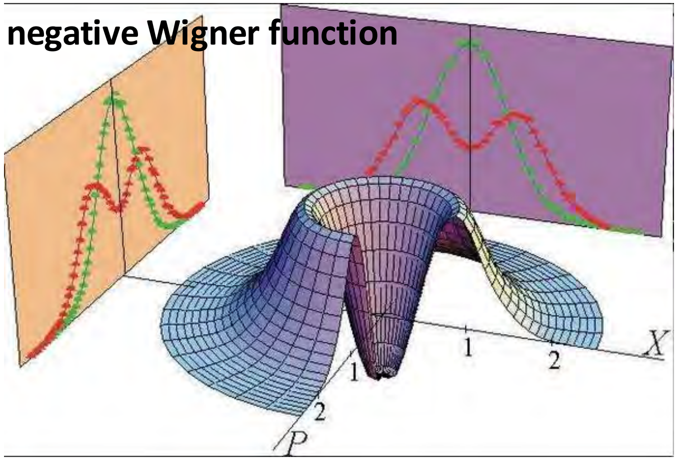


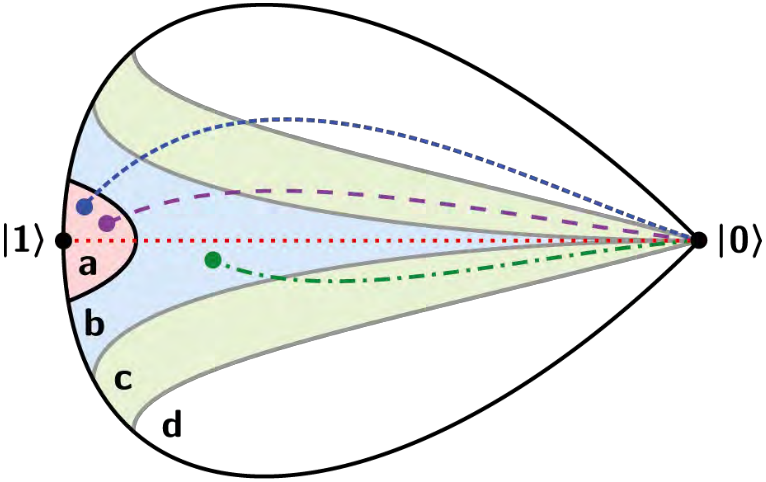




F. Redivo Cardoso, et al. Phys. Rev. Research ***7****, 013190 (2025)*

Losses resistant certification of quantum non-Gaussian states





photonic quantum states are subject to losses

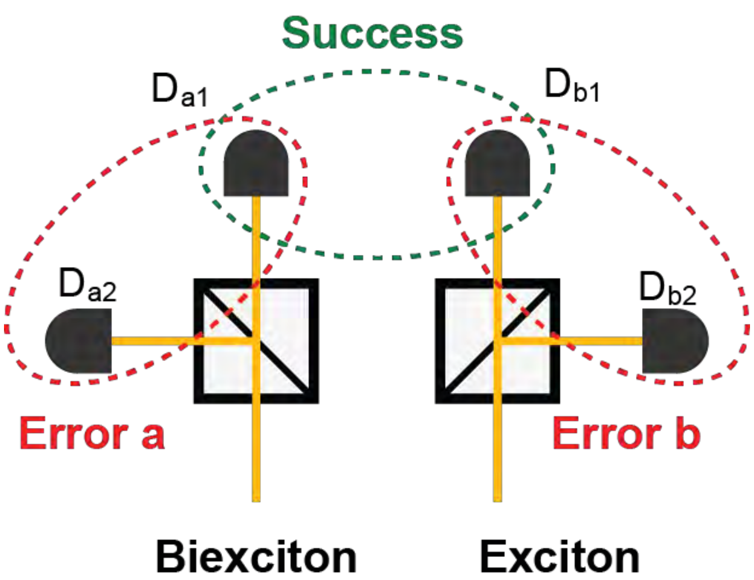
I. Straka et al Phys. Rev. Lett. 113, 223603 (2014)

a) negative Wigner function
b) quantum non-Gaussian state
c) non-classical state
d) any other

Losses resistant certification of quantum non-Gaussian states

$$P_{1,\eta}^3 \gtrsim \eta / \left[4(2-\eta)\right] P_{2,\eta}$$

η = the transmission of the lossy channel



Two mayor challenges:

a) accurate estimation of probabilities

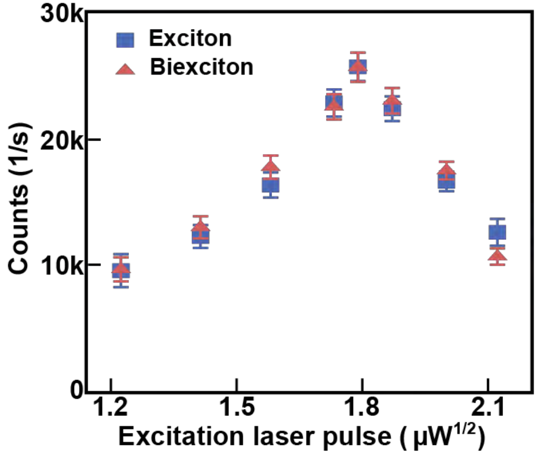
b) accurate estimation of the loss

$$P_{s,\eta} = C_s / C_0$$

$$P_{e,\eta} = (C_{e,a} + C_{e,b}) / 2C_0$$

R. Checchinato, et al. arXiv:2408.11590(2024) .

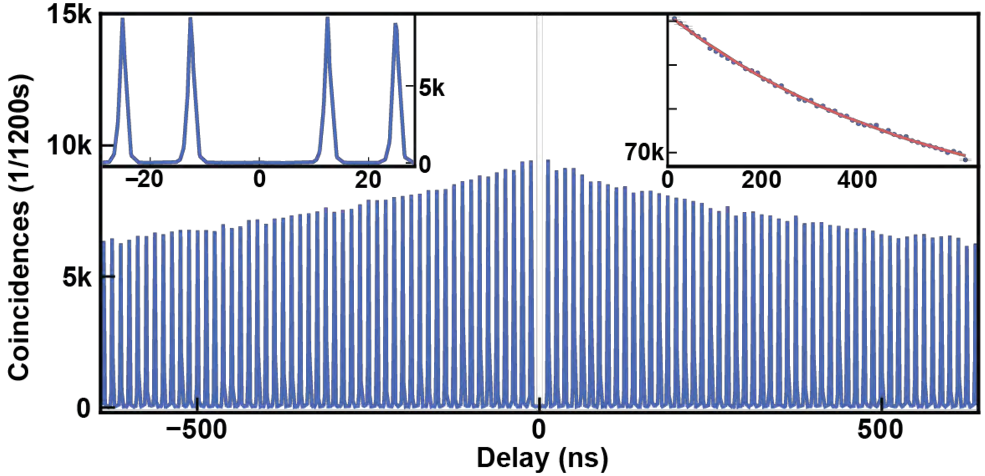
Losses resistant certification of quantum non-Gaussian states



$$P_{s,\eta} = C_s/C_0$$

$$C_0 = 11.32(12)\ \mathrm{MHz}$$

a) **blinking rate 0.56.6(6)**
b) **excitation rate π/2**
c) **polarization filtering 0.50**



R. Checchinato, et al. arXiv:2408.11590(2024) .

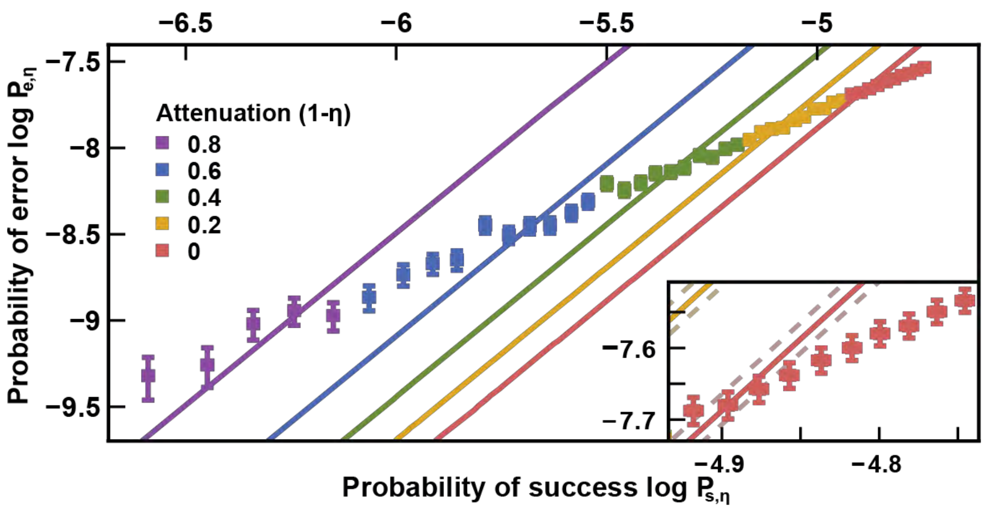
Losses resistant certification of quantum non-Gaussian states

$$P_{e,\eta} = (C_{e,a} + C_{e,b})/2C_0$$

356(18)+430(21)

$$P_{s,\eta} = 1.797 \pm 0.020 \cdot 10^{-5}$$

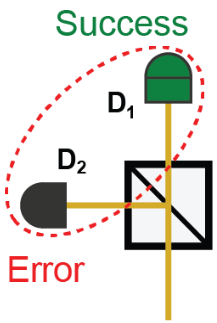
$$P_{e,\eta} = 2.93 \pm 0.11 \cdot 10^{-8}$$

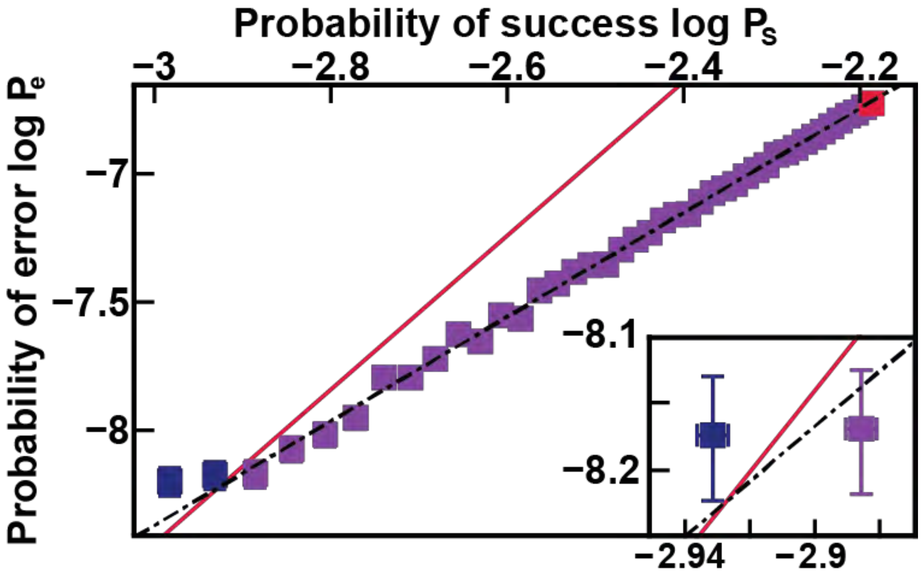


Attenuation $(1-\eta)$	non-Gaussian depth (dB)
0	0.764 ± 0.039
0.2	0.740 ± 0.035
0.4	0.710 ± 0.033
0.6	0.667 ± 0.035
0.8	0.595 ± 0.049

R. Checchinato, et al. arXiv:2408.11590(2024) .

Losses resistant certification of quantum non-Gaussian states



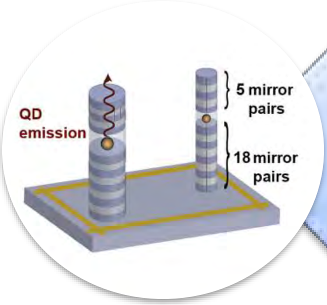


$$7.41 \pm 0.11 \text{ dB}$$

criterion is extremely resilient to losses

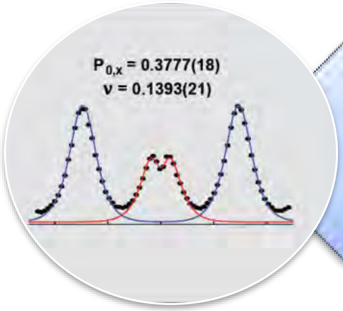
R. Checchinato, et al. arXiv:2408.11590(2024) .

Quantum sources: efficiency, characterization, and entanglement generation



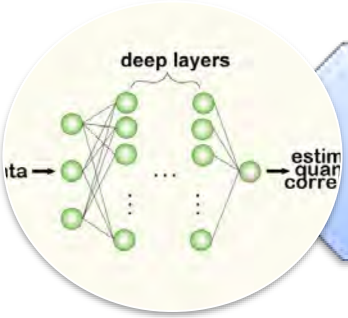
Novel sources of quantum light

Entanglement generation and efficiency engineering



Intrinsic correlations

and two-photon interference and non-Gaussianity



Machine learning for quantum technologies

Entanglement quantification

Entanglement quantification

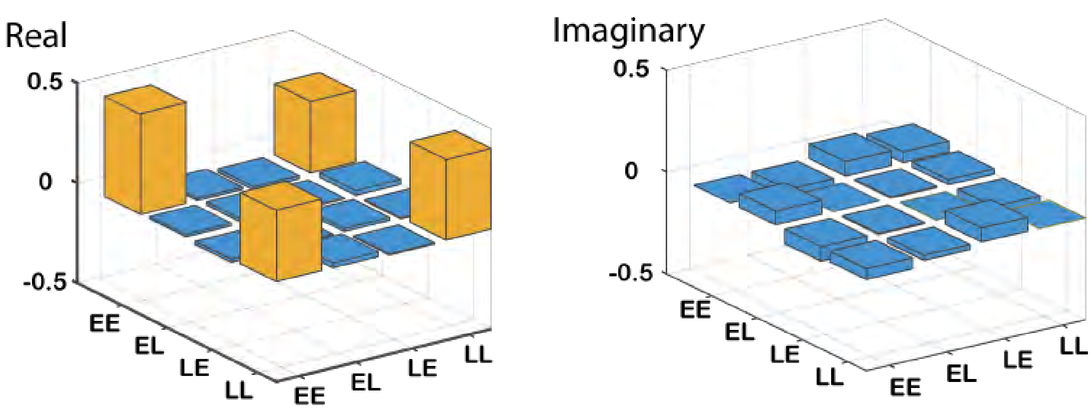
- **direct measurement by interference of identical copies of the state**
  P. Horodecki, Phys. Rev. Lett. 910, 167901 (2003).

- **quantum state tomography**
  M. Paris, J. Rehacek, Quantum State Estimation (Springer-Verlag, 2004).

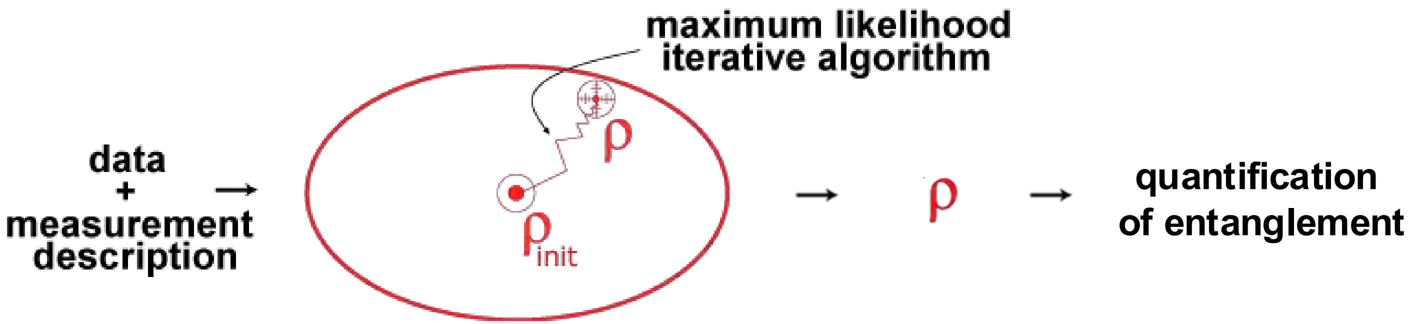
- **quantum state tomography with a priori information**
  D. Gross, et al. Phys. Rev. Lett. 105, 150401 (2010).

- **shadow tomography**
  S. Aaronson in STOC 2018: Proceedings of the 50th Annual ACM SIGACT Symposium on Theory of Computing (Association for Computing Machinery, 2018), pp. 325-388

- **entanglement witnessing**
  P. Horodecki, A. Ekert, Phys. Rev. Lett. 89, 127902 (2002).



Entanglement quantification



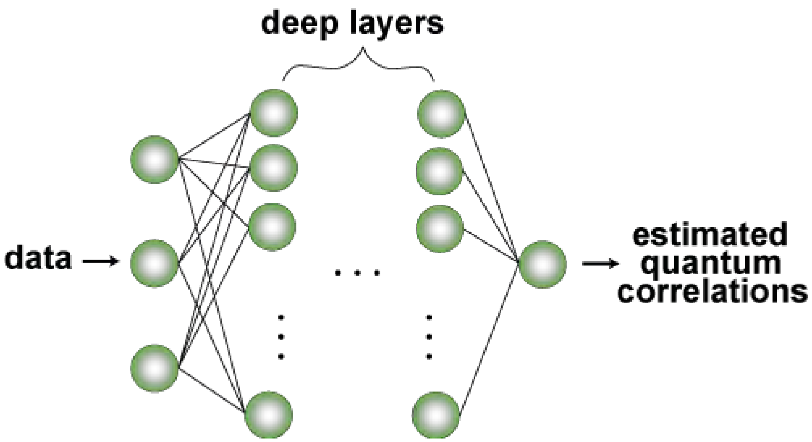
- demands the complete set of measurements (or assumptions about the state)
- inherently not scalable (example: photonic qubit 6^n, n=number of qubits)
- one needs to reconstruct ρ before entanglement can be quantified
- accuracy significantly decreased if an incomplete measurement is used

Examples of entanglement quantifiers:

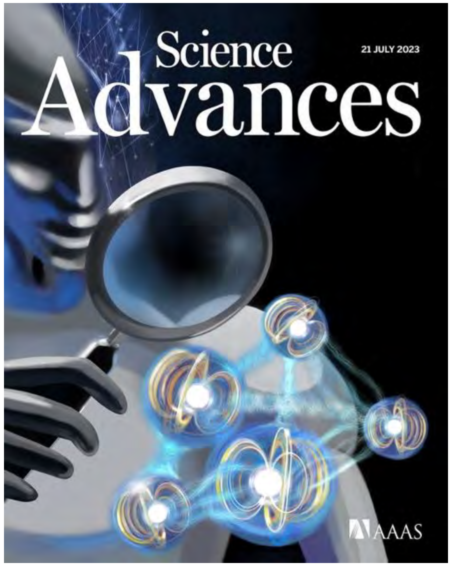
- concurrence
- negativity
- entanglement of formation
- mutual information

Entanglement quantification

- trained using simulated data
- incomplete set of measurements
- quantify the quantum correlations via concurrence (2 qubits) and mutual information (more qubits) directly without need to know the state



measurement specific



D. Koutný, et al. *Science Advances* **9** eadd7131 (2023).

Entanglement quantification

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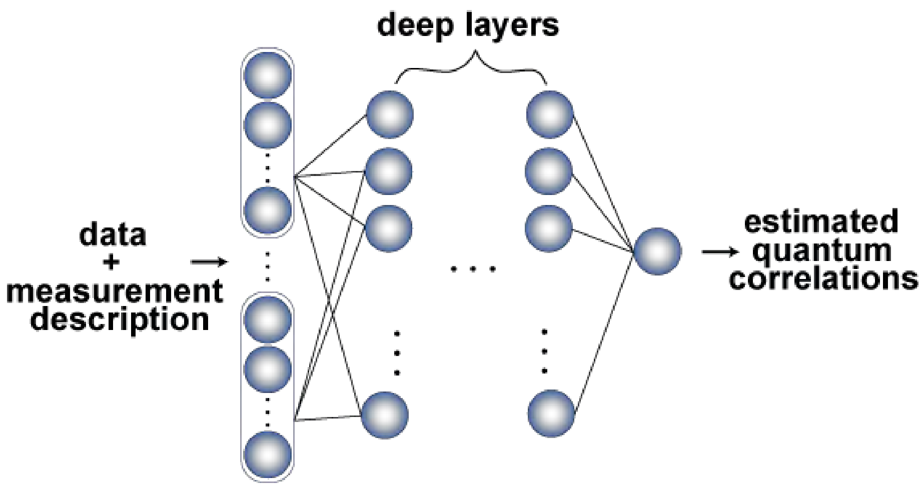
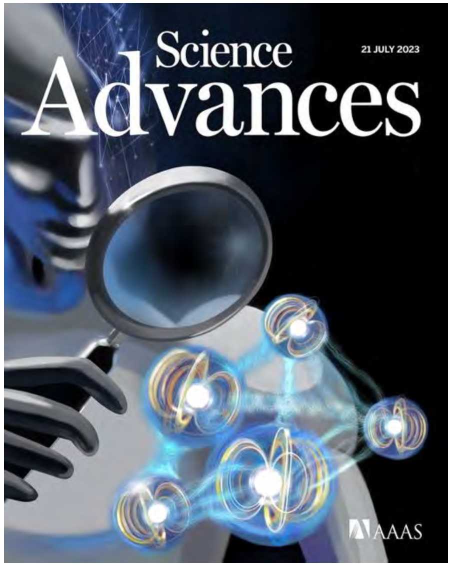


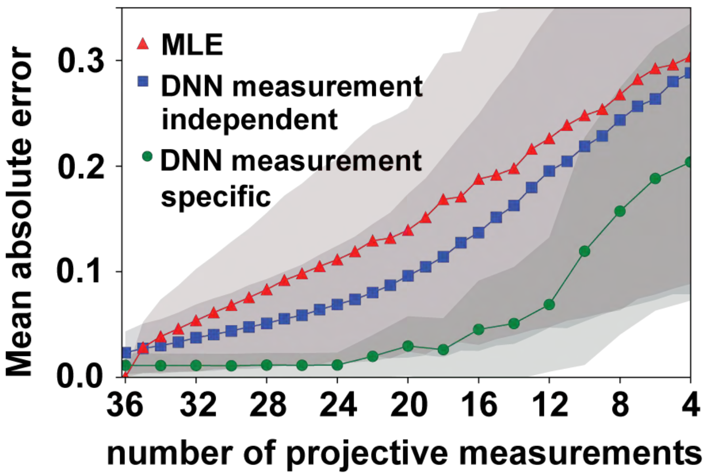
measurement independent



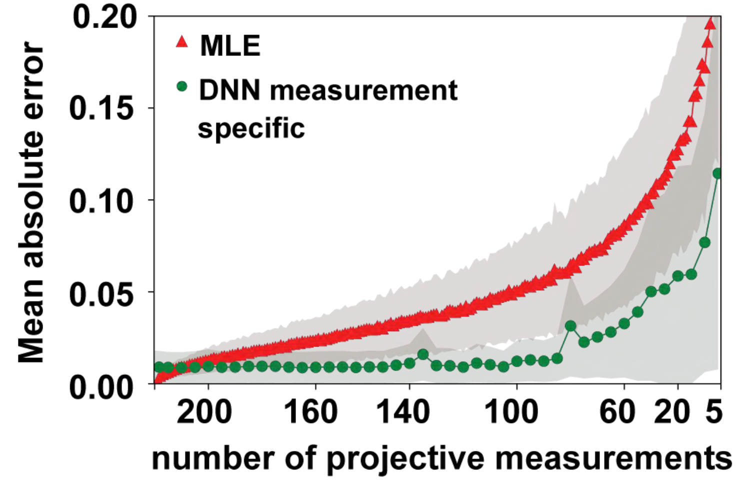
D. Koutný, et al. *Science Advances* **9** eadd7131 (2023).

Entanglement quantification

2-qubit concurrence estimation using incomplete measurements



3-qubit mutual information estimation using incomplete measurements



number of qubits	MAE		ratio of MLE and DNN MAEs
	MLE	DNN	
2	0.20 ± 0.16	0.09 ± 0.09	2.2
3	0.068 ± 0.055	0.023 ± 0.020	3.0
4	0.019 ± 0.014	0.005 ± 0.001	3.8
5	0.039 ± 0.032	0.009 ± 0.001	4.3

D. Koutný, et al. *Science Advances* **9** eadd7131 (2023).

Entanglement quantification

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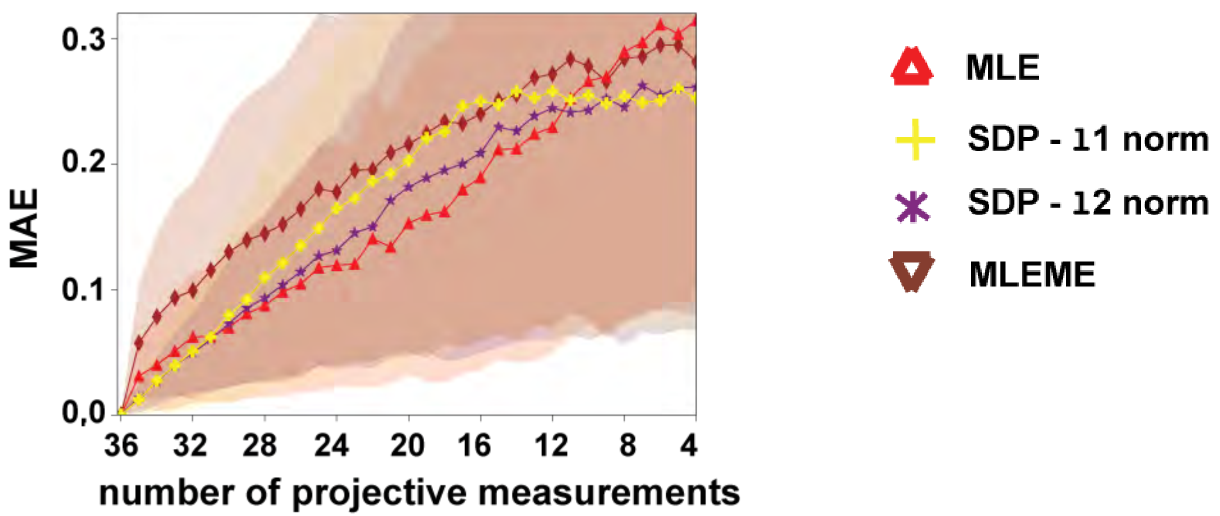
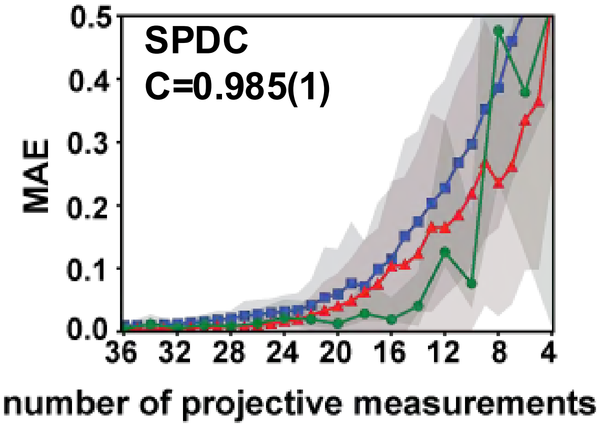
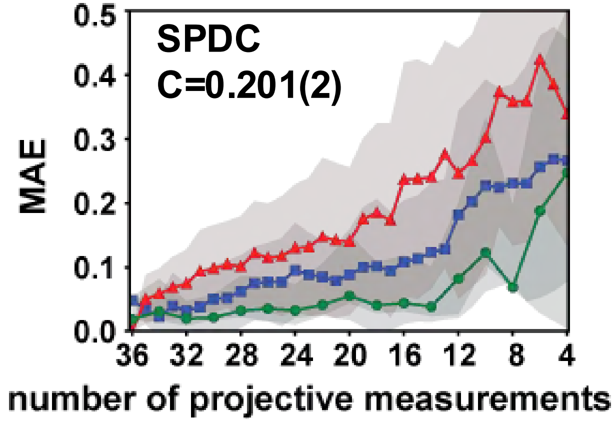
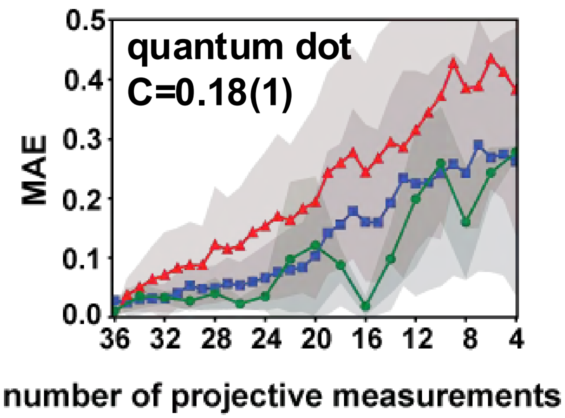


Entanglement quantification







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