Title: Building blocks for photonic quantum technologies – generation and detection of quantum light

Speakers: Kai Mueller

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Subject: Quantum Information

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Building blocks for photonic quantum technologies – generation and detection of quantum light

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Computer Engineering (QEC)

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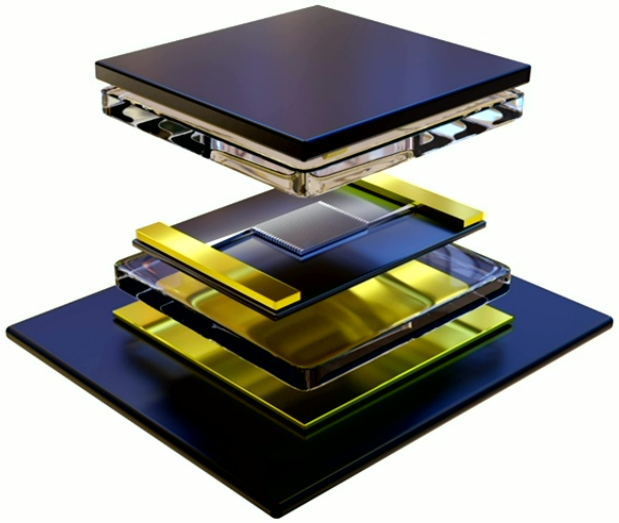
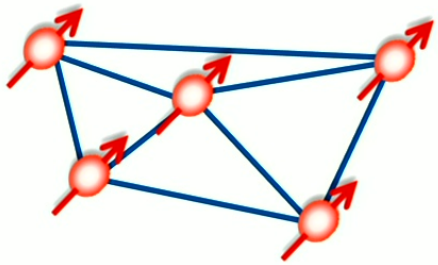


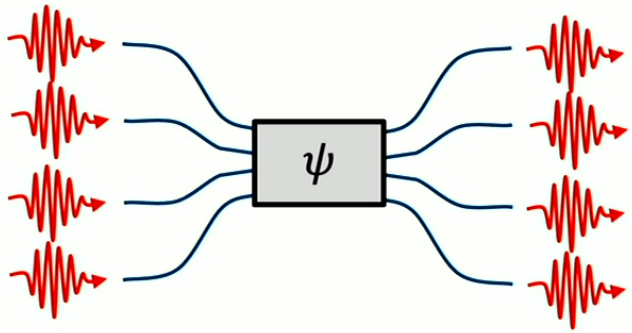
Photonic Quantum Technologies

Quantum Communication



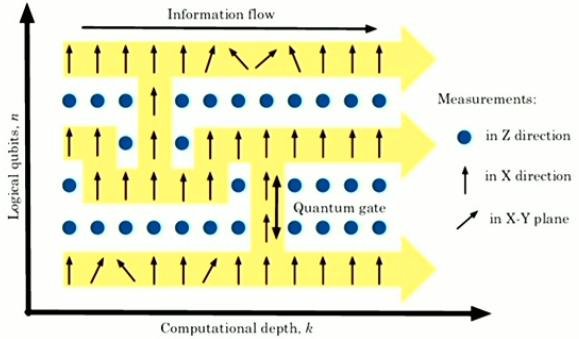
A. S. Holevo et al., Problems of Information Transmission 9, 177–183 (1973)

Quantum Simulation



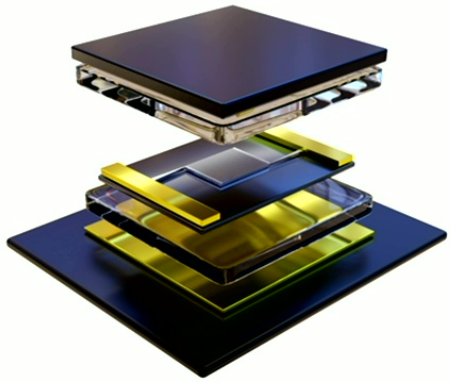
S. Aaronson et al., Theory of Computing. 9: 143–252 (2013)

Quantum Computing



R. Raussendorf et al., Phys. Rev. Lett. 86, 5188 (2001)

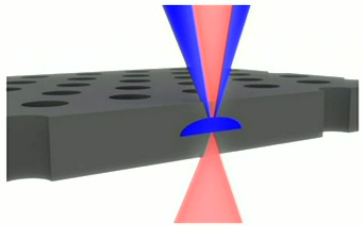
Quantum Sensing



QEC group: Research activities

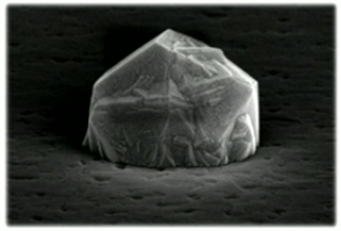
Building blocks

Quantum light sources



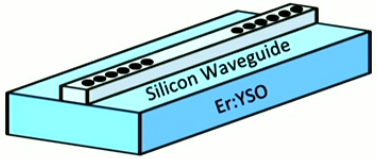
Quantum dots

Spin-photon interfaces



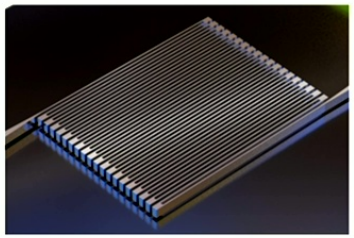
Color centers

Quantum memories



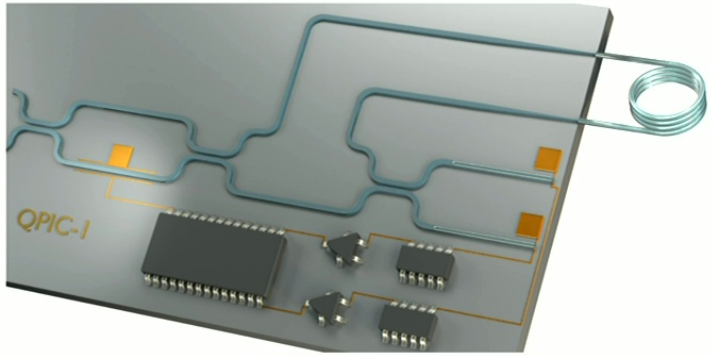
Rare-earth ions

Single-photon detectors

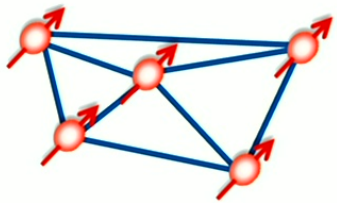


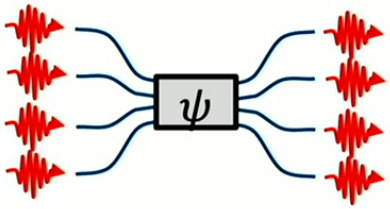
Superconducting films

Integrated photonics and devices



Demonstrator experiments

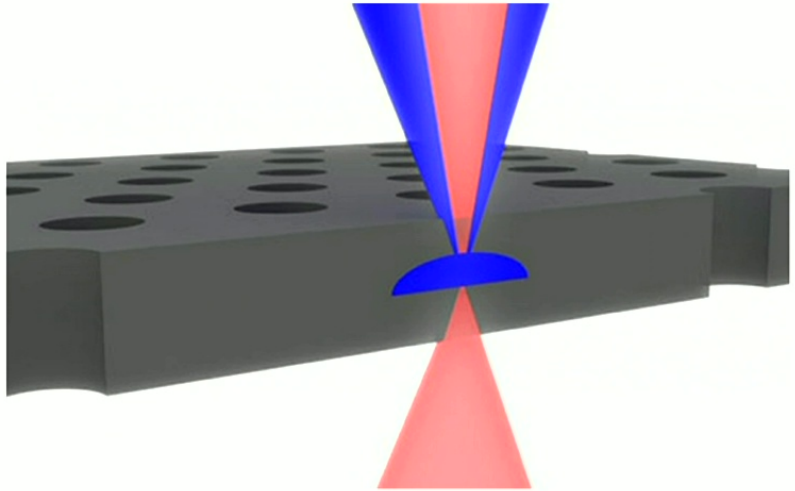




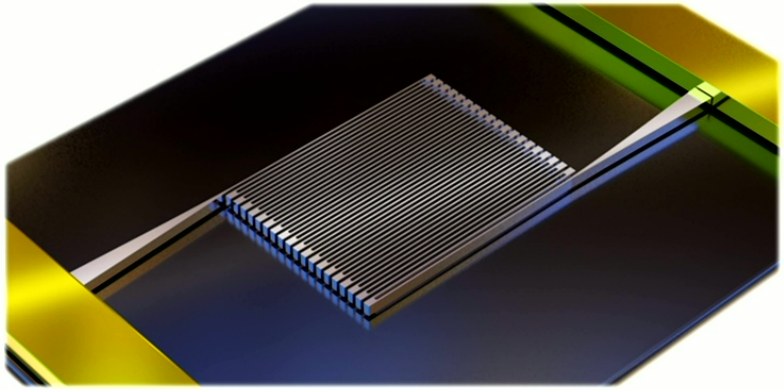
Quantum communication, Quantum computation
Quantum simulation, Quantum sensing

Outline

Dynamics of nonclassical light generation from semiconductor quantum dots



Recent advances in superconducting nanowire single-photon detectors



Outline

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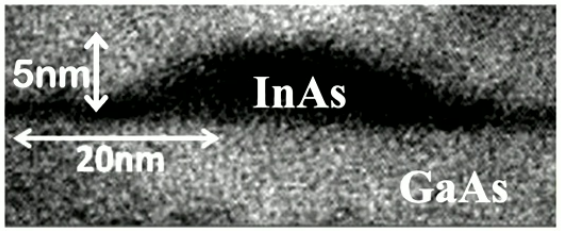
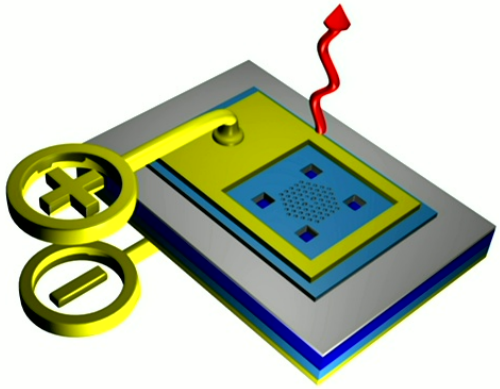
$\hat{a}$

InAs/GaAs quantum dots

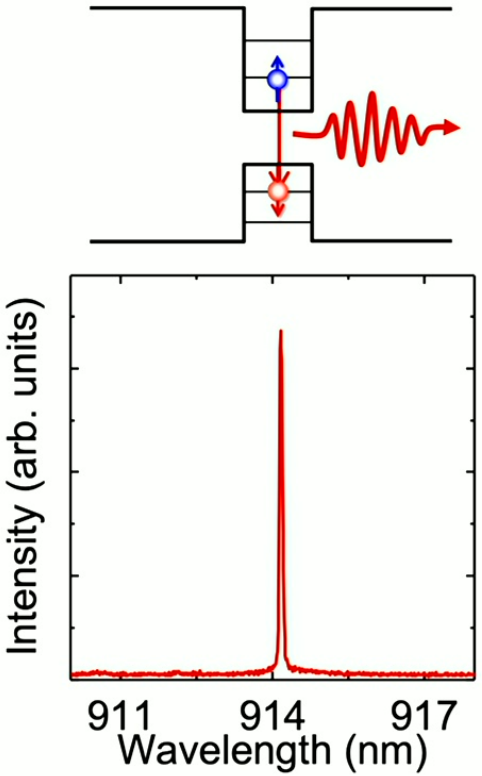
3D confinement for electrons and holes



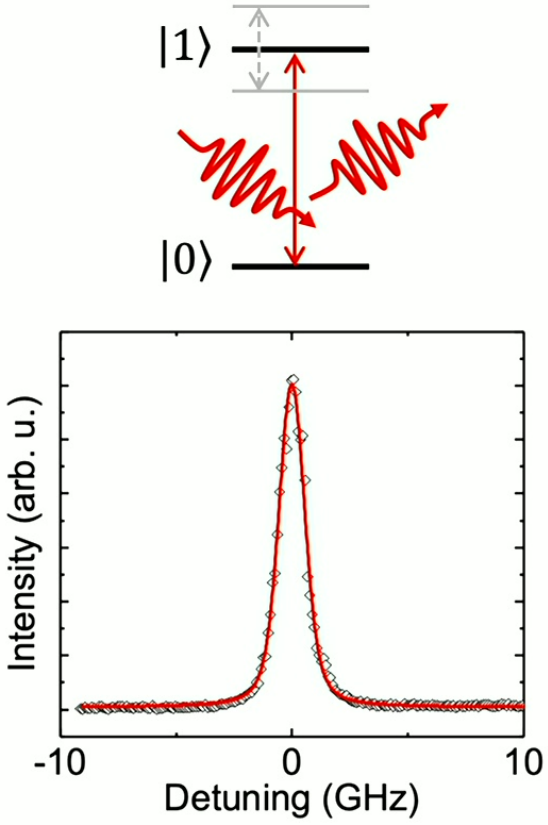
Opto-electronic integration



Strong interband transitions

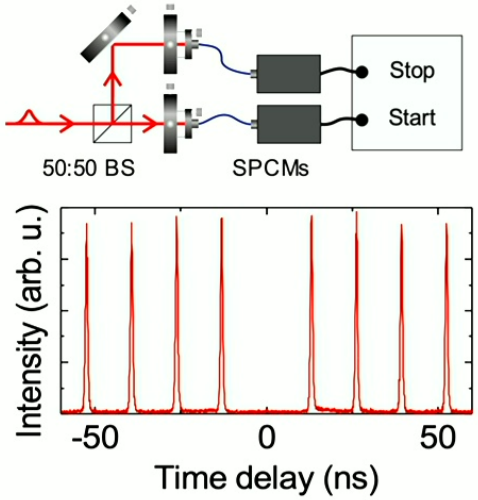


Transform-limited linewidth



Ideal single photon source

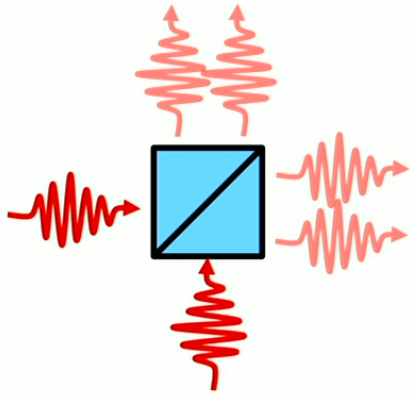
Purity



$$g^{(2)}(0) = \frac{\langle n(n-1)\rangle}{\langle n\rangle^2}$$

R. Glauber Phys. Rev. Lett. 10, 84 (1963)

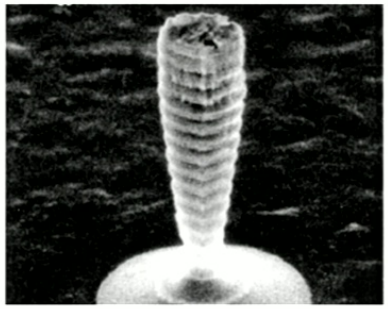
Indistinguishability



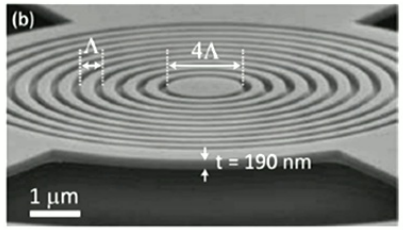
$$\psi = {}^{1}/_{\sqrt{2}}\left(|2,0\rangle_{c,d} + |0,2\rangle_{c,d}\right)$$

C.K. Hong et al. Phys. Rev. Lett. 59 (1987)

Brightness and Rate



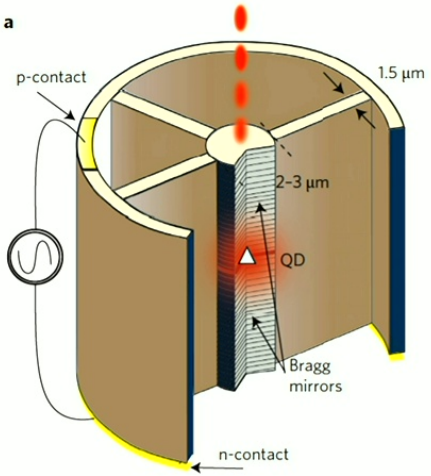
Solomon et al. PRL (2001)



M. Davanco et al., APL (2011)

Recent examples

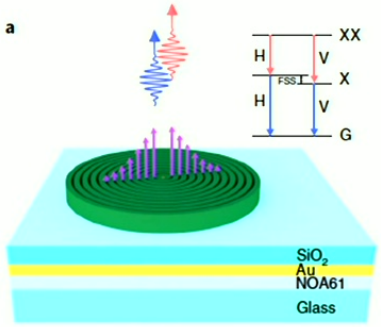
Micropillar resonators



N. Somashi et al., Nature Photonics 10, 340–345 (2016)

Groups of Pascale Senellart, Sven Höfling, Andrew Shields, …

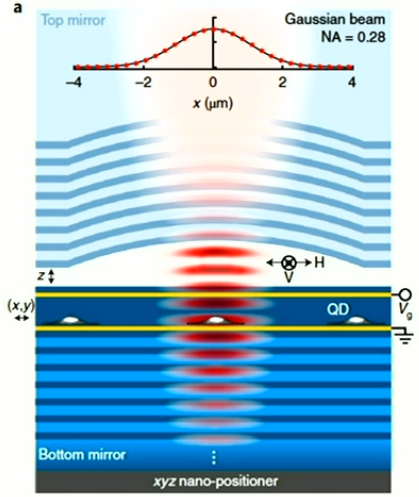
DBG resonators



J. Liu et al., Nature Nano-technology 14, 586–593 (2019)

Groups of Kartik Srinivasan, Luca Sapienza, Jin Liu, Jian-Wei Pan, Tobias Heindl, Stephan Reitzenstein, Peter Michler, Edo Waks, …

Tunable FP resonators



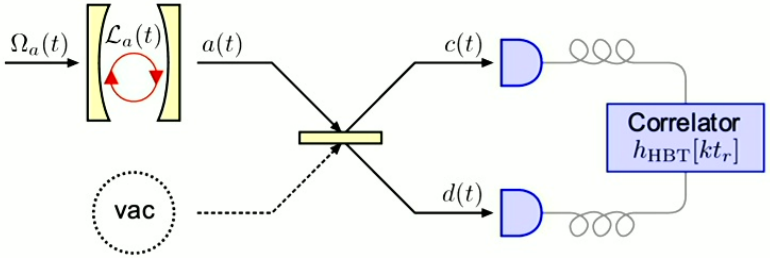
N. Tomm et al., Nature Nano-technology 16, 399–403 (2021)

Groups of Richard Warburton, Jian-Wei Pan, David Hunger, …

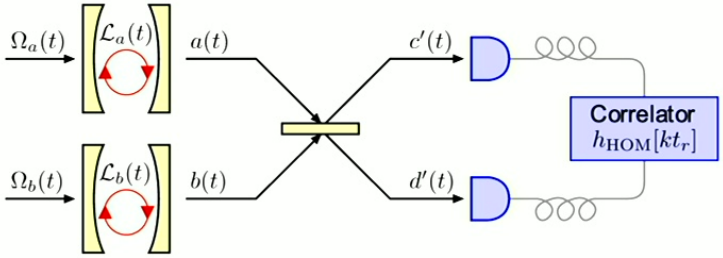
Fundamental limits? Optimized excitation?

Modelling quantum light sources

Hanbury Brown-Twiss (HBT)



Hong-Ou-Mandel (HOM)



Set up Hamiltonian, SE, Cavity, …

$$H_I = \frac{\mu E(t)}{2}(|g\rangle\langle e| + |e\rangle\langle g|)$$

$$s_e = \sqrt{\gamma_e}\,|g\rangle\,\langle e|$$

Quantum-optical master equation

$$\frac{d}{dt}\rho(t) = \mathcal{L}(t)\rho(t)$$

Correlators of the form

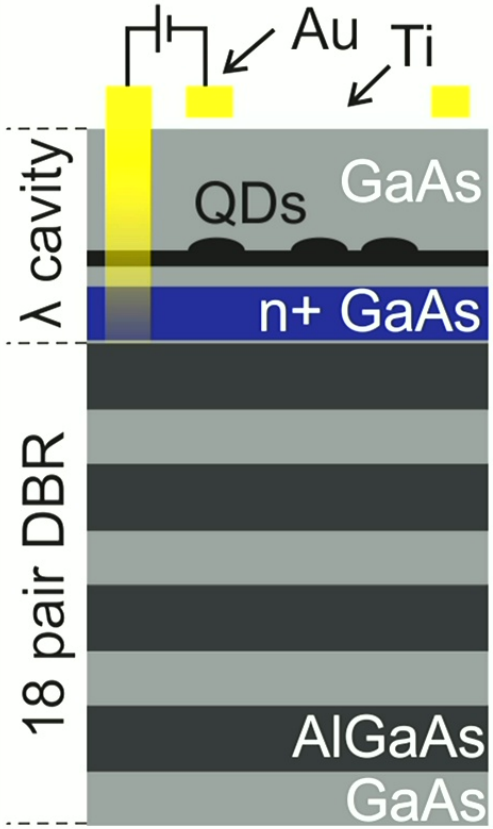
$$G(t,\tau) = \langle A(t)B(t+\tau)C(t)\rangle$$

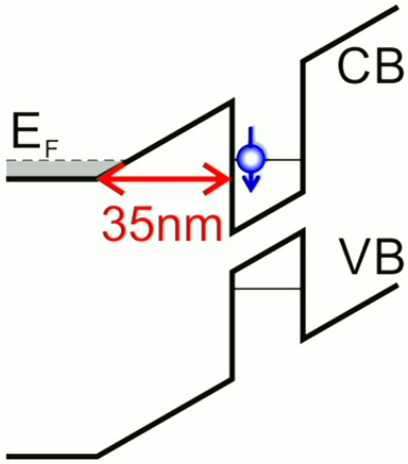
Quantum regression theorem

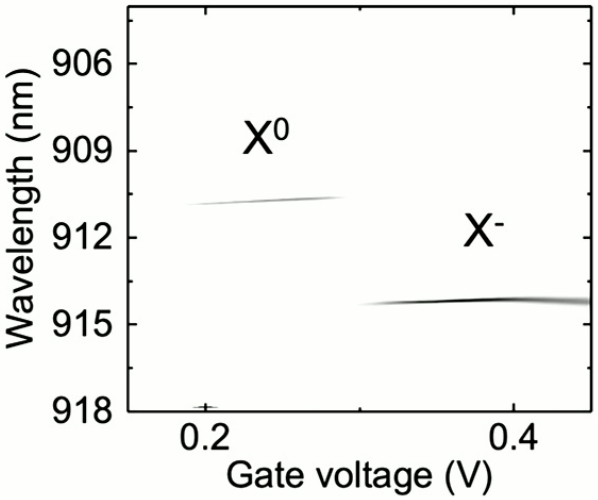
$$\langle A(t)B(t+\tau)C(t)\rangle = Tr_{sys}\{B\Lambda(t,t+\tau)\}$$

K.A. Fischer et al. NJoP 18, 113053 (2016), R. Trivedi et al. Adv. Q. Tech., 3, 1900007 (2020)

Quantum dot devices

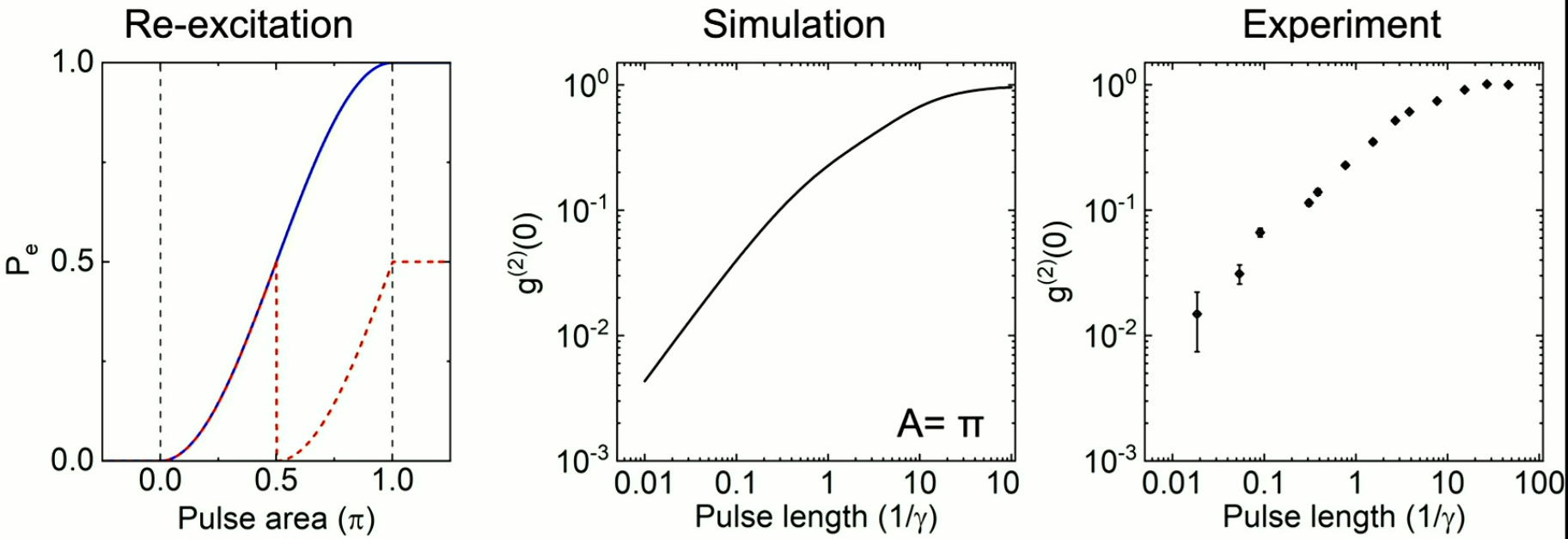






- DBR enhances photon collection efficiency
- Diode structure allows for control of emission wavelength and charge status

Resonantly driven TLS

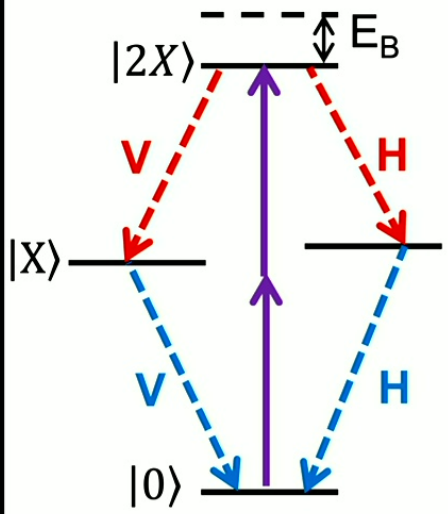


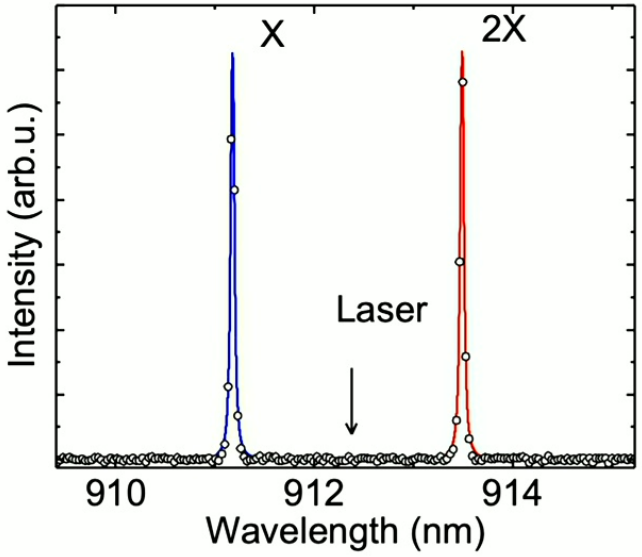
→ Emission during the presence of the pulse reduces single-photon purity

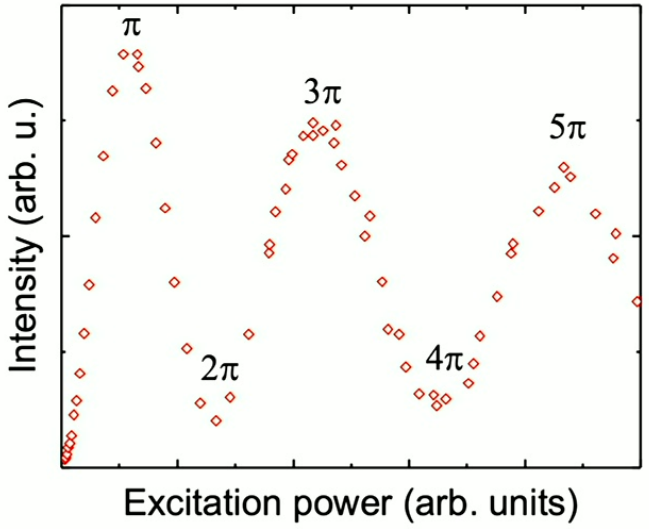
→ Lowest possible $g^{(2)}[0]$ increases with pulse length

K.A. Fischer et al. Quantum Sci. Technol. 3, 014006 (2018)

Suppressing re-excitation



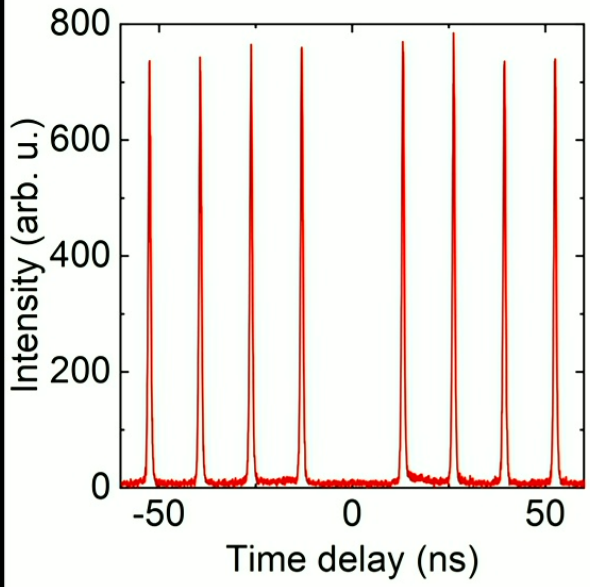


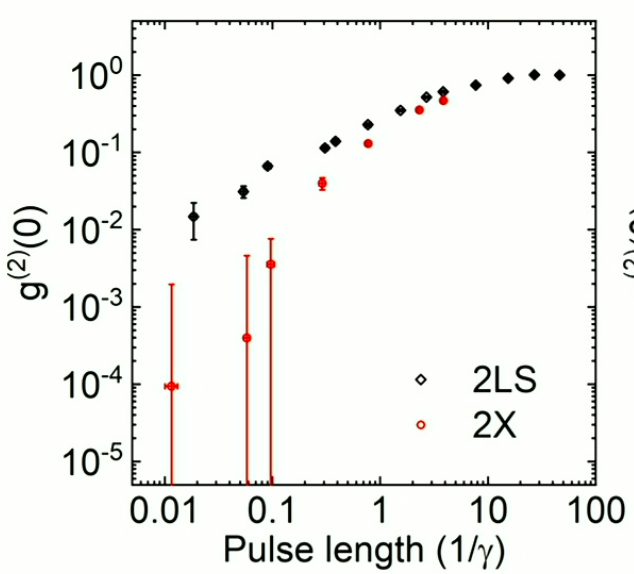


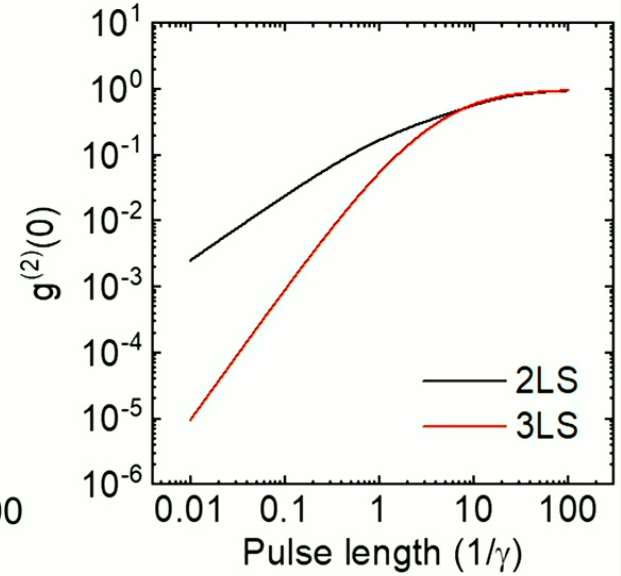
→ Energy of 2X is detuned from 2*X by the Coulomb binding energy

→ Two-photon excitation of the bi-exciton *(K. Brunner et al. , PRL 73, 1138 (1994))*

Ultra-low multiphoton probability





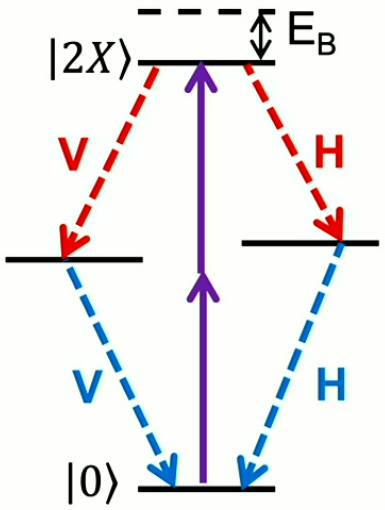


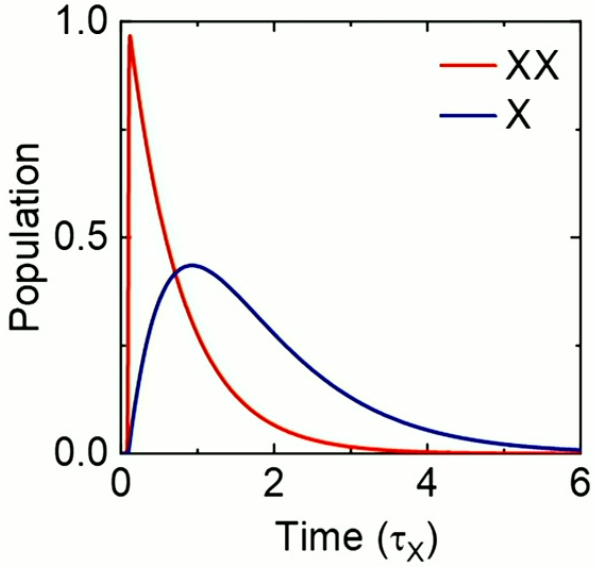
→ Ultra-low $g^{(2)}(0)$ confirms strongly suppressed re-excitation

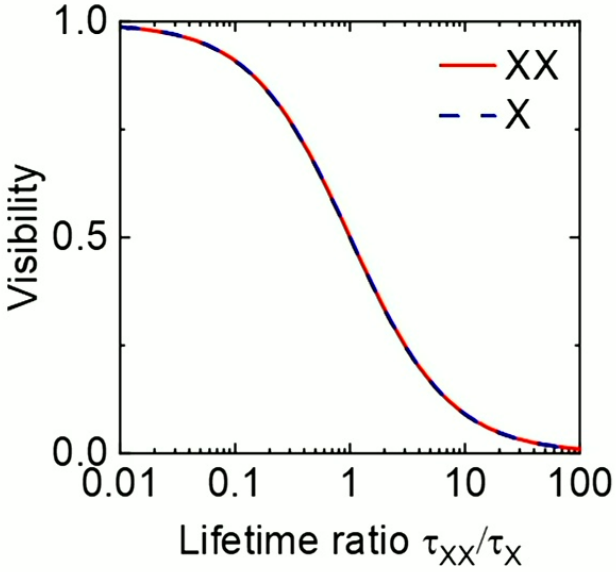
→ Quadratic dependence on pulse length

L. Hanschke et al. npj Quantum Information 4, 43 (2018)
Work from Zwiller group: L. Schweickert et al. Appl. Phys. Lett. 112, 093106 (2018)

Indistinguishability of a cascaded emission







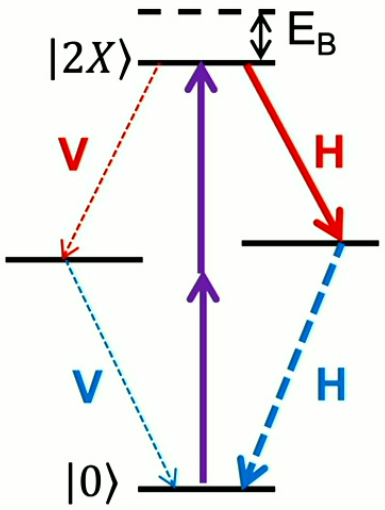
→ The emission of a cascade is entangled

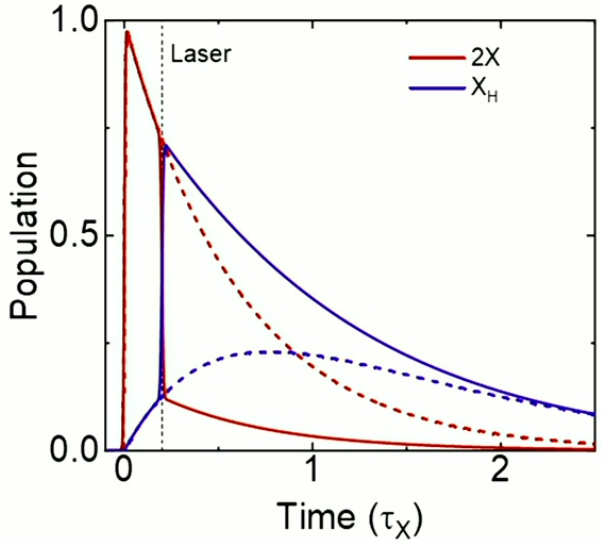
→ This limits the indistinguishability to $\gamma_{XX}/(\gamma_{XX}+\gamma_X)$

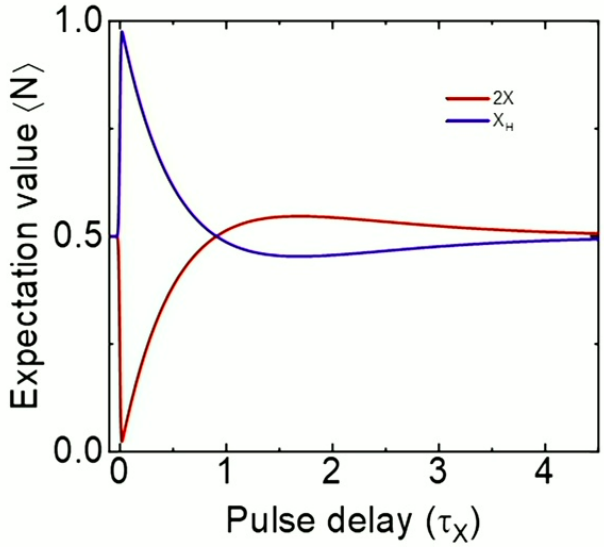
→ Excellent purity and indistinguishability via tailoring the emission rates

E. Schöll et al. Physical Review Letters 125, 233605 (2020)

Stimulated generation of single photons





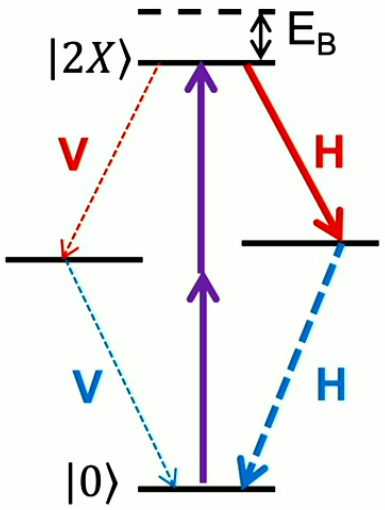


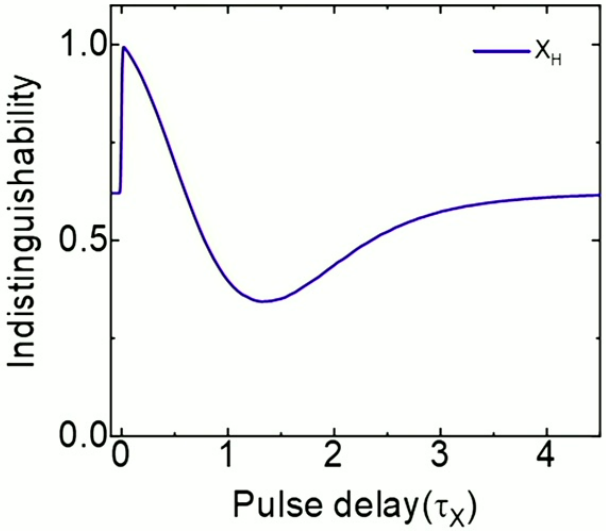
→ Additional laser pulse inverts 2X-X population

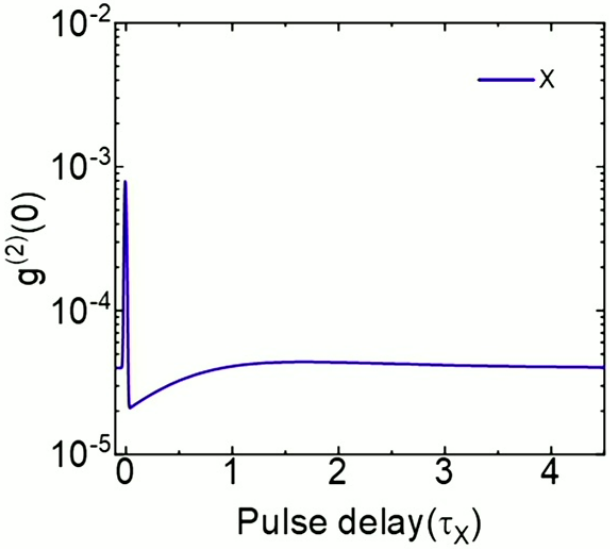
→ For short delays: Well defined X timing

F. Sbresny et al. Physical Review Letters 128, 093603 (2022)

High purity AND indistinguishability





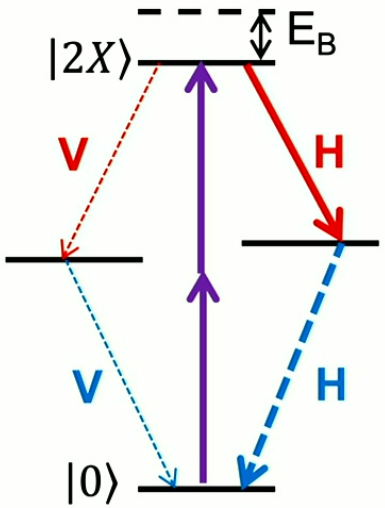


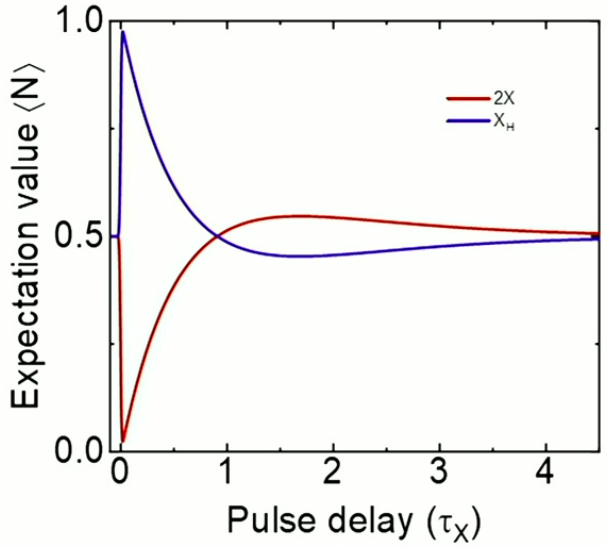
→ For short delays, near-unity indistinguishability

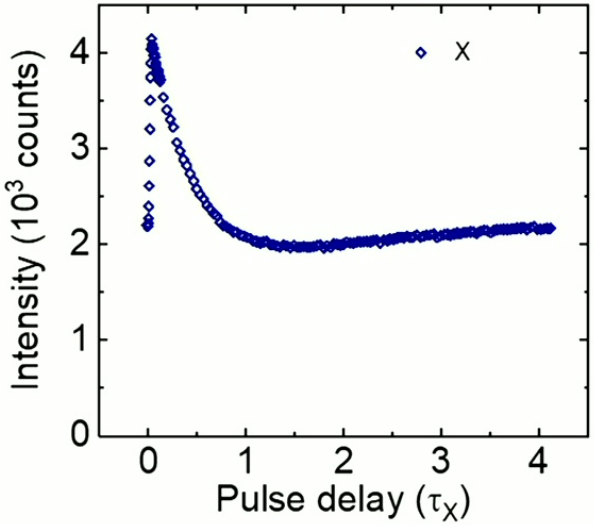
→ Excellent indistinguishability and single-photon purity

F. Sbresny et al. Physical Review Letters 128, 093603 (2022)

Experimental confirmation: Bright



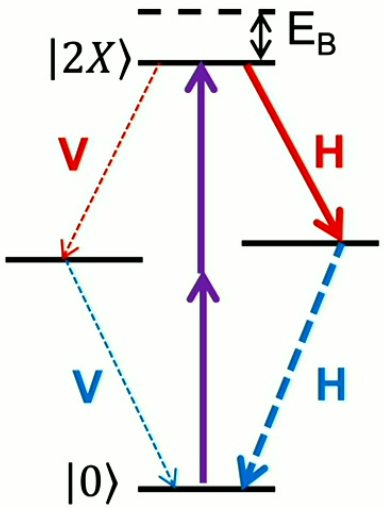


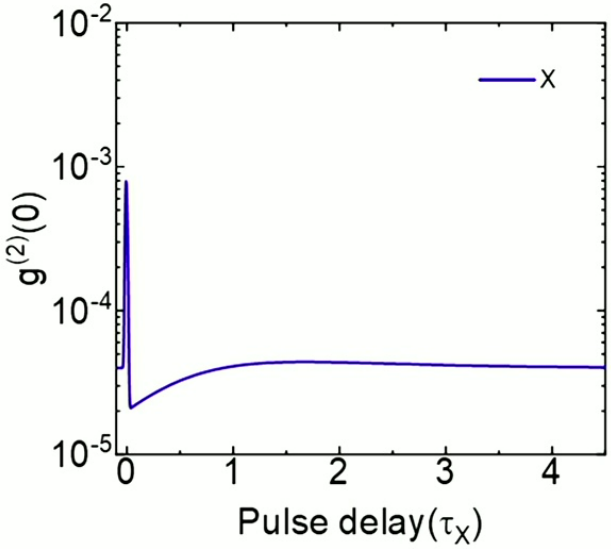


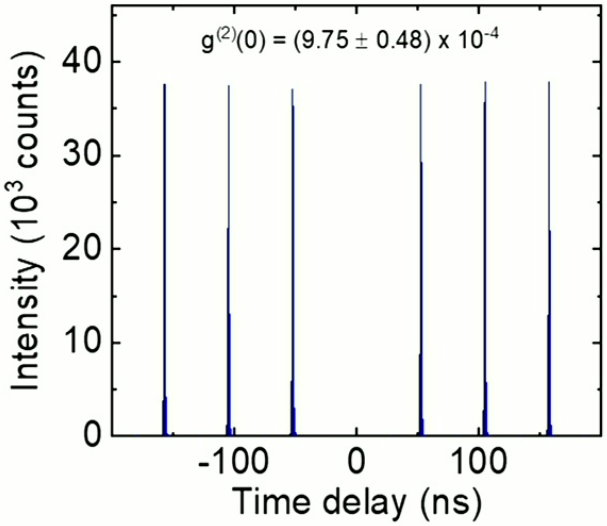
→ Bright, and with control of polarization

F. Sbresny et al. Physical Review Letters 128, 093603 (2022)

Experimental confirmation: Pure



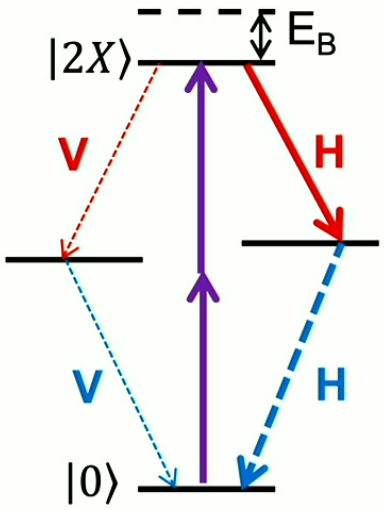


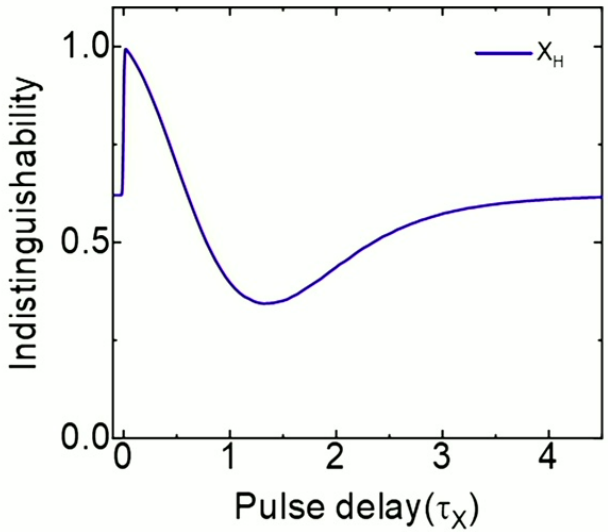


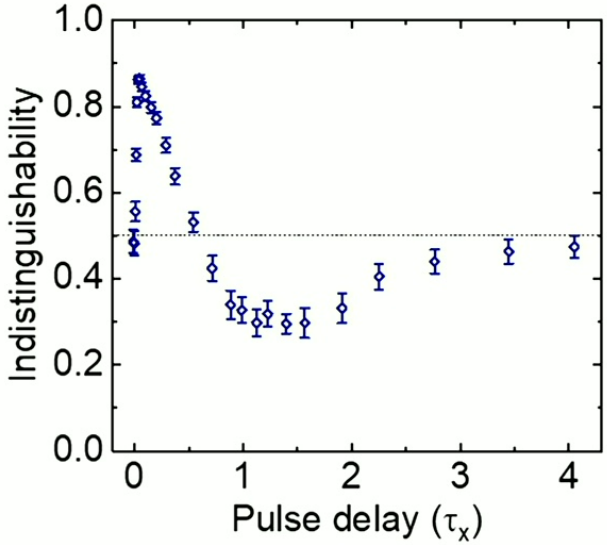
→ Excellent single-photon purity experimentally confirmed

F. Sbresny et al. Physical Review Letters 128, 093603 (2022)

Experimental confirmation: Indistinguishable







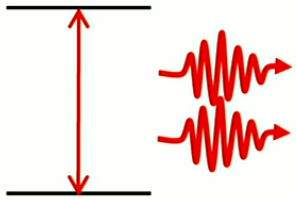
→ Theoretical model experimentally confirmed over wide parameter range

→ Bright, pure, indistinguishable and control of polarization

F. Sbresny et al. Physical Review Letters 128, 093603 (2022)

Summary

Single-photons purity limited by re-excitation

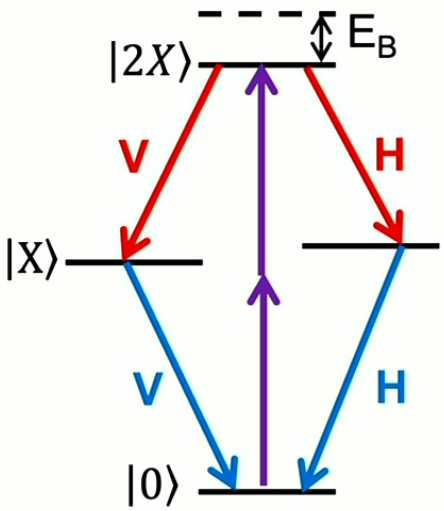


K.A. Fischer et al. NJoP 18, 113053 (2016)

K.A. Fischer et al. Nature Physics 13, 649–654 (2017)

K.A. Fischer et al. QST, 3, 1 (2017)

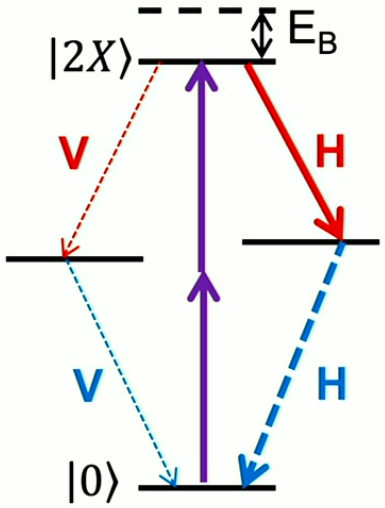
Ultra-pure single photons



L. Hanschke et al. npj Quantum Information 4, 43 (2018)

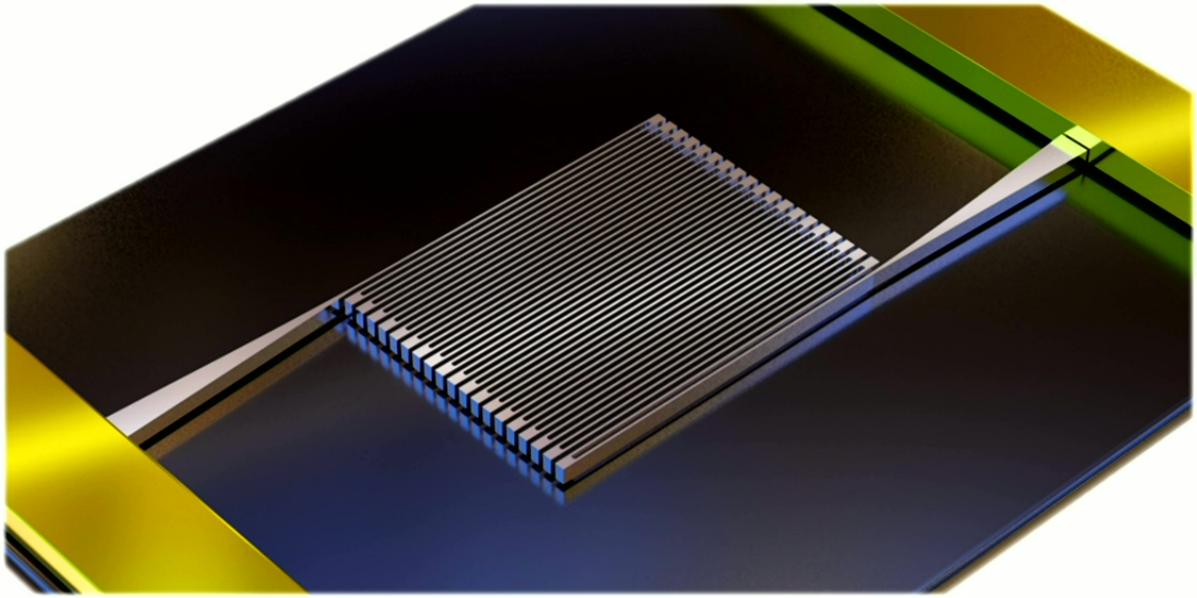
E. Schöll et al. Physical Review Letters 125, 233605 (2020)

Stimulated generation of single photons

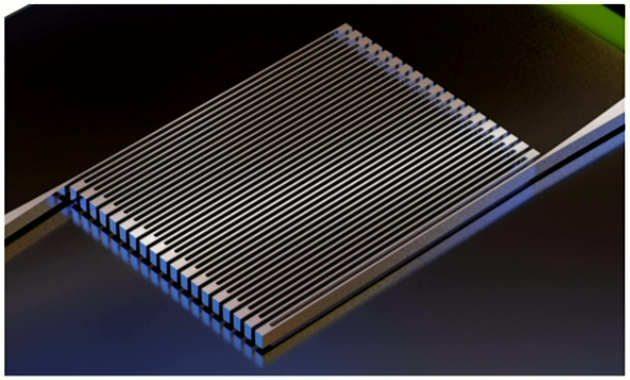


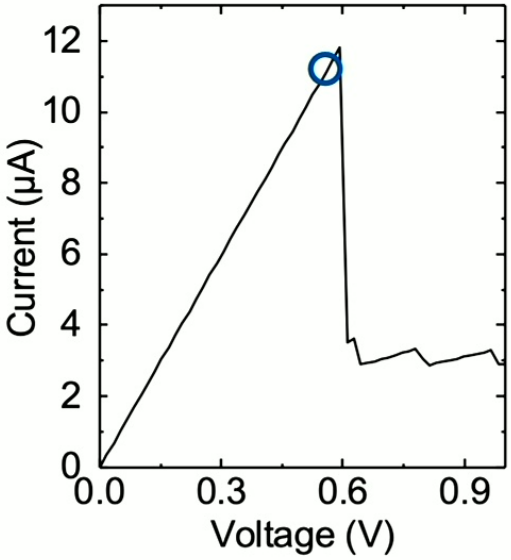
F. Sbresny et al. Physical Review Letters 128, 093603 (2022)

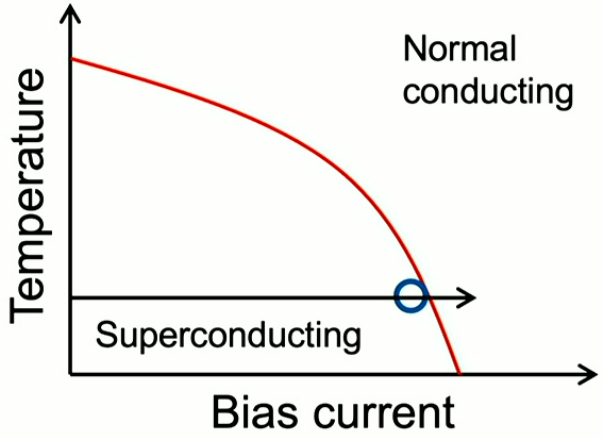
Part II: Superconducting Nanowire Single-Photon Detectors



Superconducting single-photon detectors

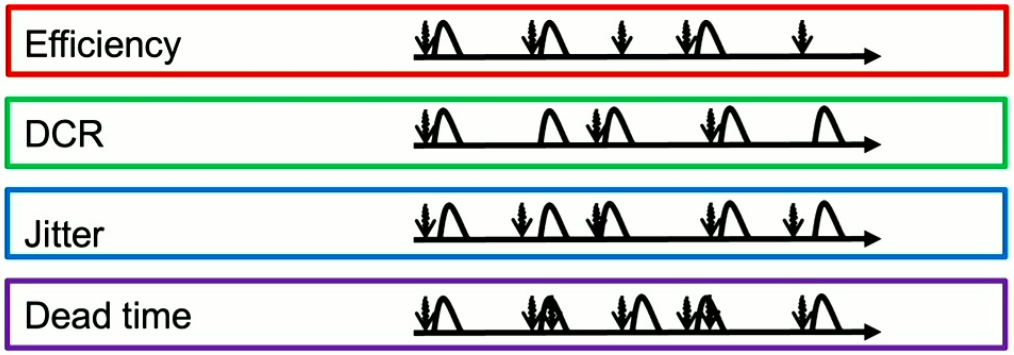


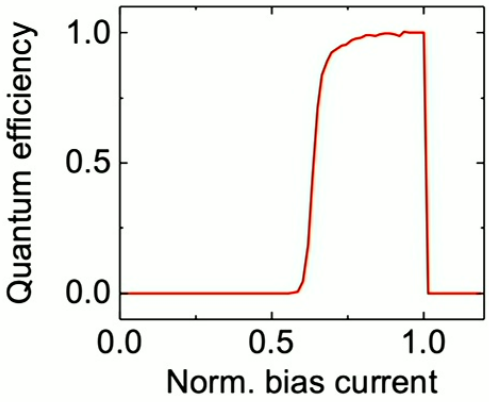


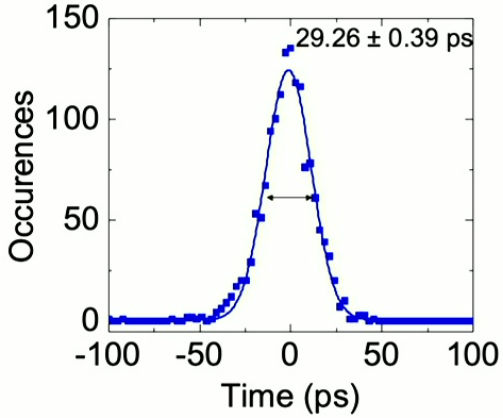


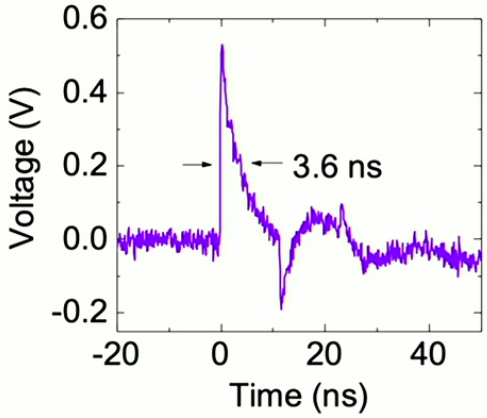
- Apply bias current slightly below critical current

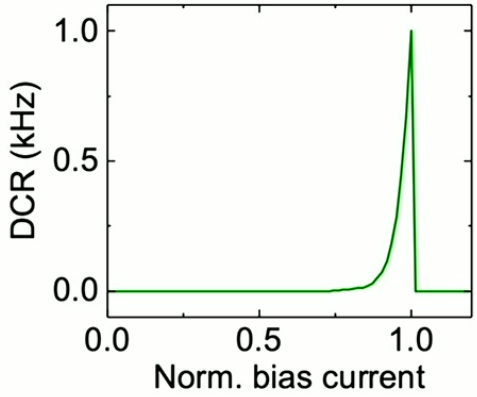
Typical NbTiN SNSPD performance



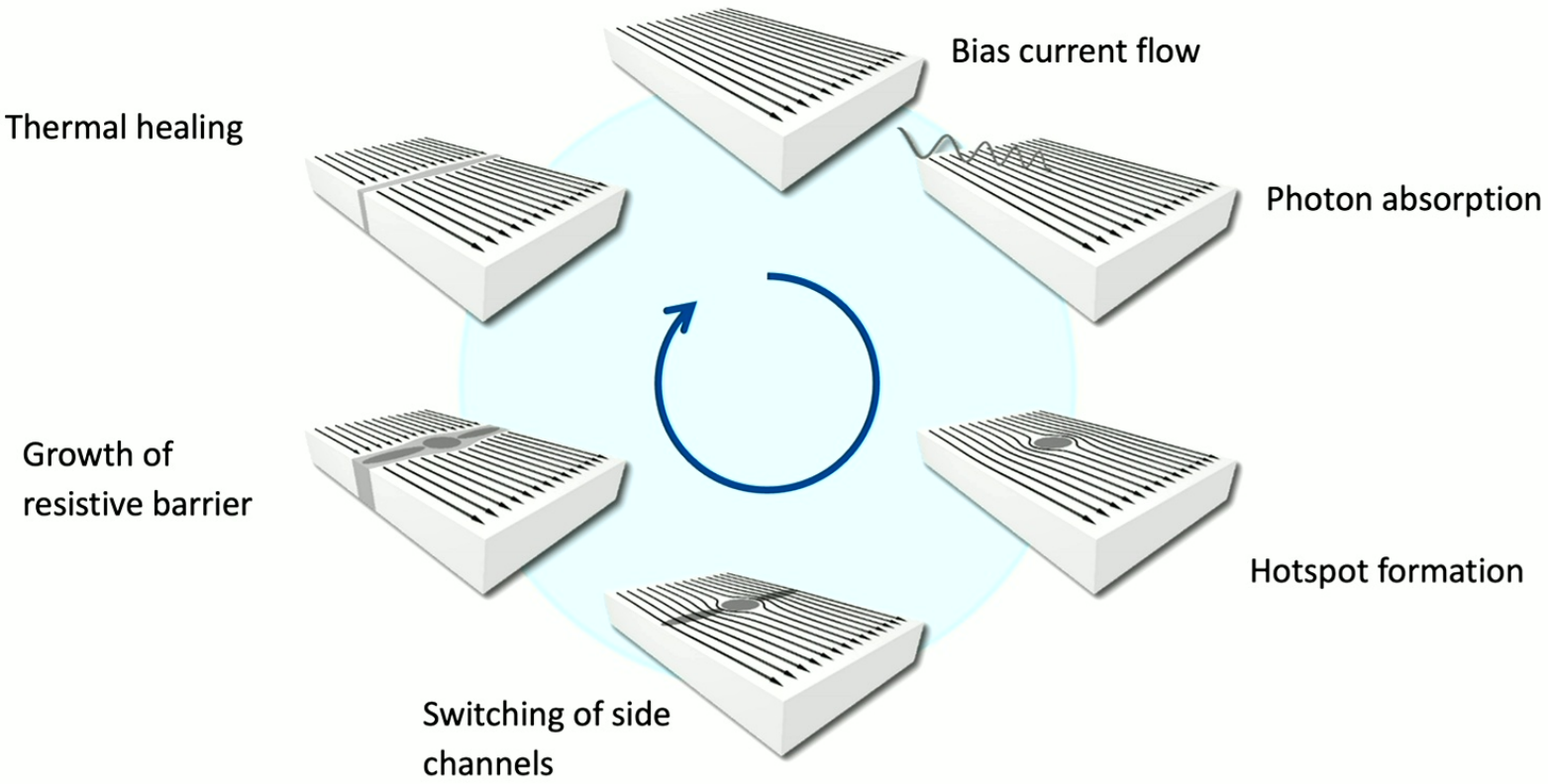






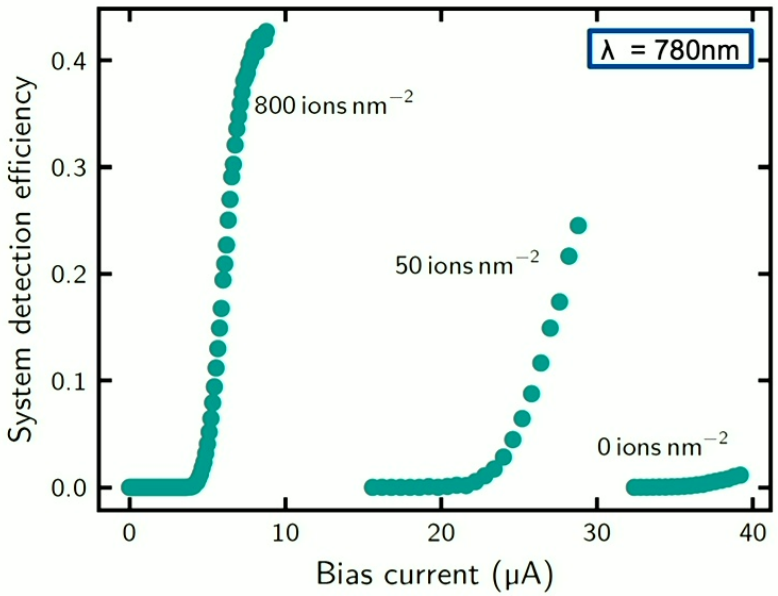


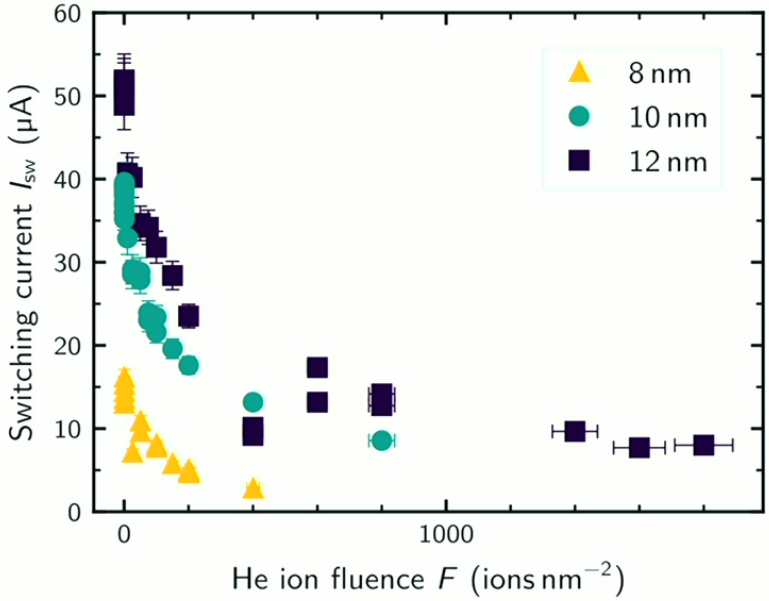
Operating principle



G. N. Gol'tsman et al., Appl. Phys. Lett. 79 705–7 (2001)

Helium ion irradiation of SNSPDs

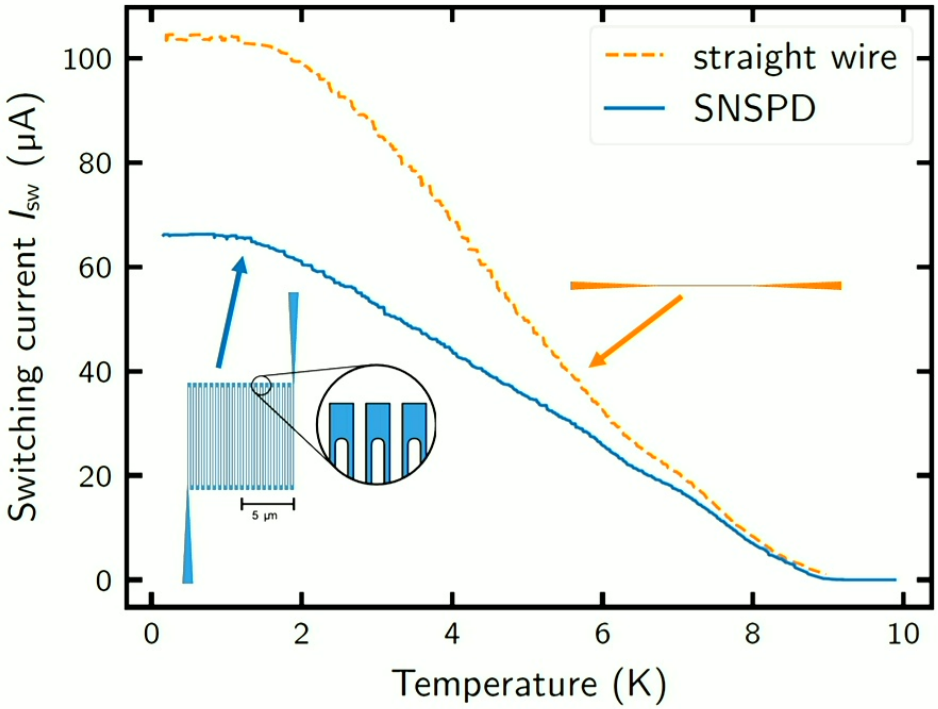


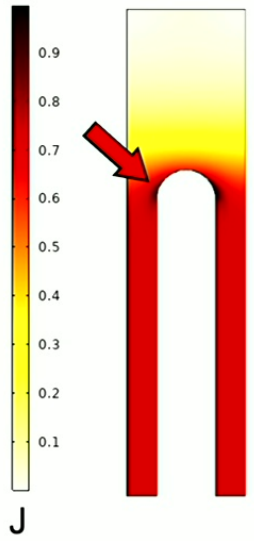


- Increase of system detecton efficiency from < 2% → 43%
- Decrease of switching current from 39.2 μA → 8.6 μA

S. Strohauer et al., Adv. Quantum Technol. 6, 2300139 (2023)
W. Zhang et al., Physical Review Applied 12, 044040 (2019)

Current crowding in SNSPDs



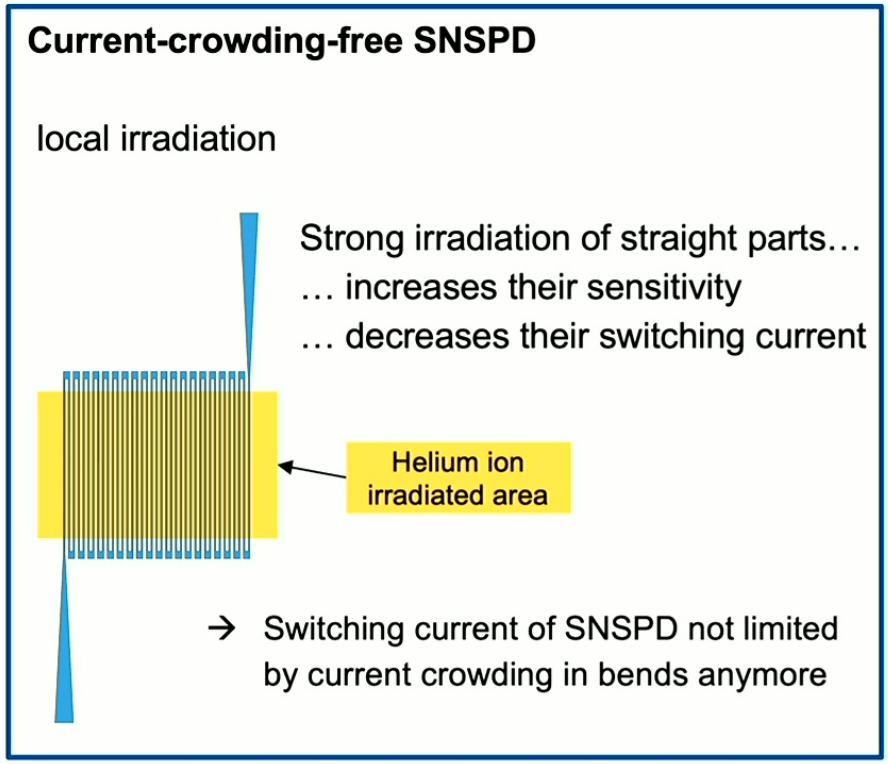


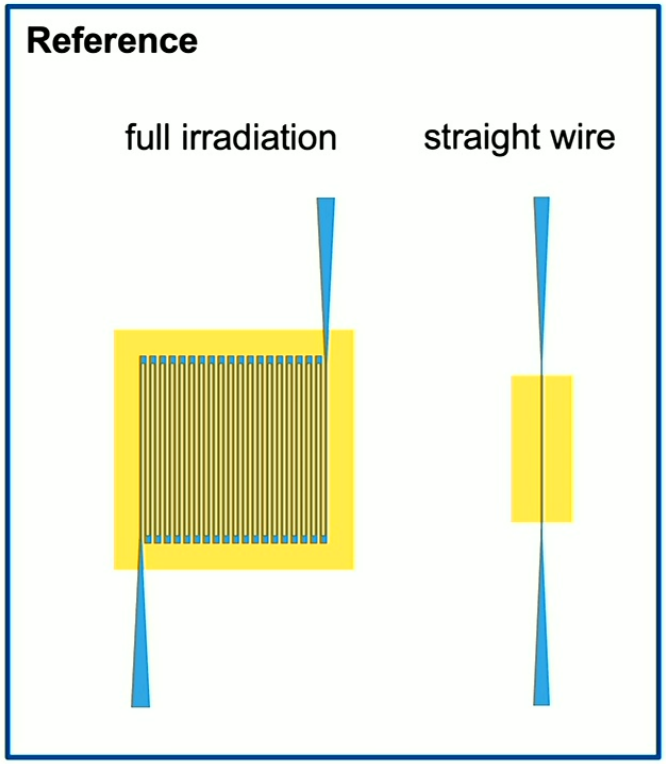
Local increase of current density in bends

→ Limits switching current of SNSPD

J.R. Clem & K. K. Berggren, Physical Review B 84, (2011)
D. Henrich et al., Phys. Rev. B 86, 144504 (2012)

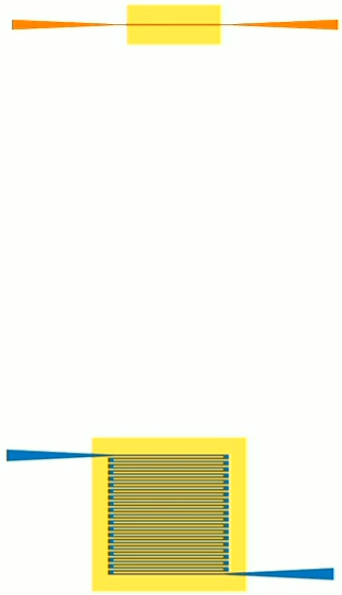
Concept of current-crowding-free SNSPDs

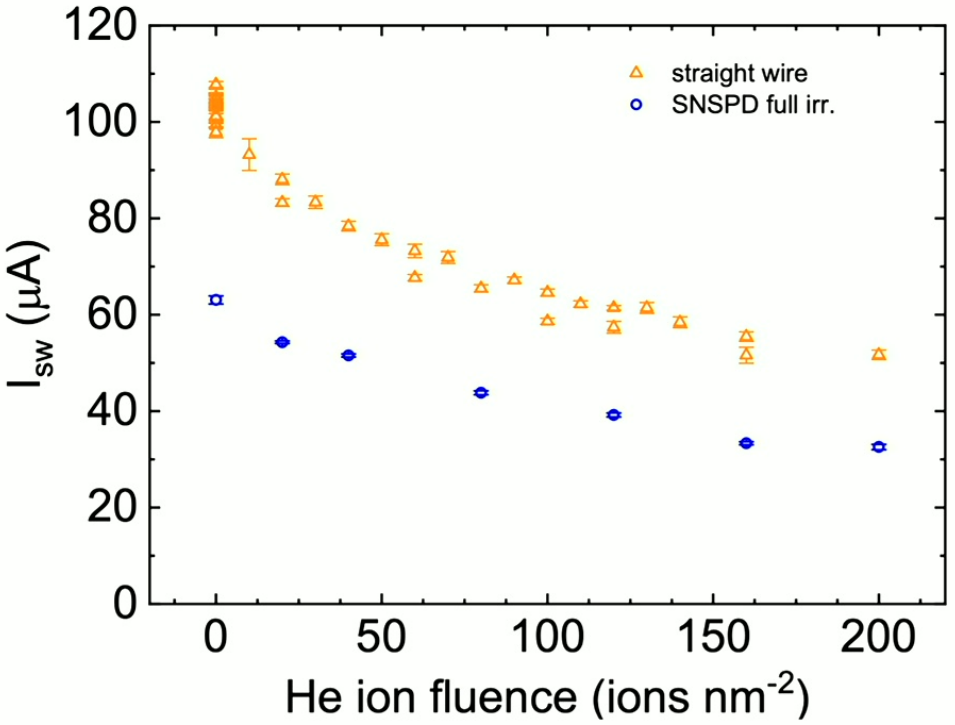




S. Strohauer et al. arXiv:2407.14171 (2024)

Advantage of locally irradiated SNSPDs





S. Strohauer et al. arXiv:2407.14171 (2024)

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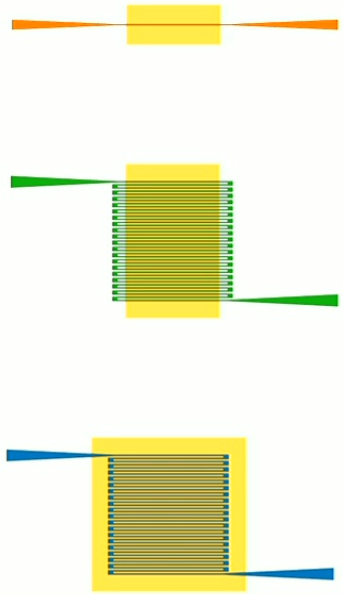
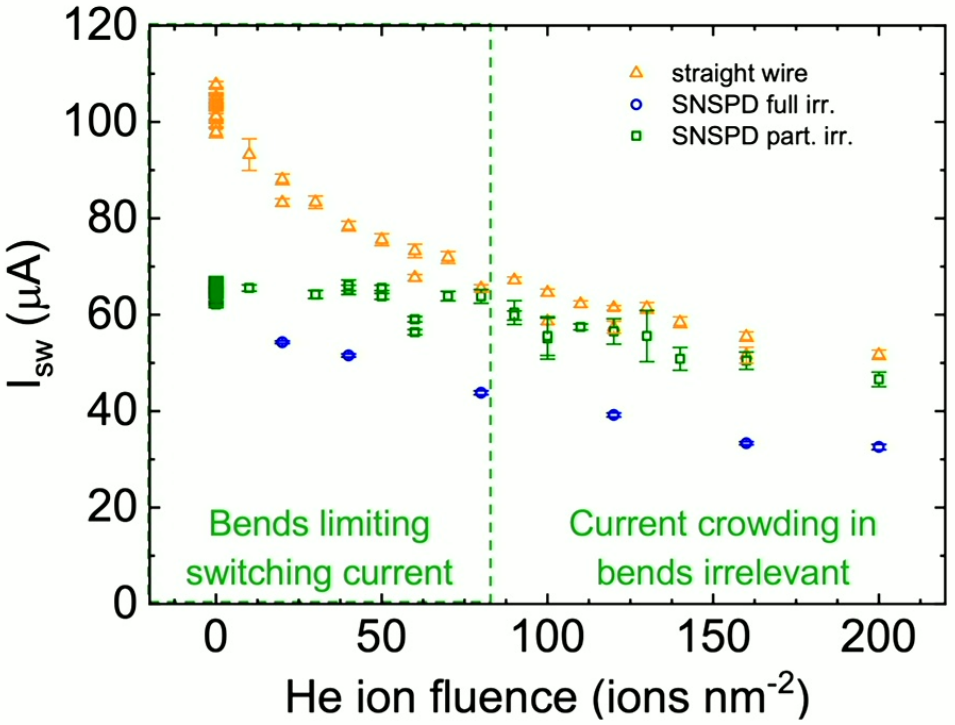
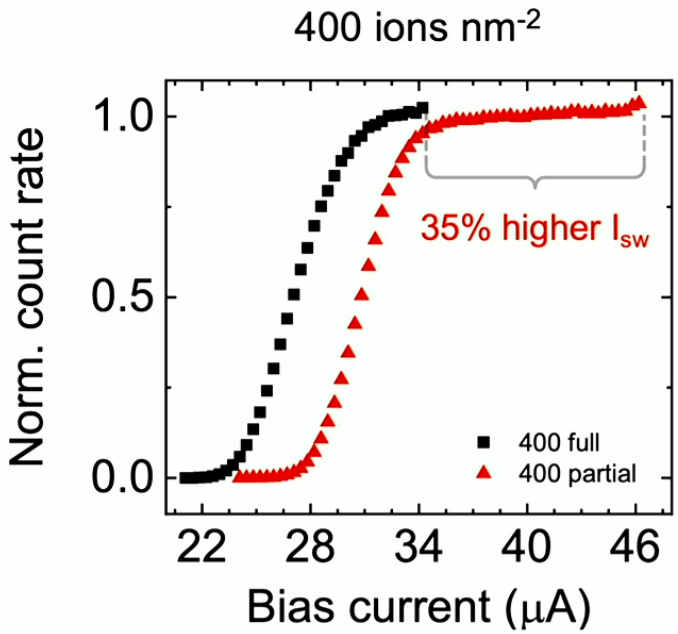
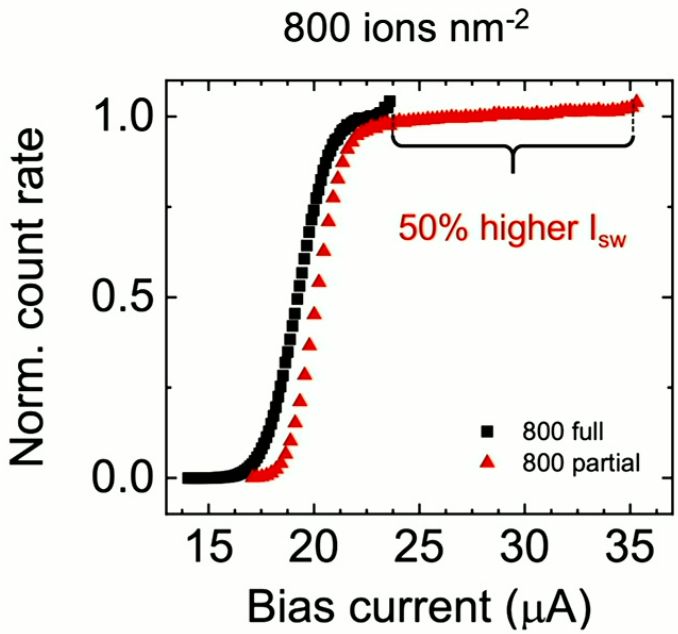




S. Strohauer et al. arXiv:2407.14171 (2024)

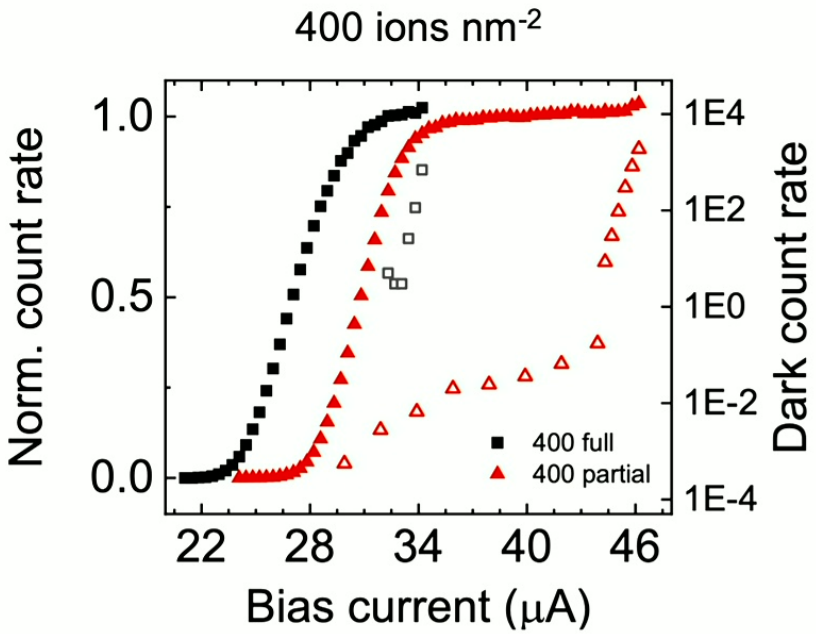
Extending the saturation regime

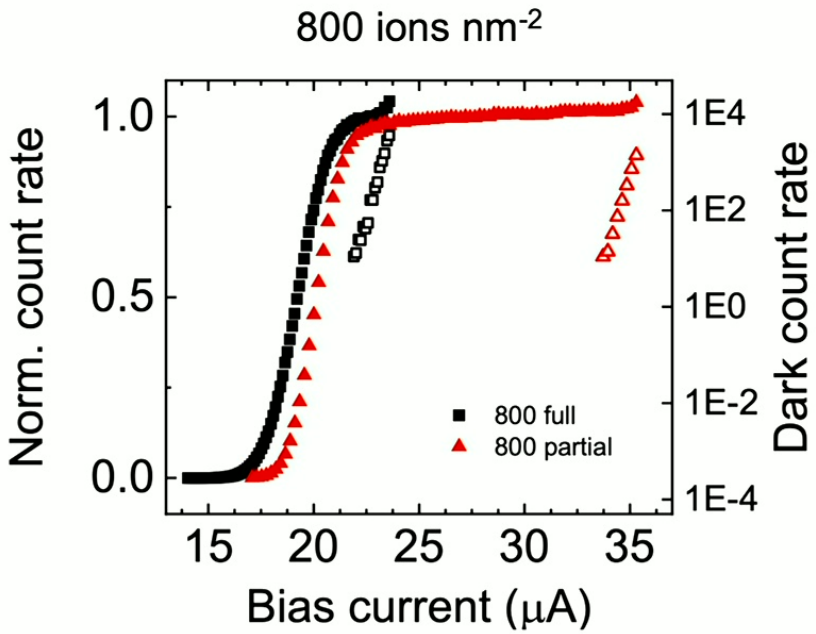




S. Strohauer et al. arXiv:2407.14171 (2024)

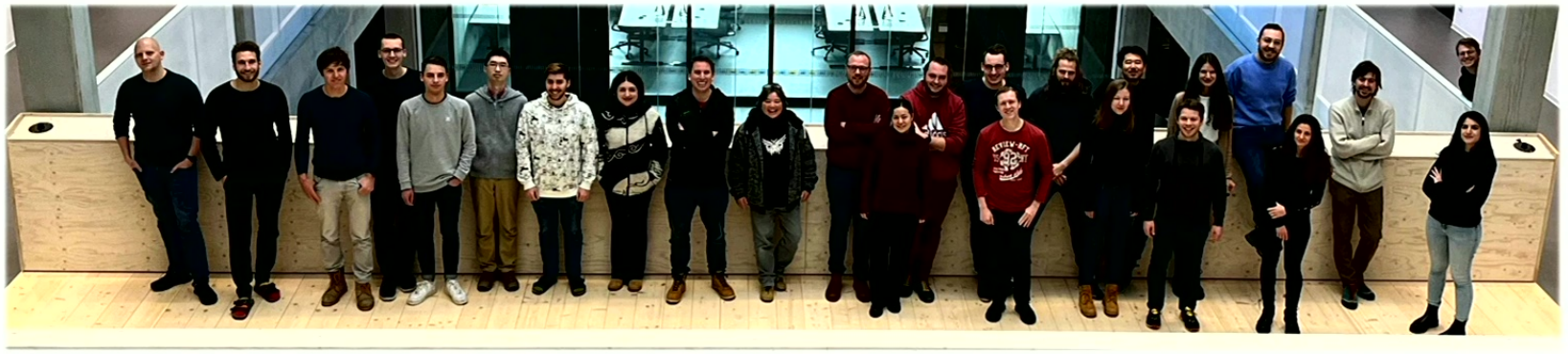
Very low dark count rates





S. Strohauer et al. arXiv:2407.14171 (2024)

QEC group



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