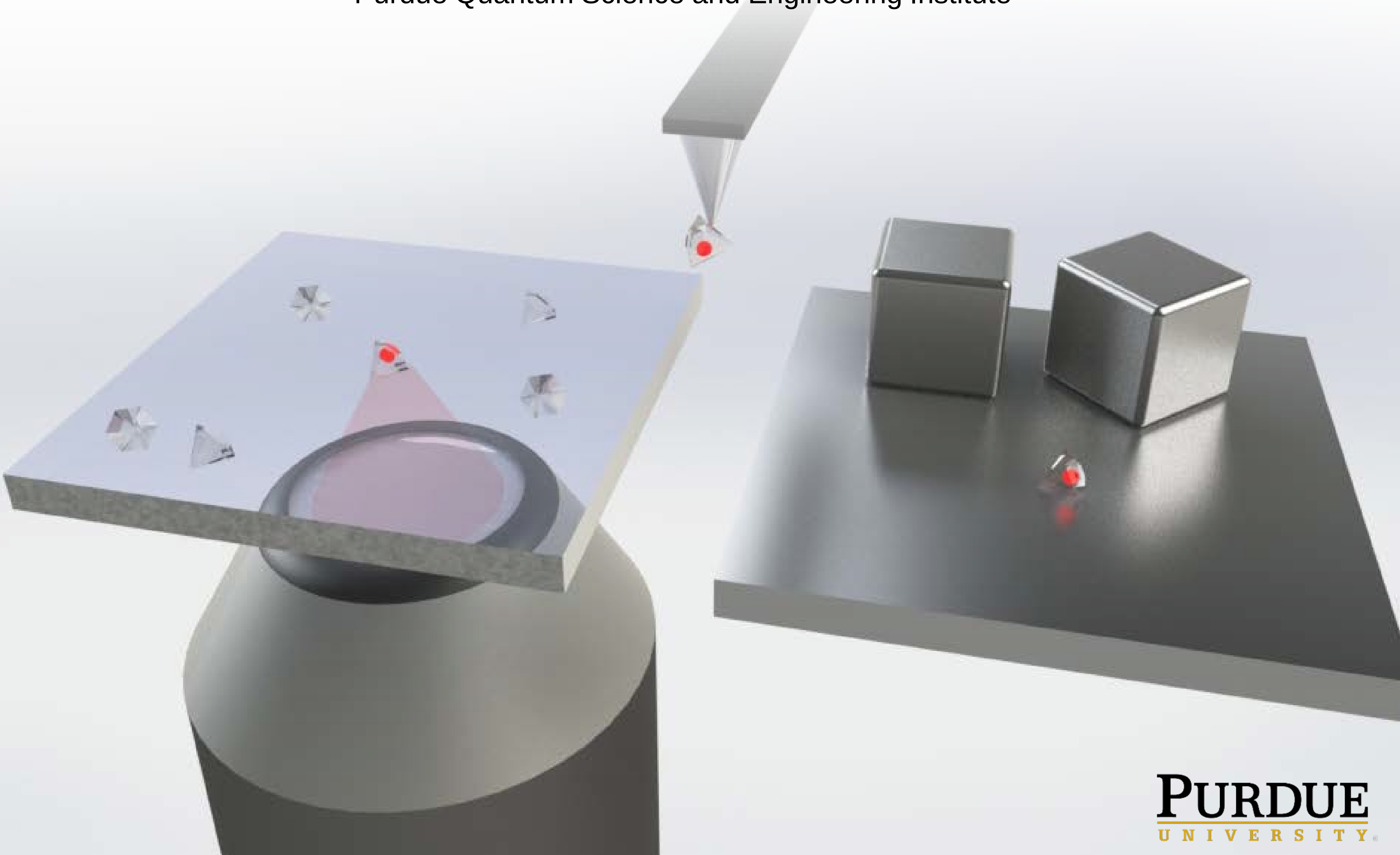
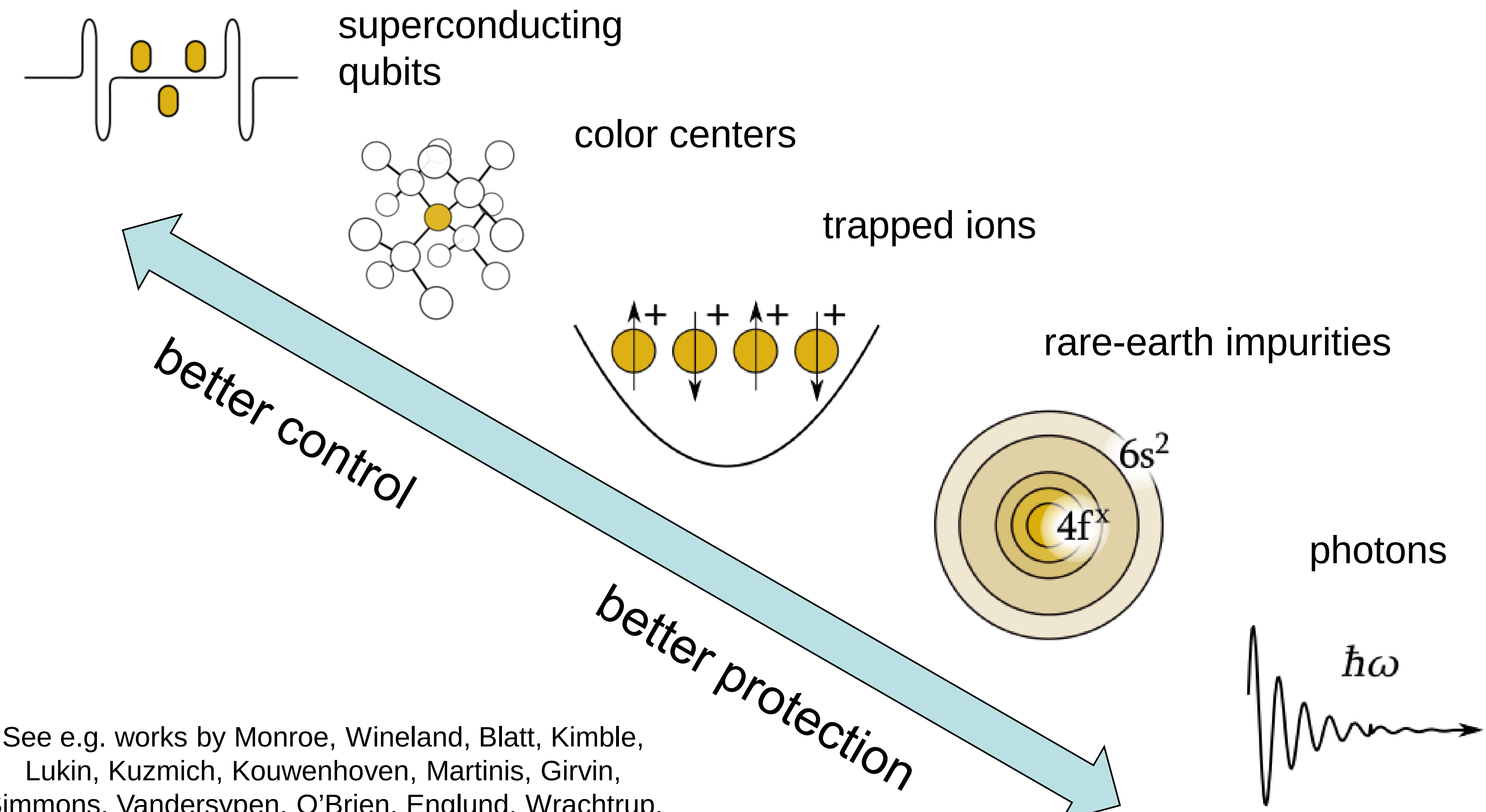
High-Speed Quantum Photonics with Plasmonic Metamaterials

Vladimir M. Shalaev
with S. Bogdanov, O. Makarova, Z. Kudyshev, A. Lagutchev, A. Kildishev and A. Boltasseva
Purdue Quantum Science and Engineering Institute



PURDUE UNIVERSITY

Qubit implementations



See e.g. works by Monroe, Wineland, Blatt, Kimble, Lukin, Kuzmich, Kouwenhoven, Martinis, Girvin, Simmons, Vandersypen, O'Brien, Englund, Wrachtrup, Kwiat, Rempe, Vuckovic, Zeilinger, Cornell, Greene, Zoller, Moore, Manfra, Gisin, Pan, Sennelaert, Walmsley, Walther and others

Promises of quantum photonic technologies

- Speed of light!
- Exceptionally immune to decoherence

nature photonics FOCUS | REVIEW ARTICLES
PUBLISHED ONLINE: 30 DECEMBER 2009 | DOI: 10.1038/NPHOTON.2009.229

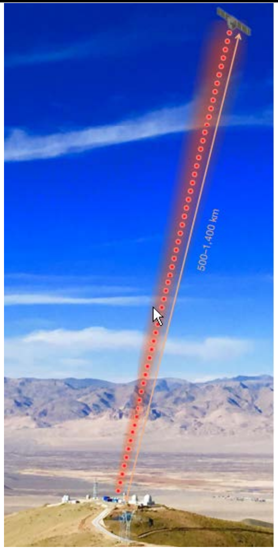
Photonic quantum technologies

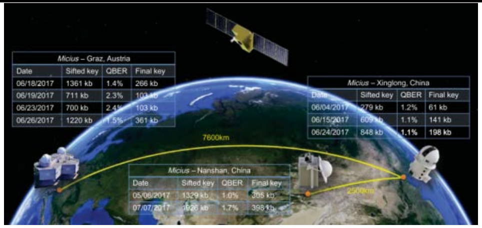
Jeremy L. O'Brien[1*], Akira Furusawa[2] and Jelena Vučković[3]

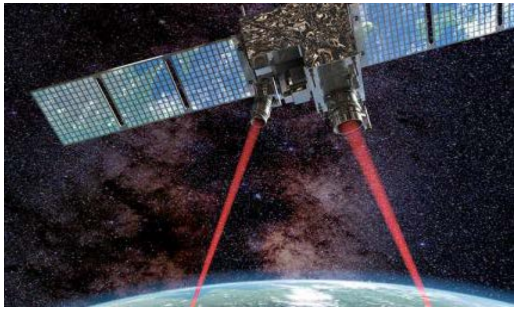
NATURE | Vol 453 | 19 June 2008 | doi:10.1038/nature07127 INSIGHT REVIEW

The quantum internet

H. J. Kimble[1]

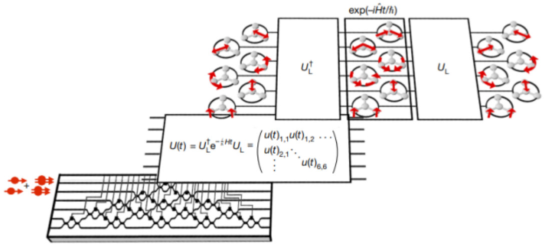




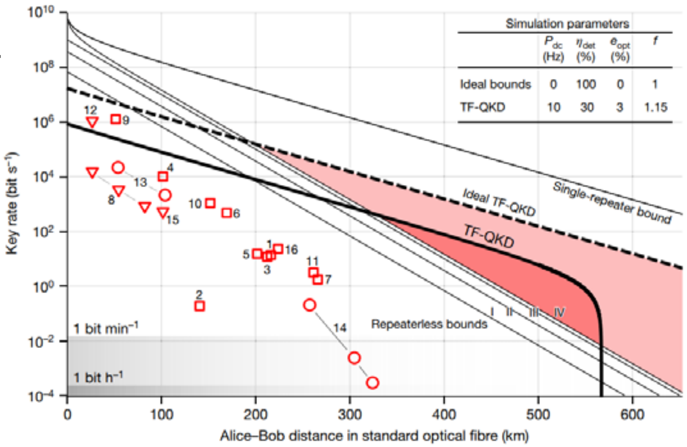


Satellite-mediated QKD, WCS
1-10 kbps, QBER 1%; trusted satellite. Liao et al. *PRL* (

Photonic Quantum Simulatior



Sparrow et al. *Nature* (2018)



Lucamarini et al. *Nature*

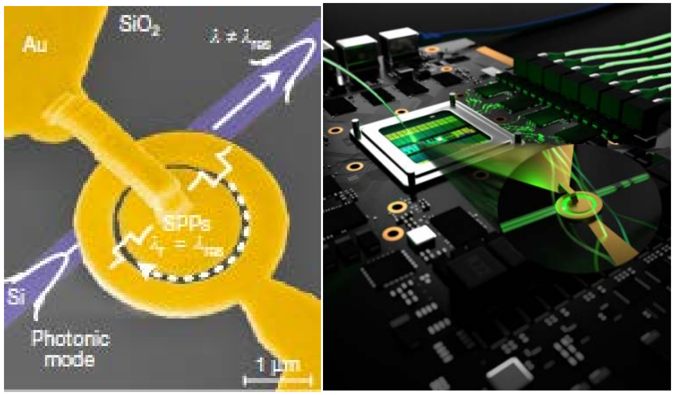
Ground-to-satellite quantum teleportatio
8 Hz, Fidelity 80%. Ren et al. *Nature* (2

Satellite-based entanglement distributio
1 Hz, Fidelity 87%. Yin et al. *Science* (2

FAST YET SLOW!

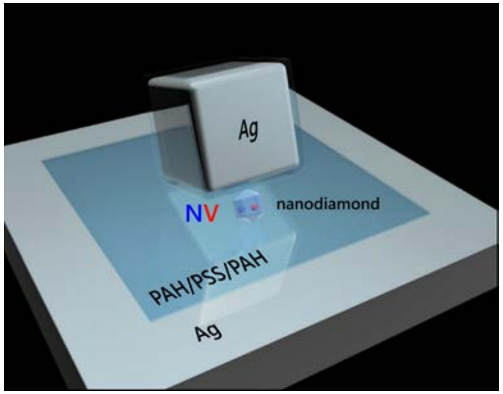
OUTLINE: Plasmonics Metamaterials Meet Quantum

Plasmonics for ultrafast modulators



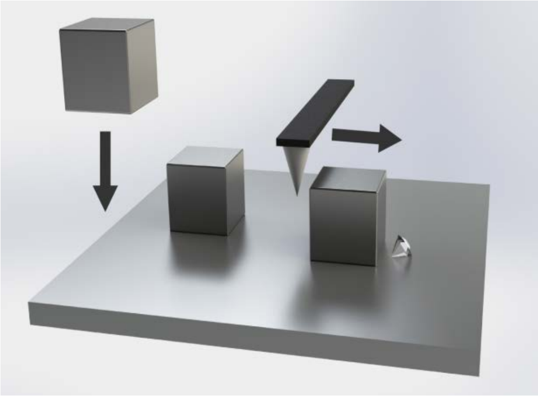
C. Haffner, et al., *Nature* (2018)
(with ETH)

Single photons at high rate



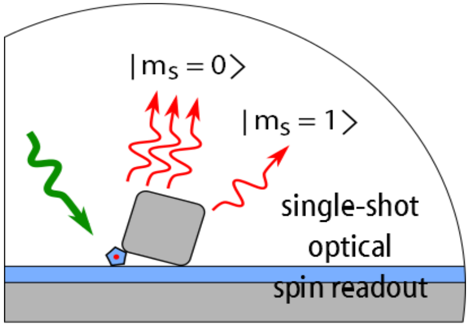
Bogdanov et al., Science (2019); *Nano Lett.* (2018)

Deterministic assembly



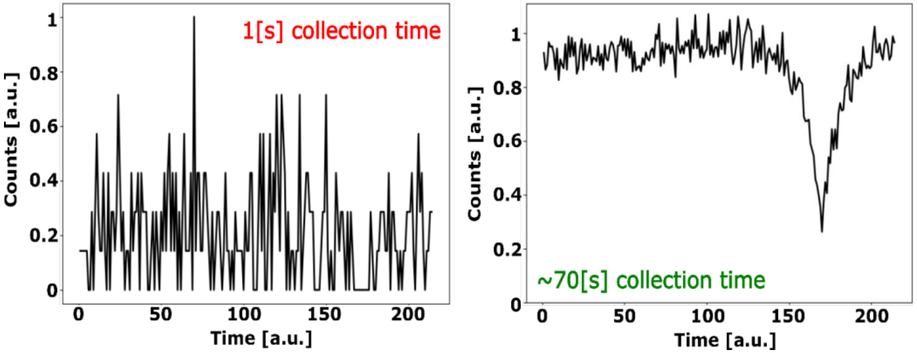
S. Bogdanov et al, arxiv (2019)

Plasmonics for single-shot optical spin read-out



S. Bogdanov et al, arxiv (2019); in preparation

Machine Learning for Quantum Photonics

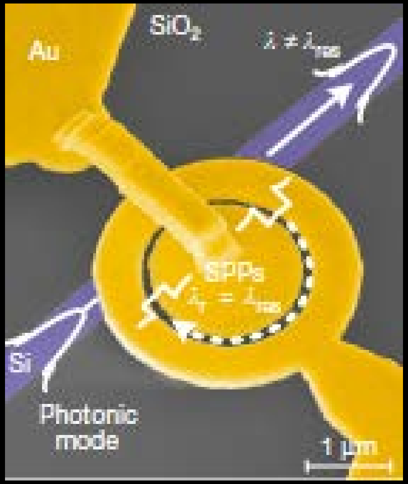


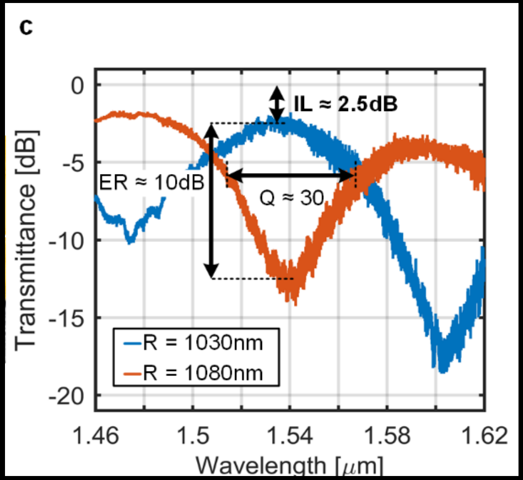
Z. Kudyshev et al, in preparation (2019)

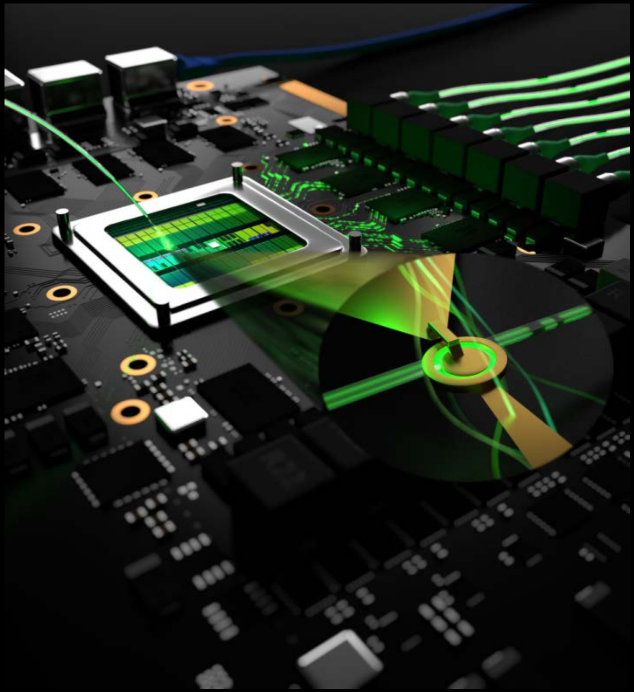
PLASMONICS FOR ULTRAFAST MODULATOR

See poster by Soham Saha

Ultrafast low-loss plasmon-assisted electro-optic modulator







Si waveguide mode couple SURFACE PLASMON when LOSS is ON!

COMPACT (footprint of a few square micrometres)

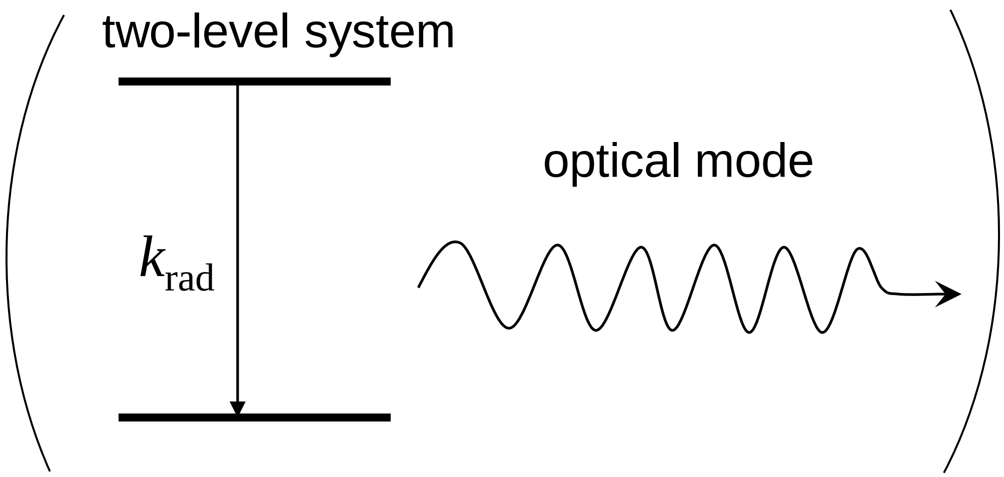
HIGH SPEED (~ THz) and LOW LOSS (< 3 dB); 12 fJ/bit

Efficient modulation: 10dB extinction ratio

In collaboration with ETH: J. Leuthold, UW: L. Dalton and VCU: N. Kinsey

C. Haffner, et al., *Nature* (2018)

Light-matter coupling in photonics & plasmonics



$$\text{Purcell Factor} \sim \left(\frac{\lambda_0}{n}\right)^3 \frac{Q}{V}$$

$\lambda_0 =$ wavelength in vacuum

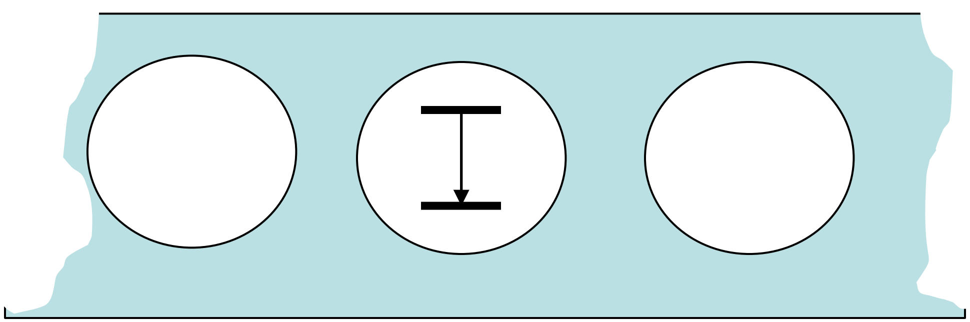
$n =$ refractive index

$Q =$ optical mode quality factor

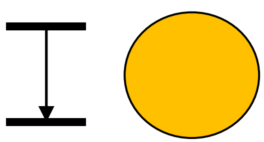
$V =$ optical mode volume

$$k_{rad} = k_{rad}^{vac} \times \text{Purcell Factor}$$

Photonic resonator
(High Q, large V)



Plasmonic resonator
(Low Q, small V)



100x brighter

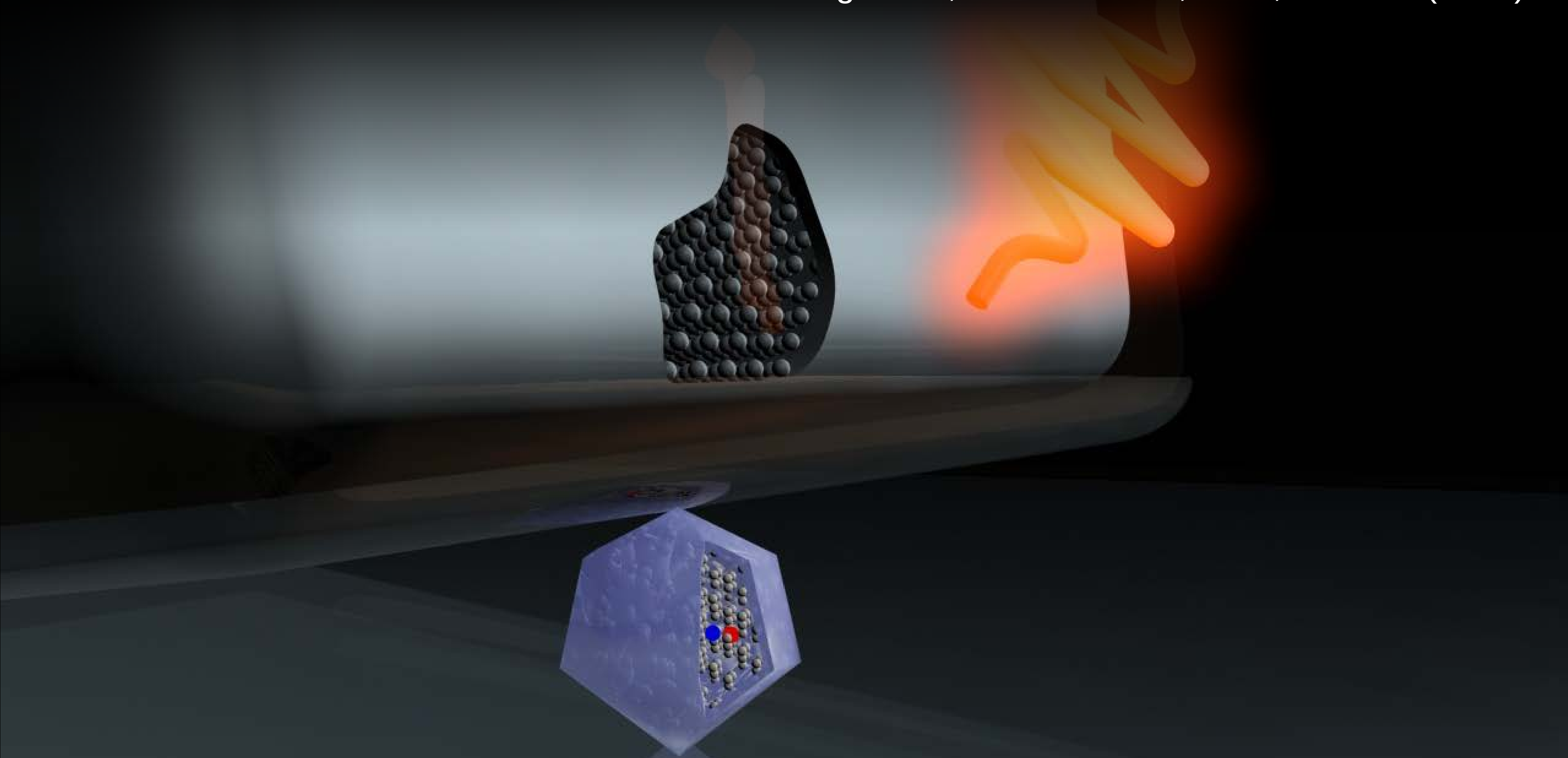
Stockman

Bozhevolnyi, Khurgin, Optica (20

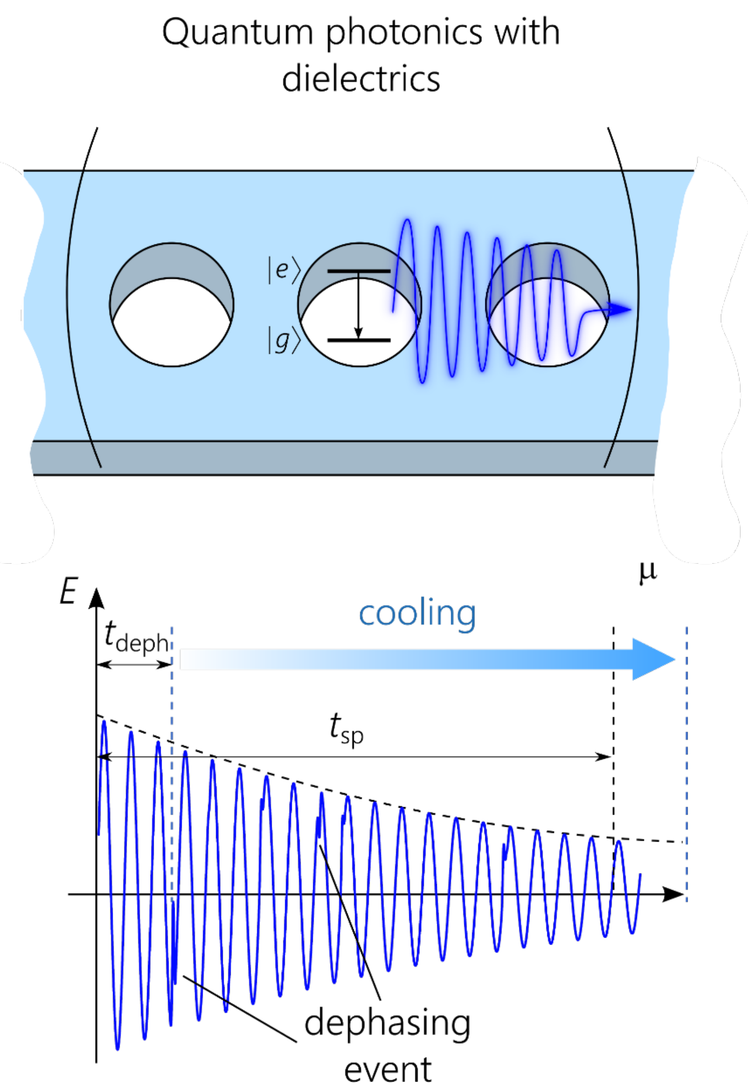
Plasmonic Metamaterials Meet Quantum:

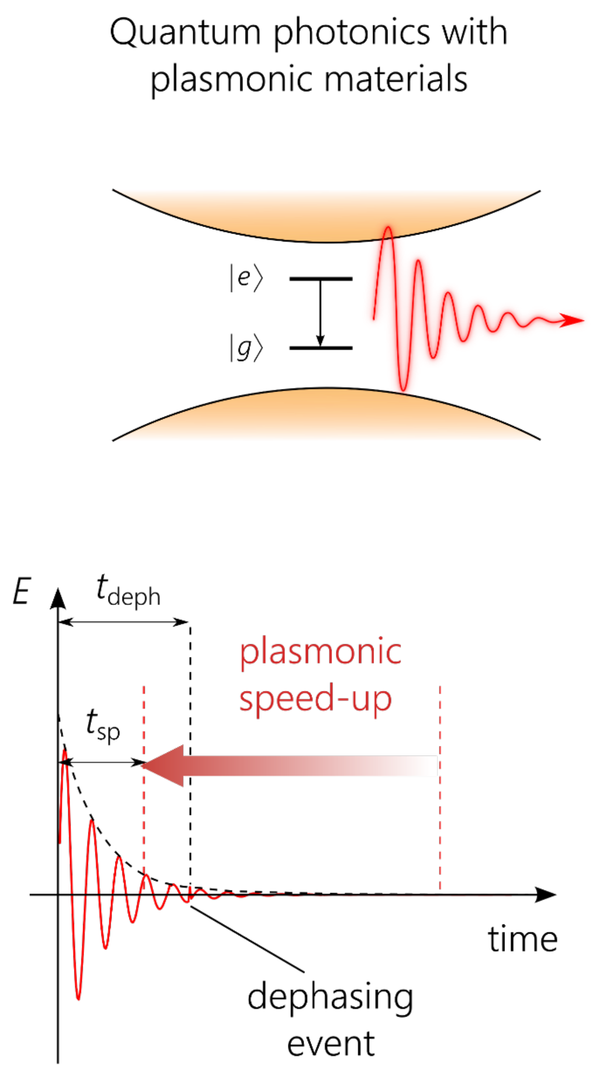
Overcoming Quantum Decoherence with Plasmoncs

S. Bogdanov, A. Boltasseva, VMS, Science (2019)



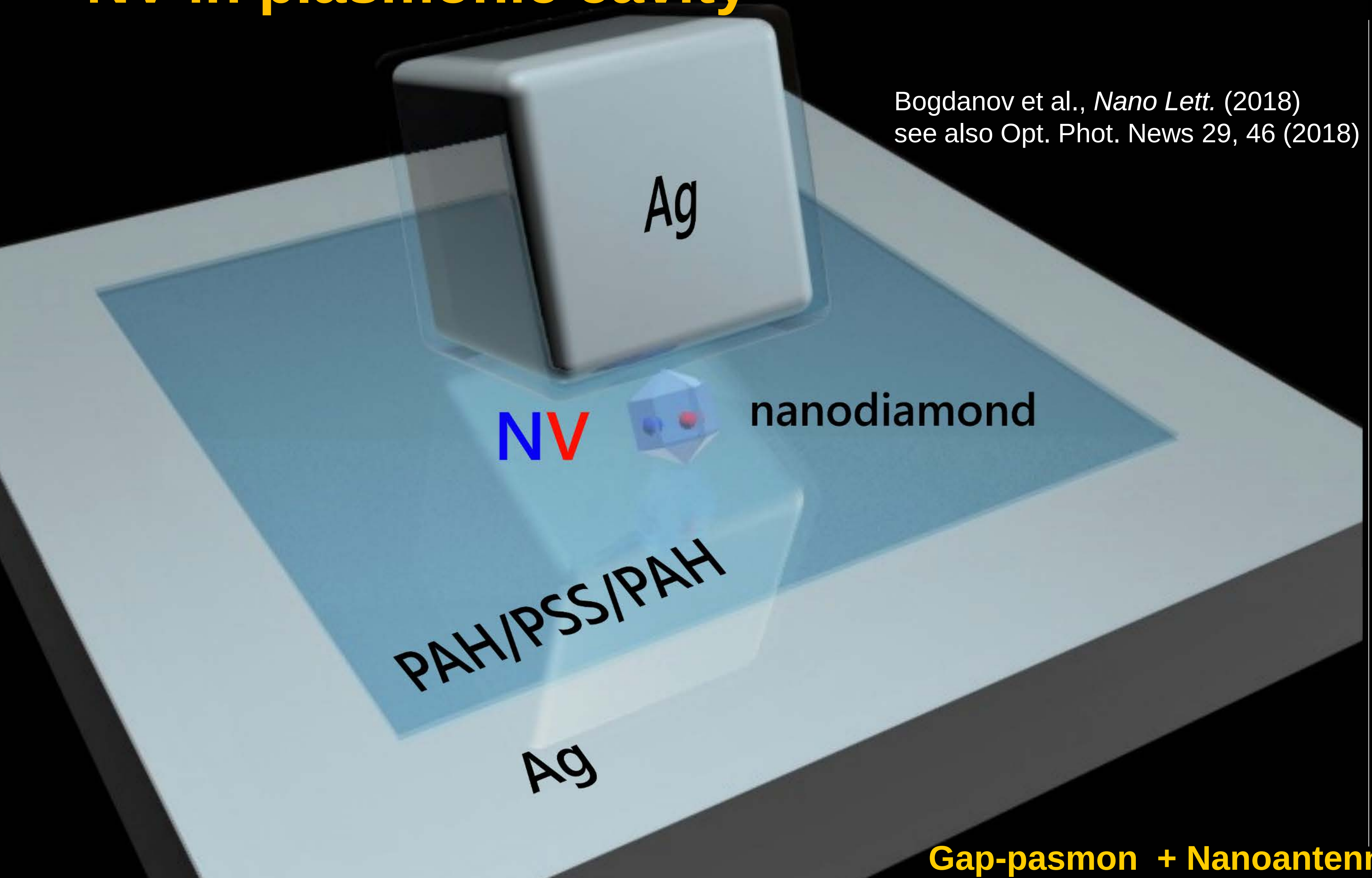
Outpacing Quantum Decoherence with Plasmonics





Record-bright RT single-photon source: NV in plasmonic cavity

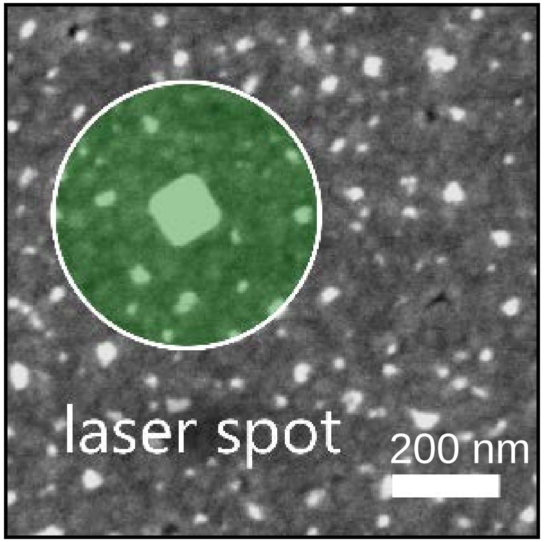
Bogdanov et al., *Nano Lett.* (2018)
see also Opt. Phot. News 29, 46 (2018)



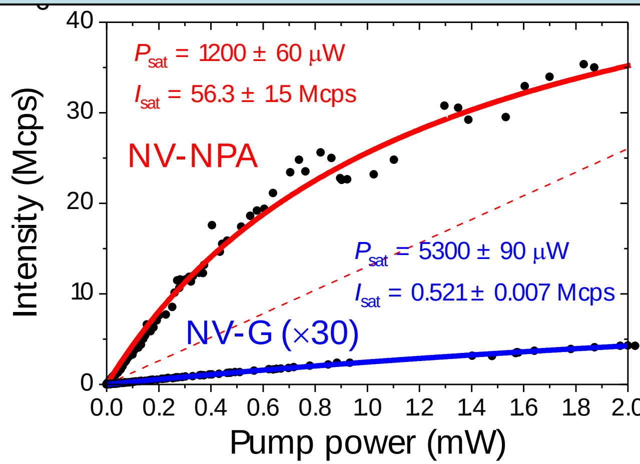
Gap-pasmon + Nanoantenn

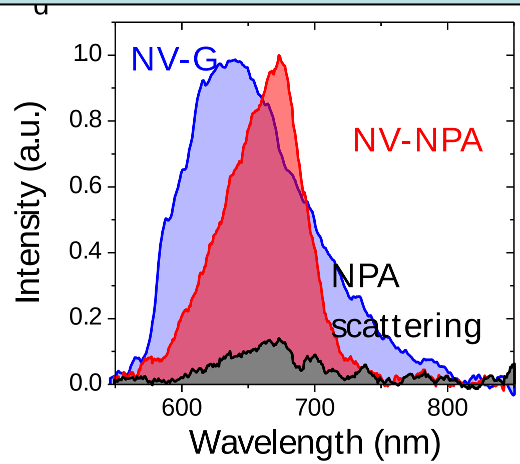
Single-photon emission at record-high rates: NV center in nano-patch antenna (NPA)

SEM 1x1 µm of Ag substrate



photon emission rate
into far field ~ 0.5 GHz





Nanodiamonds randomly dispersed on silver substrate

Nanocubes randomly dispersed over nanodiamonds

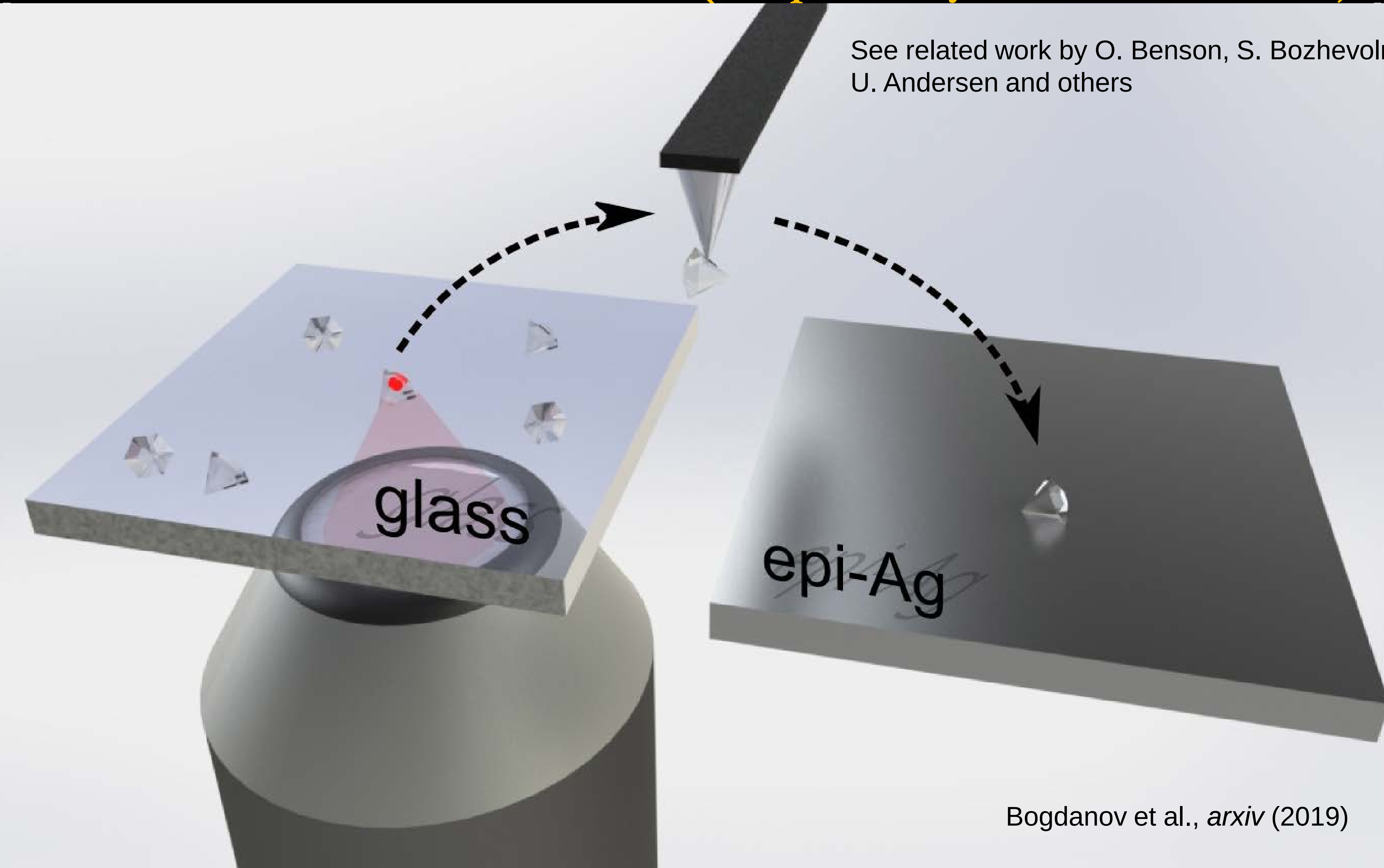
Bogdanov et al., *Nano Lett.* (2018)

See also works by M. Mikkelsen, S. Strauf, J. Baumberg, B. Hecht, V. Sandoghdar, N. van Hulst and others

Deterministic Assembly of NPAs for SPS

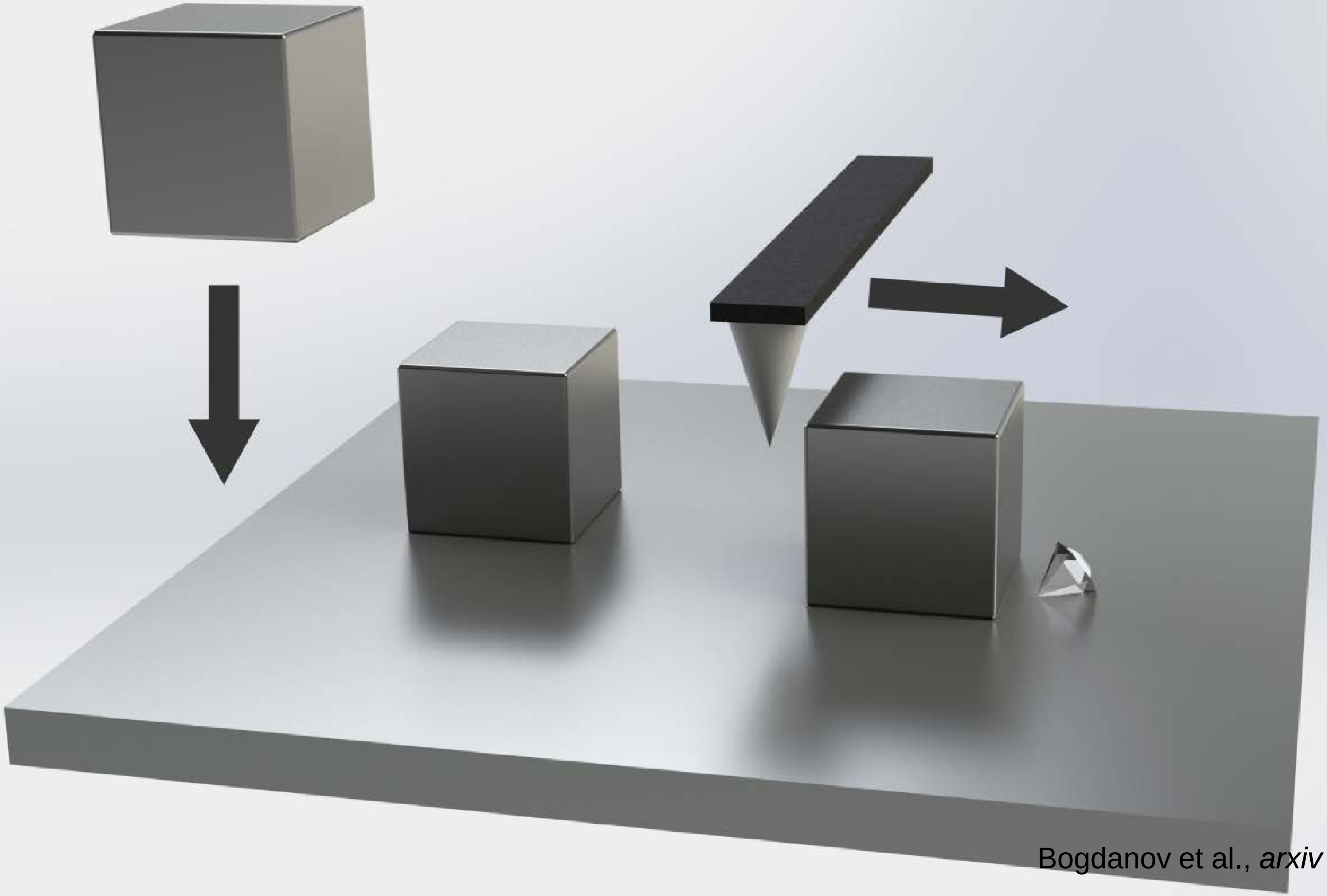
(see poster by Oksana Makarova)

See related work by O. Benson, S. Bozhevol
U. Andersen and others



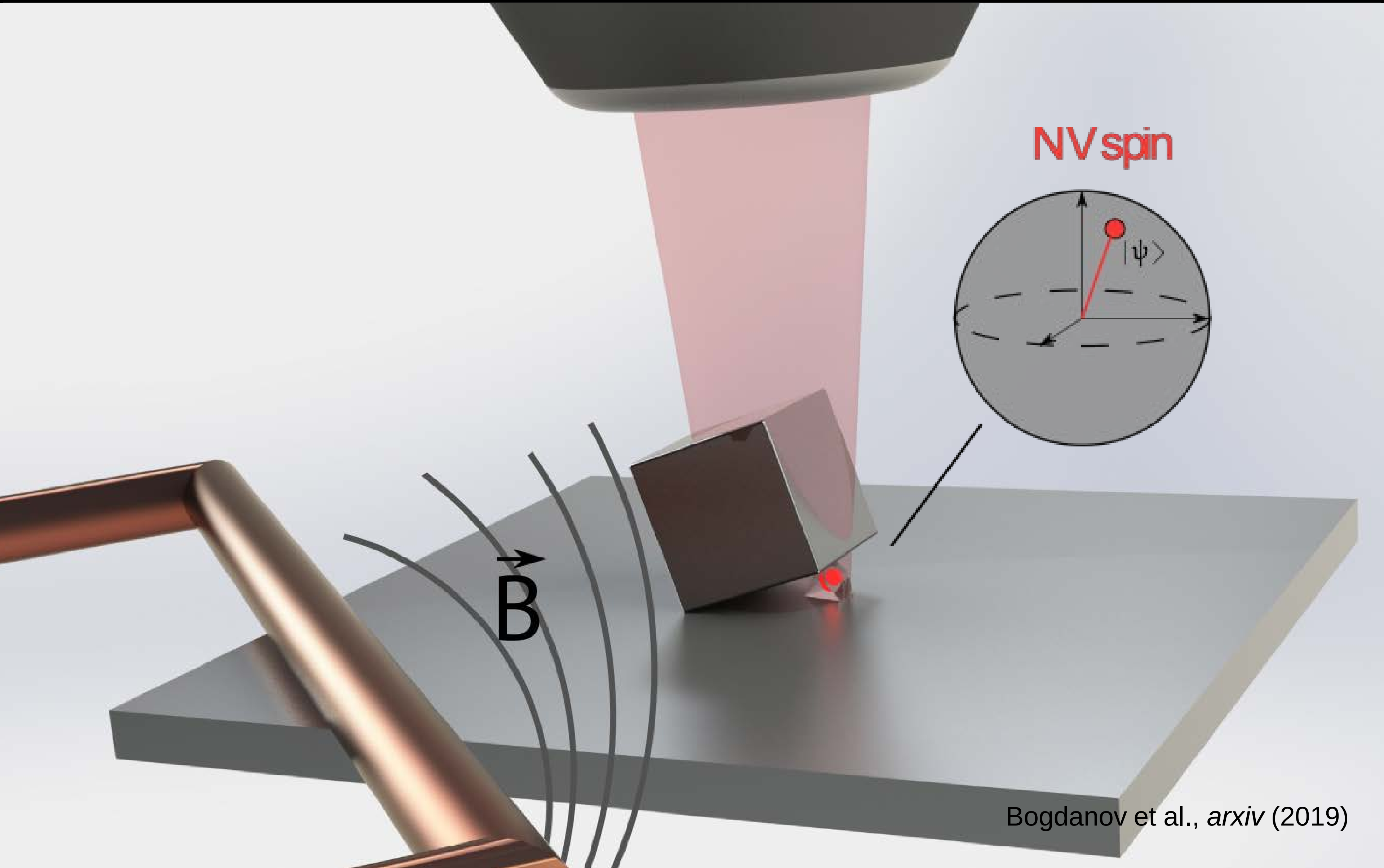
Bogdanov et al., *arxiv* (2019)

Deposition and nudging of the nanocubes



Bogdanov et al., *arxiv* (2019)

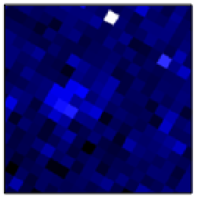
Single-photon nanoantenna characterization

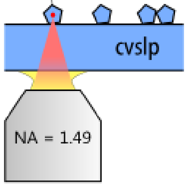


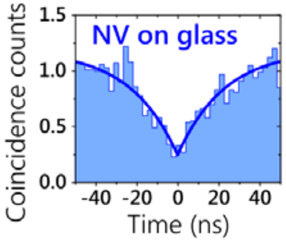
Bogdanov et al., *arxiv* (2019)

Deterministic assembly of a single-photon nanoantenna

Optical characterization

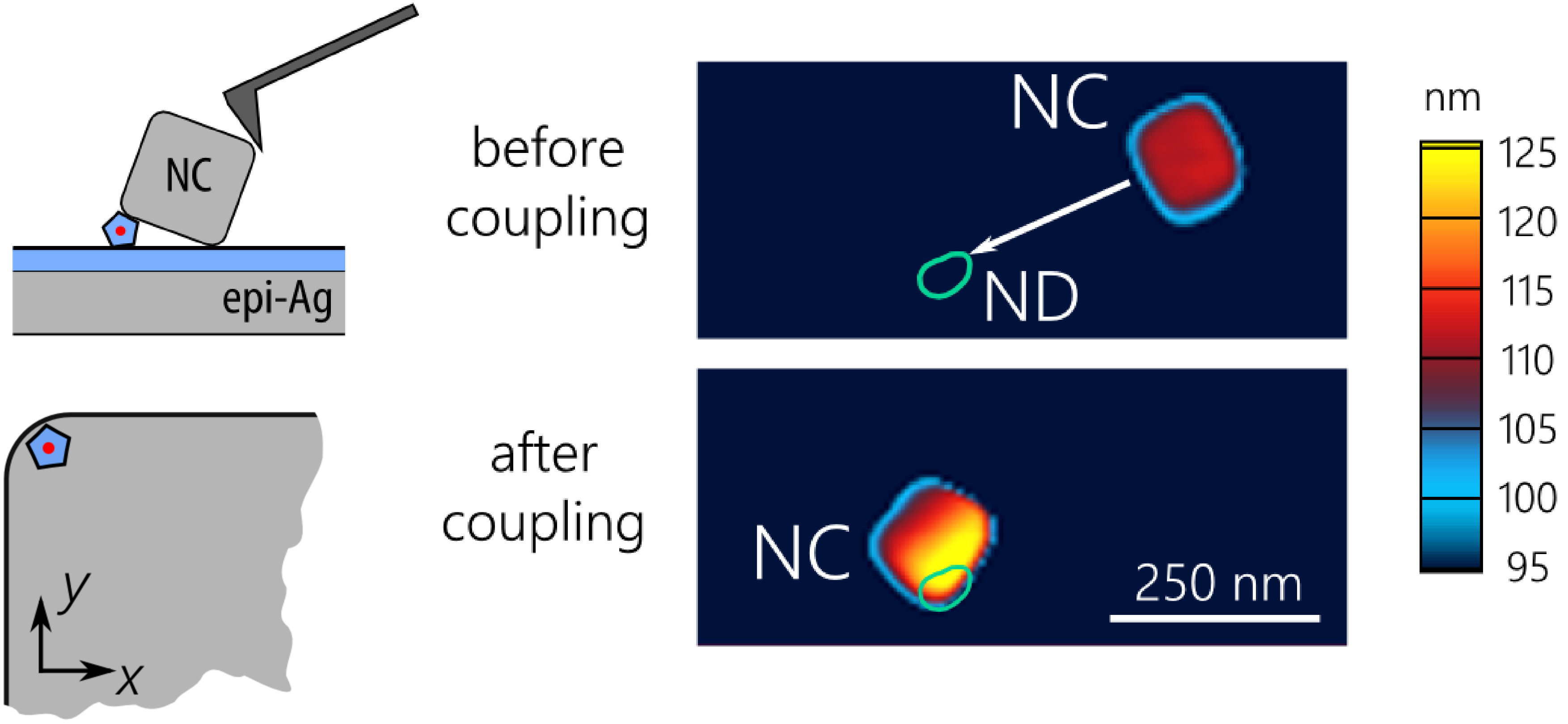






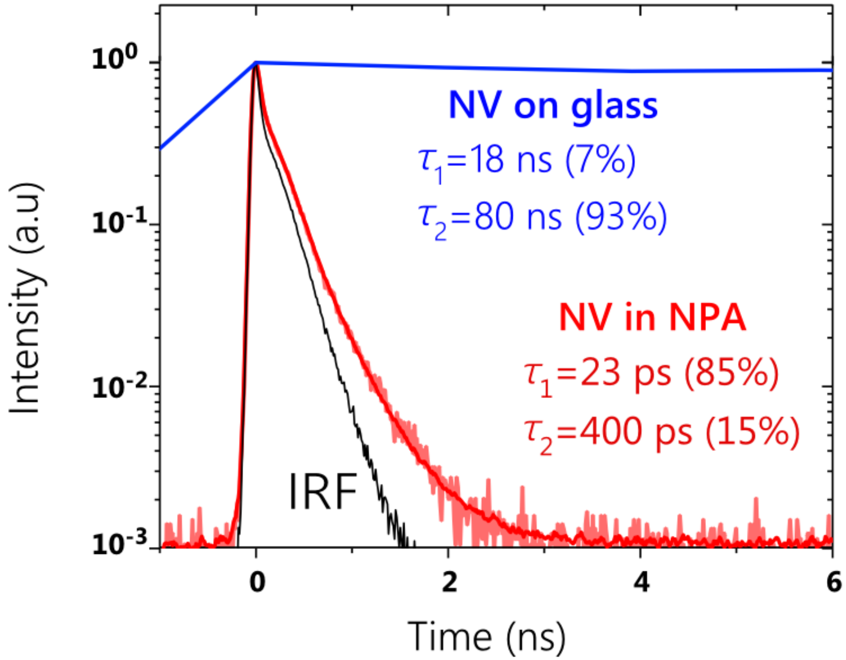
Realizing the optimal antenna configuration

Optimal enhancement
with diamond under cube corner



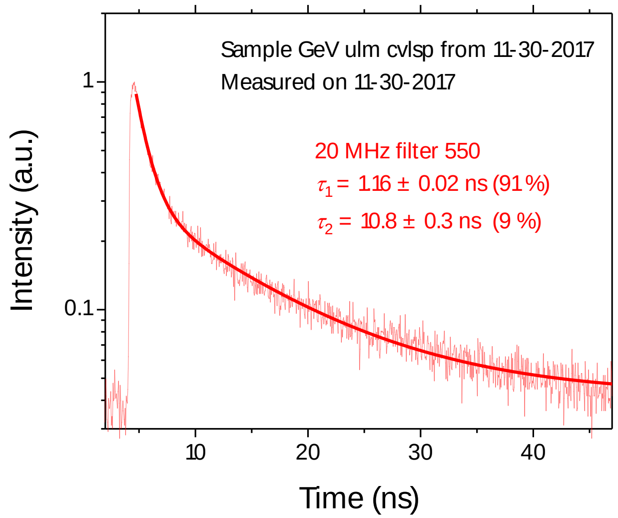
Bogdanov et al., *arxiv* (2019)

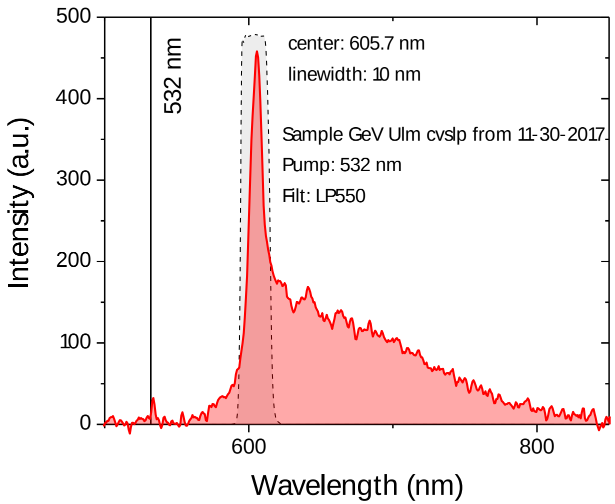
Characterizing optimal single-photon nanoantennas



Lifetime shortening of 3,500 times:
record-fast decay rate
for a single NV center (23 ps)

Indistinguishable photons in GeVs?





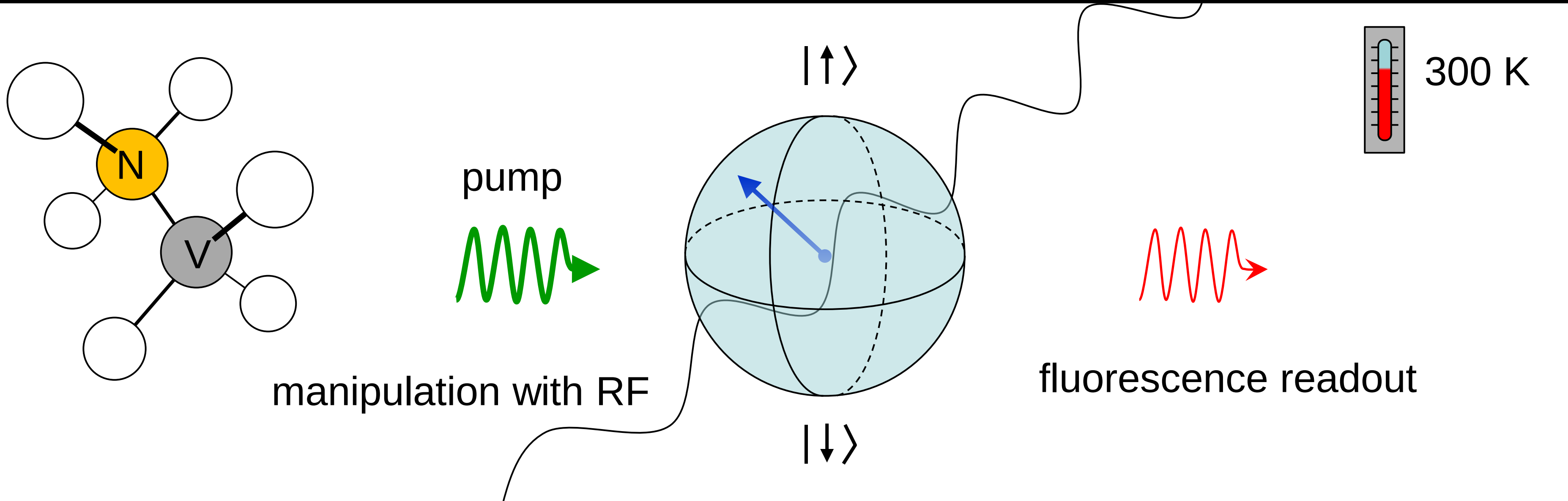
τ_{sp} = 1 ns

10^3-10^4

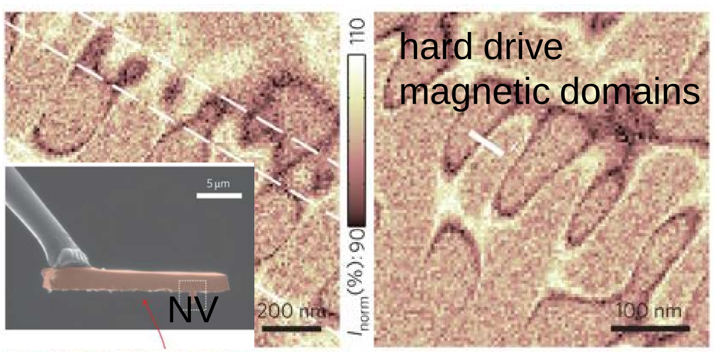
t_{deph} = 0.1 - 1 ps

necessary lifetime shortening = 10^3-10^4

Nitrogen-vacancy center in diamond

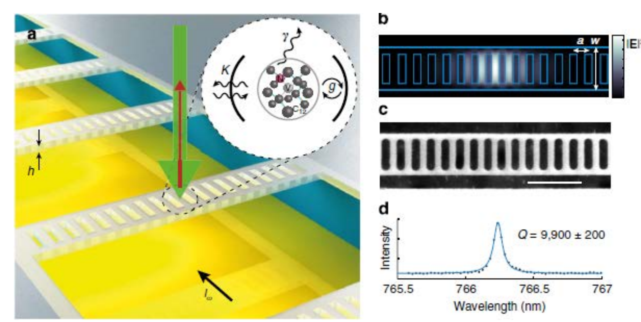


Nanoscale sensing



Maletinsky et al., *Nat. Nano* (2012)

Quantum information processing

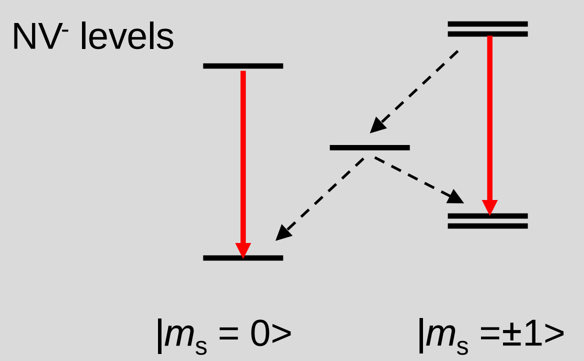


Li et al., *Nat. Comm* (2014)

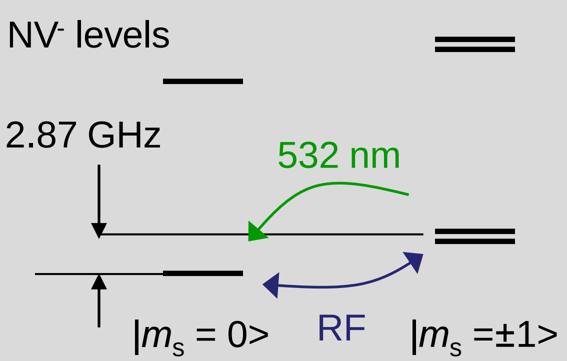
See also works by M. Lukin, R. Walsworth, D. Awschalom, D. Budker, C. Becher, F. Jelezko, K. Fang, P. Hemmer, a

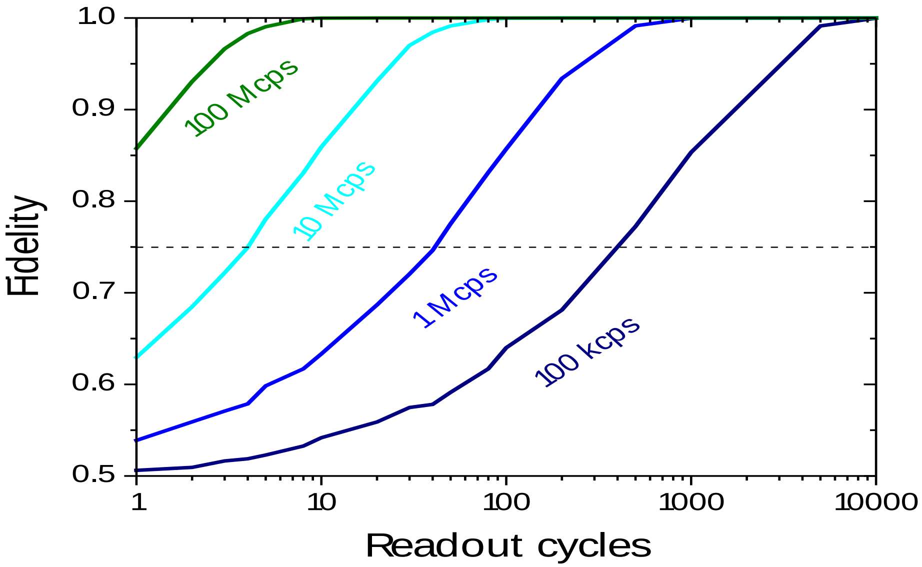
Single-shot optical spin readout

Brightness depends on spin state

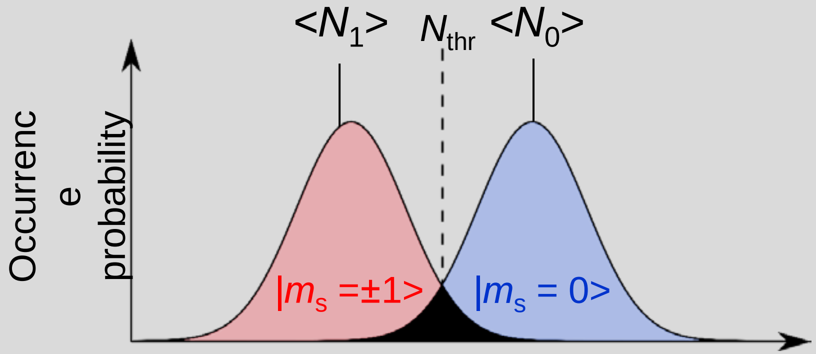


Initialize and rotate spin at 300K

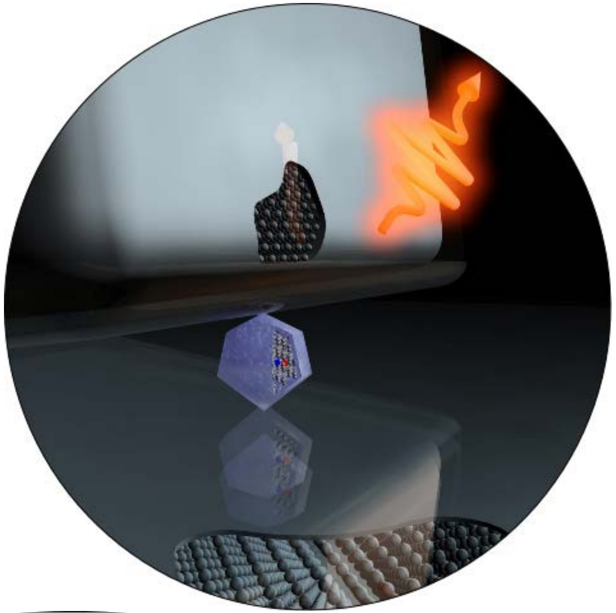




Spin readout fidelity depends on N_0

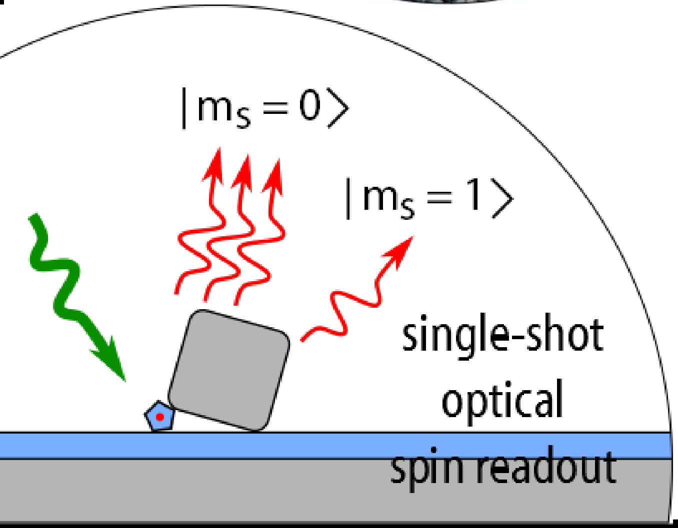


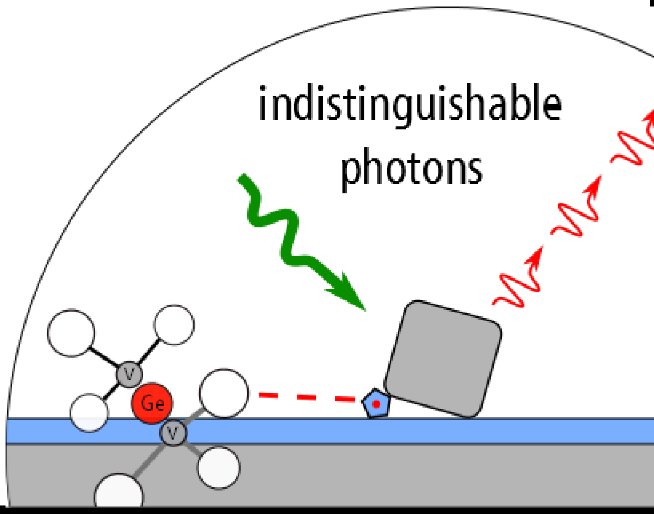
Outpacing quantum decoherence with plasmonics



- 30 Mcps – brightest RT single-photon source
- 0.5 GHz emission rate into far field at RT
- x3,500 plasmonc speed-up (23ps emission)

S. Bogdanov, A. Boltasseva, VMS, Science (2019)

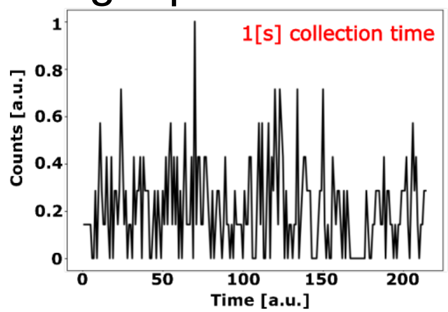


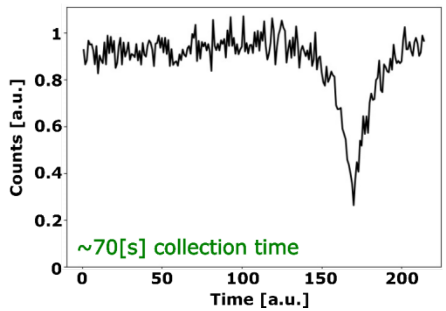


Machine learning for quantum photonics

(see poster by Z. Kudyshev)

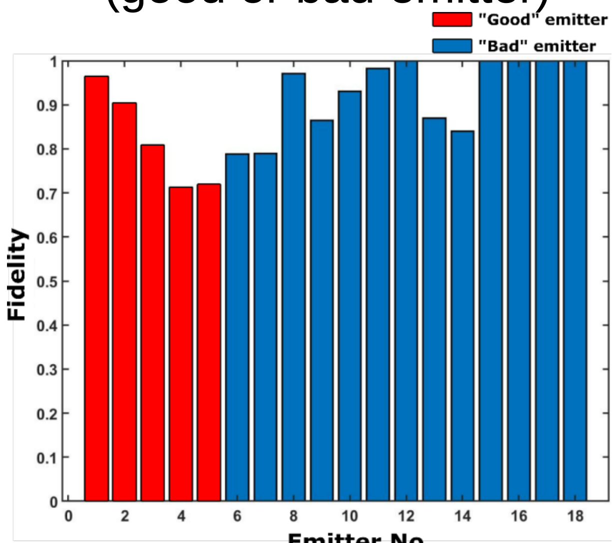
fast single-photon autocorrelation measurement





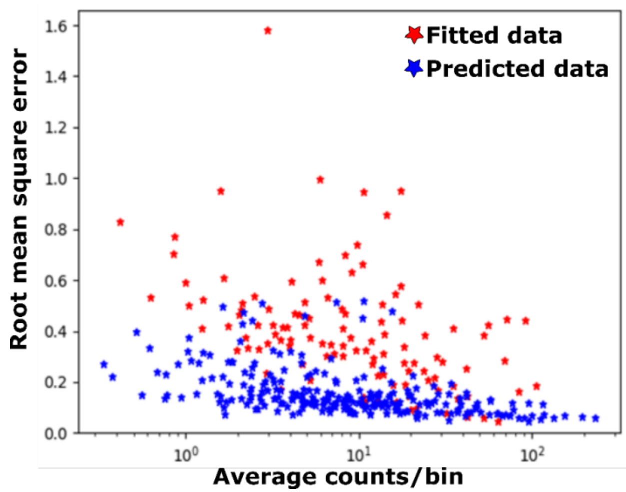
Is it possible to identify good emitters from 1[s] data?

- Classification problem: (good or bad emitter)

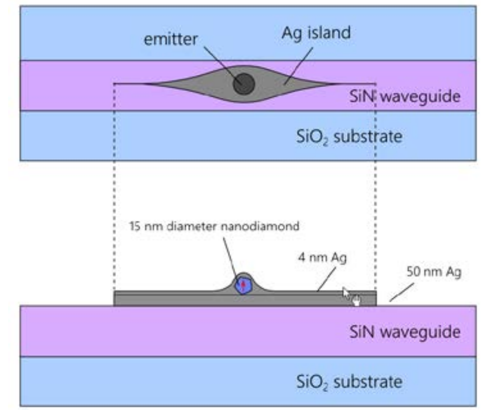


Neural network trained on 15 emitters' 1s data sets

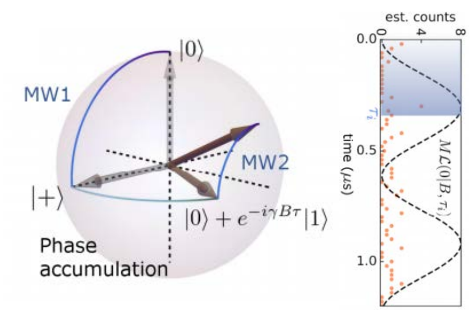
- Estimation of exact value of g2 (sparse data analysis):



ML assisted topology optimization

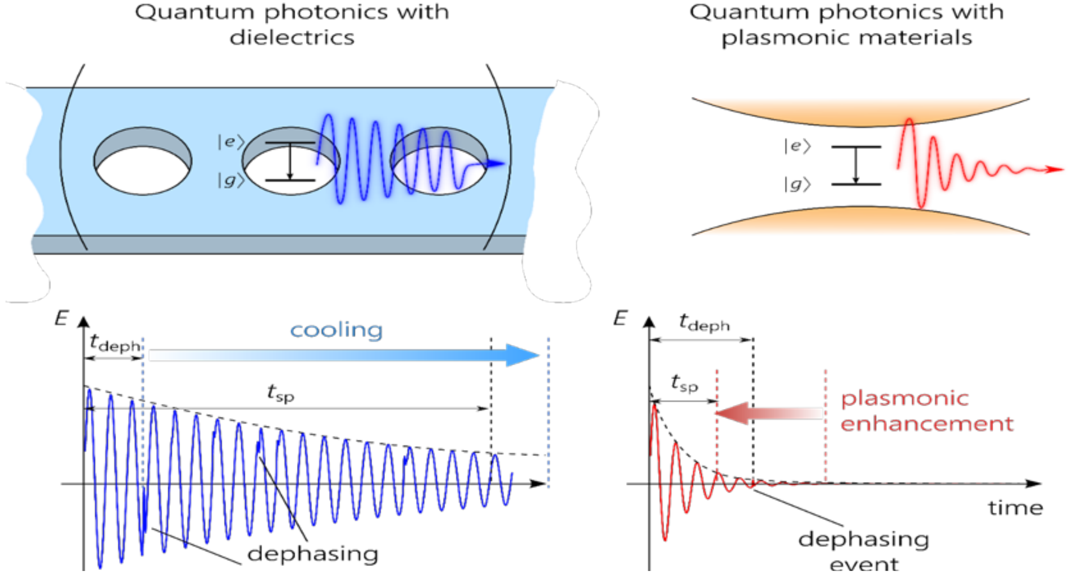


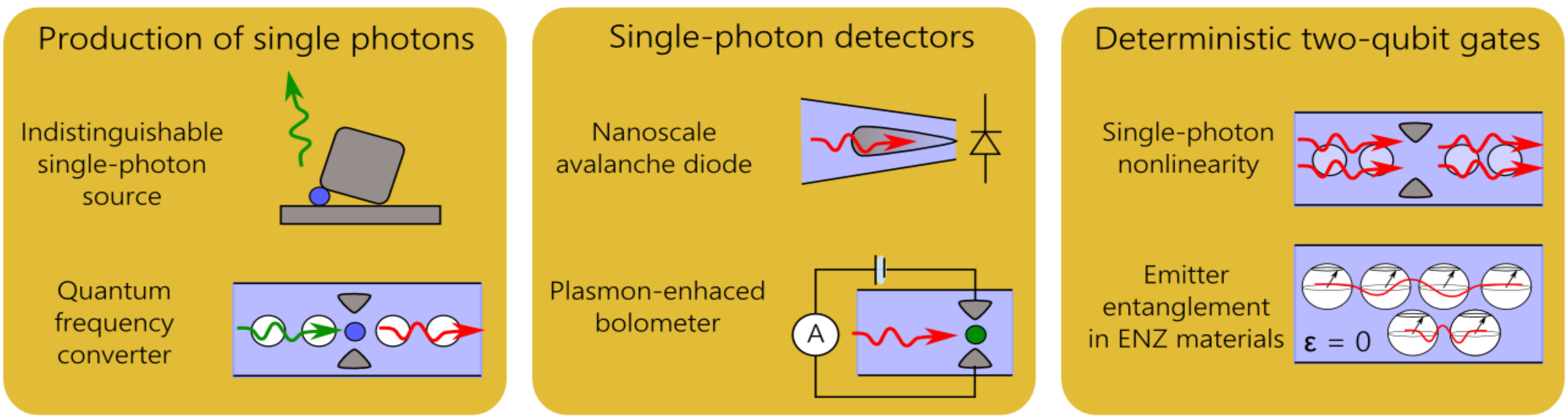
ML for spin readout



Santagati et al., *arxiv* 2018

High-speed room-temperature platform for quantum information

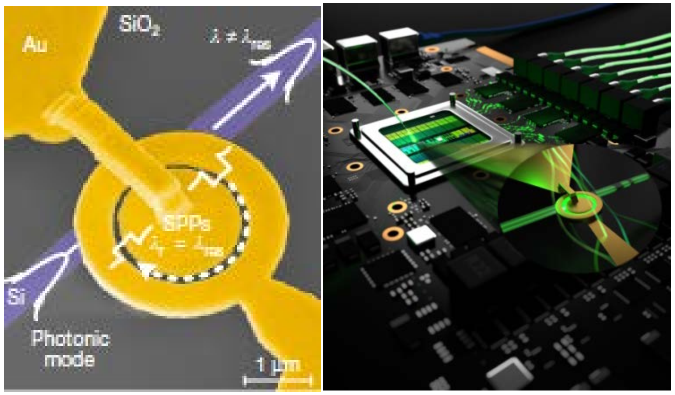




Interaction between qubits strongly enhanced by nanophotonics results in high speed quantum dynamics immune to loss and decoherence at RT

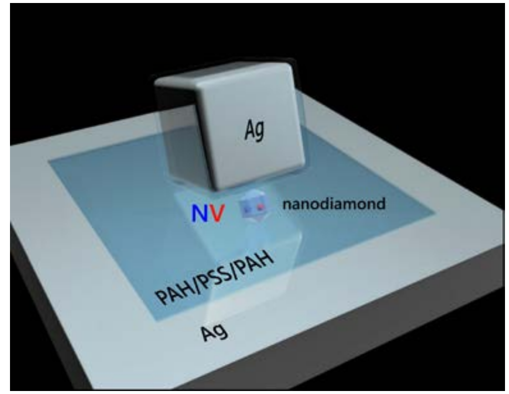
High-Speed Quantum Photonics with Plasmonic Metamaterials

Plasmonics for ultrafast modulators



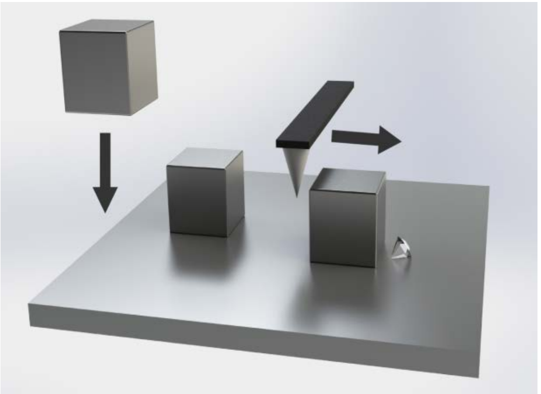
C. Haffner, et al., *Nature* (2018)
(with ETH)

Single photons at high rate



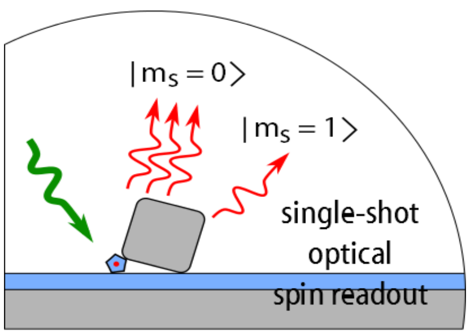
Bogdanov et al., Science (2019); *Nano Lett.* (2018)

Deterministic assembly



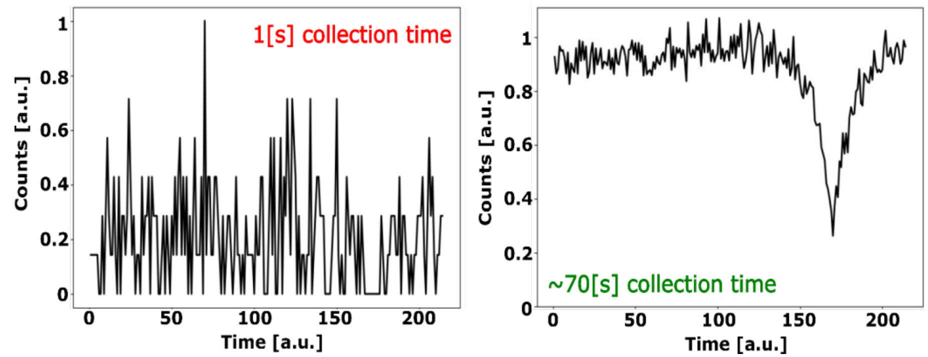
S. Bogdanov et al, arxiv (2019)

Plasmonics for single-shot optical spin read-out



S. Bogdanov et al, arxiv (2019); in preparation

Machine Learning for Quantum Photonics



Z. Kudyshev et al, in preparation (2019)

TEAM

TEAM AND SUPPORT

Students

- Aveek Dutta
- Sajid Choudhury
- Krishnakali Chaudhuri
- Harsha Reddy
- Deesha Shah
- Soham Saha
- Clayton DeVault
- D. Wang

-

Collaborations

- Prof. A. Boltasseva (Purdue)
- Prof. Y. Gogotsi (Drexel)
- Prof. A. Calzolari (CNR)
- Prof. I. Bondarev (NC Central)
- Prof. A. Kildishev (Purdue)
- Prof. Ferrera (Heriot-Watt)
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