Quantum optics with photons, phonons and plasmons

Alexander Huck, Amine Laghaout, Bo Melholt Nielsen, Ulrich Busk Hoff, Anders Tipsmark, Lars Madsen, Jonas Neergaard-Nielsen, Ying Wei Lu, Shailesh Kumar, Christian Kothe, Mikael Lassen, Niels Israelsen, Adriano Berni, Mario Usuga and Ulrik L. Andersen

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Uni Erlangen (G. Leuchs, Ch. Marquardt, Ch. Wittmann, Ch. Muller, Ch. Gabriel...)
Uni Queensland (W. Bowen, G. Harris, T. Ralph)
Kista (G. Bjork)
Uni. Copenhagen (A. Sørensen, P. Lodahl, E. Polzik)
Brussel Uni (N. Cerf, J. Niset)

Forsknings- og Innovationsstyrelsen
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LUNDBECKFONDEN
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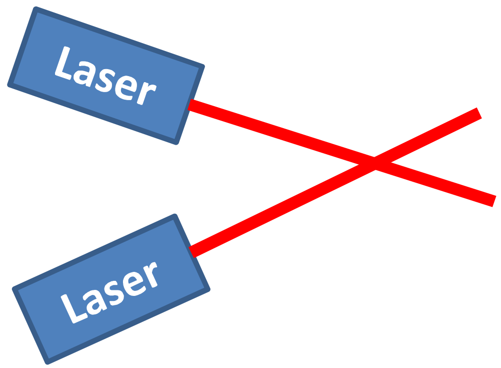
It is good to have LARGE non-linearities



Measurement induced nonlinearities -> Linear optical computing

Not resource efficient!

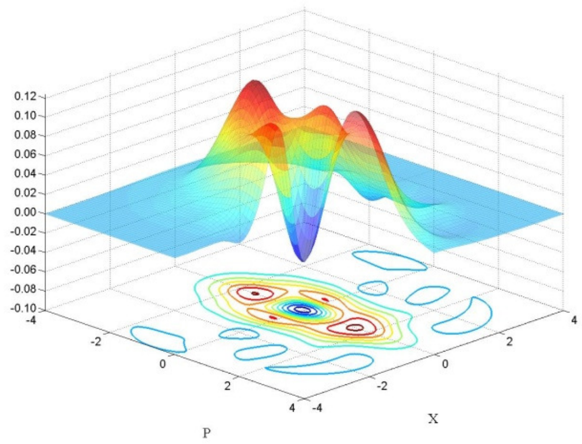
Giant non-linearity between photons -> Deterministic quantum logic gates

Large nonlinearity between photons -> Near-Deterministic quantum logic gates

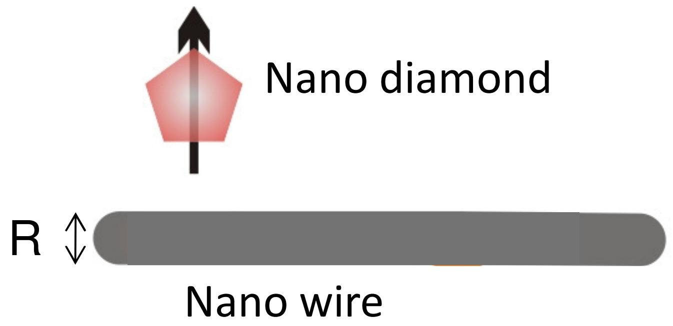
Giant non-linearity -> Non-Gaussian states

Outline

Measurement induced nonlinearity



Potential candidate for deterministic large nonlinearities.



Measurement induced giant nonlinearity: **Implementation of a Hadamard gate for coherent states**

A. Tipsmark[1], R. Dong[1], M. Jezek[1,2], A. Laghaout[1], P. Marek[2], ULA[1]

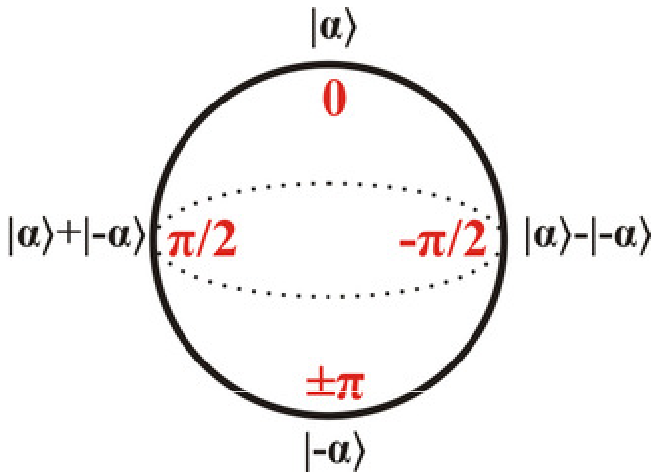
1) Technical University of Denmark (DTU)
2) Palacky University, Olomouc, Czech Republic

Cat state quantum computing

Ralph et al PRA 68, 042319 (2003)

Computational basis: $|\alpha\rangle, |-\alpha\rangle$

Diagonal basis: $|\alpha\rangle \pm |-\alpha\rangle$



Universal set of gates:

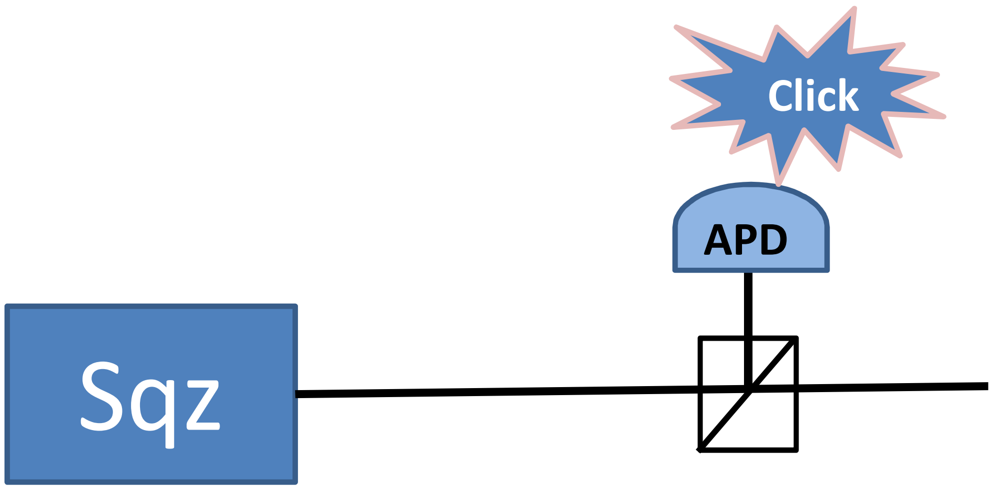
X-gate $|\alpha\rangle \to |-\alpha\rangle$

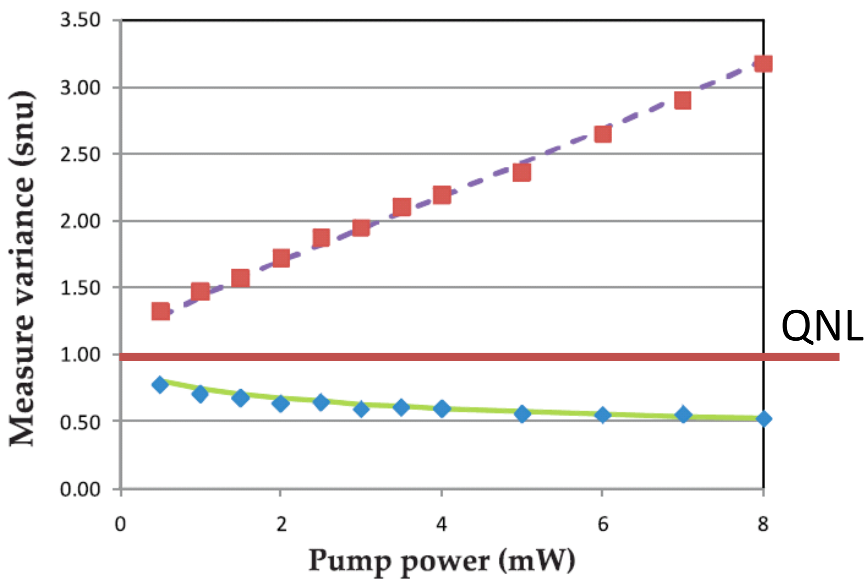
Z-rotation $|\alpha\rangle + |-\alpha\rangle \to |\alpha\rangle + e^{i\theta}|-\alpha\rangle$

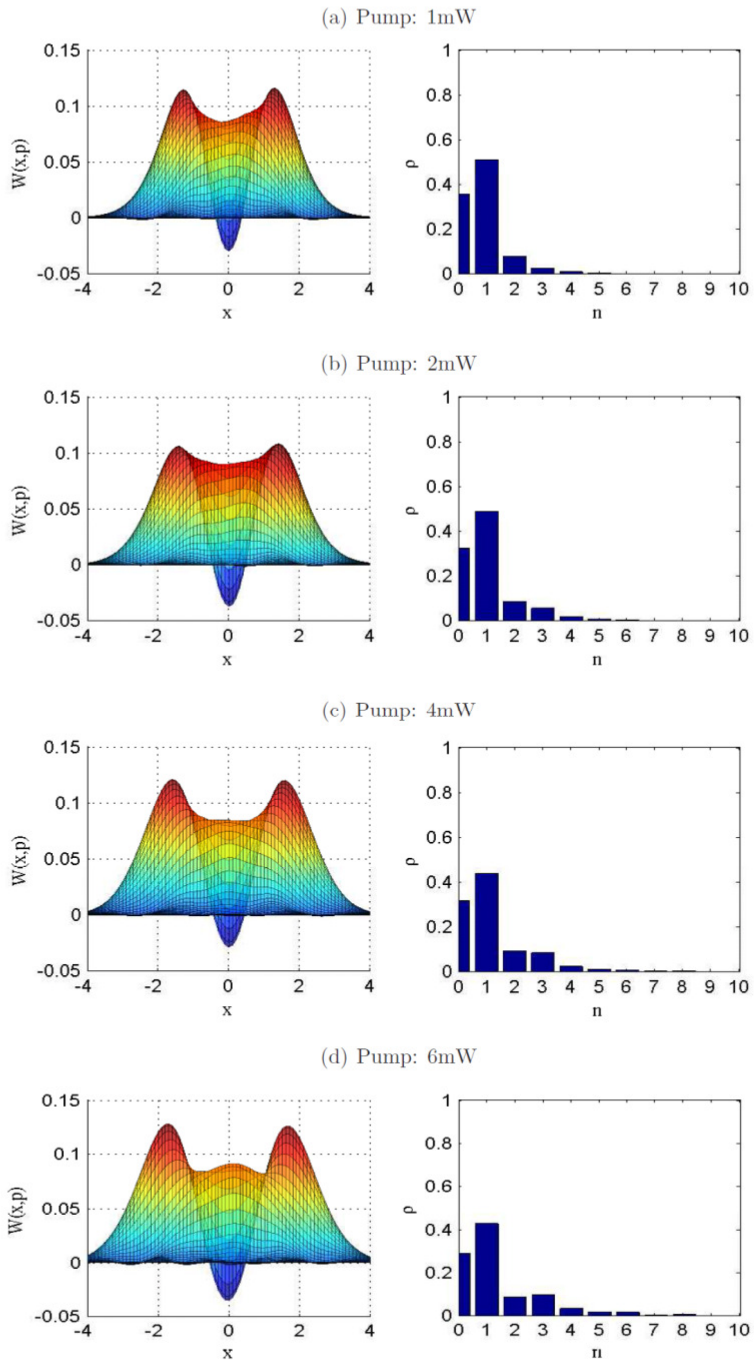
Hadamard gate $|\pm\alpha\rangle \to |\alpha\rangle \pm |-\alpha\rangle$

Controlled Z-rotation

Preparation of odd cats







Ourjoumtsev et al Science 312, 83 (2006); Nielsen et al PRL 97, 083604 (2006); Wakui et al, Opt. Express 15, 3568 (2007).

Implementing the gates by teleportation

Lund, Ralph, Haselgrove PRL 100, 030503 (2008)

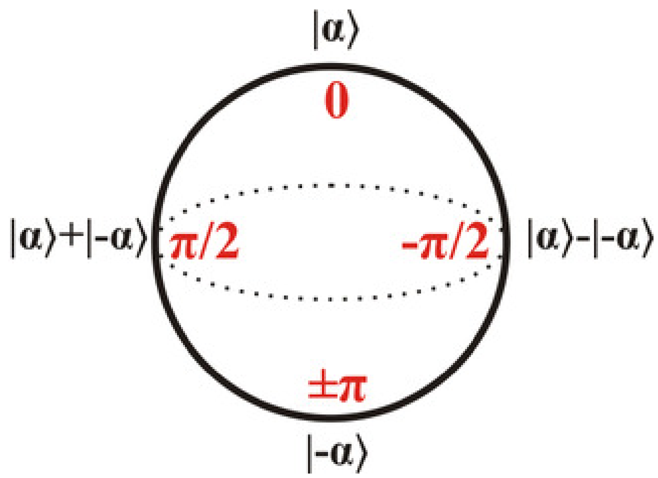
Universal set of gates:

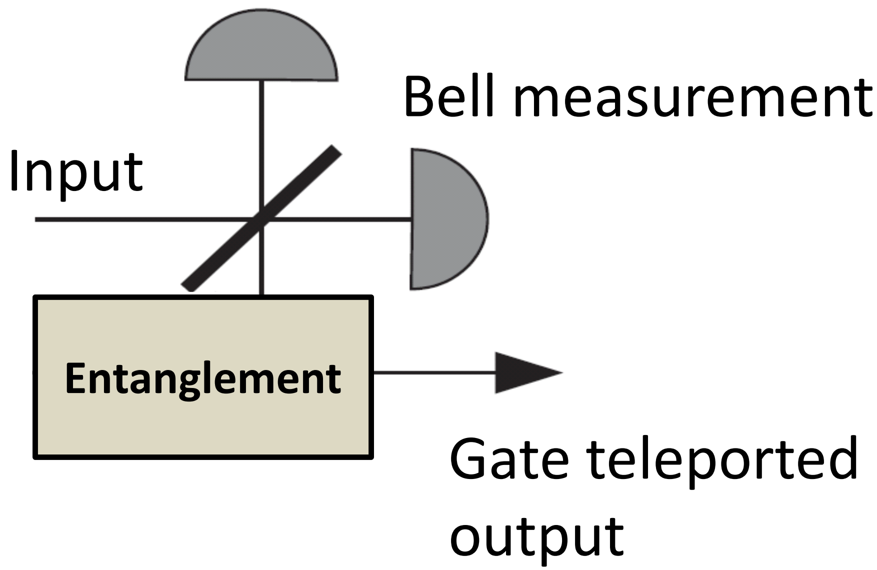
X-gate

Z-rotation

Hadamard gate

Controlled Z-rotation

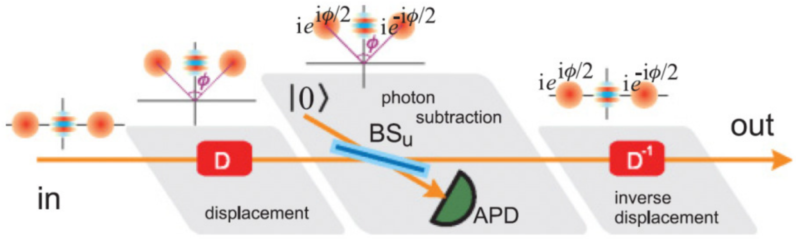




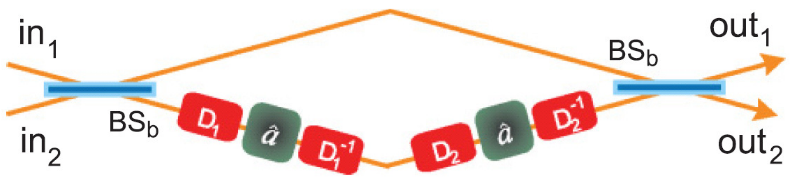
Probabilistic implementation

Marek and Fiurasek, PRA **82**, 014304 (2010)

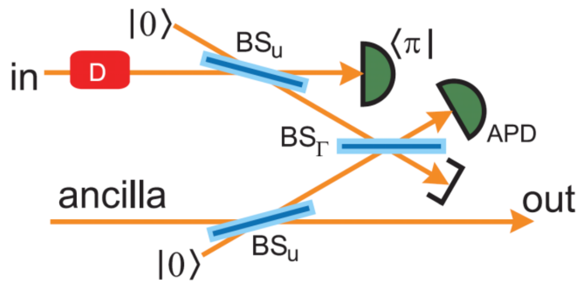
Z-rotation gate



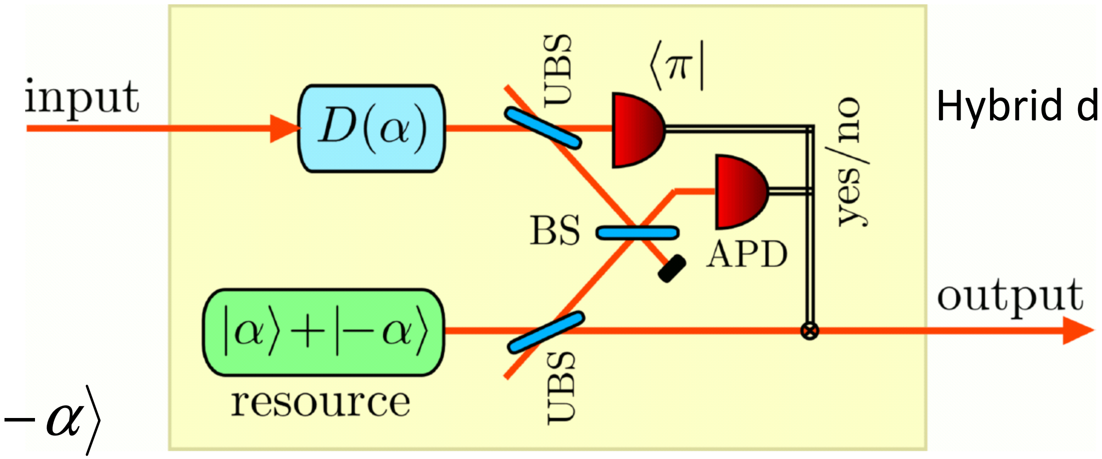
Controlled Z-rotation gate



Hadamard gate

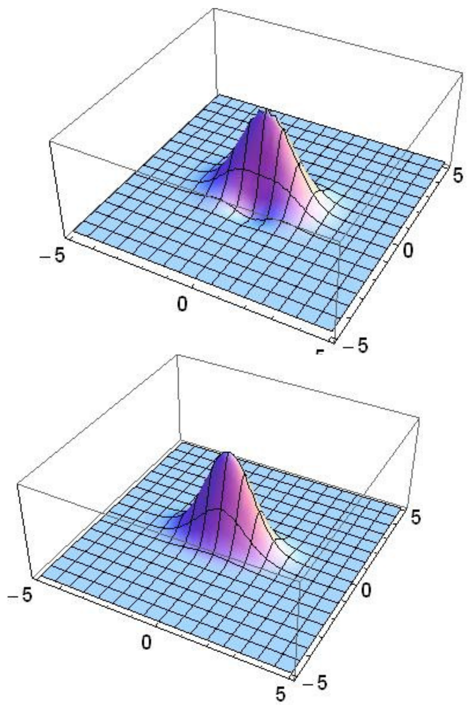


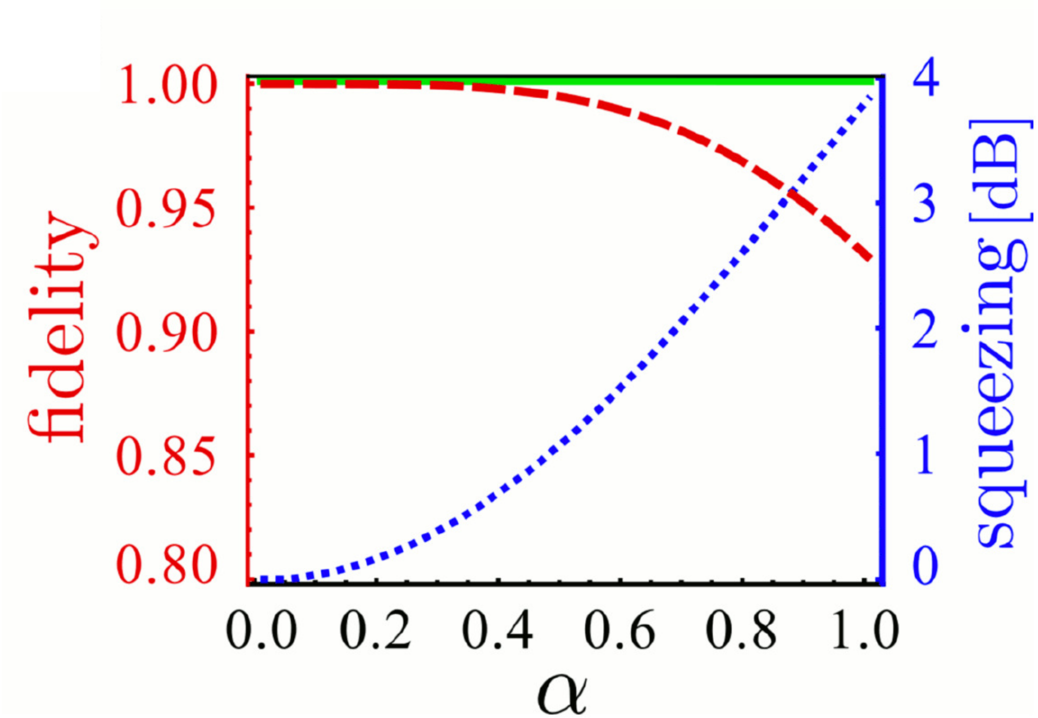
Hadamard gate $|\pm\alpha\rangle \rightarrow |\alpha\rangle \pm |-\alpha\rangle$



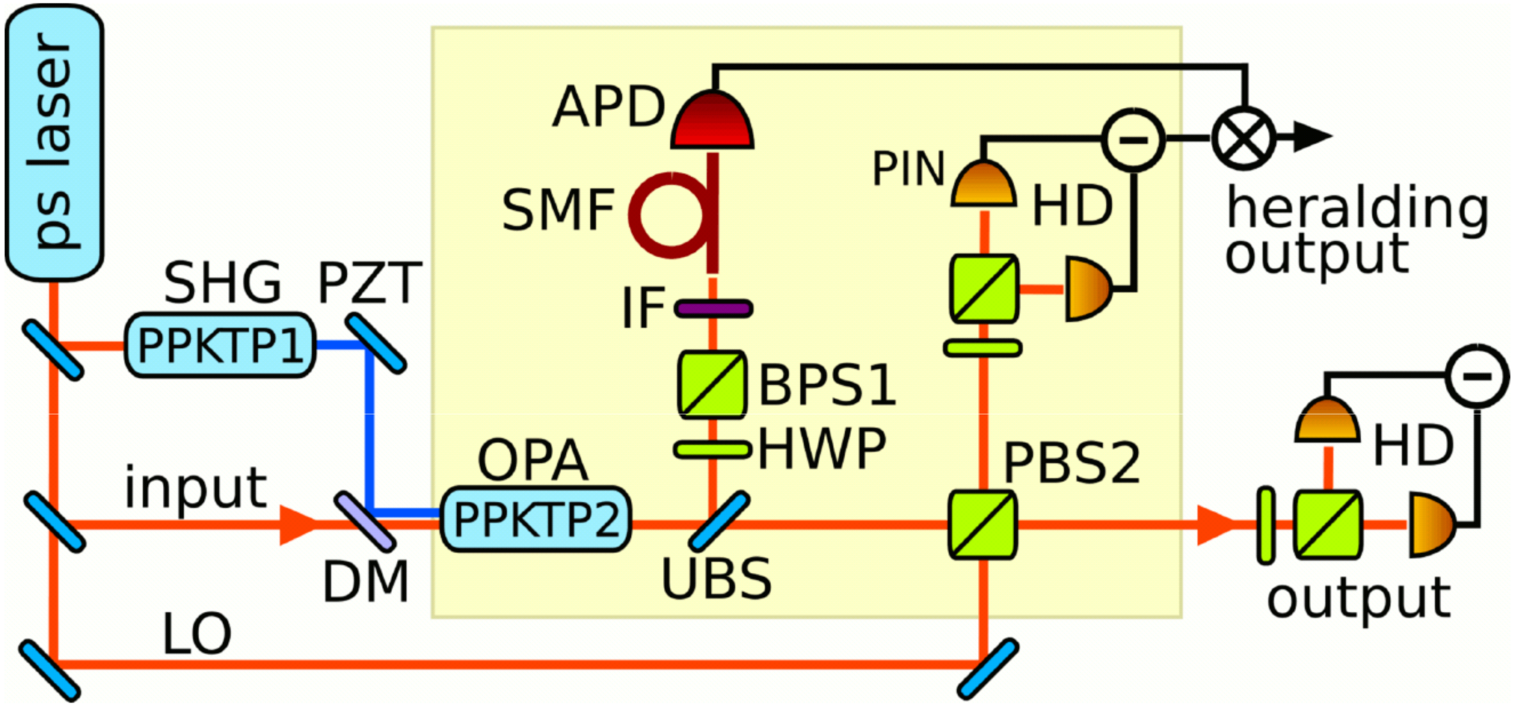
Hybrid detection

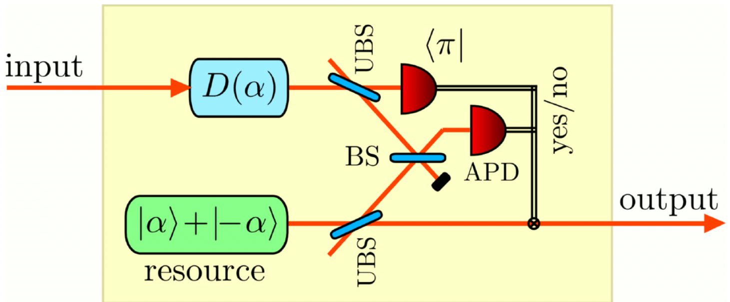
$|Sqz\rangle \approx |\alpha\rangle + |-\alpha\rangle$





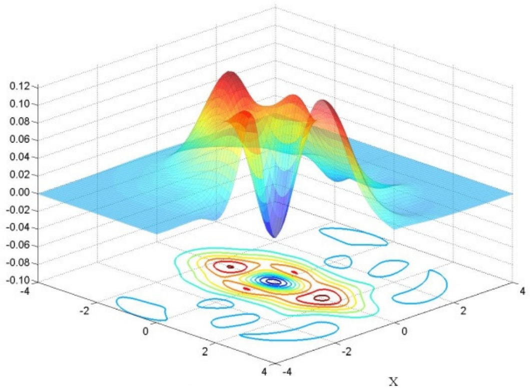
Experimental Setup





Experimental results for α = 0.8

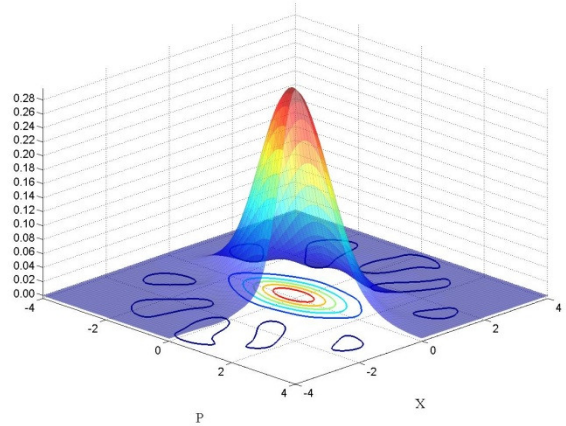
$|-\alpha\rangle \rightarrow$



$|\alpha\rangle - |-\alpha\rangle$

F = 0.65 for α = 0.8

$|\alpha\rangle \rightarrow$

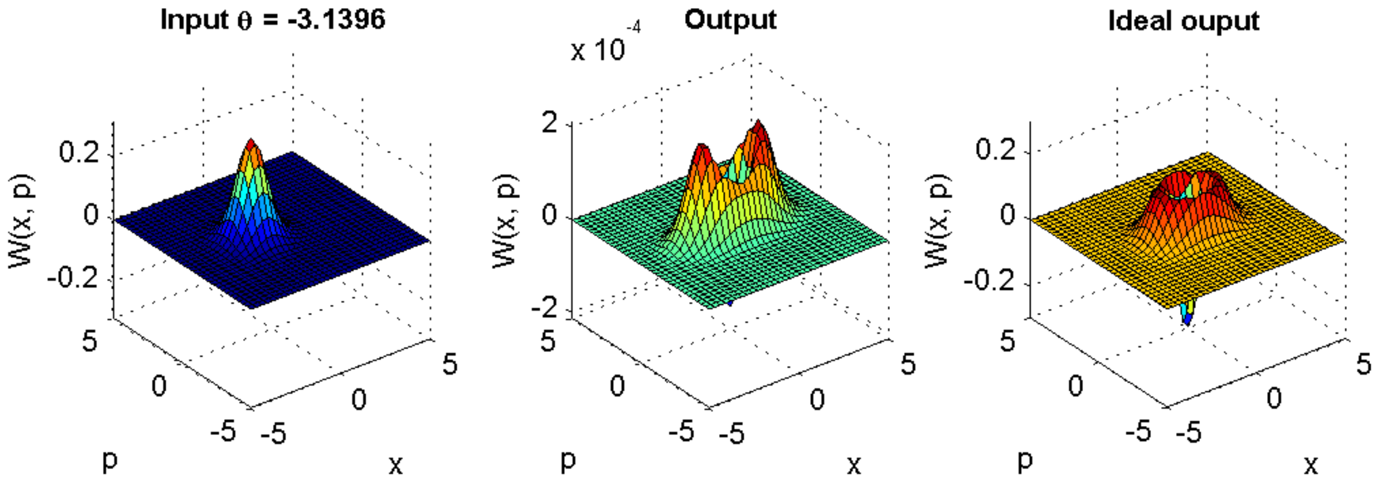


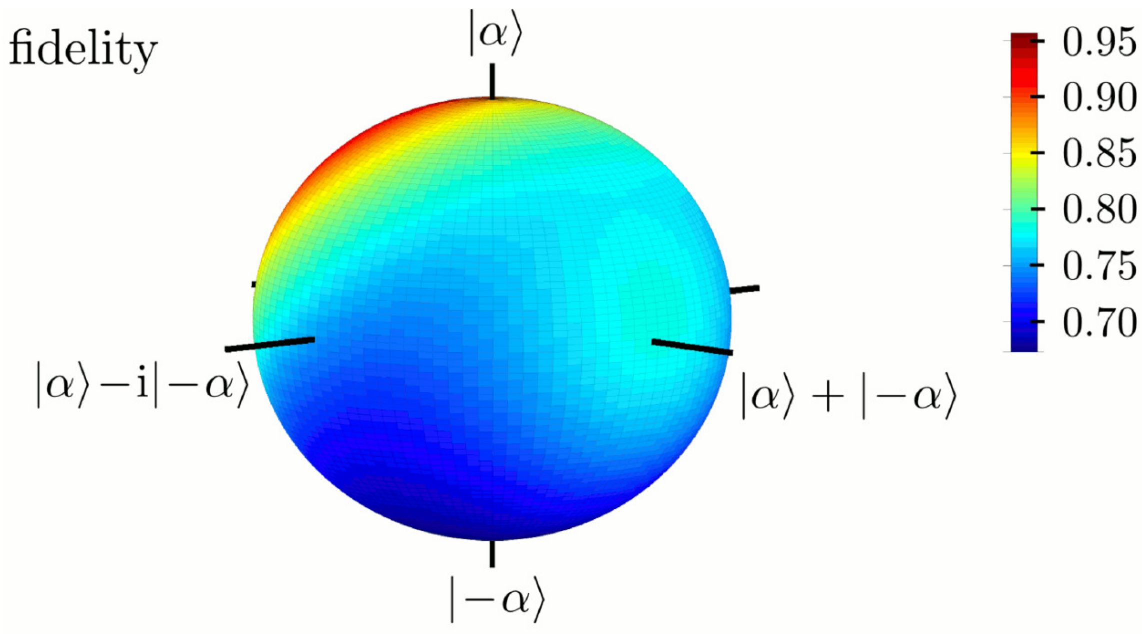
$|\alpha\rangle + |-\alpha\rangle$

F = 0.94 for α = 0.8

A. Tipsmark, R. Dong, A. Laghaout, P. Marek, M. Jezek, U.L. Andersen, arXiv:1107.0822

Simulations based on experimental parameters





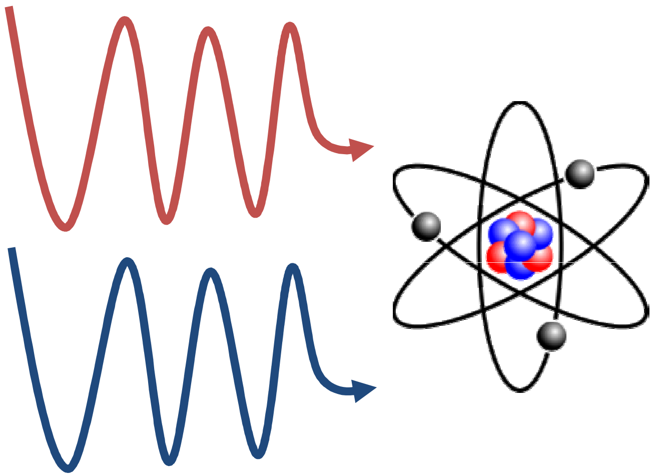
F_{ave} = 78%

Towards non-linear interactions mediated by plasmons

Alexander Huck, Shailesh Kumar, Ying Wei Lu and Ulrik L. Andersen

Department of Physics
Technical University of Denmark

Strong light-matter coupling is what we need!



Saturation
Photon blockade
Kerr effect

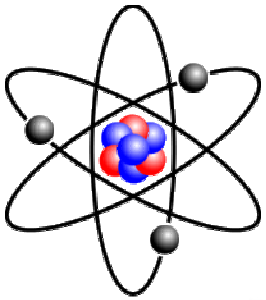
↓

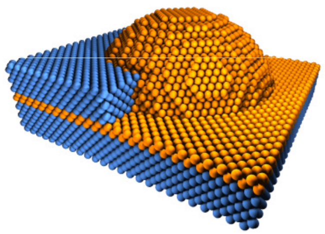
Quantum computing
Quantum repeater

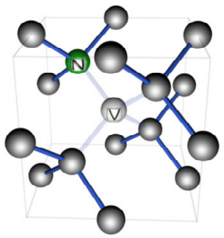
How is efficient coupling obtained?

Decay rate: $$\Gamma \propto \mu^2 \; E^2 g(\omega)$$

Dipole moment







Electric field density

$$E^2 \propto \frac{1}{V}$$

Density of states

$$g(\omega) \propto \frac{1}{d\omega / dk}$$

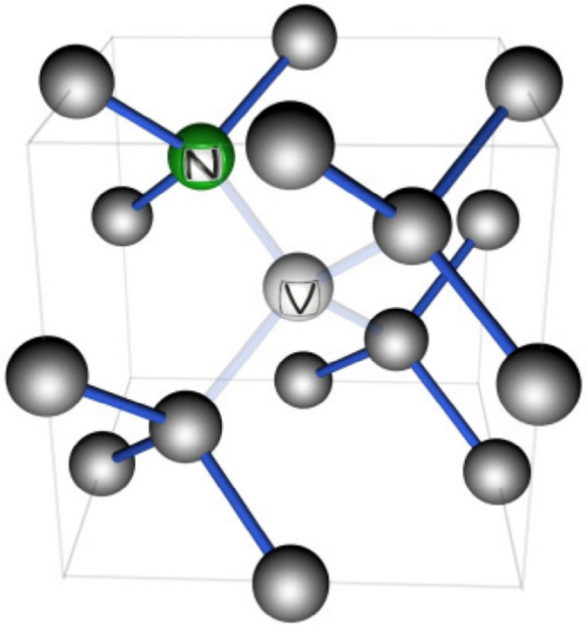
Large oscillation strength!

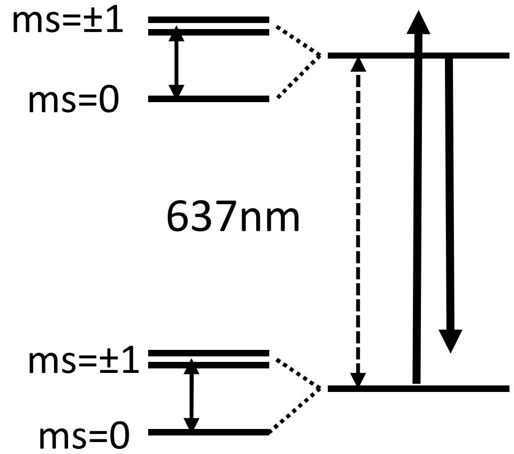
Strong field confinement!

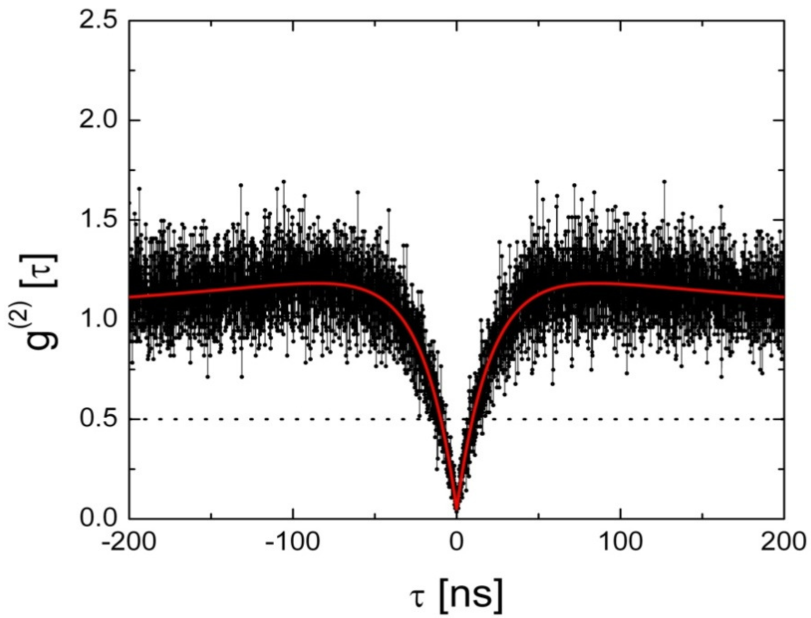
Small group-velocity!

Nitrogen-Vacancy center in diamond

Diamond crystal with NV







How is efficient coupling obtained?

Decay rate: $$\Gamma \propto \mu^2 \ E^2 g(\omega)$$

Dipole moment

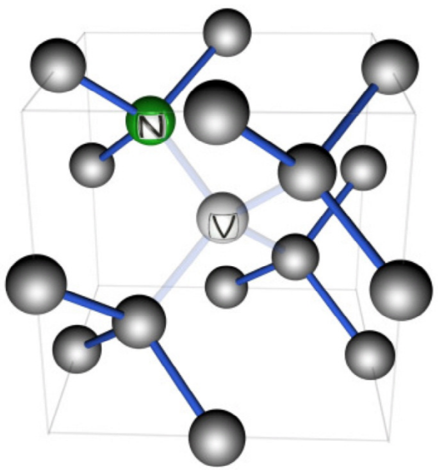
Electric field density

$$E^2 \propto \frac{1}{V}$$

Density of states

$$g(\omega) \propto \frac{1}{d\omega / d\beta}$$

$$\propto Q$$



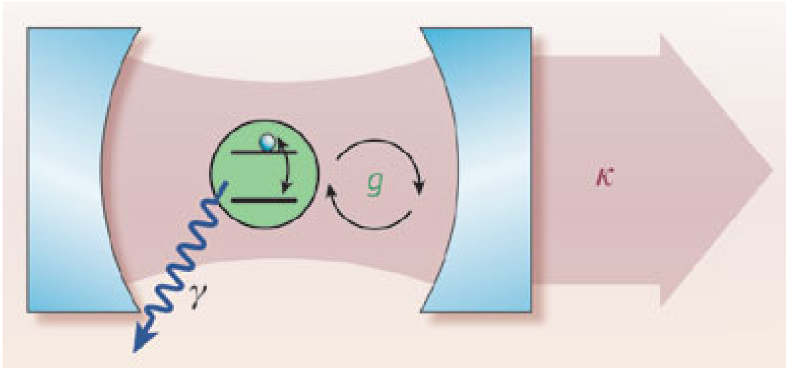
Large oscillation strenght!

Strong field confinement!

Small group-velocity!

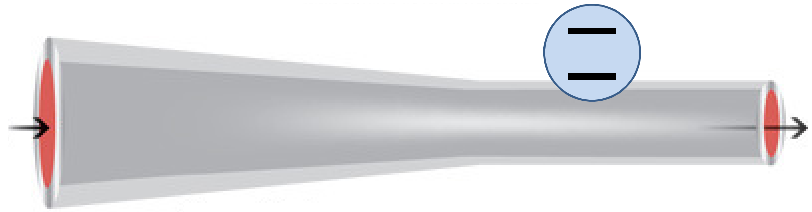
How is efficient coupling obtained?

Cavity QED



Thompson et al, PRL 68, 1132 (1992)

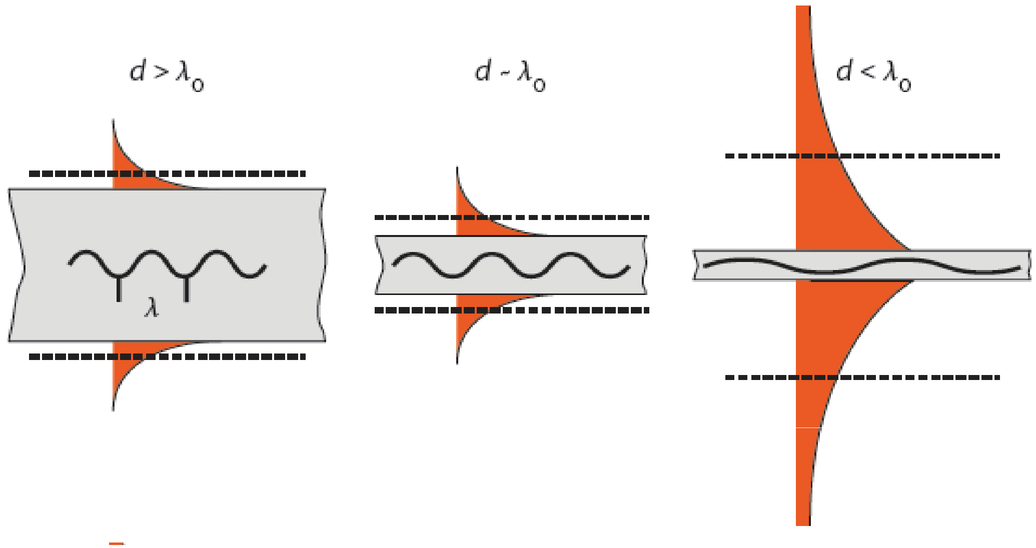
Coupling to fiber mode



Going beyond the diffraction limit

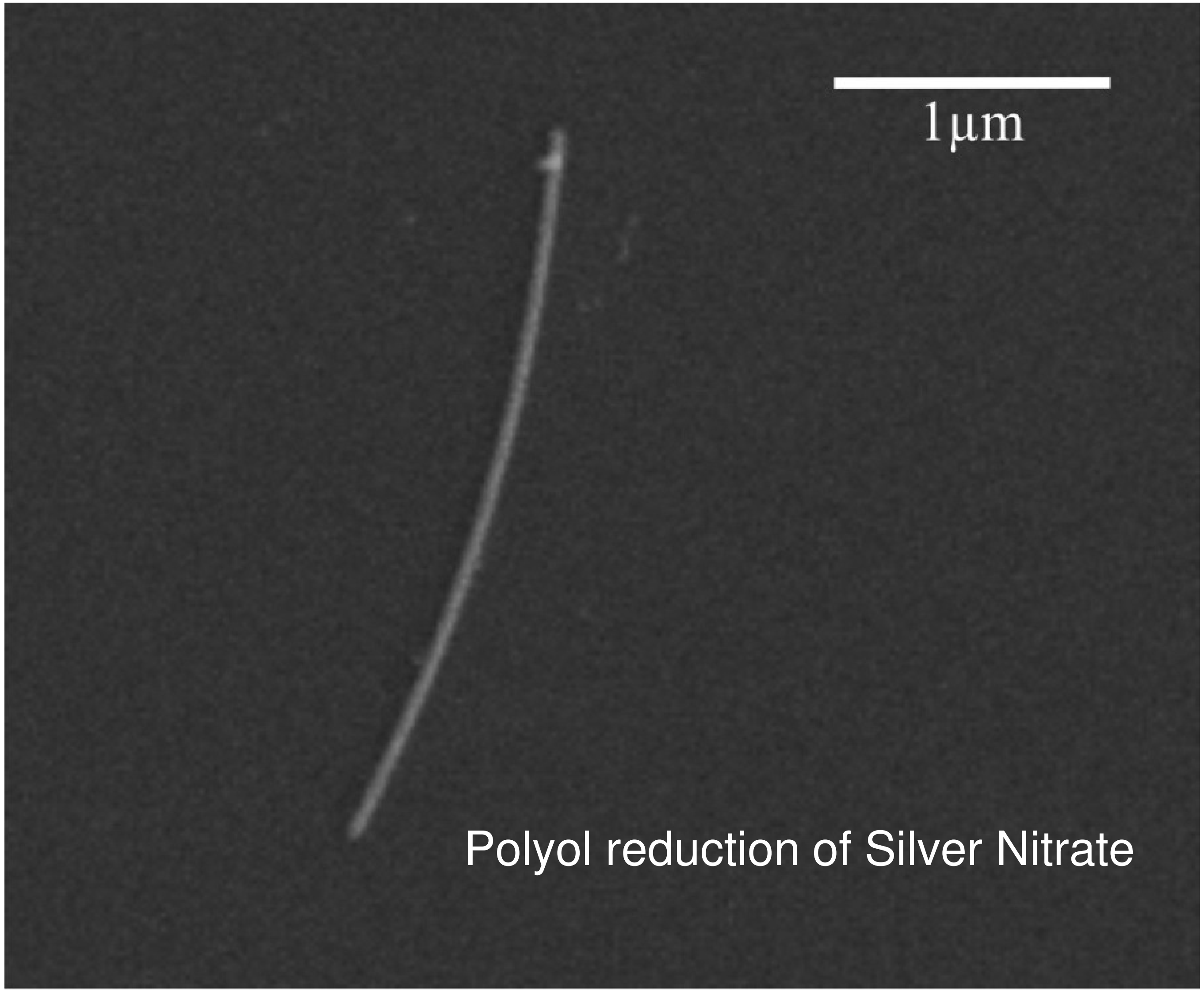
- Fiber modes:

  Limited by diffraction.

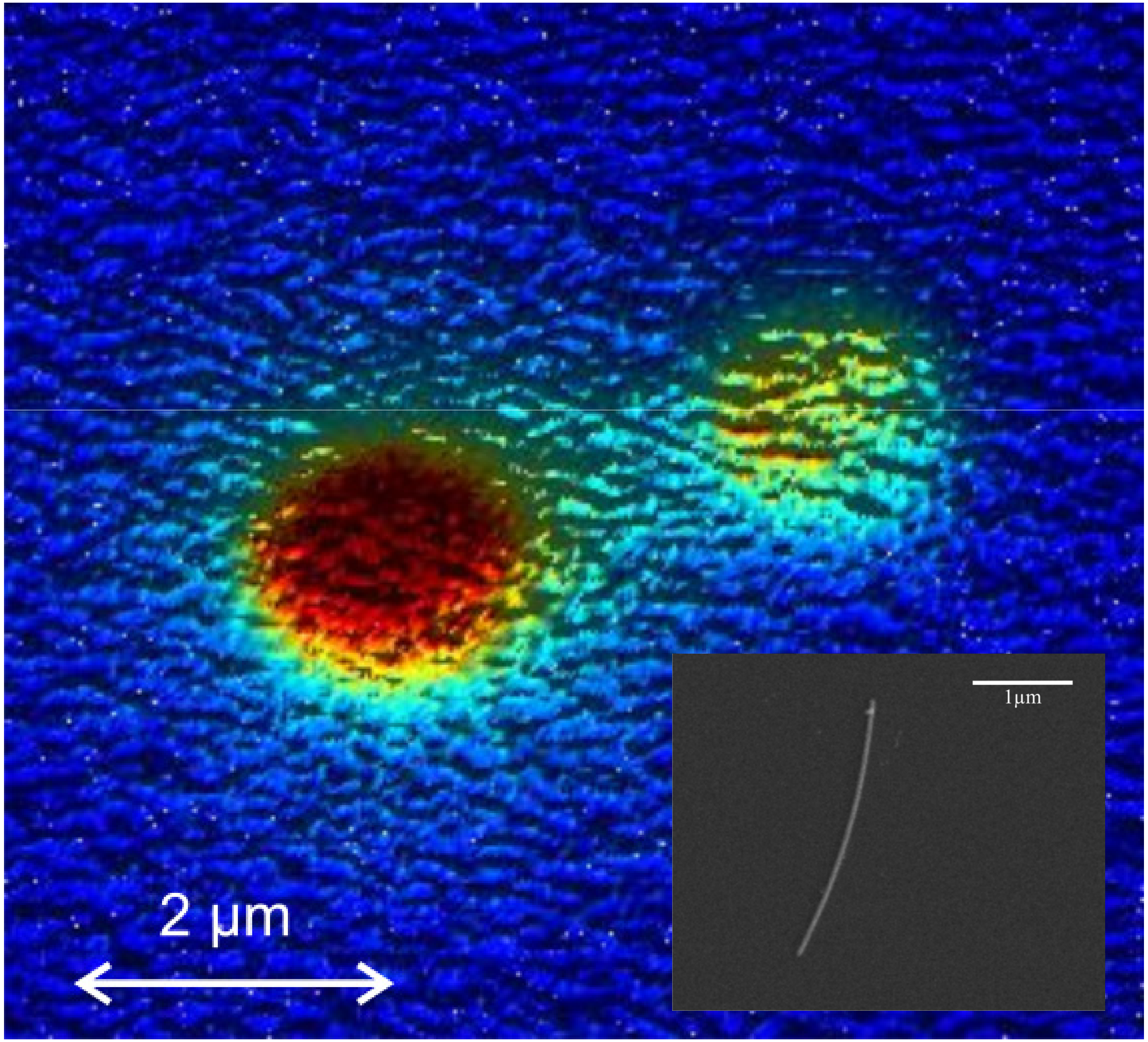


D. Gramotnev and S. Bozhevolnyi, Nat. Phot. 4, 83 (2010)

Mono-crystalline silver wires

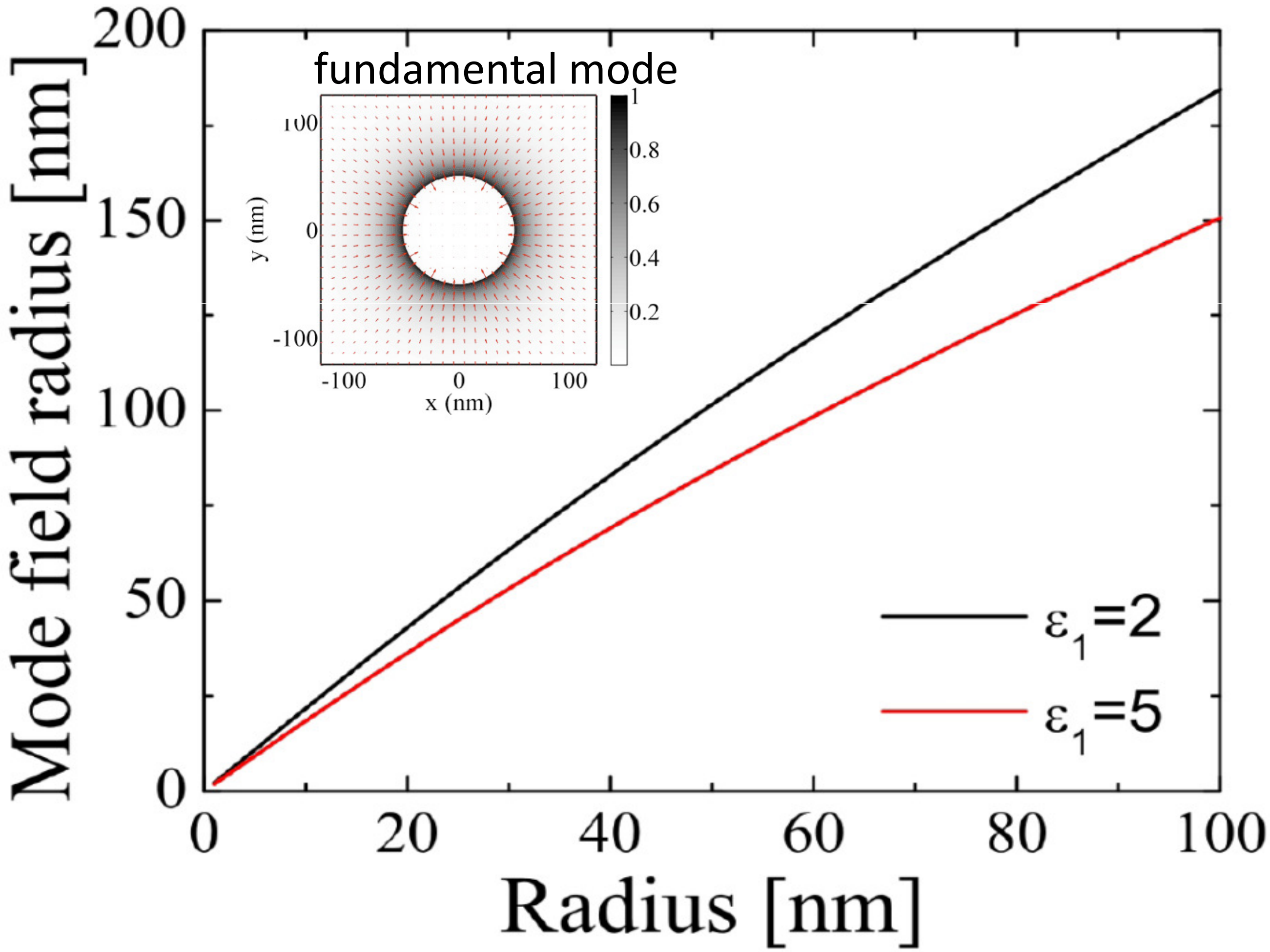


Plasmon propagation



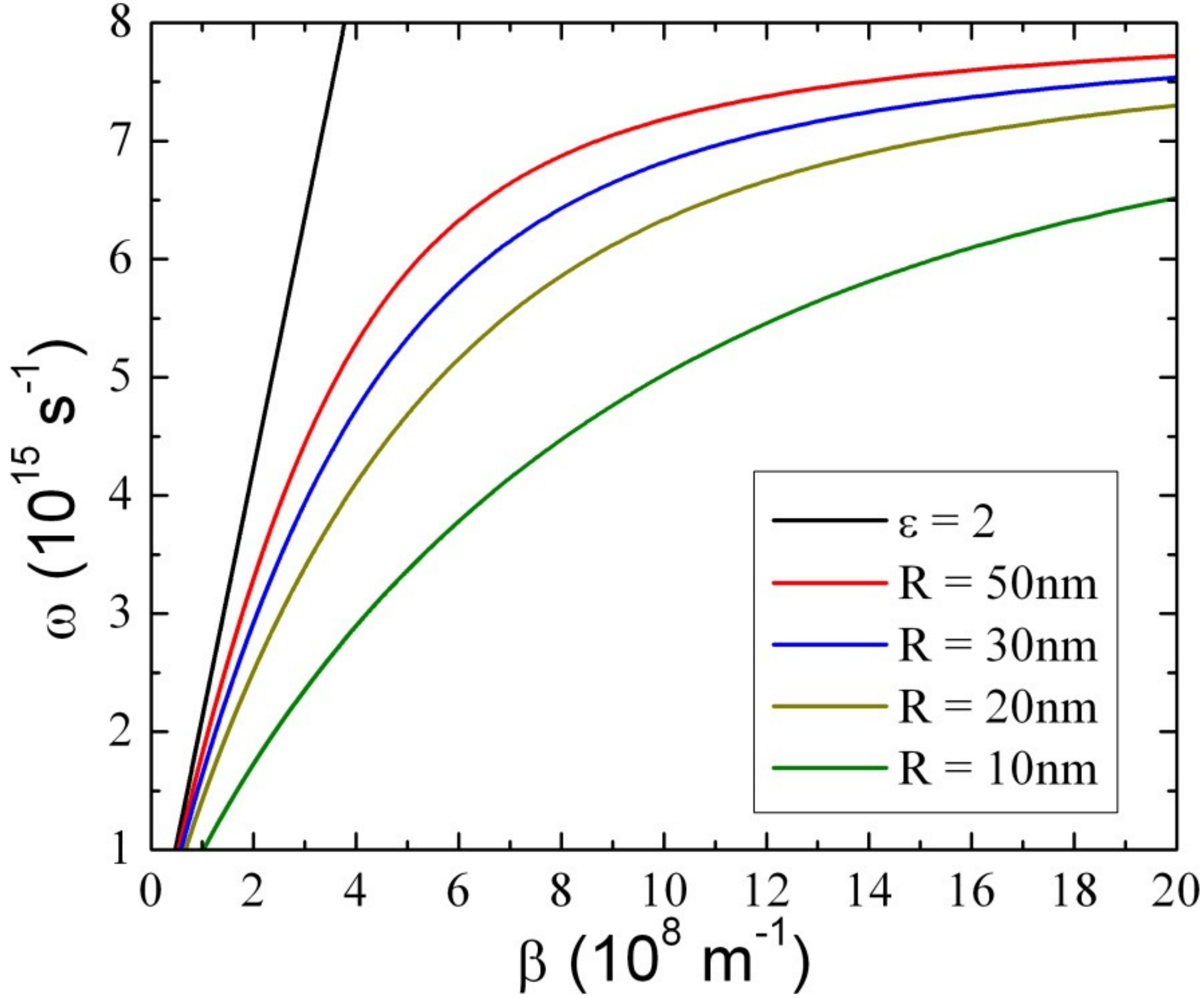
Decay rate: $$\Gamma \propto \mu^2 \; E^2 g(\omega)$$

$$E^2 \propto \frac{1}{A} \propto \frac{1}{R^2} \propto \frac{1}{(Wire\ radius)^2}$$

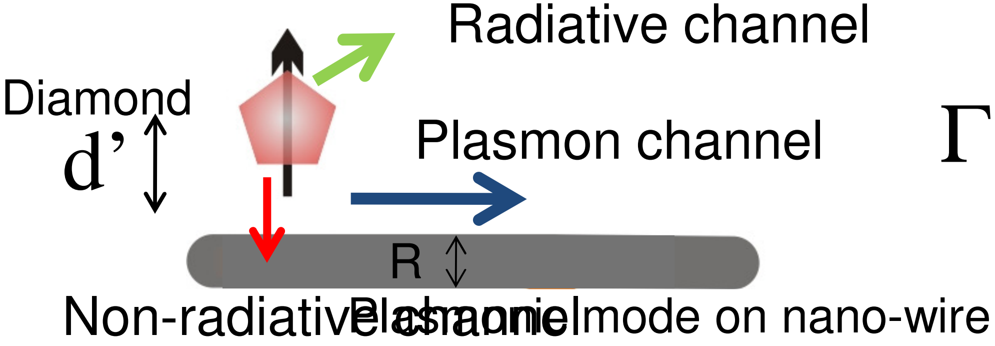


Decay rate: $$\Gamma \propto \mu^2 \ E^2 g(\omega)$$

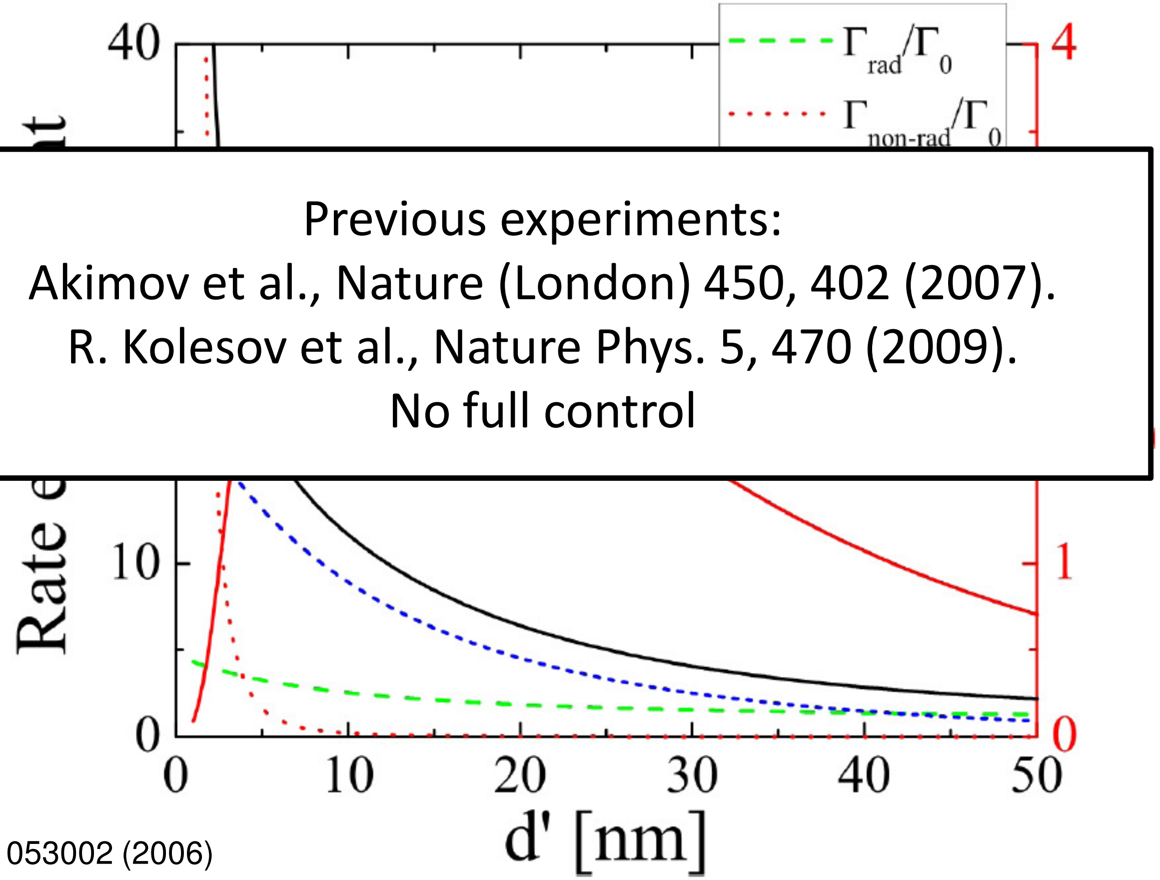
$$g(\omega) \propto \frac{1}{d\omega / d\beta} \propto \frac{1}{Wire\ radius}$$



Increasing the decay rate into one plasmonic mode



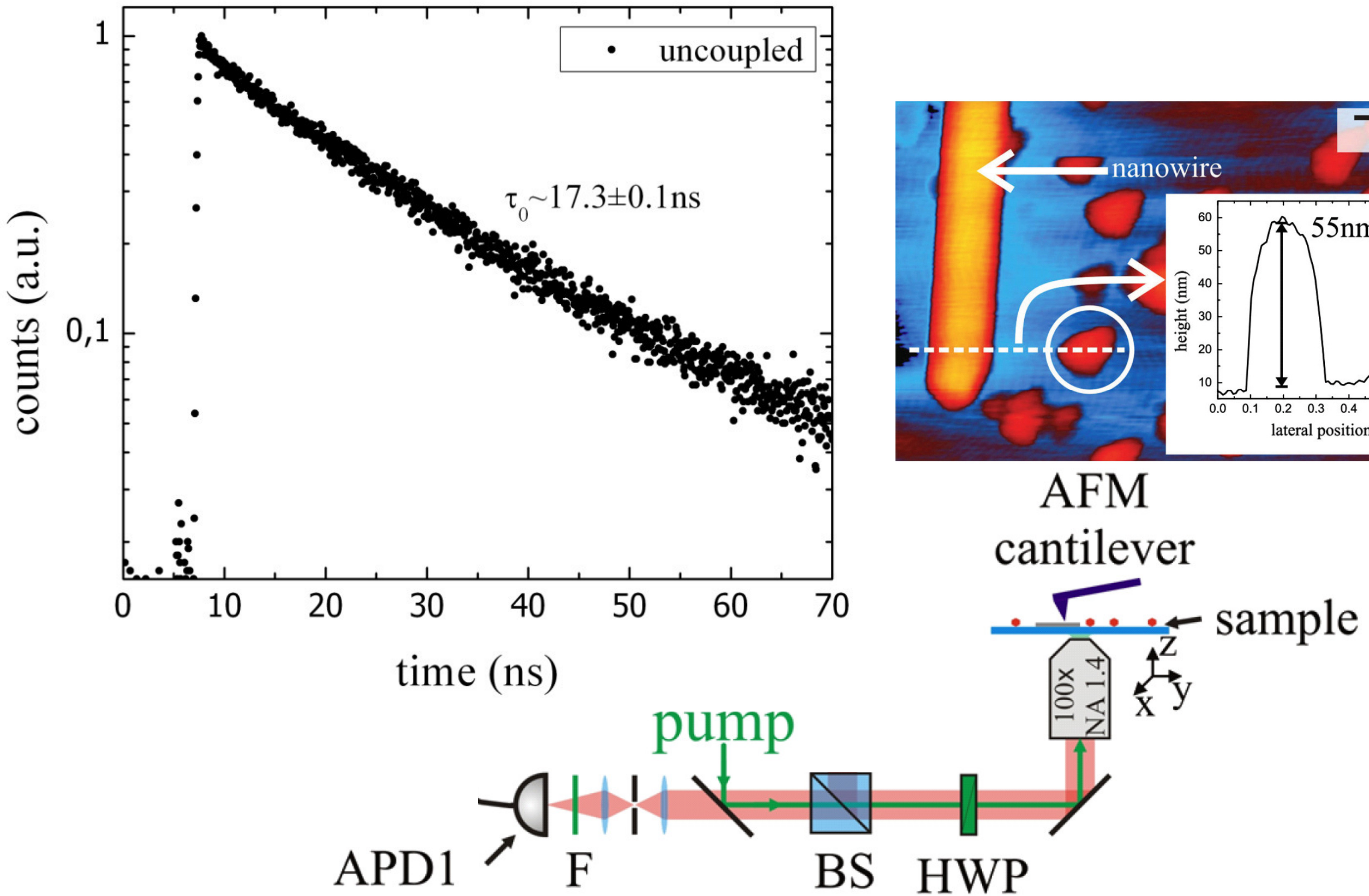
$$\Gamma^{plas} \propto \frac{\lambda}{(Wire\ radius)^3}$$



Previous experiments:
Akimov et al., Nature (London) 450, 402 (2007).
R. Kolesov et al., Nature Phys. 5, 470 (2009).
No full control

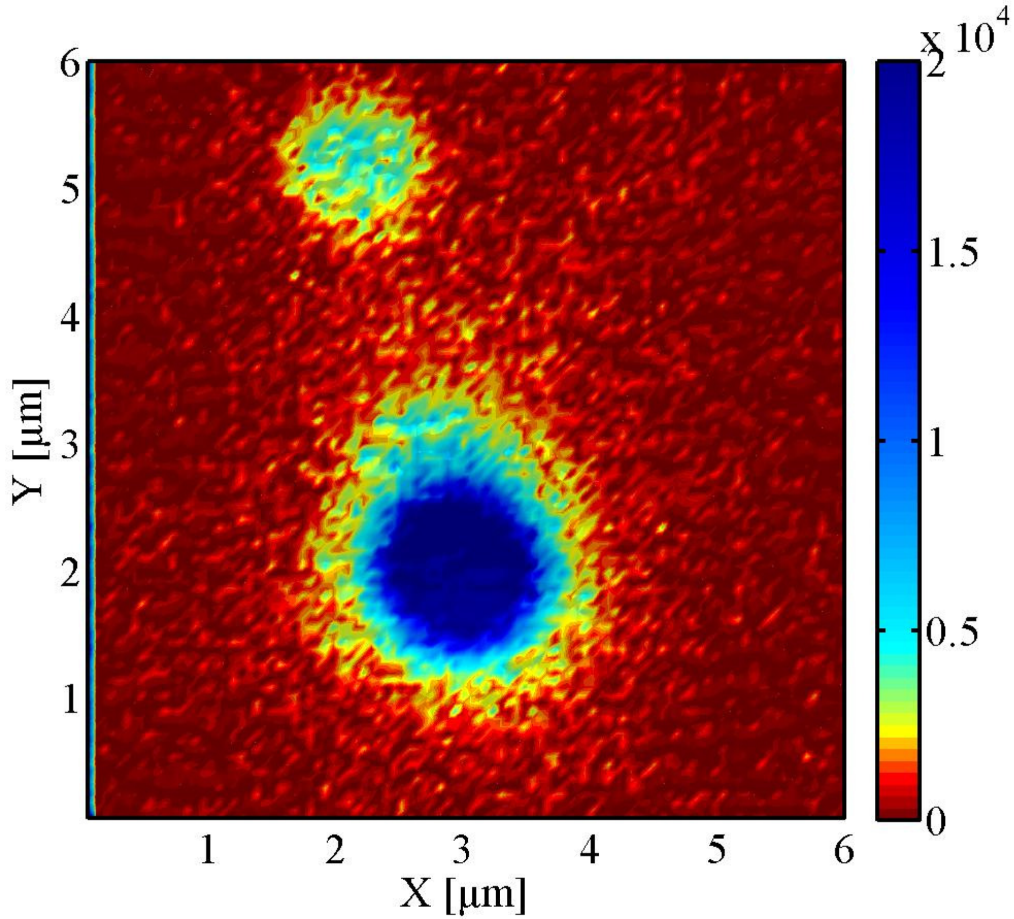
Chang et al., Phys. Rev. Lett. 97, 053002 (2006)

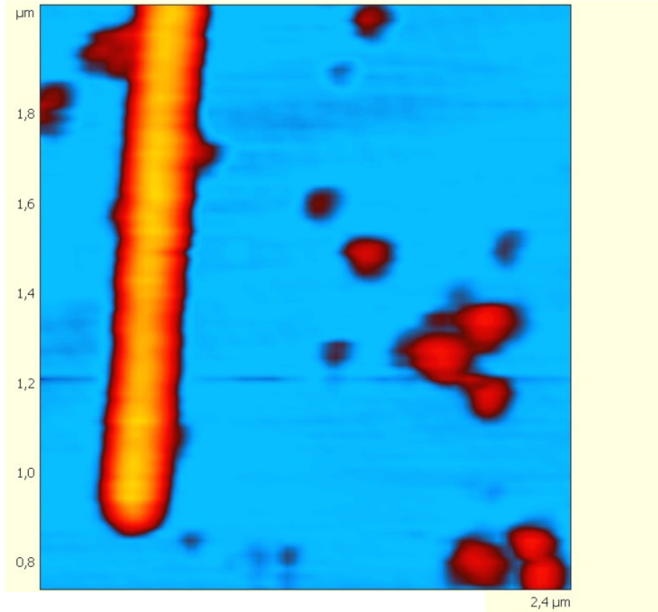
Integrated Confocal and AF microscope

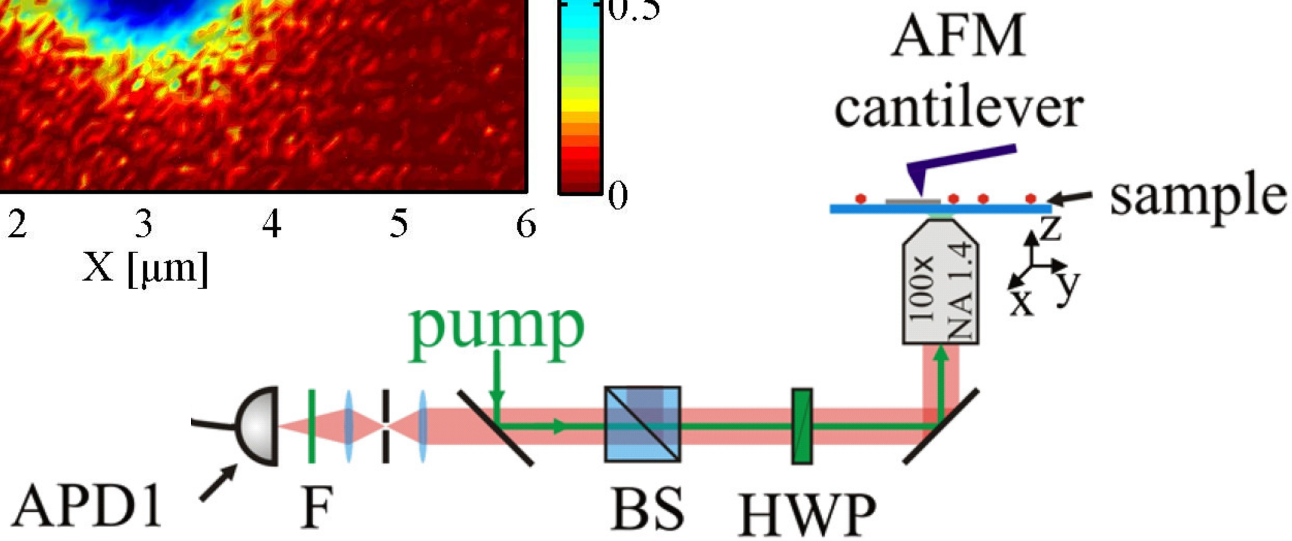


A. Huck, S. Kumar, A. Shakoor, U. L. Andersen, Phys. Rev. Lett. 106, 096801 (2011)

Increasing the decay rate by a factor of 3.6

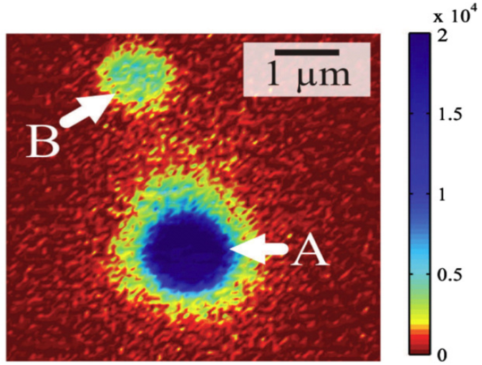


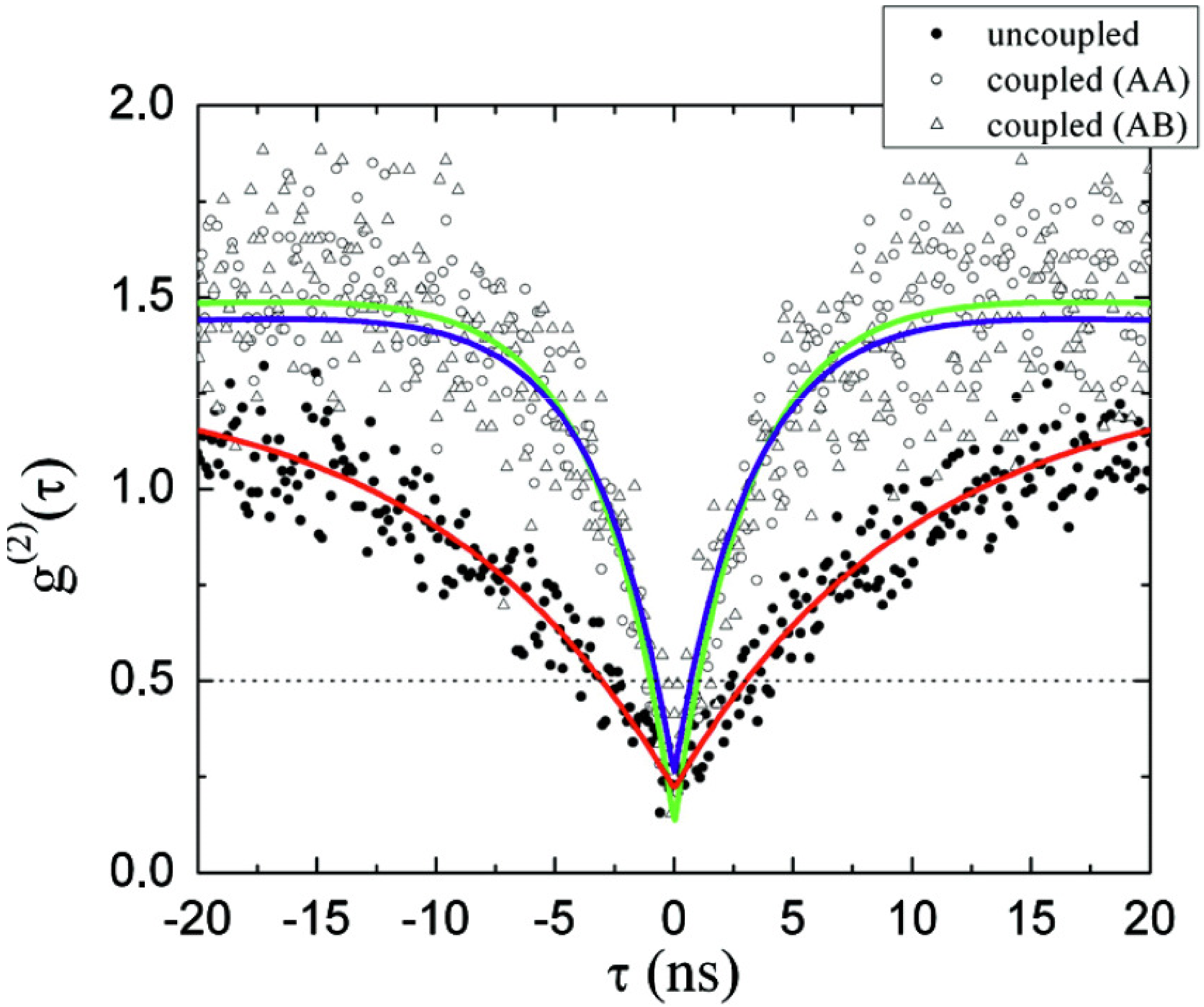




A. Huck, S. Kumar, A. Shakoor, U. L. Andersen, Phys. Rev. Lett. 106, 096801 (2011)

Single plasmons are generated



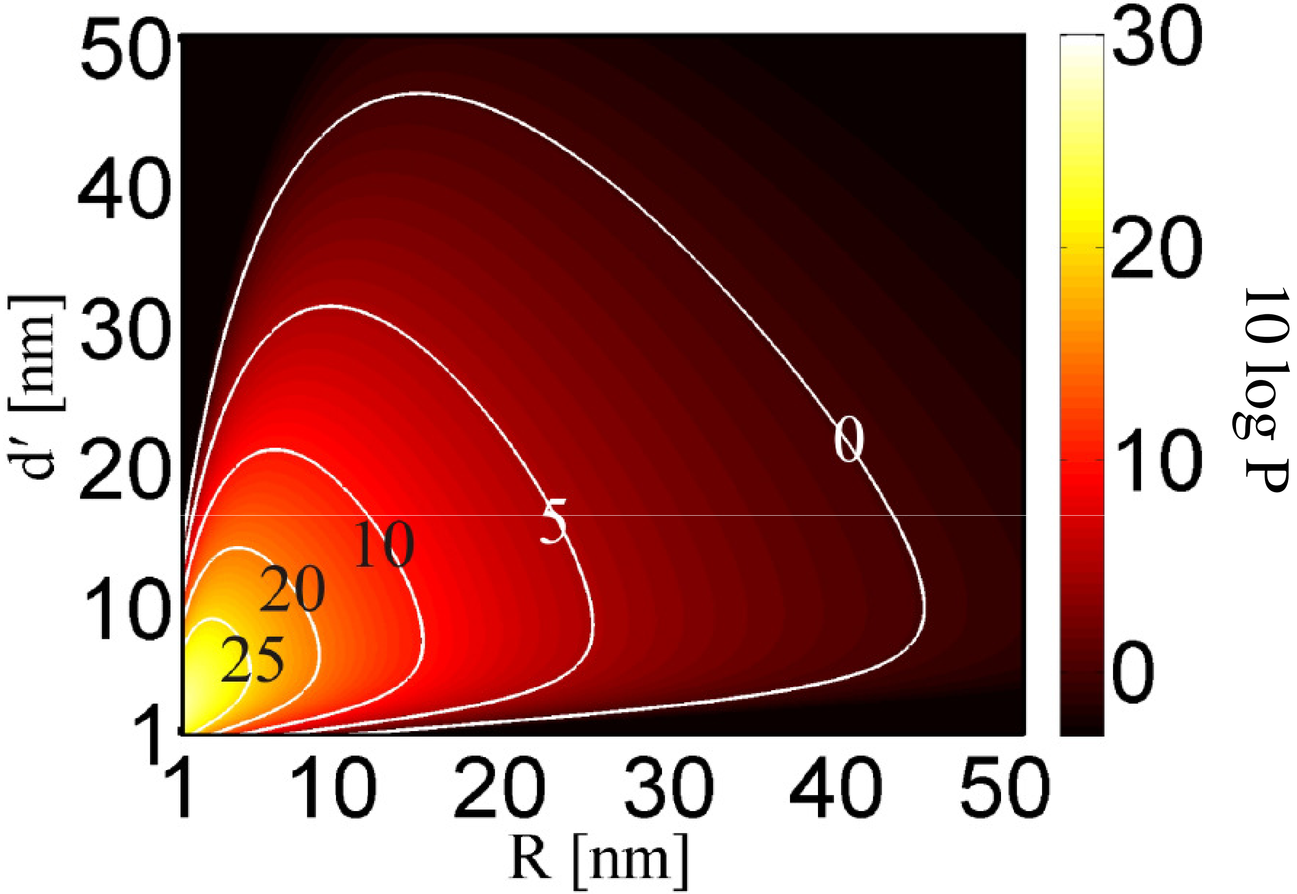


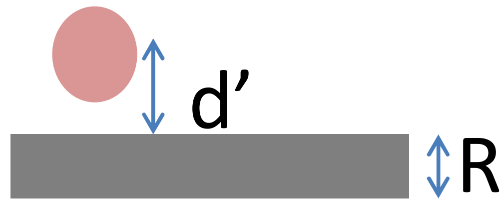
Single plasmon propagation:

$$g^{(2)}(0) < 0.5$$

A. Huck, S. Kumar, A. Shakoor, U. L. Andersen, Phys. Rev. Lett. 106, 096801 (2011)

How do we get stronger coupling?

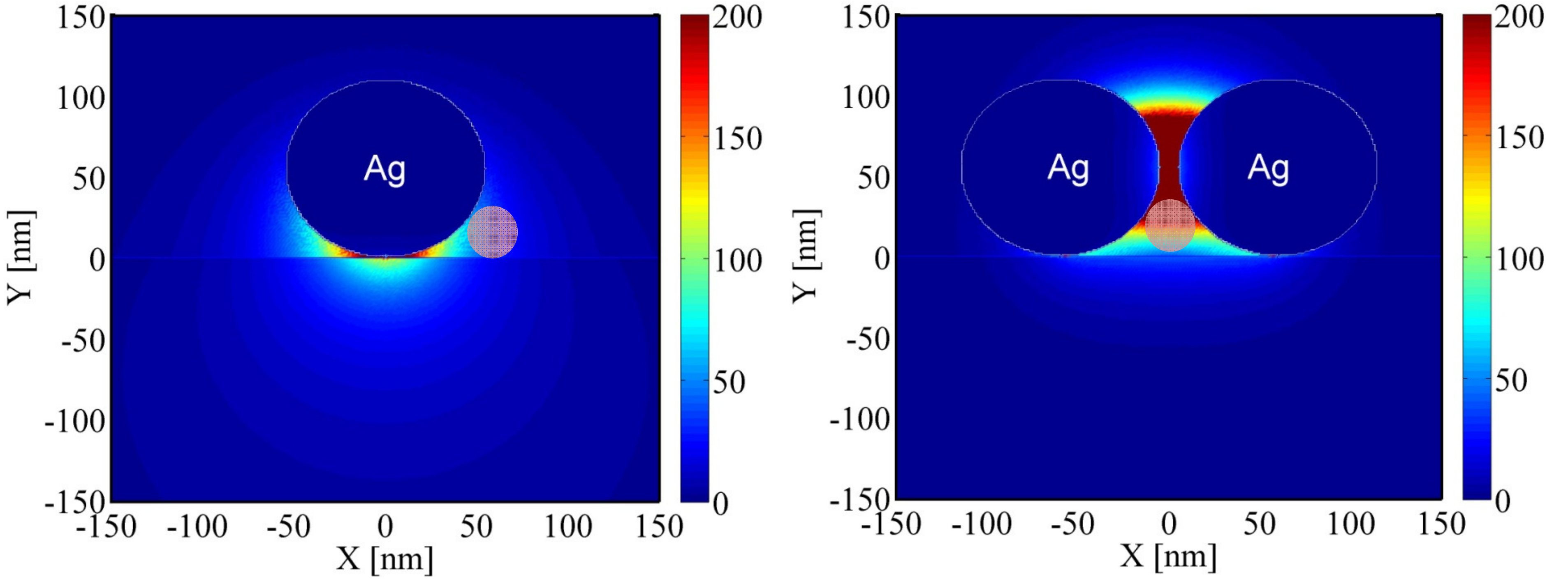


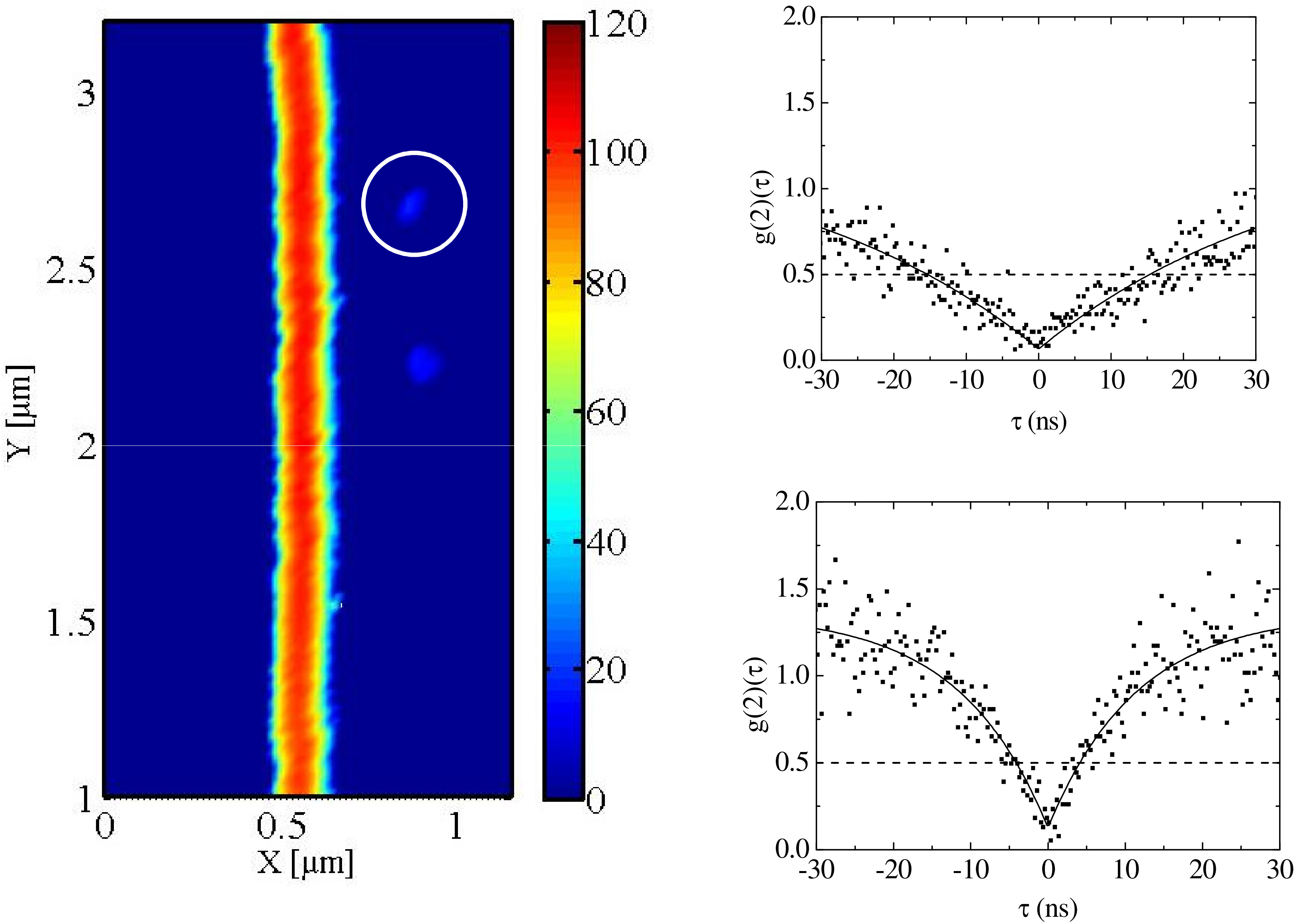


Smaller wires …. but not too small!

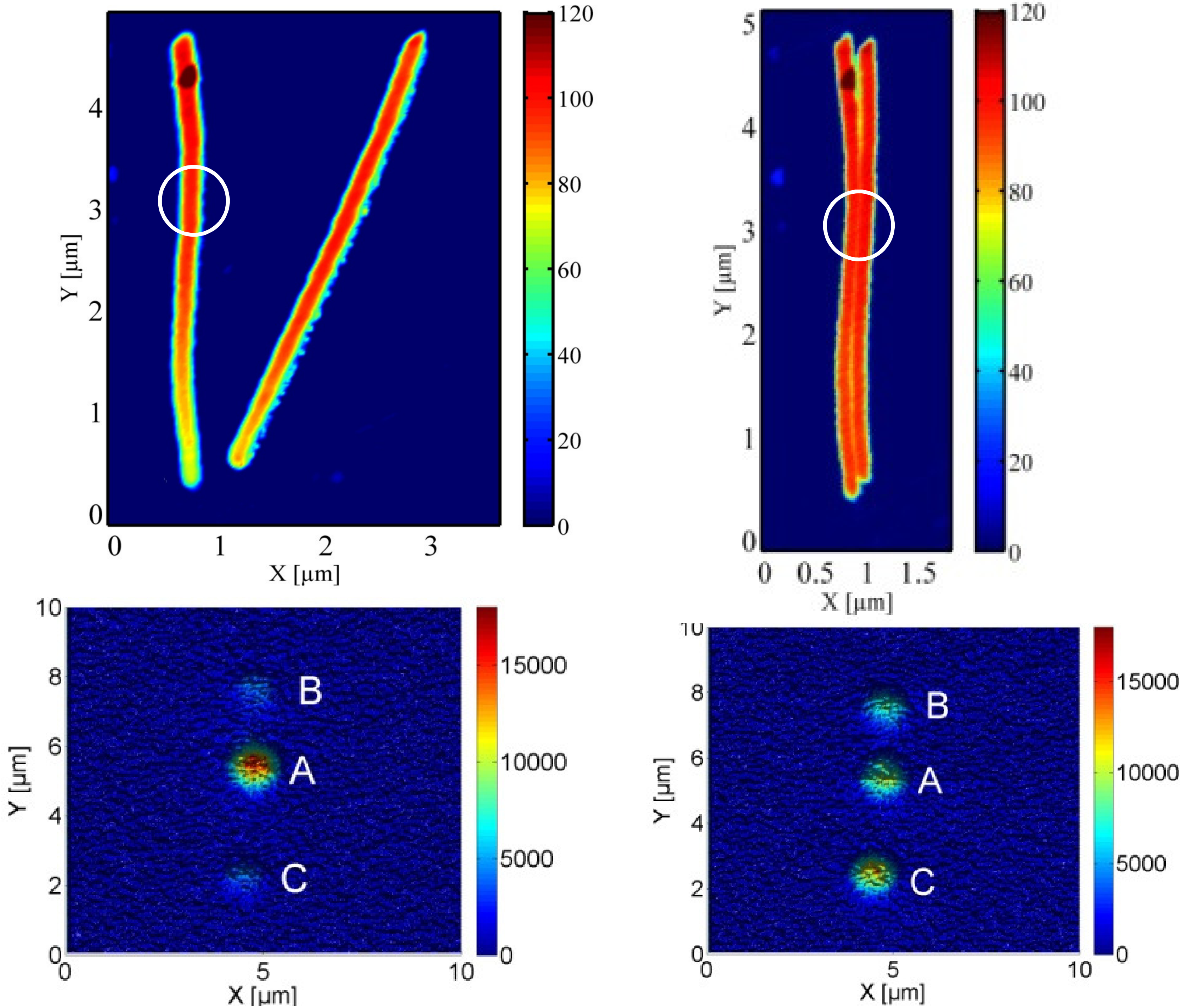
Smaller diamonds …. but not too small!

How to access the strong field

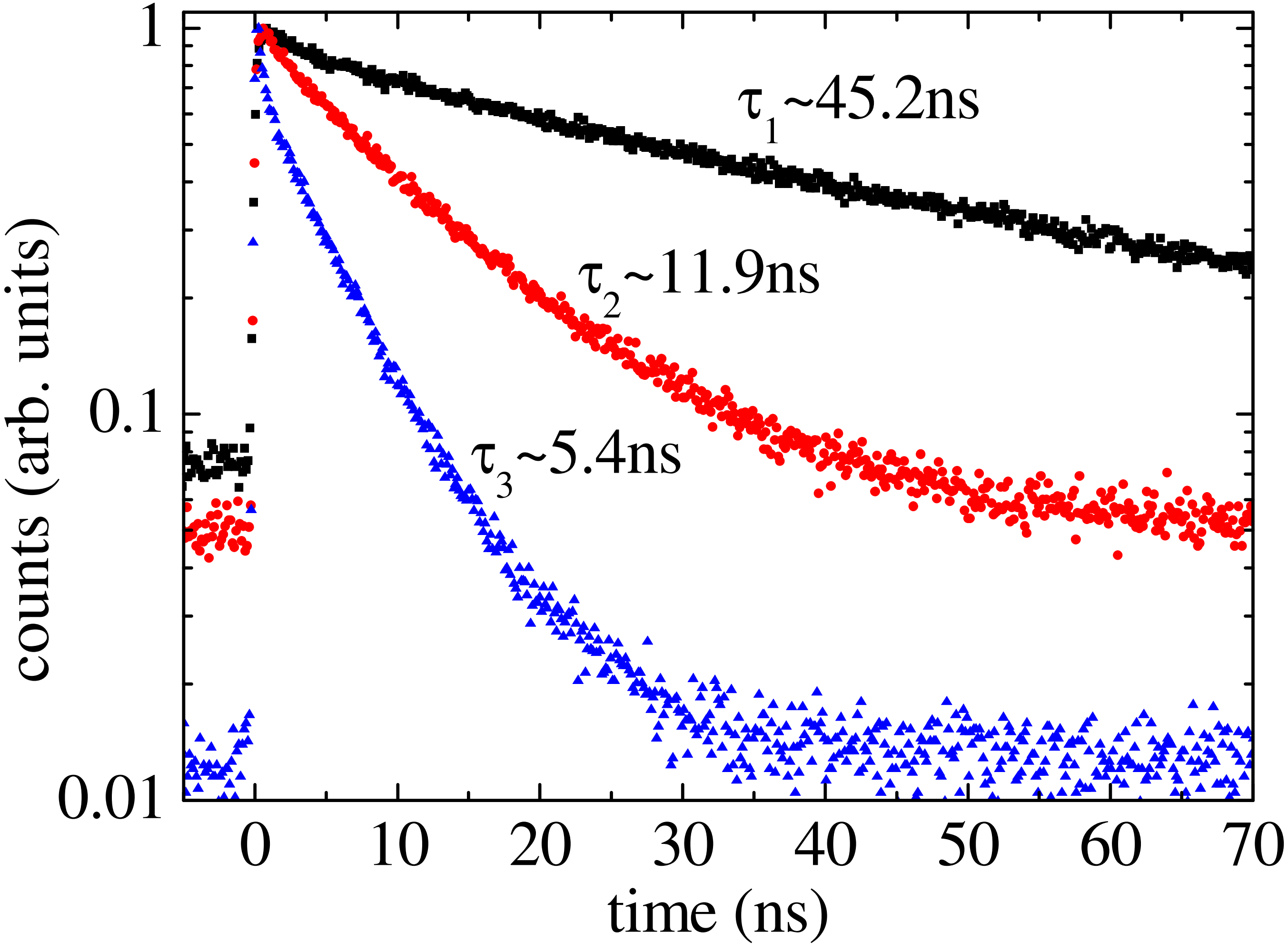


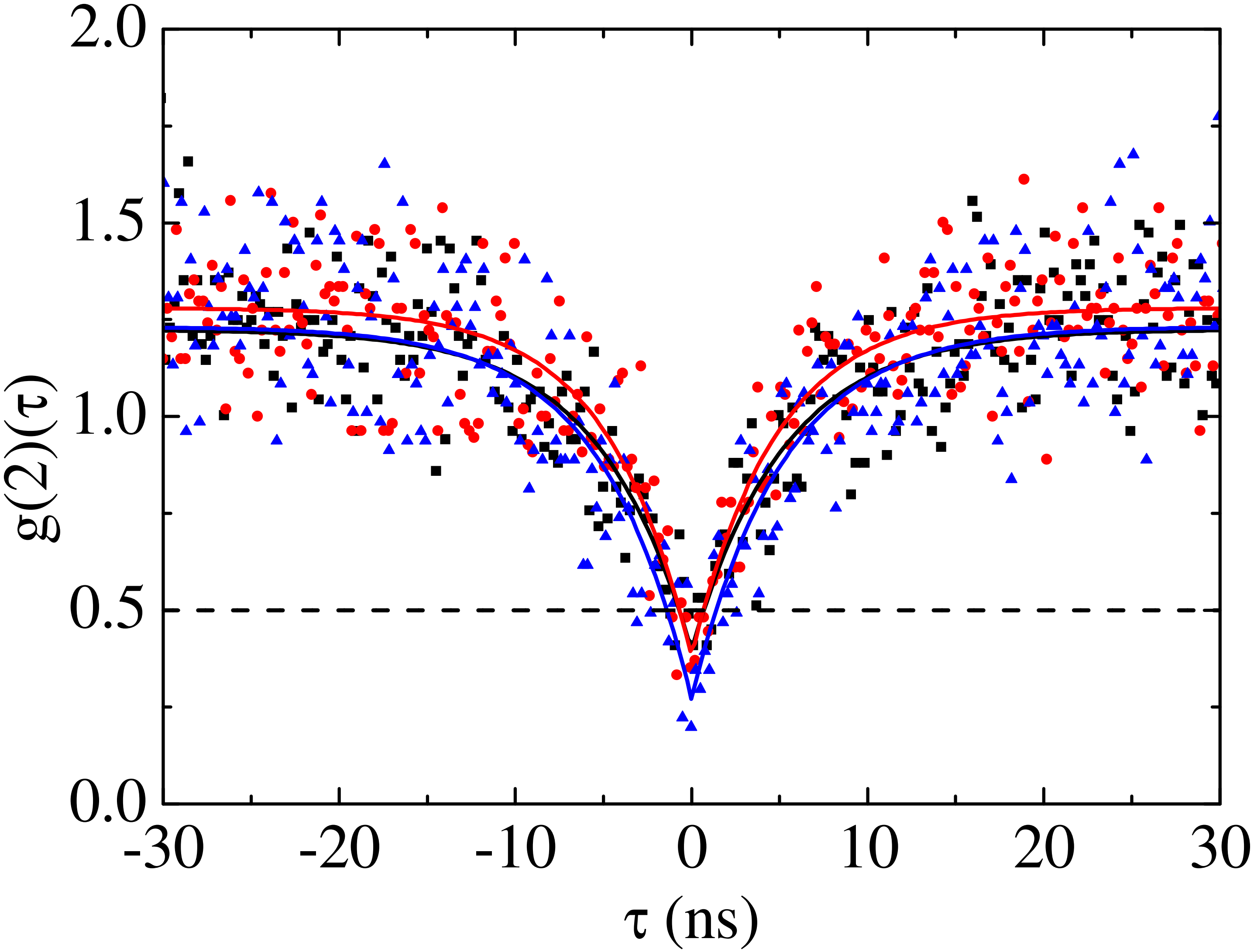


Y [μm]
X [μm]
0
0.5
1
1.5
2
2.5
3
120
100
80
60
40
20
0
g(2)(τ)
τ (ns)
2.0
1.5
1.0
0.5
0.0
-30
-20
-10
0
10
20
30
g(2)(τ)
τ (ns)


Y [µm]
X [µm]
0
1
2
3
4
120
100
80
60
40
20
0
Y [µm]
X [µm]
0
0.5
1
1.5
2
3
4
5
Y [µm]
X [µm]
0
5
10
2
4
6
8
15000
10000
5000
B
A
C
Y [µm]
X [µm]
B
A
C

Increasing the decay rate by a factor of 8.3



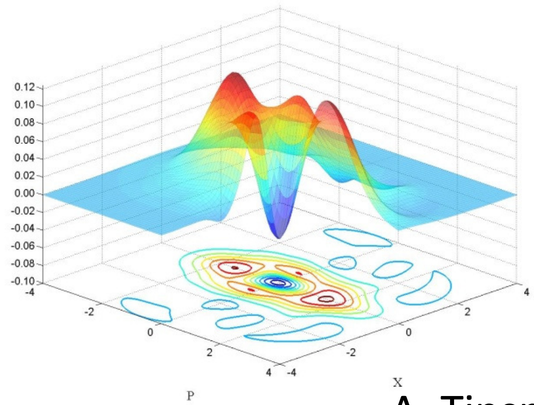


2.0
1.5
1.0
0.5
0.0
g(2)(τ)
-30
-20
-10
0
10
20
30
τ (ns)

Towards large non-linearity

Measurement induced nonlinearity: Hadamard gate

$$|-\alpha\rangle \rightarrow$$



A. Tipsmark et al arXiv:1107.0822

Strong coupling

Max rate enhancement of 8.3

Huck et al, PRL 106, 096801 (2011)

What next?

- Tailored structures
- Smaller diamonds
- Resonant coupling at low temperature