Surface Plasmons – considerations about losses in cavities and in the quantum regime

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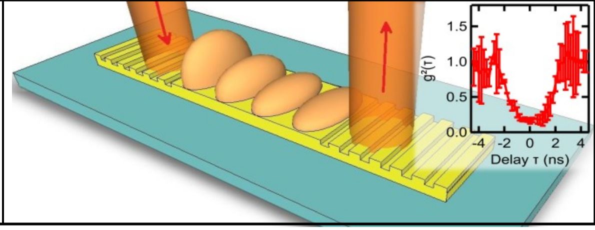
Plasmonics group at Imperial - 2008



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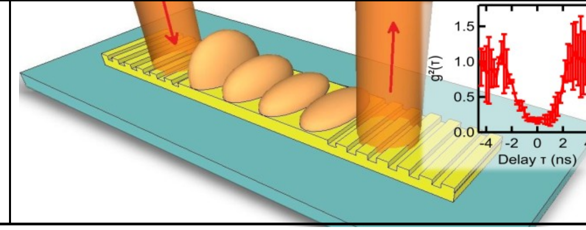

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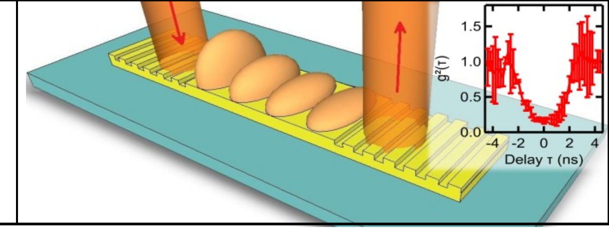


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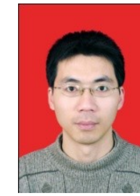
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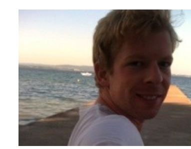
Aeneas Wiener


Binghao Ng


Themis Sidiropoulos


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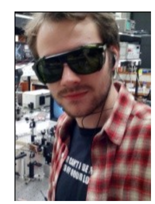
Markus Schmidt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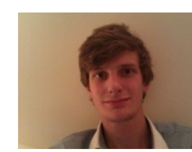
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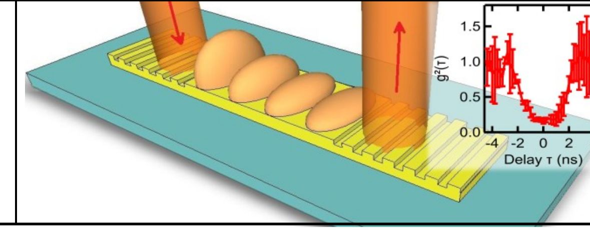


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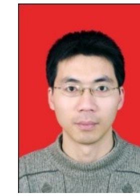
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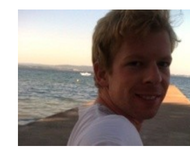
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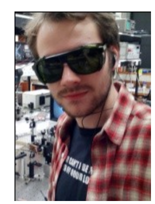
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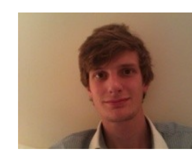
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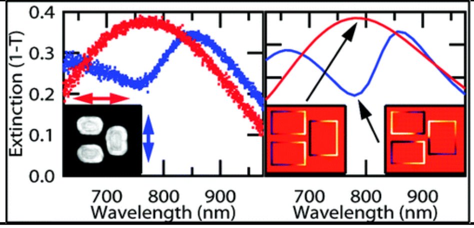
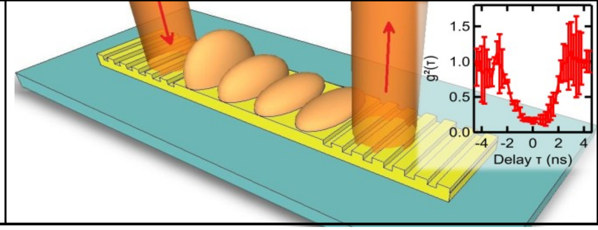


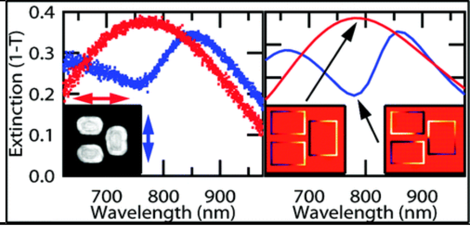
Outline



1. Losses in plasmonic cavities
   - Super/subradiant modes
   - Fano resonances

2. Losses in waveguides in the quantum regime

3. Non related bonus (if time avails)



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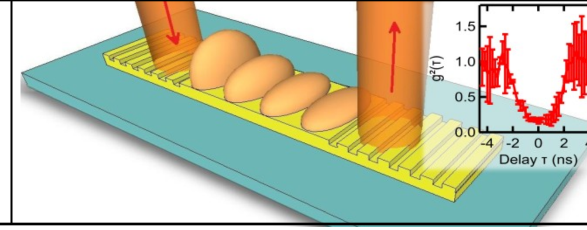

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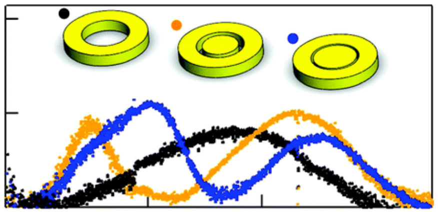
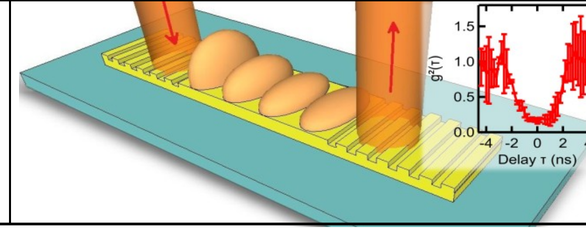
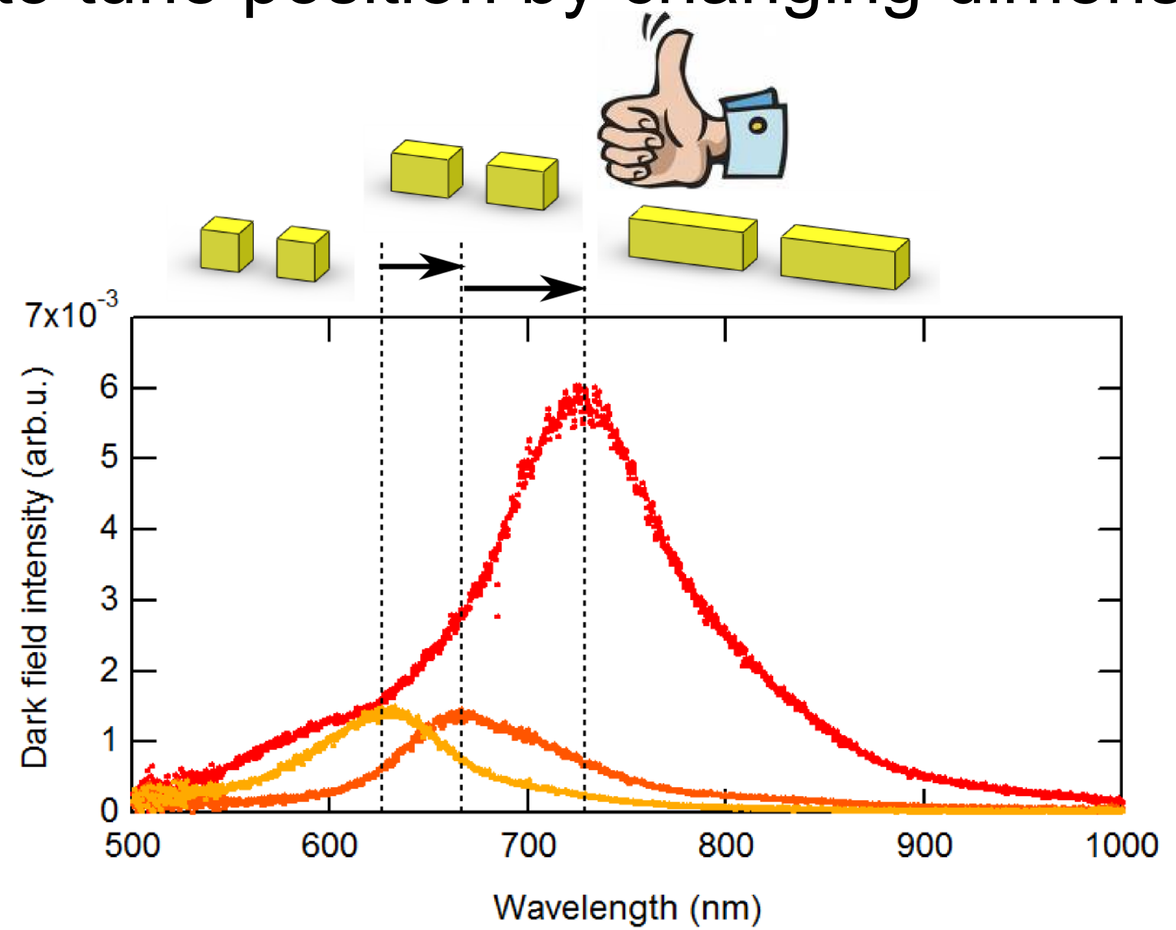
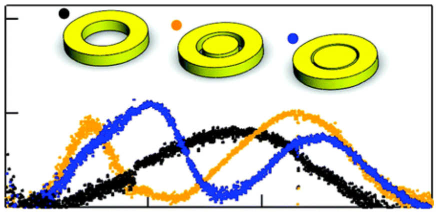


LSPR – tuning

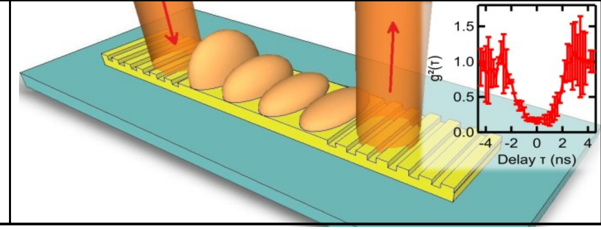


- Enhanced scattering/absorption at resonance
- Easy to tune position by changing dimension

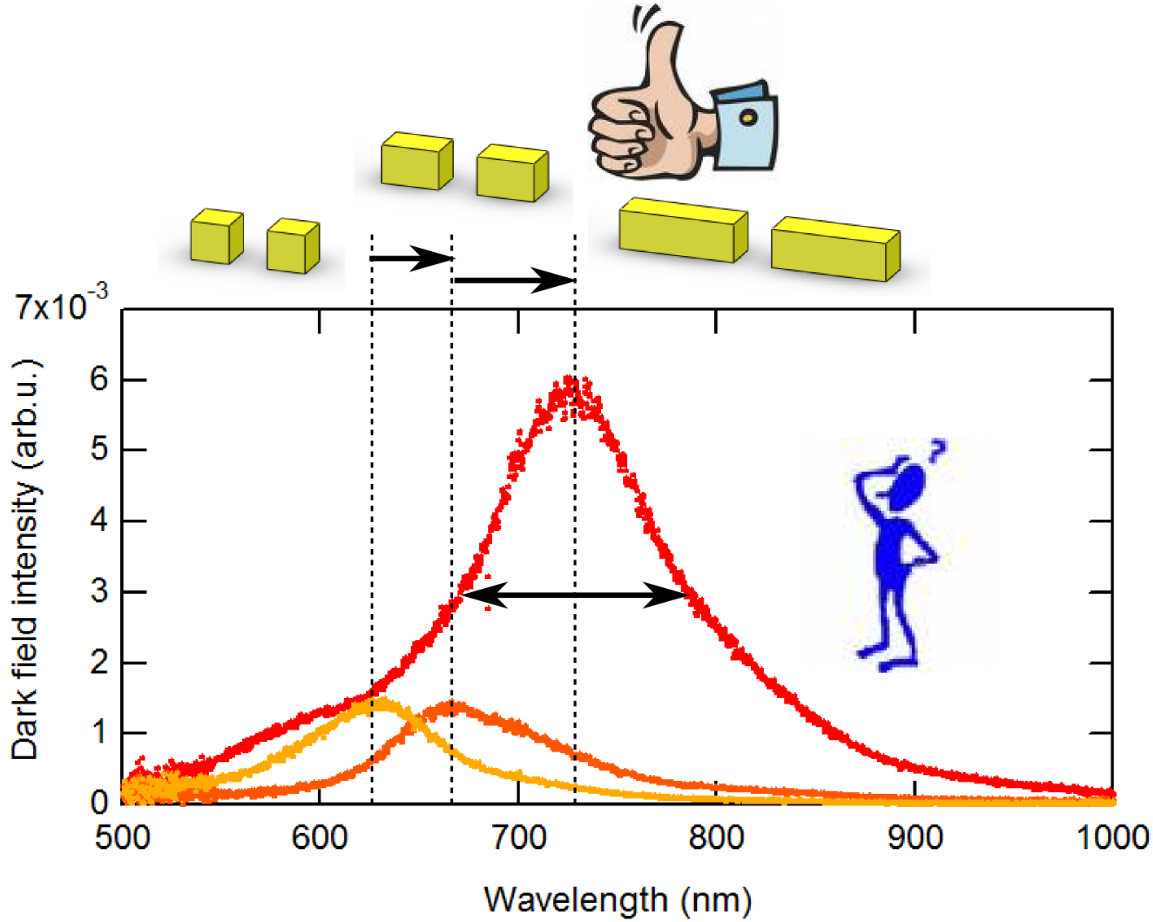




LSPR – lineshape?



- How to change lineshape?



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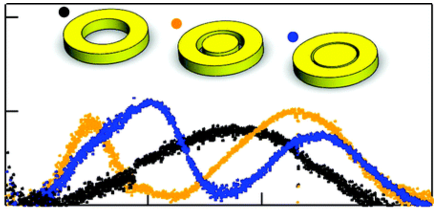
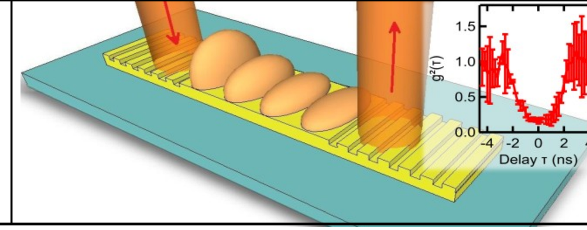
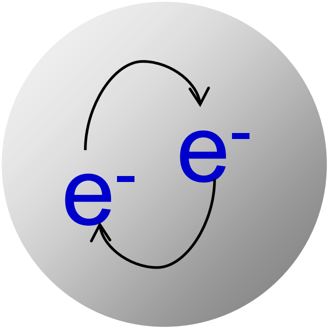


LSPR – sources of damping

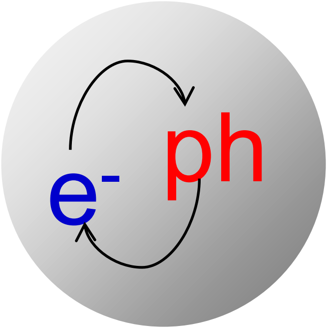


Damping sources:

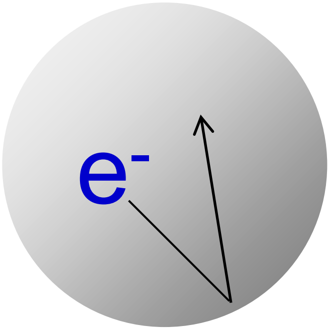
- ➢ Electron – electron scattering



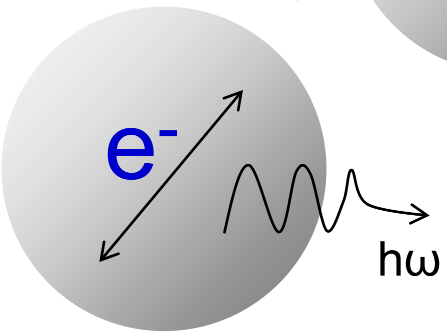
- ➢ Electron – phonon scattering

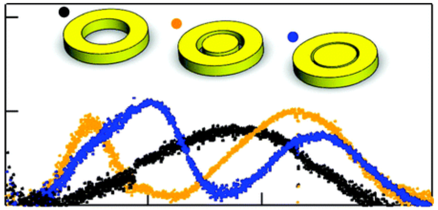


- ➢ Electron – surface scattering

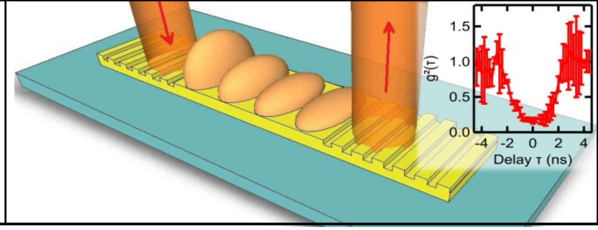


- ➢ Radiation damping



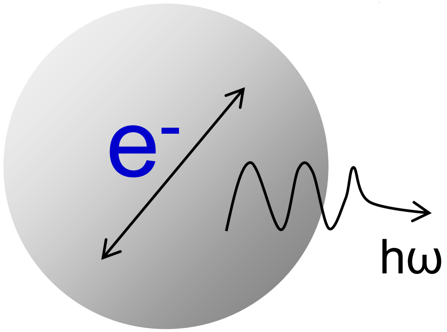


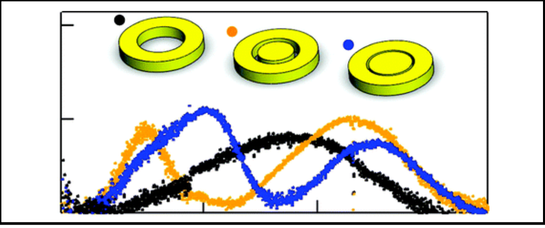
LSPR – sources of damping



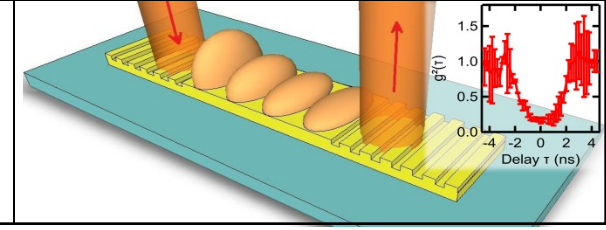
Damping sources:

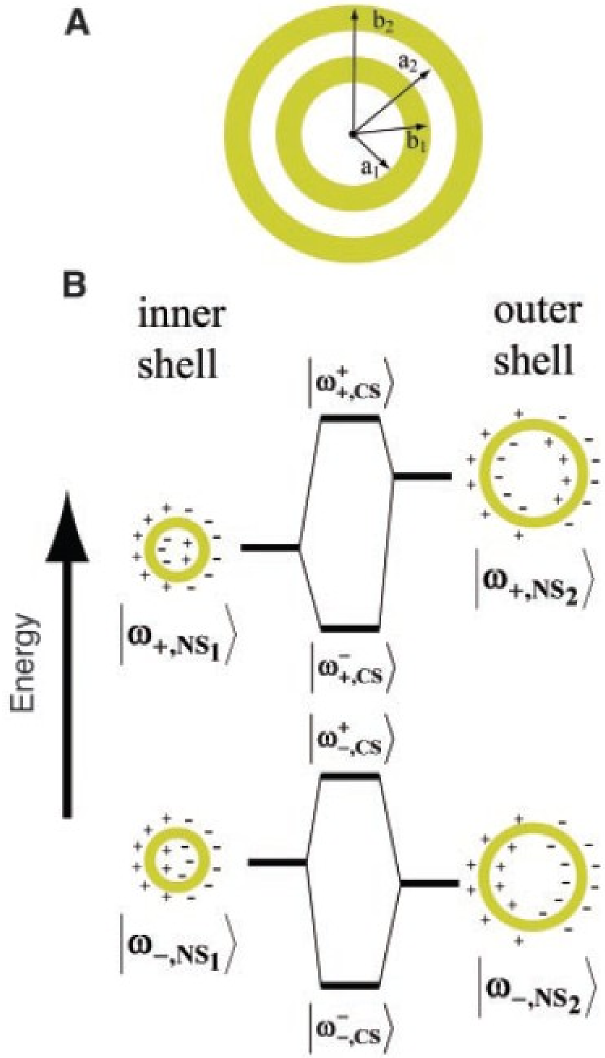
➢ Radiation damping





Concept of hybridisation





- Creation of ‘plasmonic molecules’

- The plasmonic resonances of the ‘atoms’ hybridise to create new states in the ‘molecule’

E. Prodan, P. Nordlander et al., Science 302, 419 (2003)

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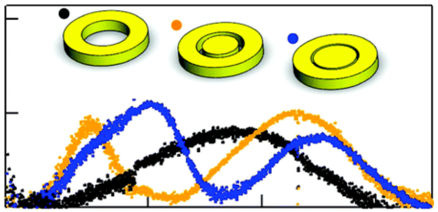
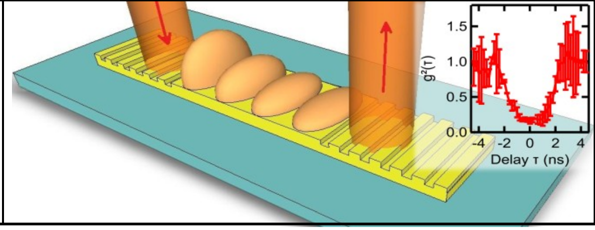
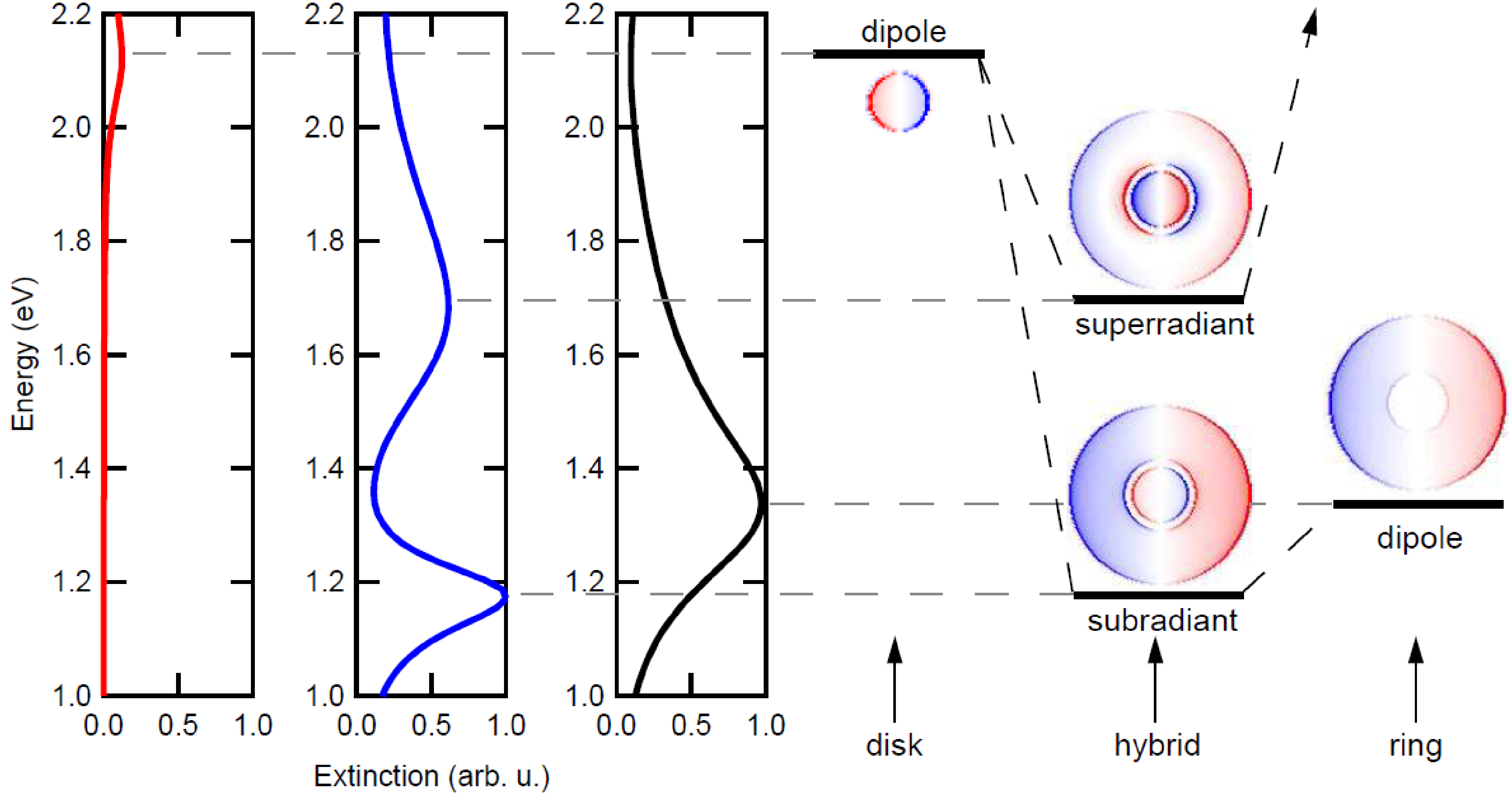


Disks and rings, hybridisation – sims





Y. Sonnefraud et al., *ACS Nano* **4**, 1664 (2010)

RICE Unconventional Wisdom

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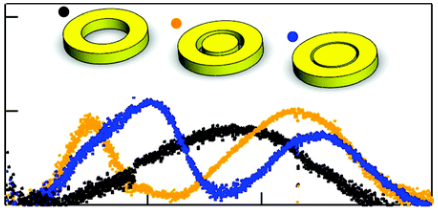

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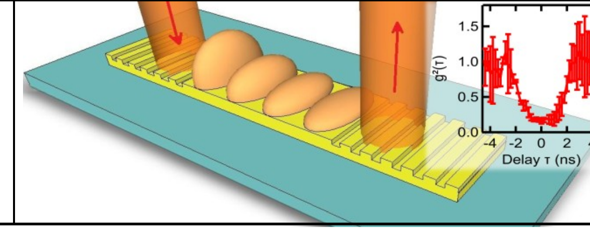
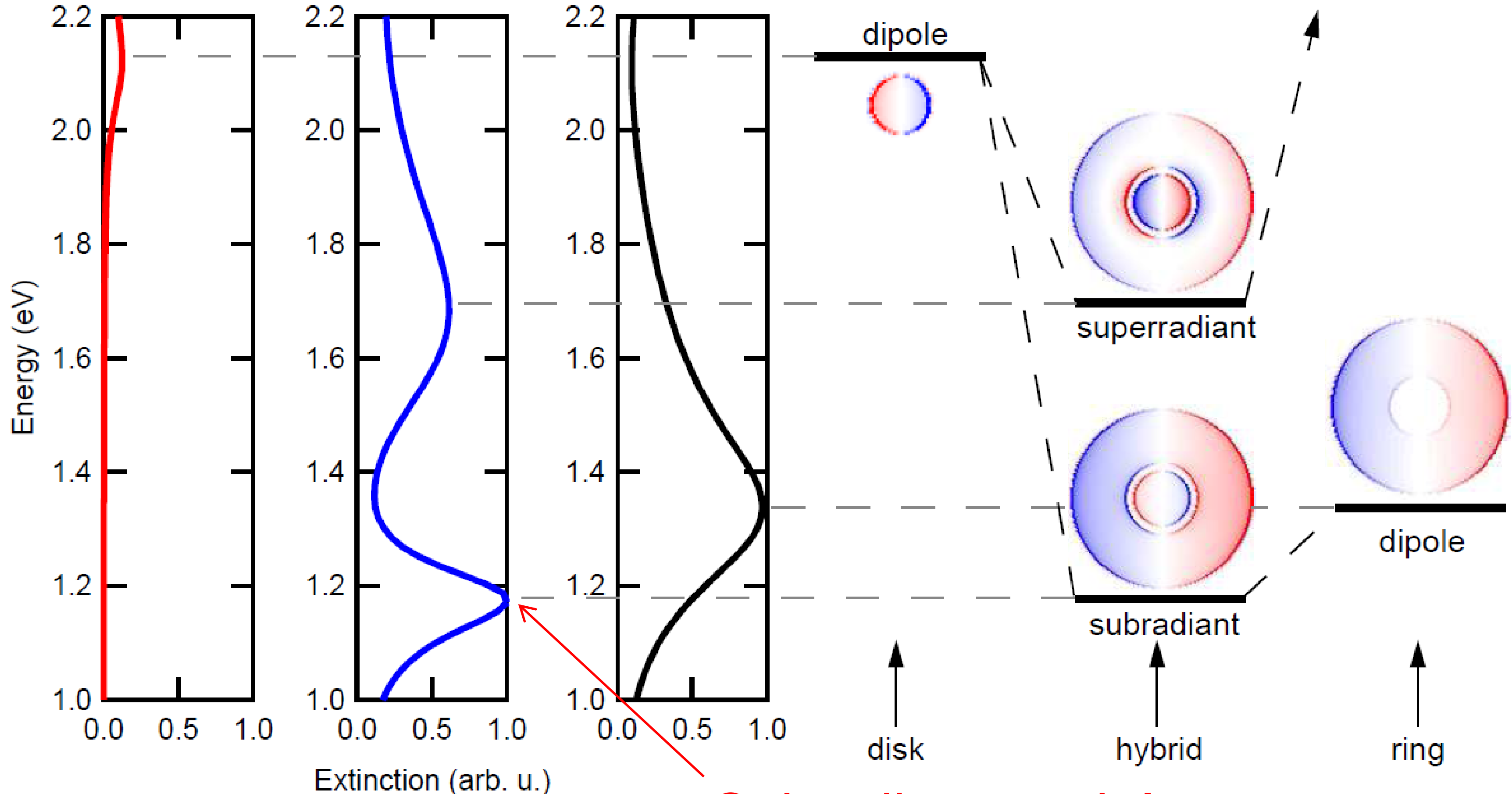
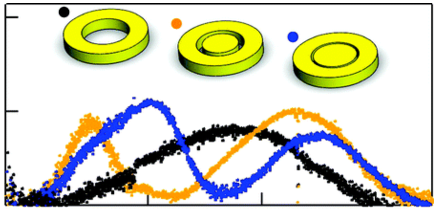


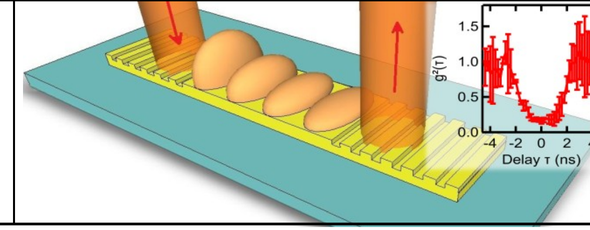


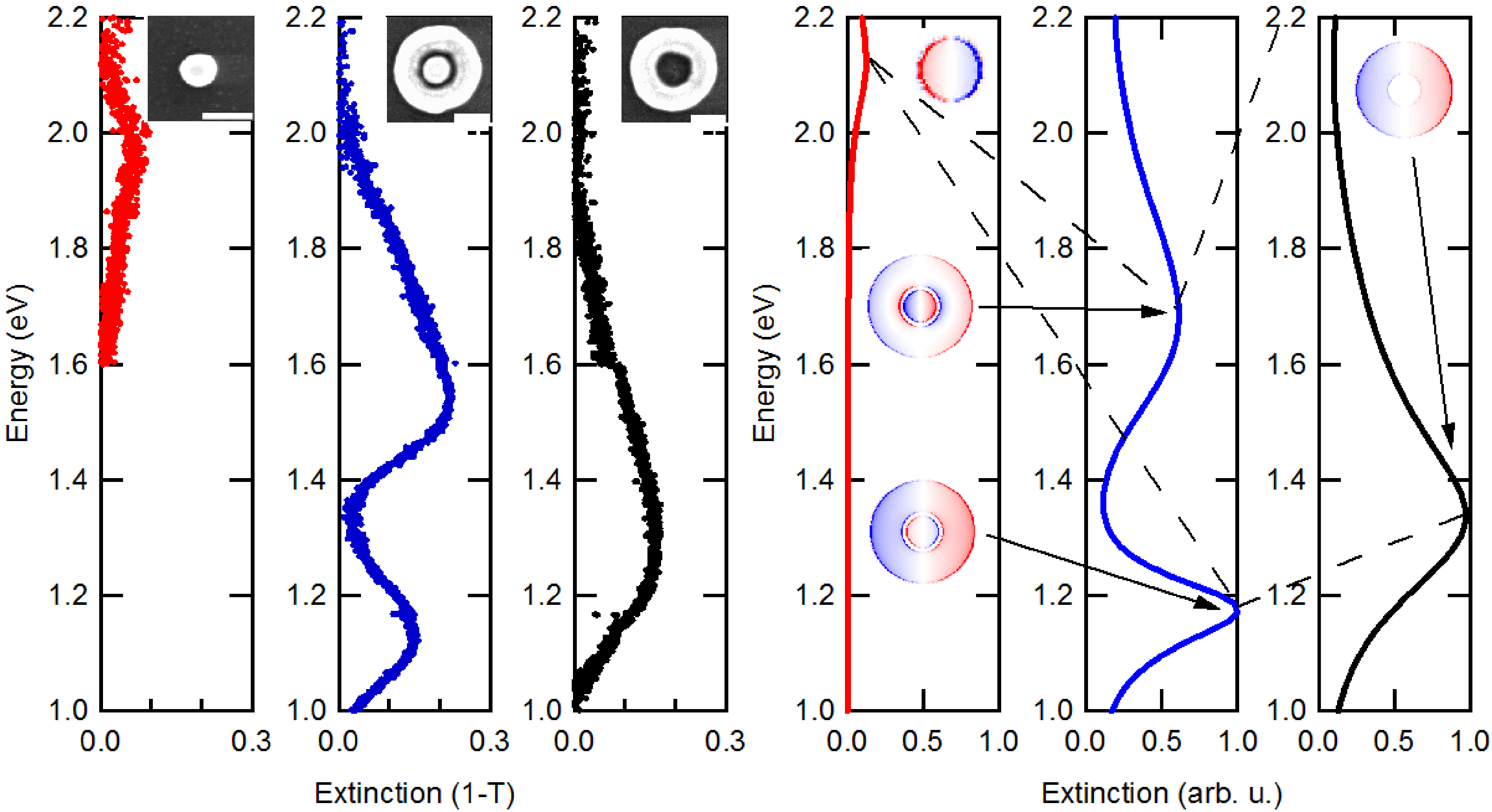
Subradiant mode!

Y. Sonnefraud et al., *ACS Nano* **4**, 1664 (2010)



Disks and rings, hybridisation – exp.





RICE Unconventional Wisdom

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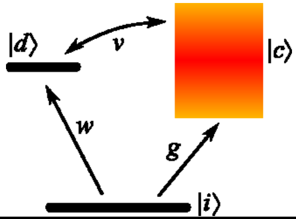
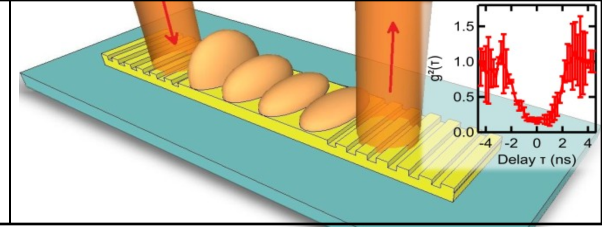
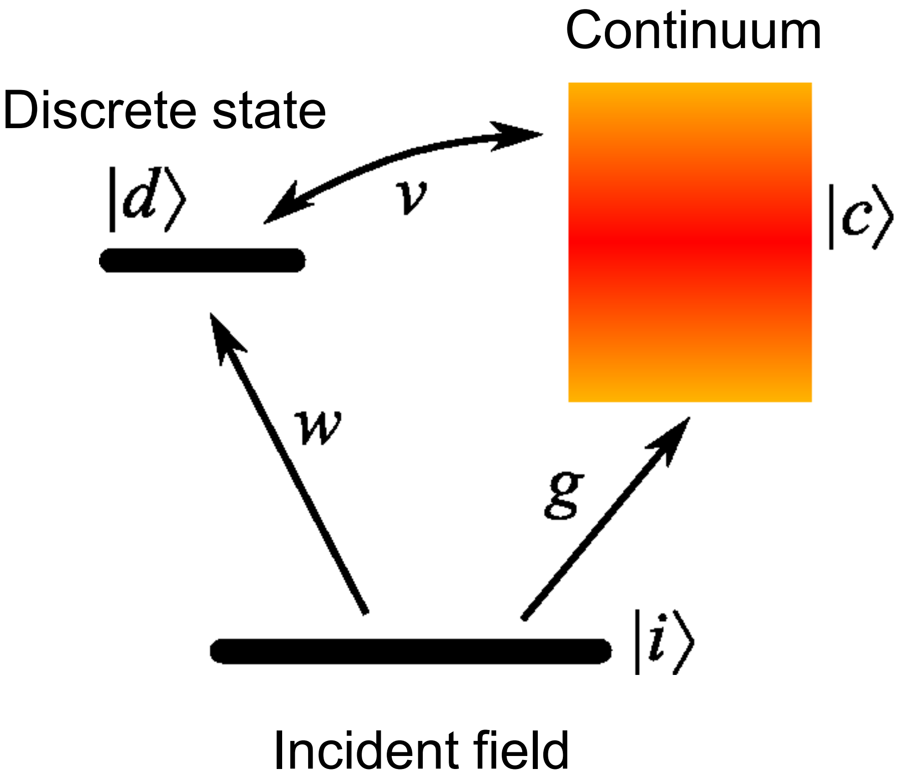
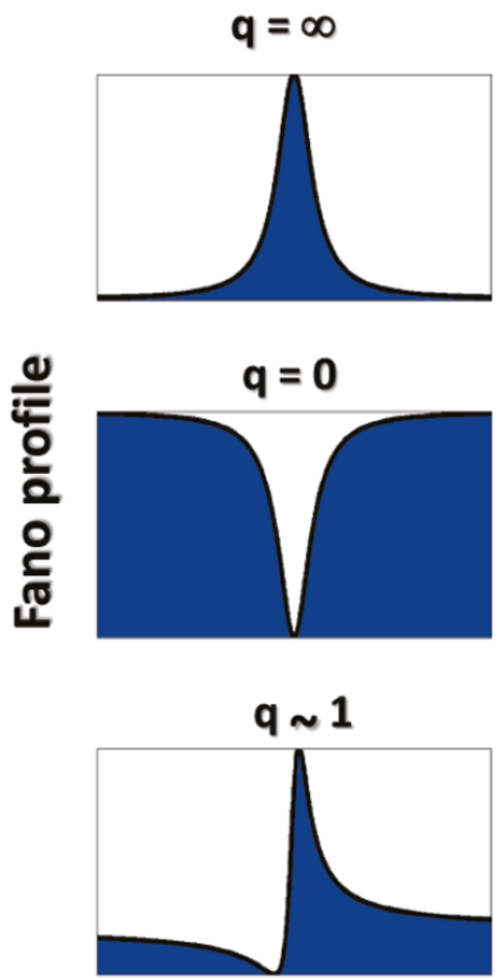


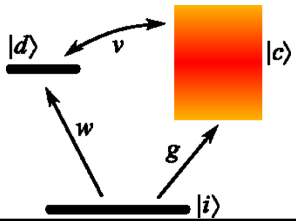
Fano resonances



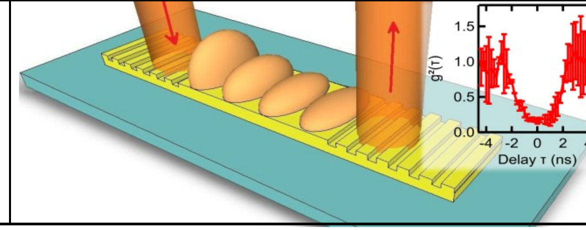


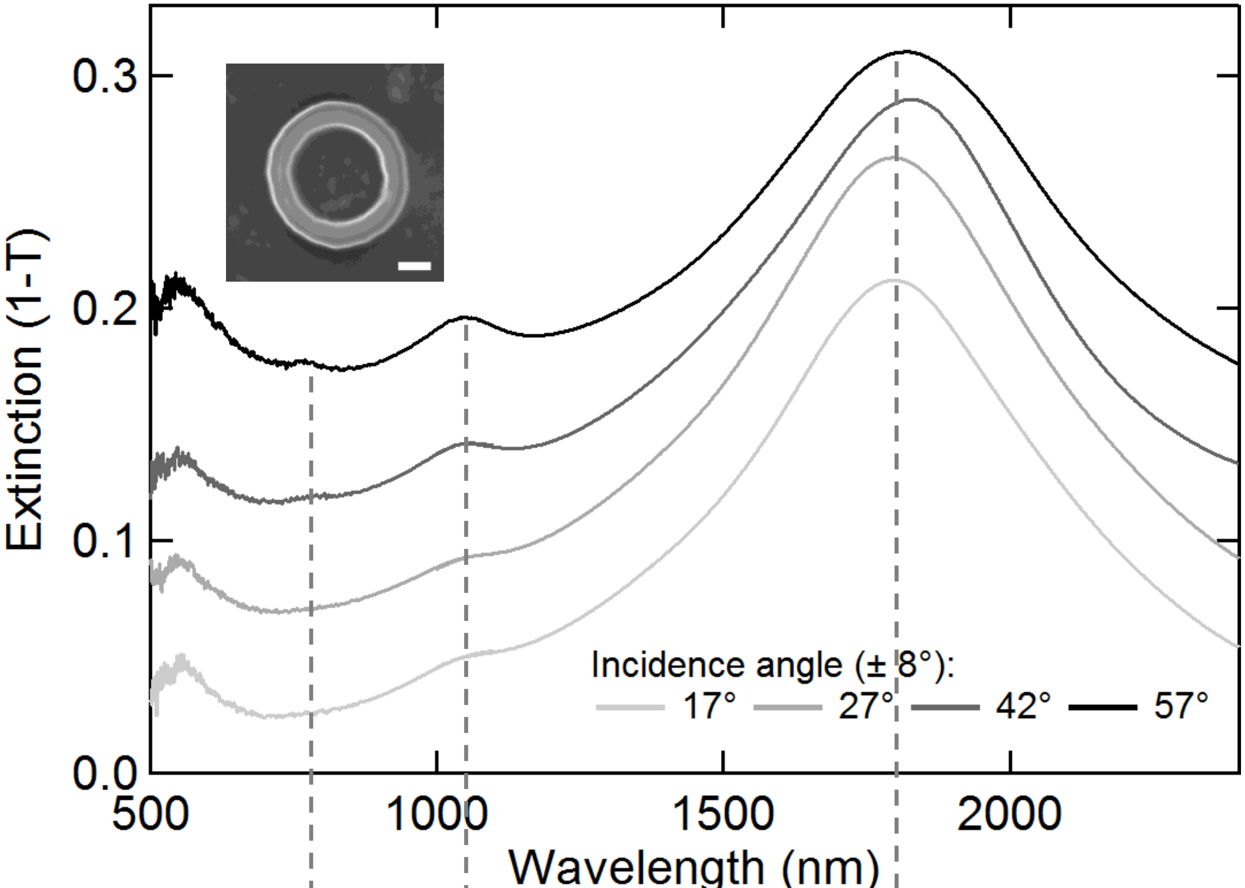


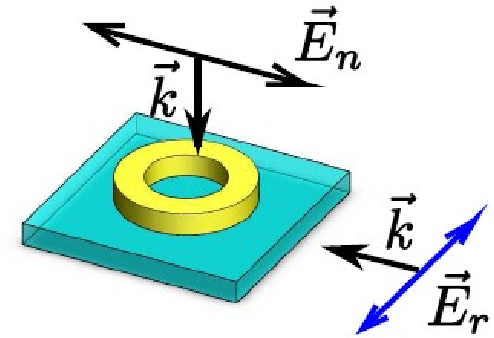
Fano, *Nuovo Cimento* **12**, 156 (1935)
Giannini et al., *Nano Letters* **11**, 2835 (2012)



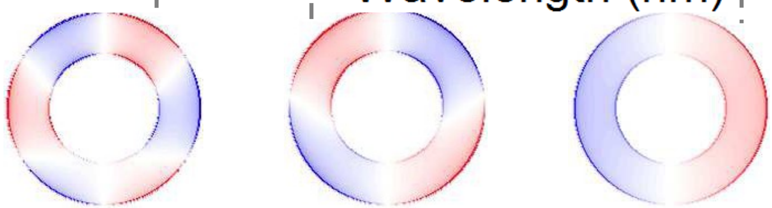
Dark modes in rings



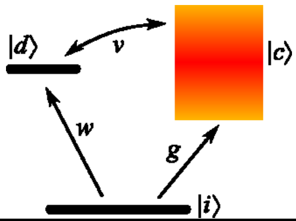




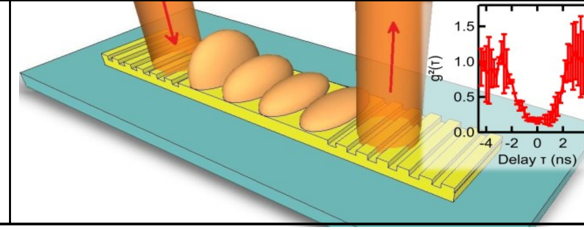
- Observation: non-normal incidence
- Retardation excites dark modes

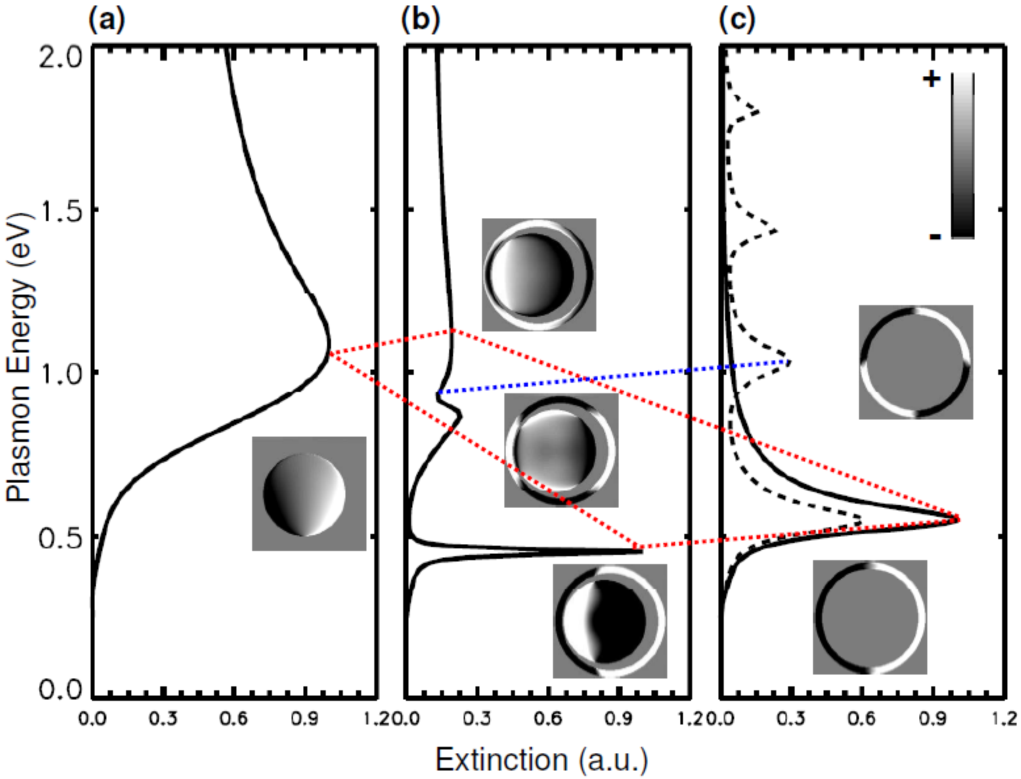


Charge distributions

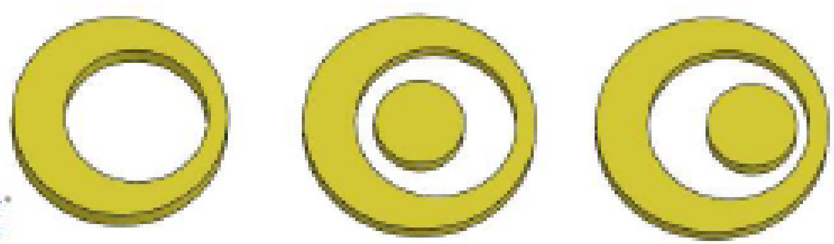


Symmetry breaking – Fano resonances

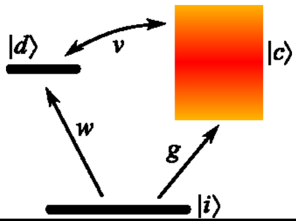




- Non concentric cavities
- Disk dipole couples to ring dark modes
- Fano resonance appears



F. Hao et al.,
ACS Nano **3**, 643 (2009)



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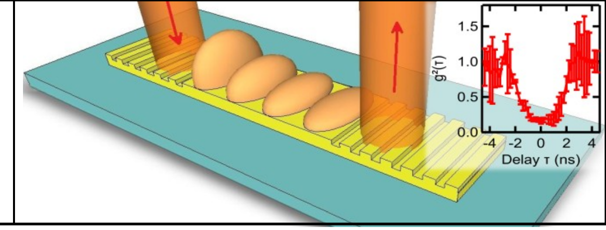

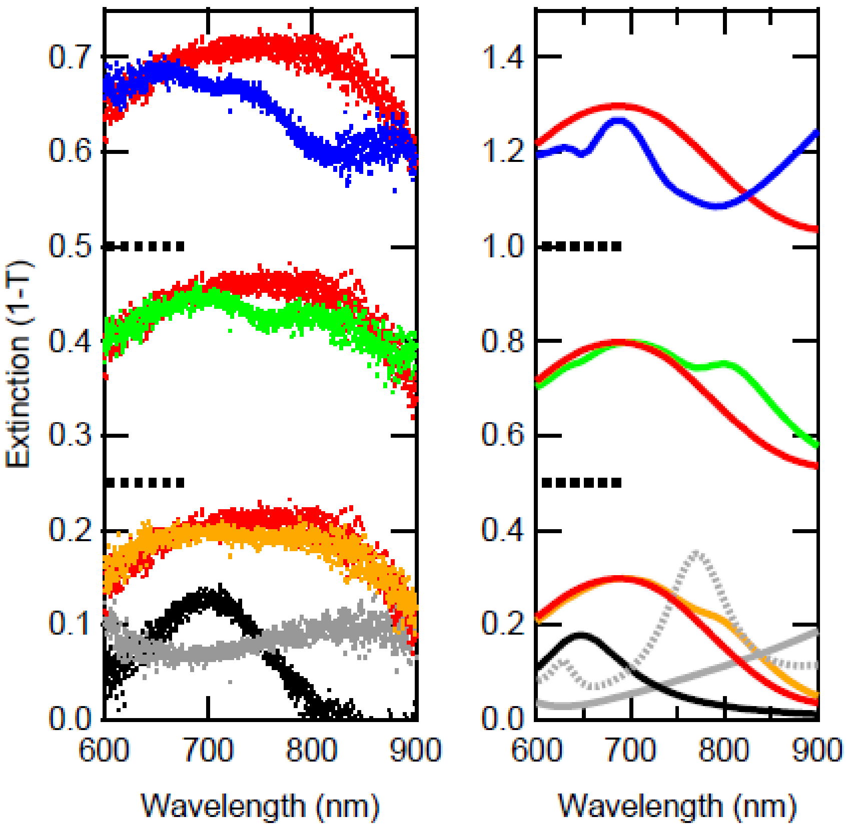

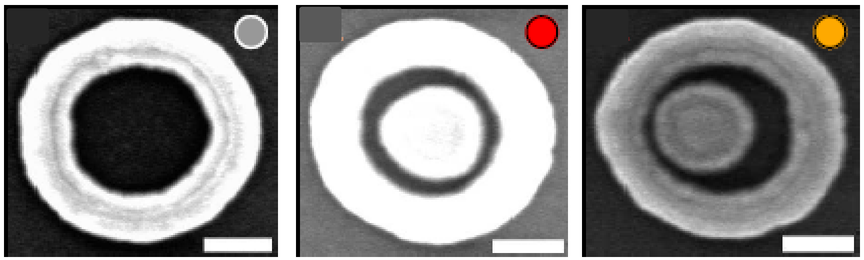

Fano resonances in disk and rings systems:

experimental demonstration

N. Verellen *et al.*, *Nano Letters* **9**, 1663 (2009)

Y. Sonnefraud *et al.*, *ACS Nano* **4**, 1664 (2010)

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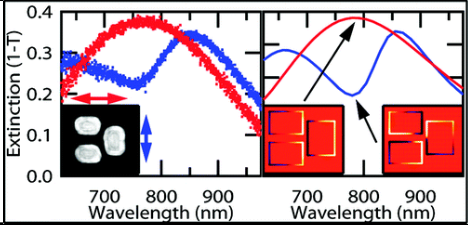

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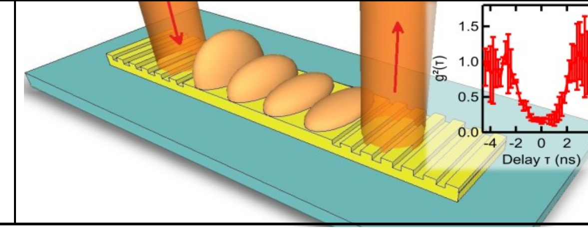

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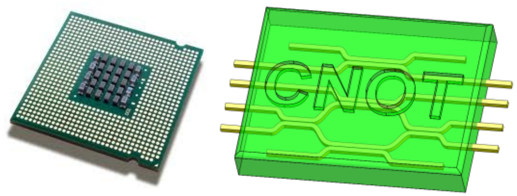
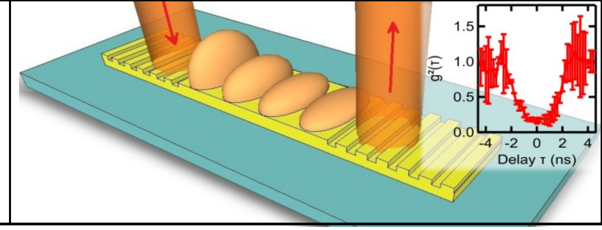
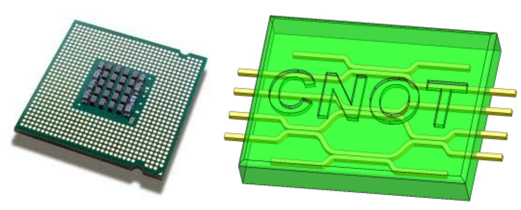


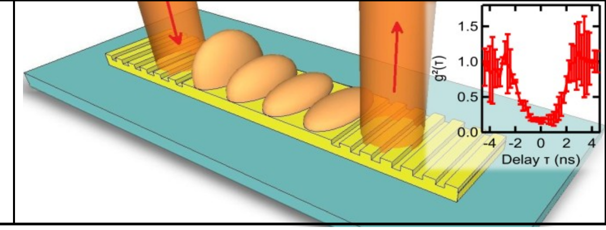
Quantum optics



- Quantum cryptography
- Quantum computing
- Limited by diffraction
- Possibility to use plasmonics?
- Enhanced non linearities, quantum gates…



Quantum Plasmonics?



Demonstrations of quantum properties of photons preserved when converted into SPPs

-Transmission entangled photons

Altewischer et al., Nature 2002

Moreno et al., PRL 2004

- Energy-time entanglement

Fasel et al., PRL 2005

- Quantum superposition

Fasel et al., New J. Phys 2006

-Wave-particle duality

Kolesov et al., Nature Phys. 2009

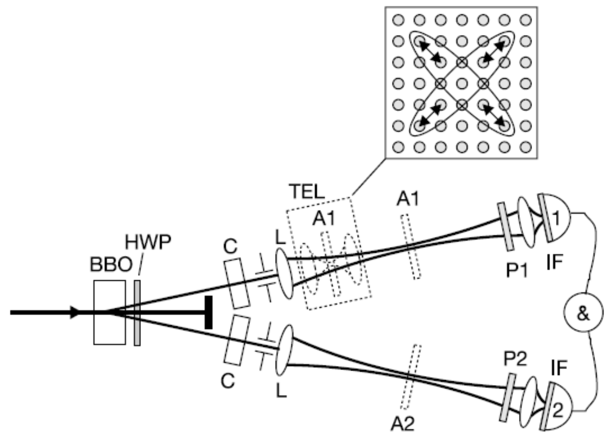
- On-chip single plasmon detection

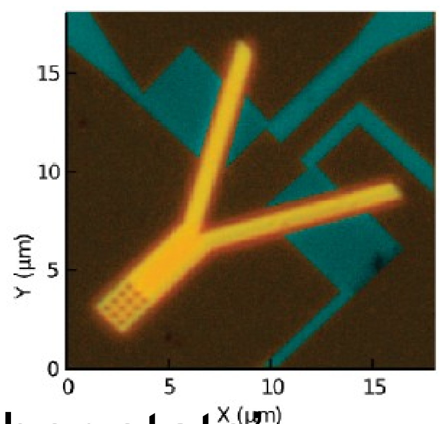
Heeres et al., Nano Lett. 2010

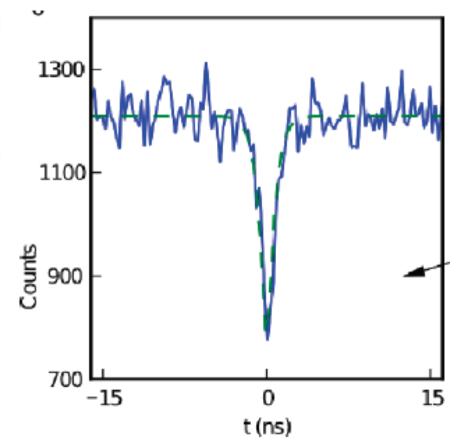
- Etc…

- Quantum degree of freedom ‘number state’

Di Martino et al., Nano Lett. **12**, 2504 (2012)







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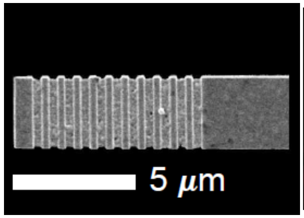
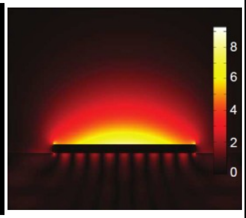
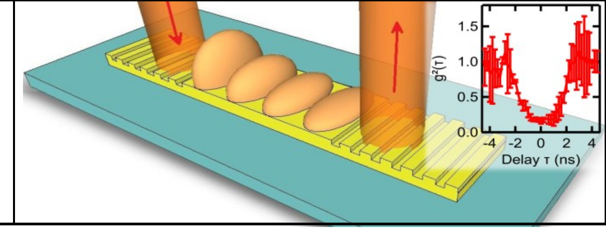
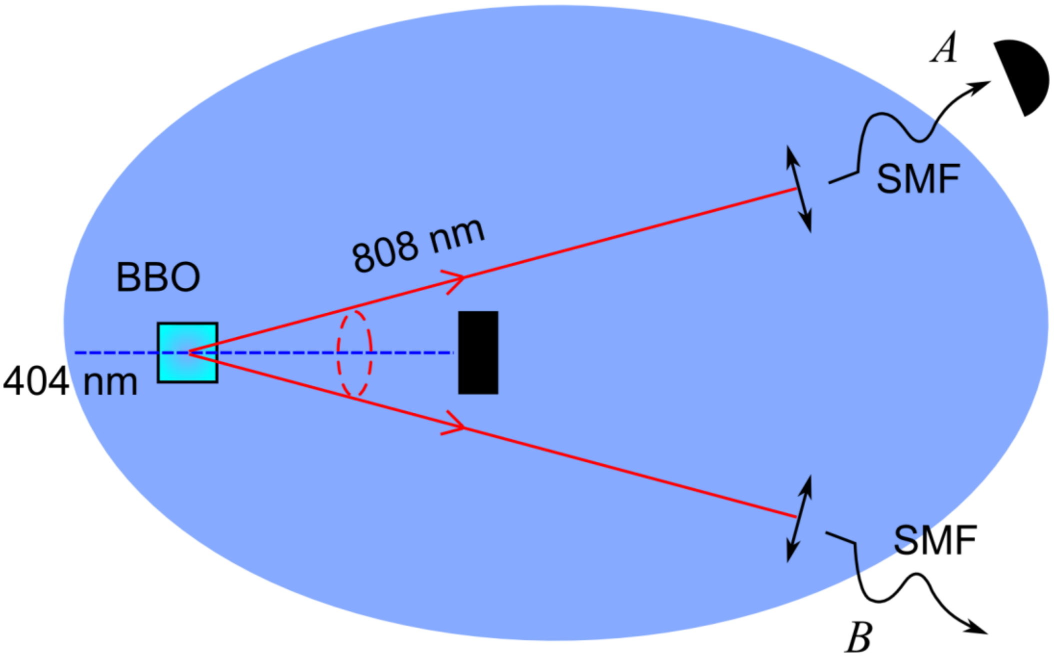




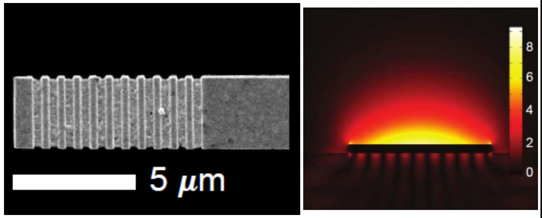
Experiment – single photons



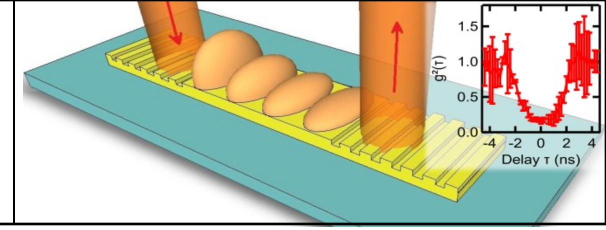
Heralded single photons: type-I spontaneous parametric down conversion



- Conditioned detection, “heralded” single photons
- Generation rate~10^5/s

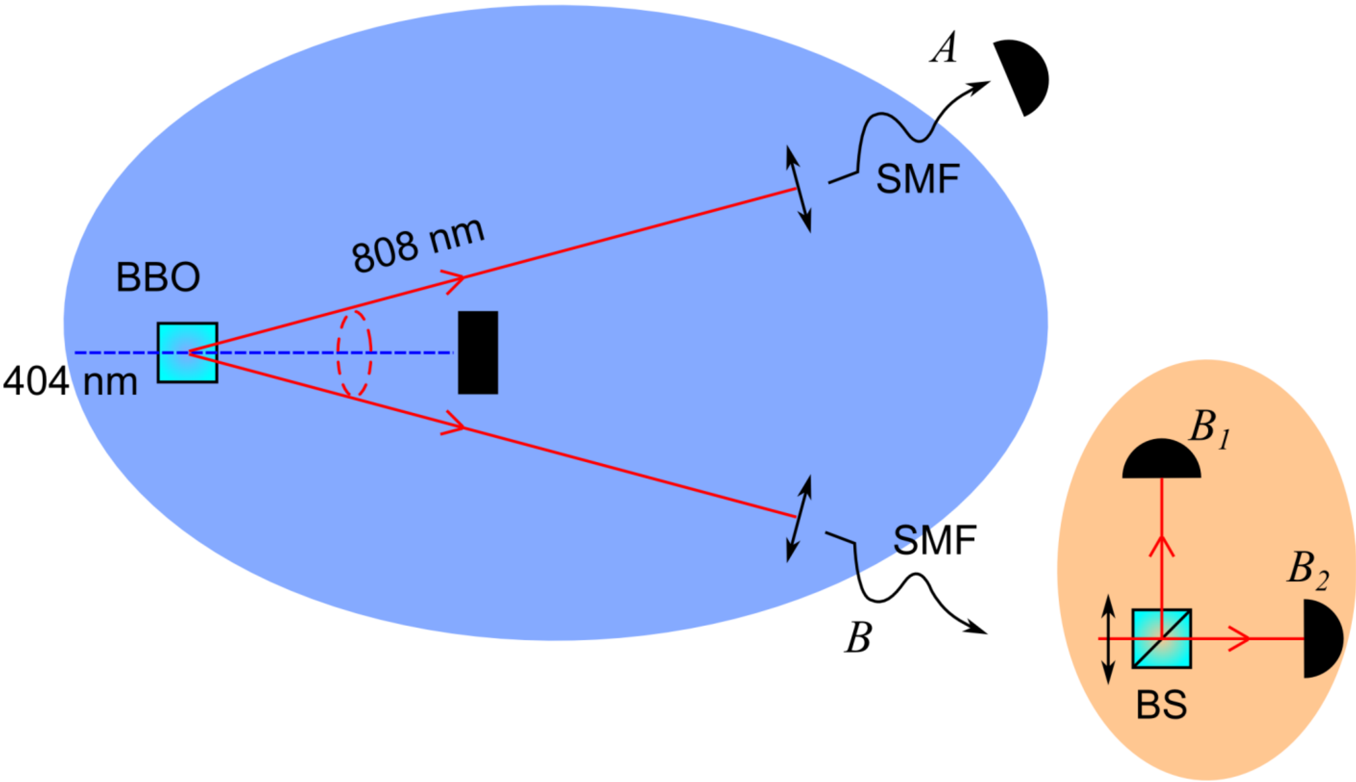


Experiment – single photons



Heralded single photons: type-I spontaneous parametric down conversion

Measurement $g^2(\tau)$ with Hanbury-Brown and Twiss interferometer



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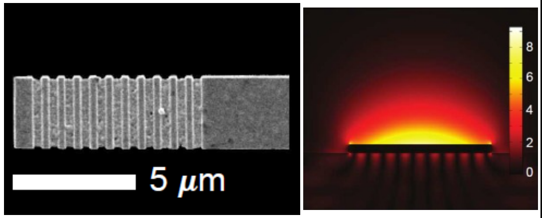
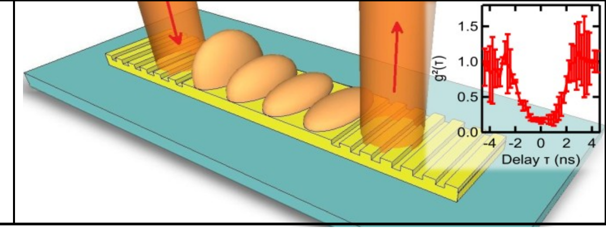


Experiment – single photons



Heralded single photons: type-I spontaneous parametric down conversion

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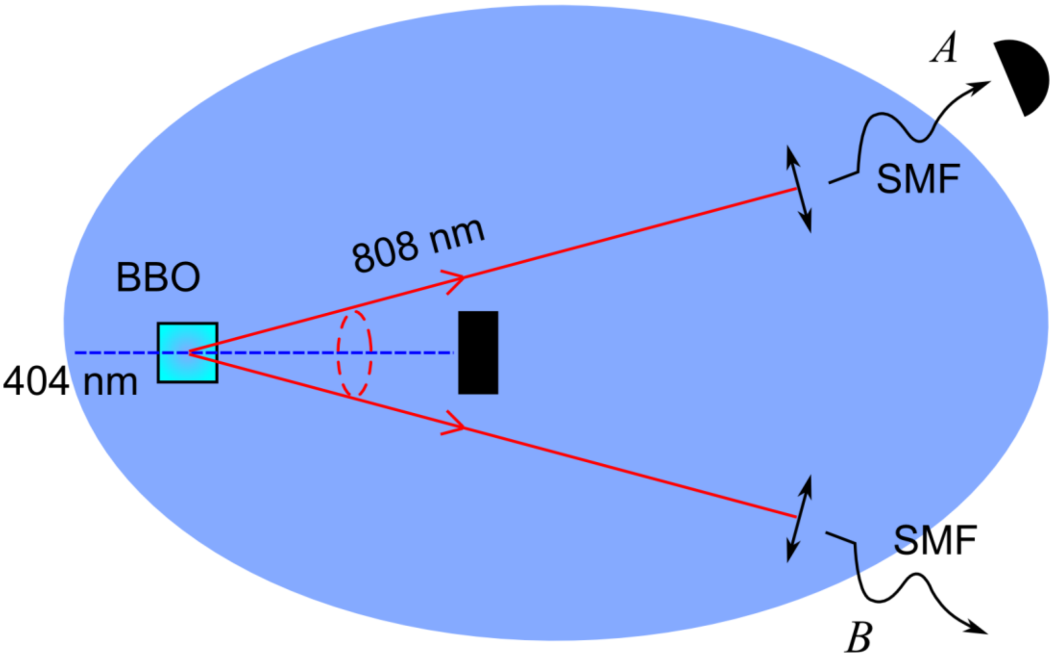
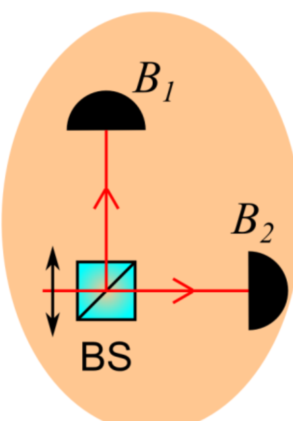
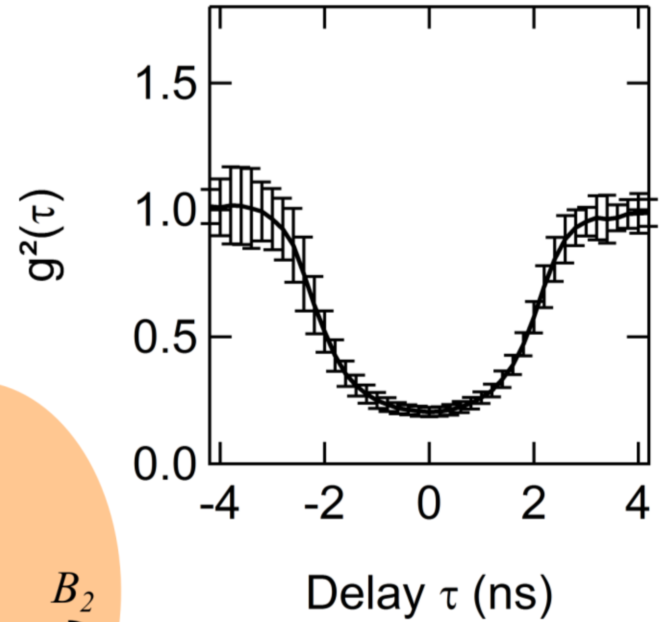
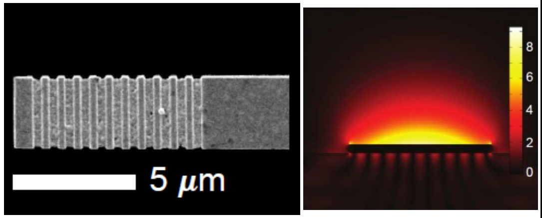


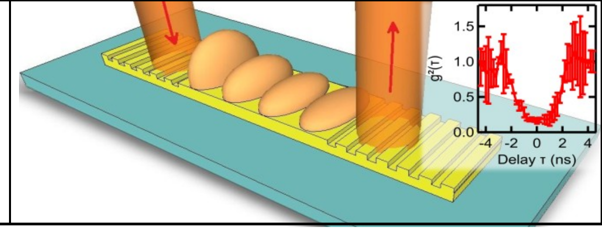




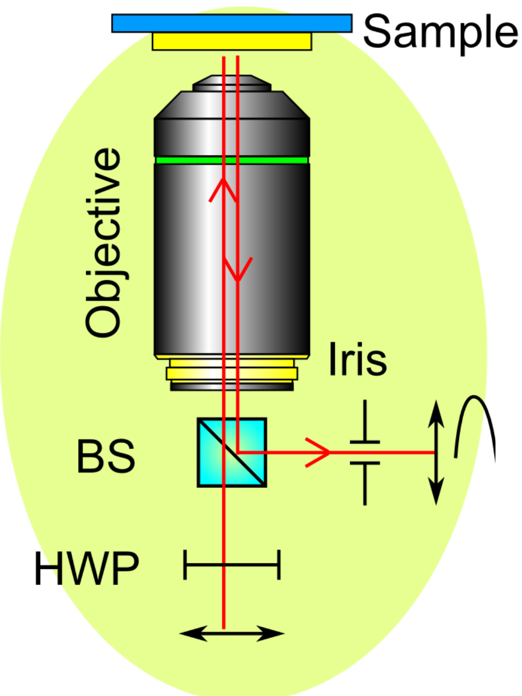
Pure number state:
$g^{(2)}(0)=1-1/n$

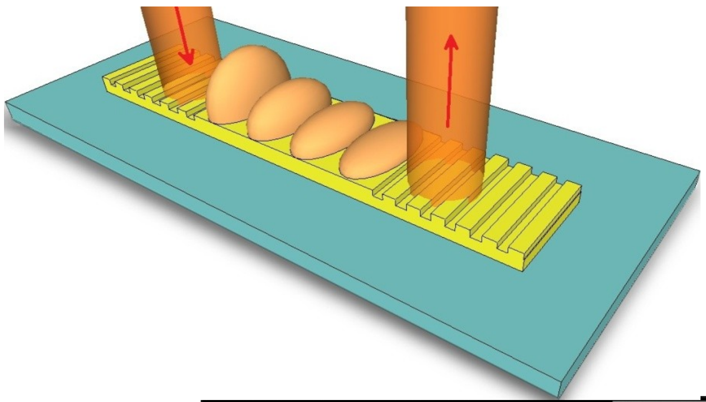


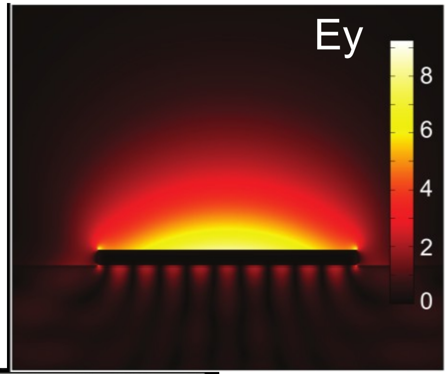
Experiment – microscopy

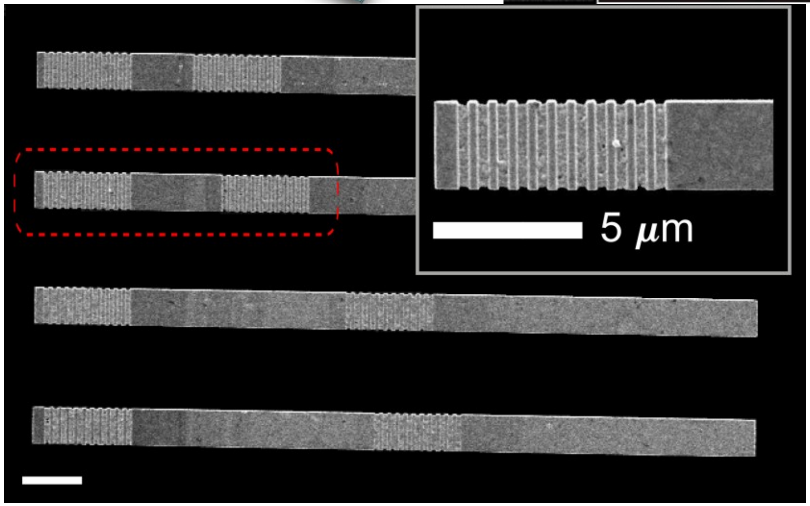


Excitation of quanta of leaky SPPs in thin waveguides









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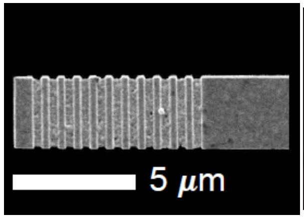
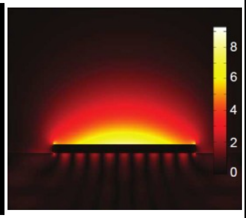
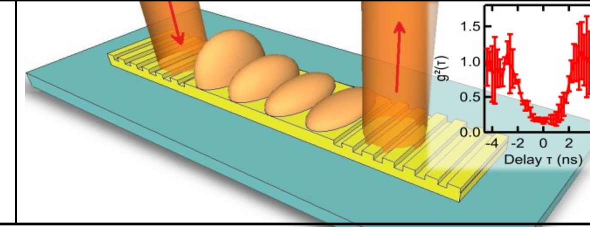


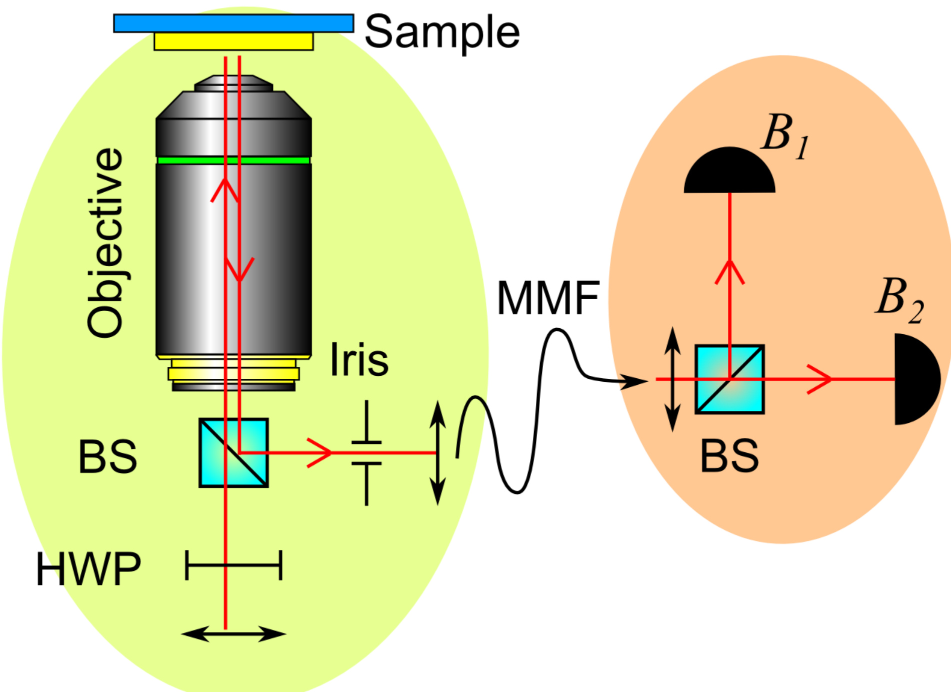


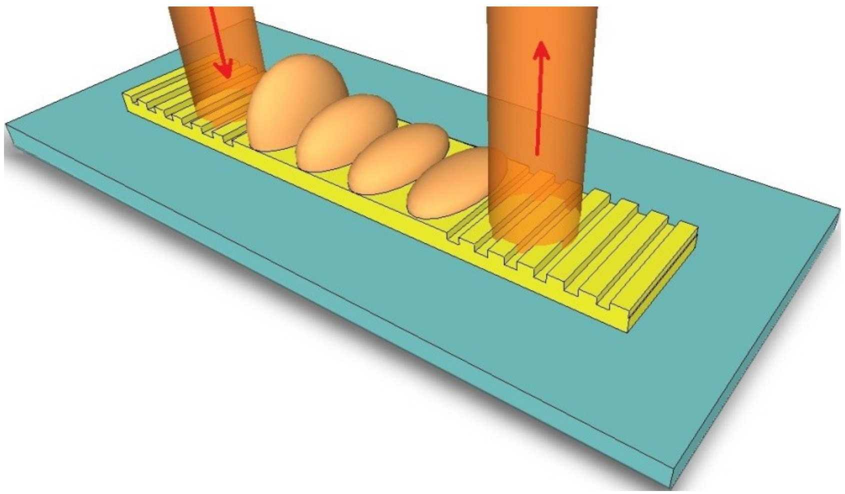
Experiment – microscopy

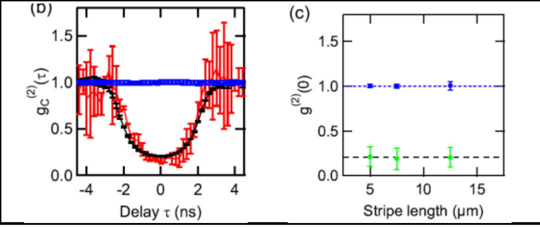


Excitation of quanta of leaky SPPs in thin waveguides

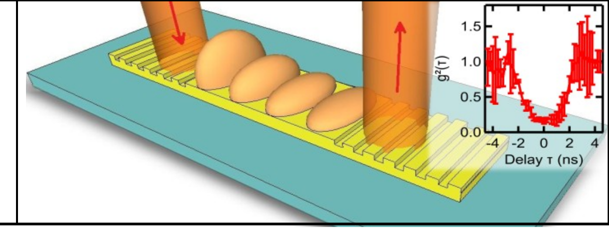
Measurement $g^2(\tau)$ with Hanbury-Brown and Twiss interferometer



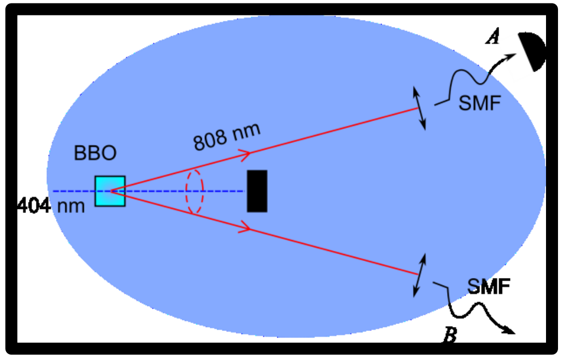


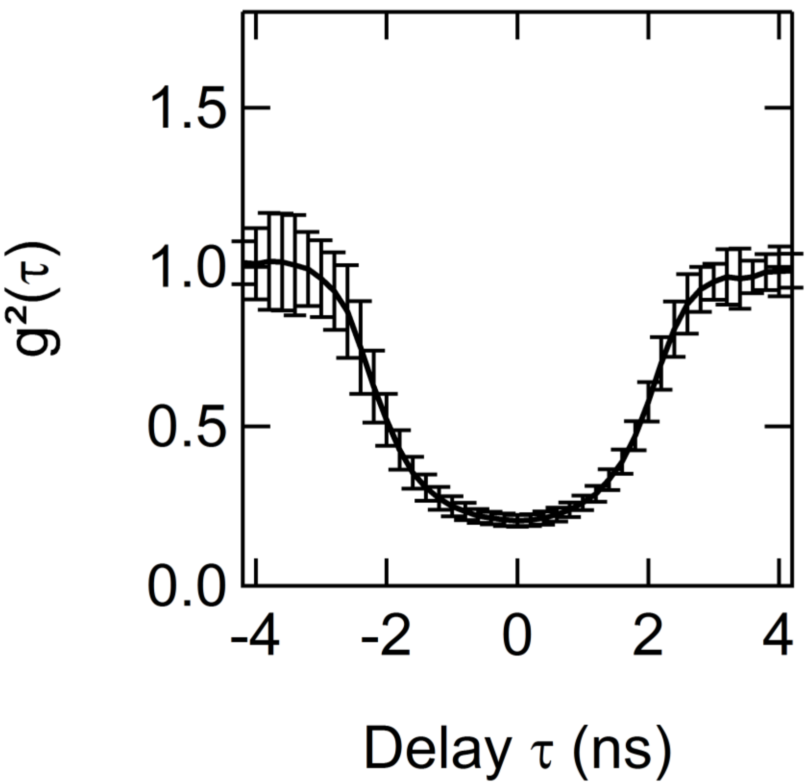


Results – $g^2(\tau)$

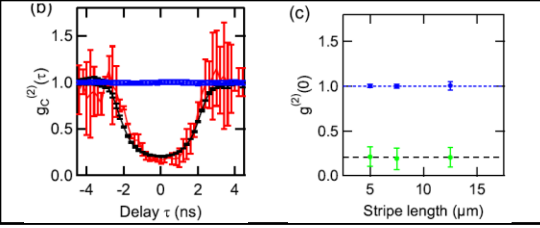


Single photon source

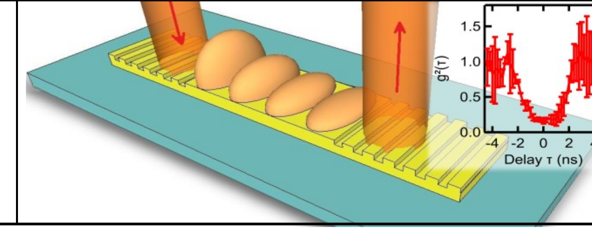




$g^{(2)}(0)=1-1/n$

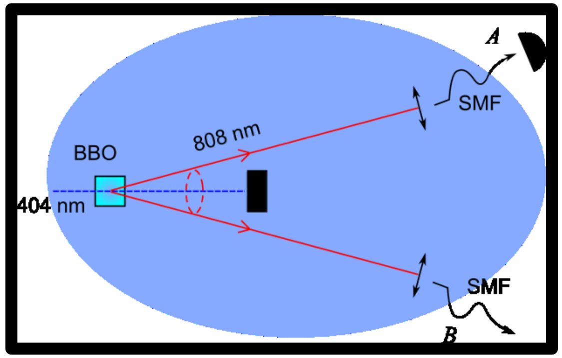


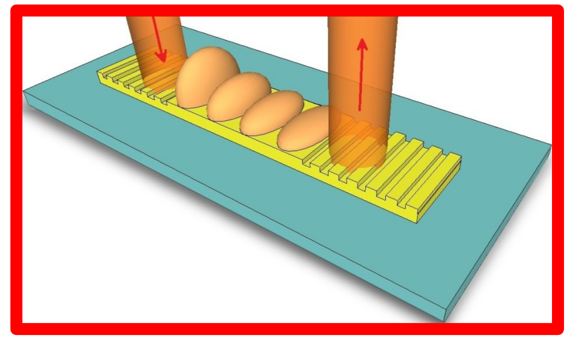
Results – $g^2(\tau)$

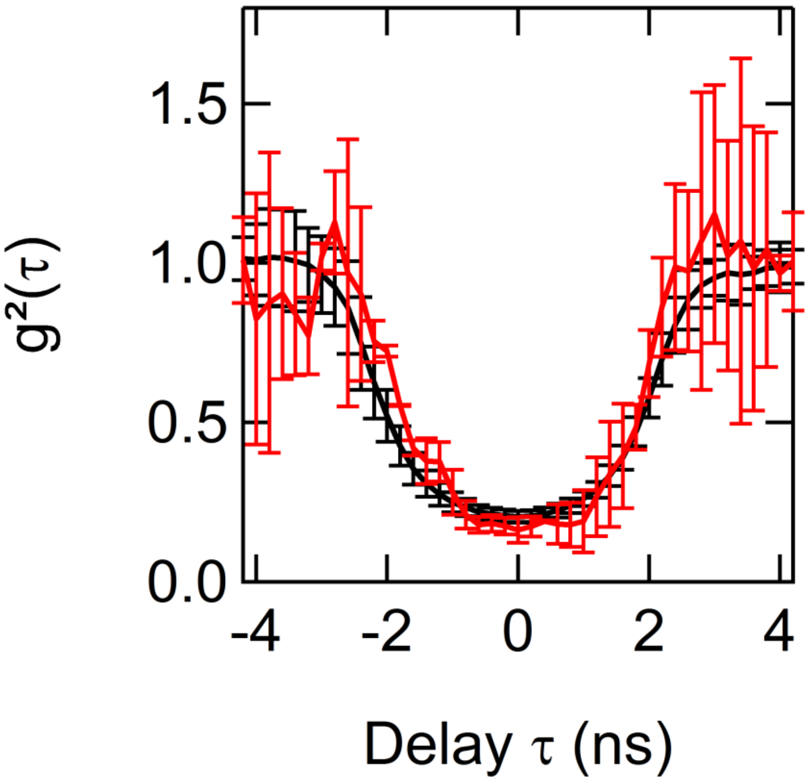


Single photon source

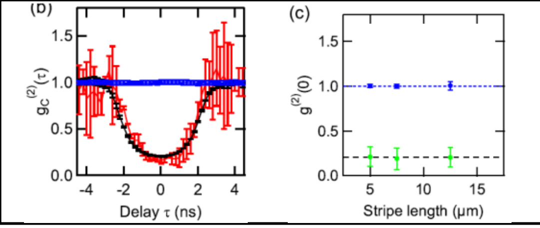
Through a waveguide



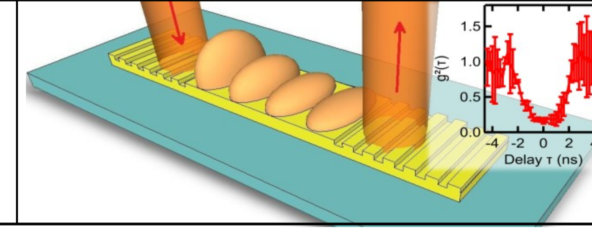




$g^{(2)}(0)=1-1/n$



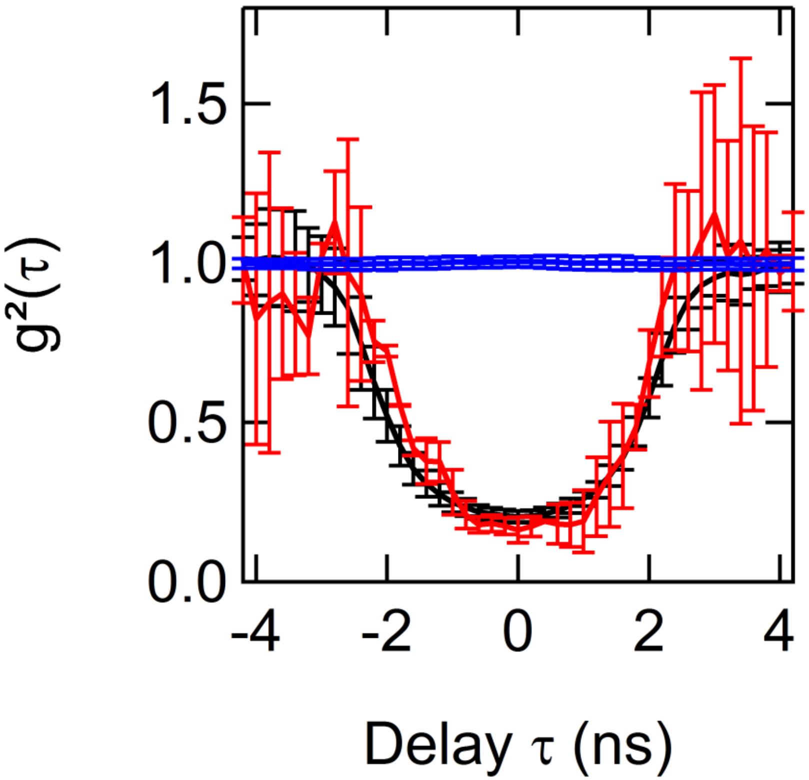
Results – $g^2(\tau)$

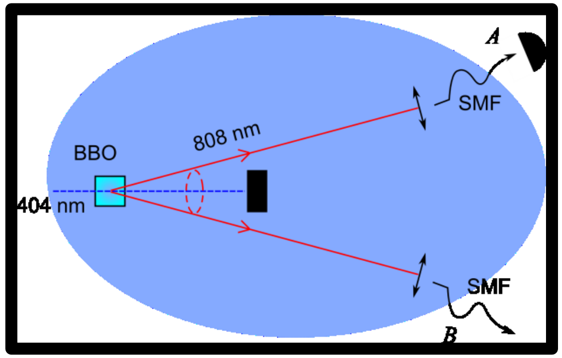


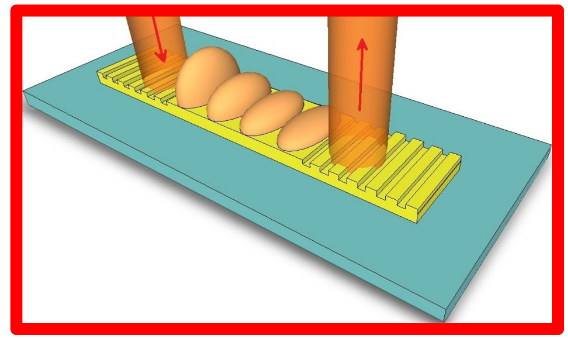
Single photon source

Through a waveguide

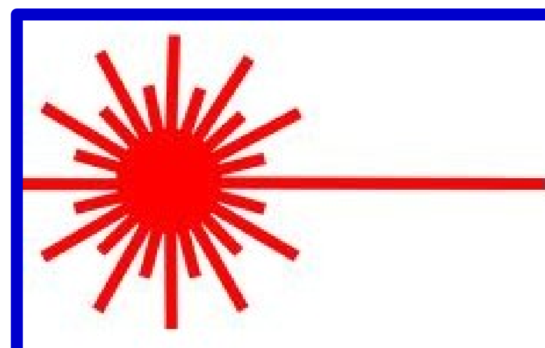
Laser through waveguide







$g^{(2)}(0)=1-1/n$



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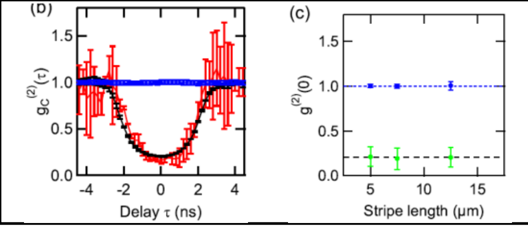
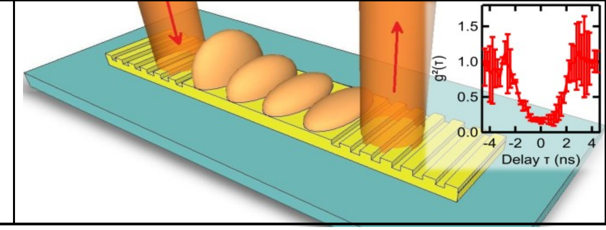
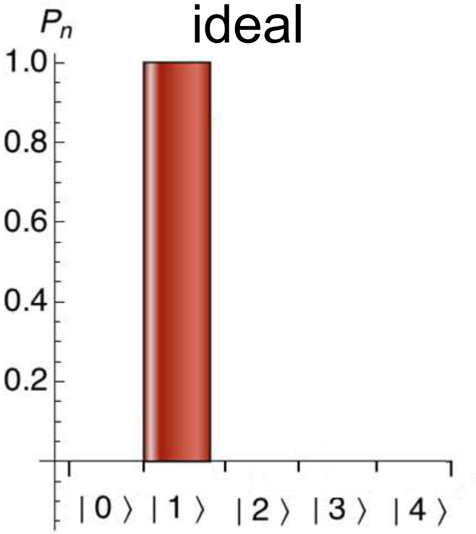


Results – Fock states reconstruction



Single photons

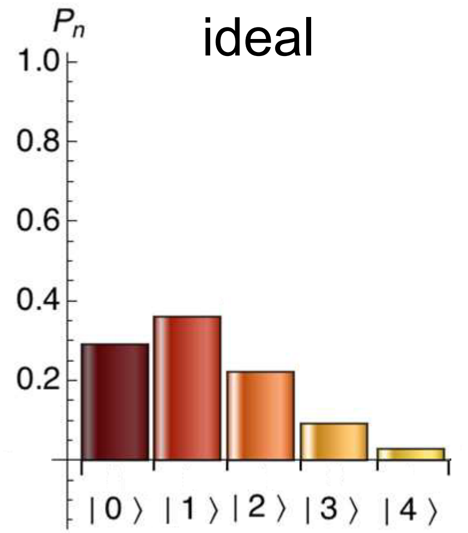
ideal



experiment

Attenuated laser

ideal



experiment

Zambra & al.,
Phys. Rev. Lett. 2005, 95, 063602.

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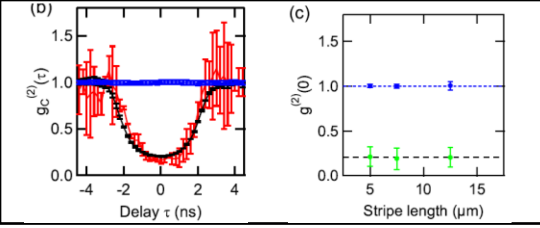
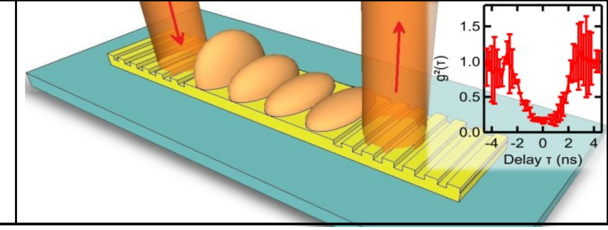
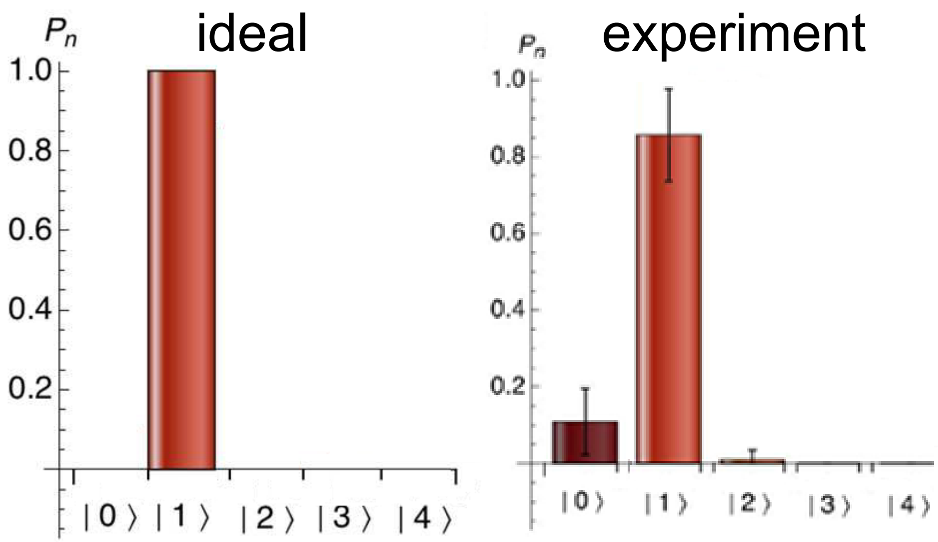


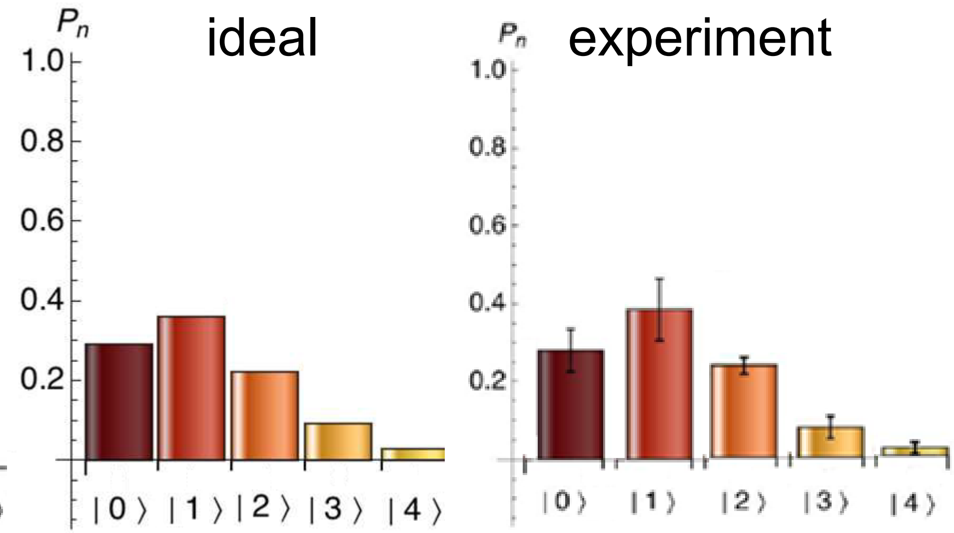
Results – Fock states reconstruction



Single photons

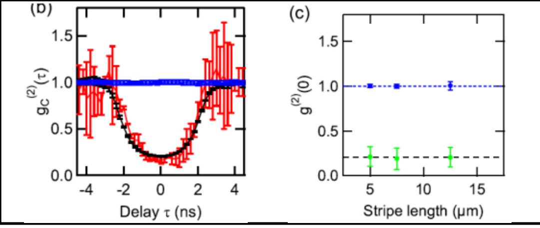


Attenuated laser

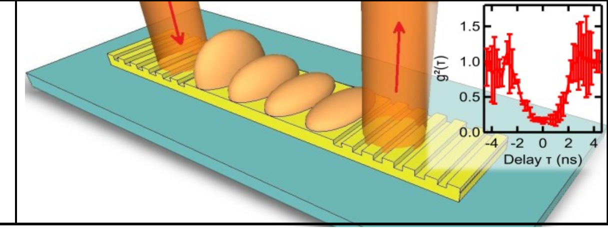


- Source output and detected SPPs are found to be in a nearly pure number state: $|1\rangle$
- Reconstruction from SPPs excited with an **attenuated laser** is consistent with a coherent state of mean excitation number $\langle n \rangle \sim 1$

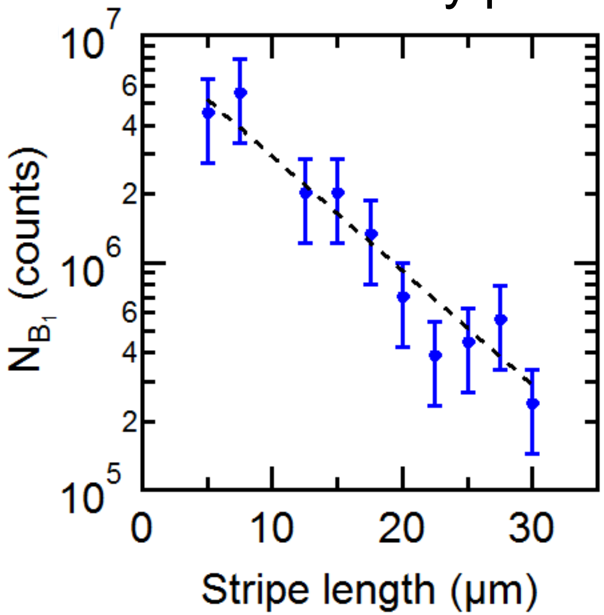
Zambra & al.,
Phys. Rev. Lett. 2005, 95, 063602.



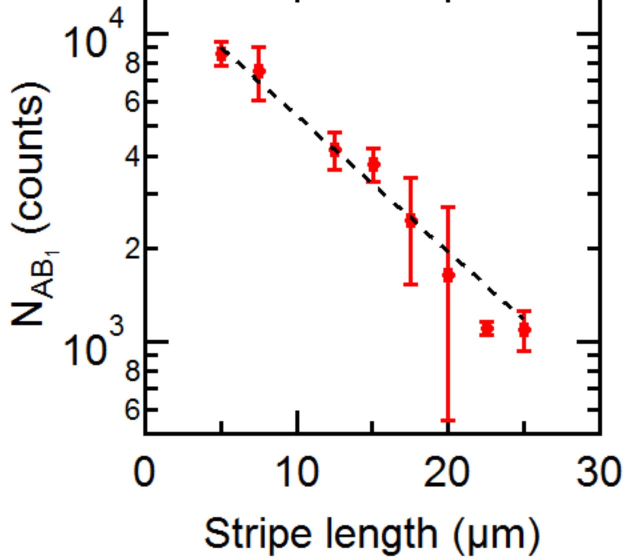
Results – effect of losses



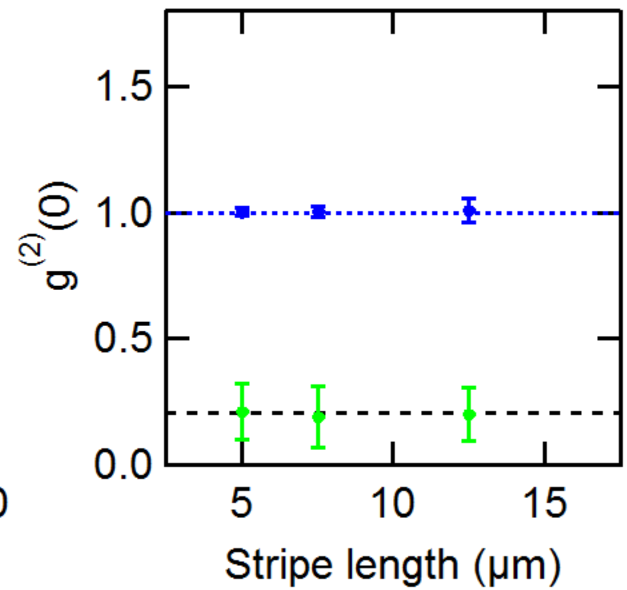
Laser decay plot



Single photon decay plot



$g^{(2)}(0)$ varying length



- Decay length measured with single photons identical to measured with laser excitation
- $g^{(2)}(0)$ **unchanged** with stripe length
- Consistent with a **linear uncorrelated Markovian loss model**

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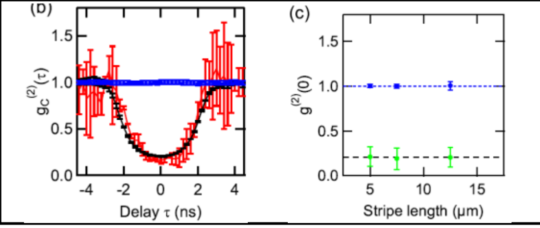
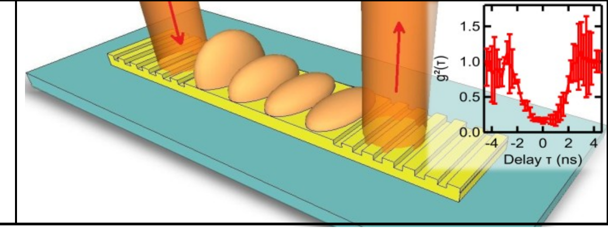
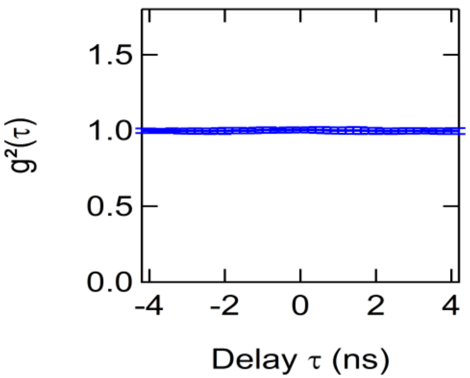
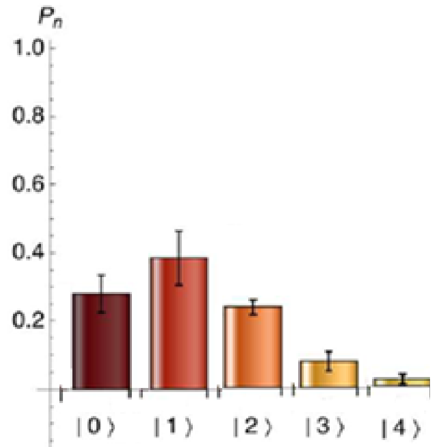


Conclusions

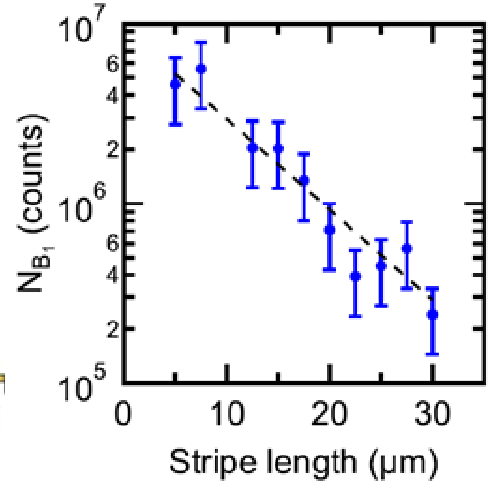


- **Classical regime**

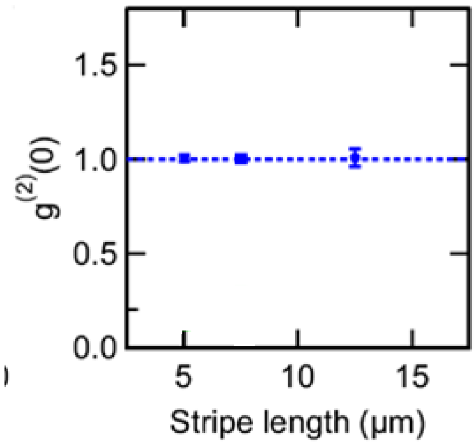




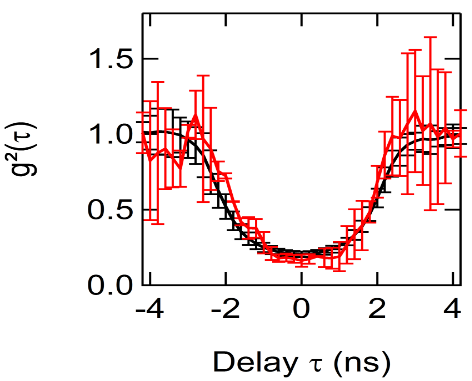
Laser decay plot

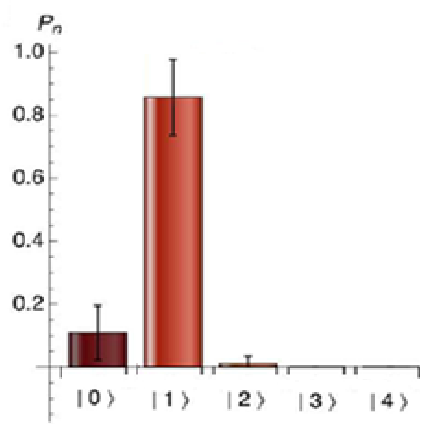


$g^{(2)}(0)$ varying lengths

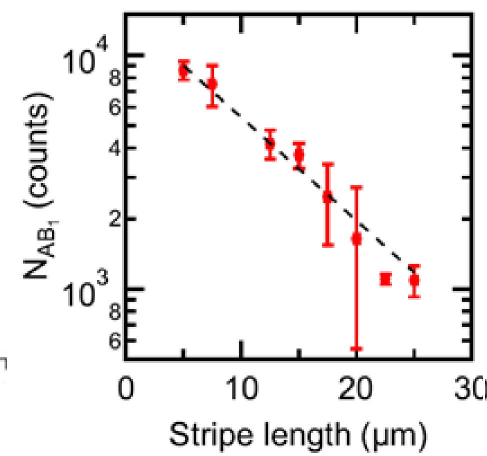


- **Single excitation regime**

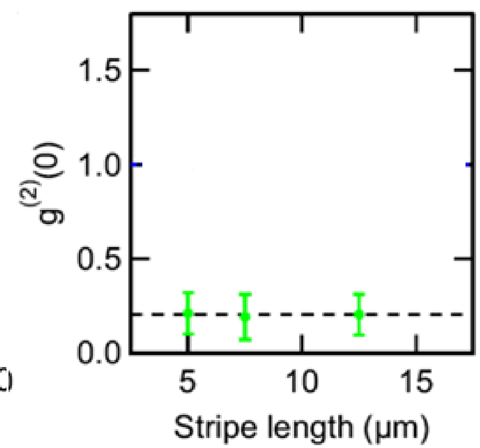




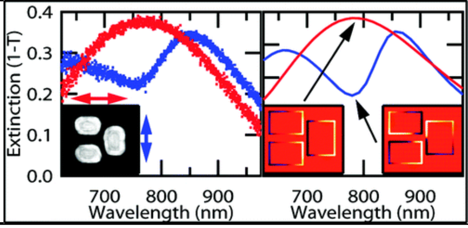
Single photon decay plot



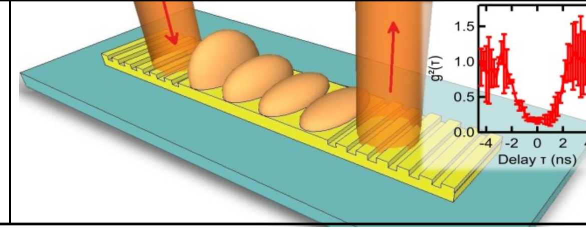
$g^{(2)}(0)$ varying lengths



Di Martino et al., Nano Lett. 12, 2504 (2012)



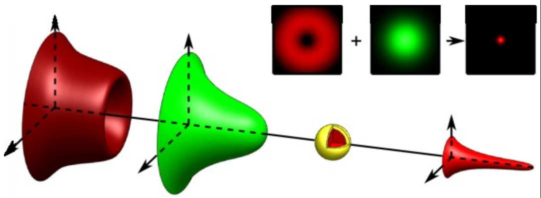
Outline

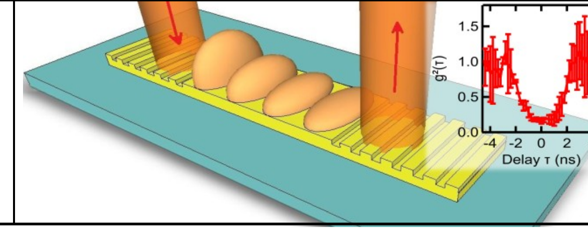


1. Losses in plasmonic cavities
   - Super/subradiant modes
   - Fano resonances

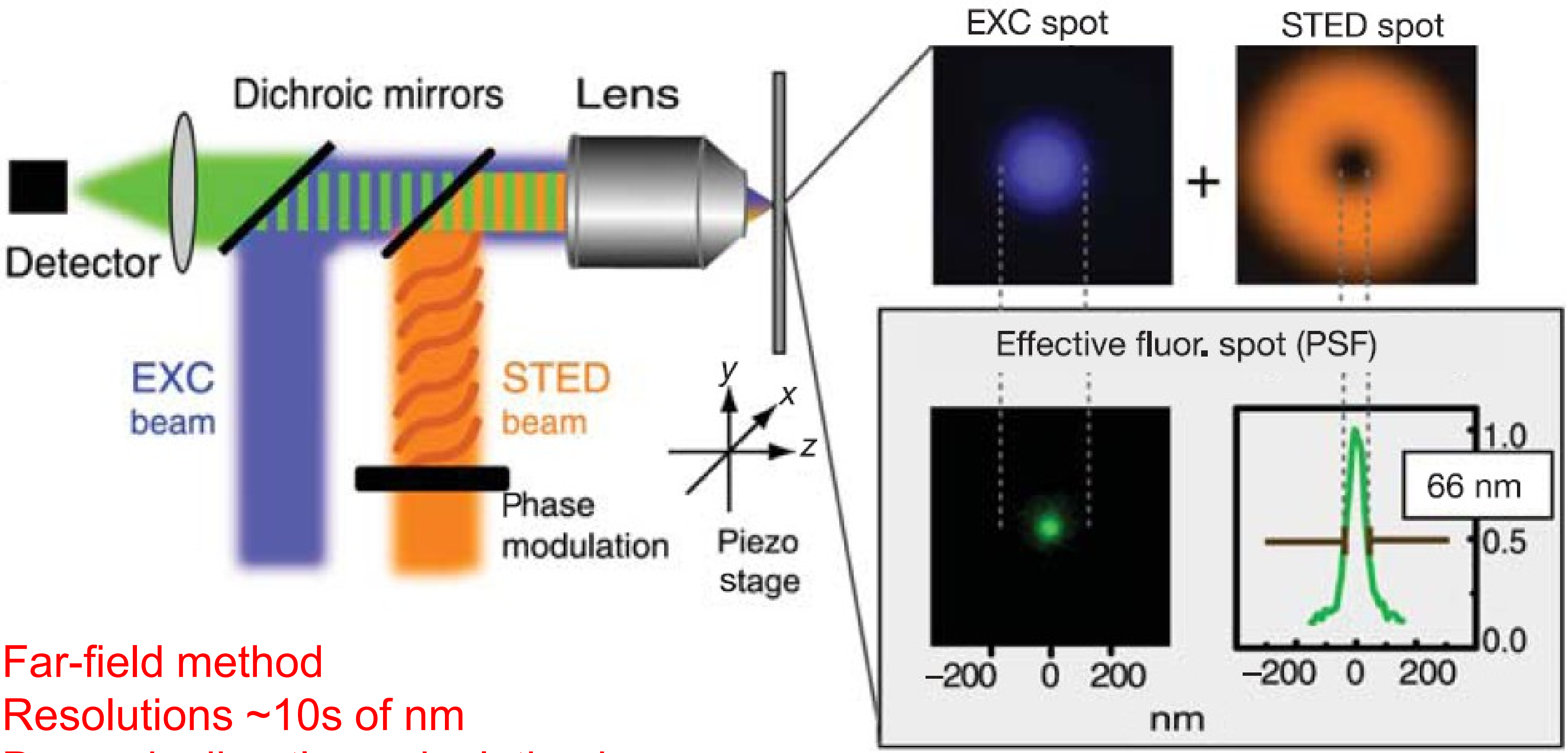
2. Losses in waveguides in the quantum regime

3. Non related bonus (if time avails)



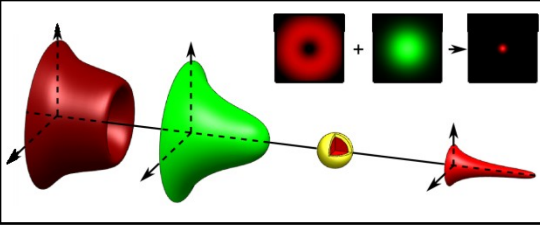


STED



Far-field method
Resolutions ~10s of nm
Depends directly on depletion beam power

Willig et al., *Nature* **440**, 935 (2006)



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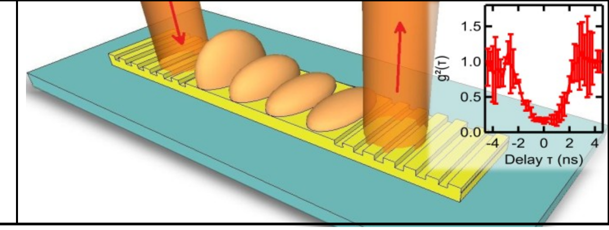
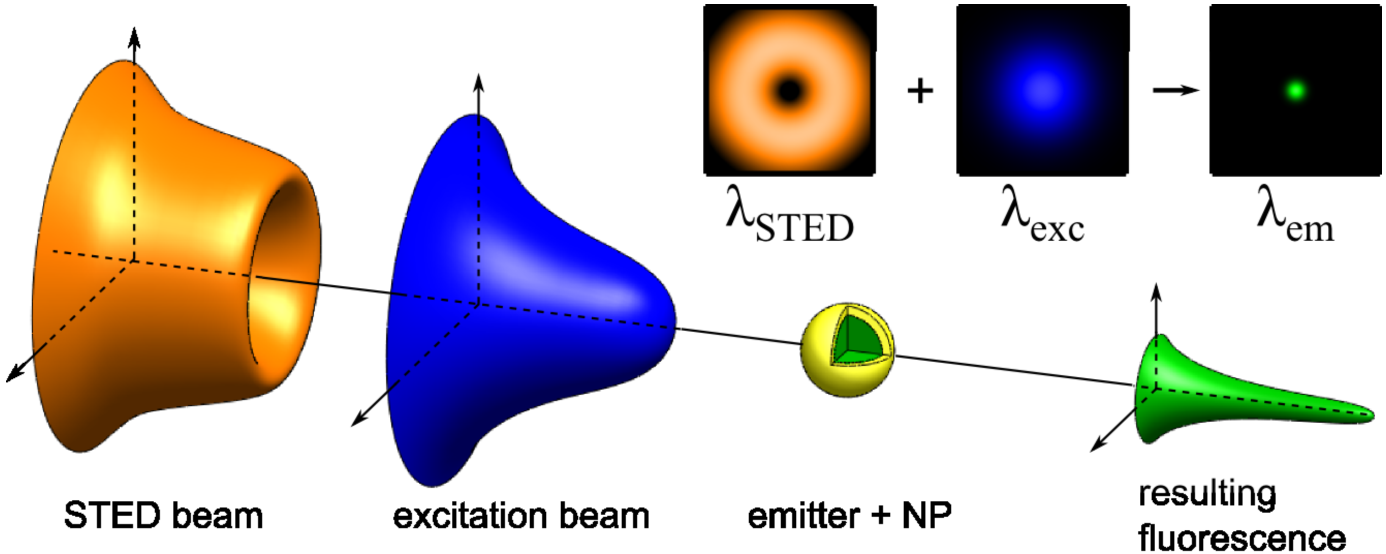
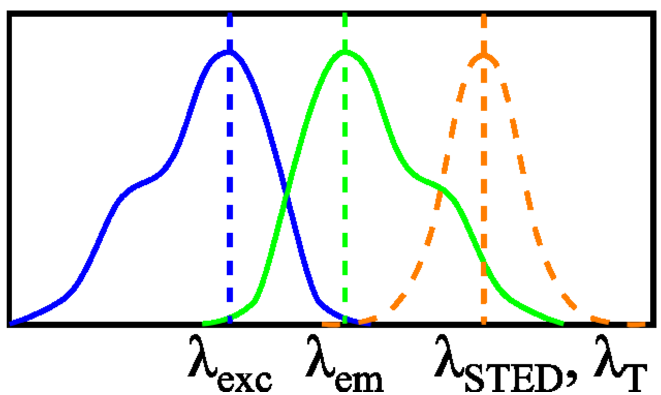
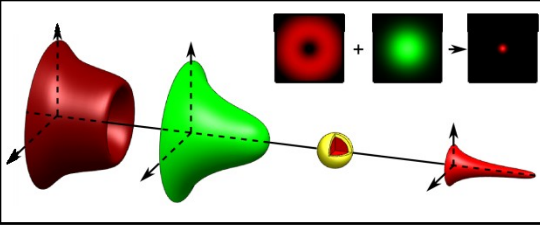






Sivan et al., *ACS Nano* **6**, 5291 (2012)



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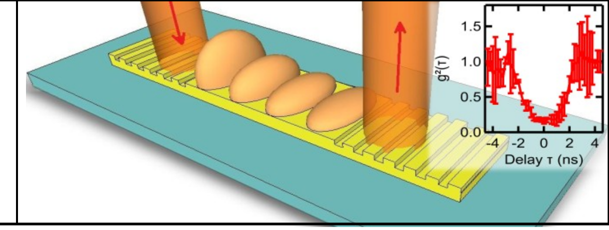
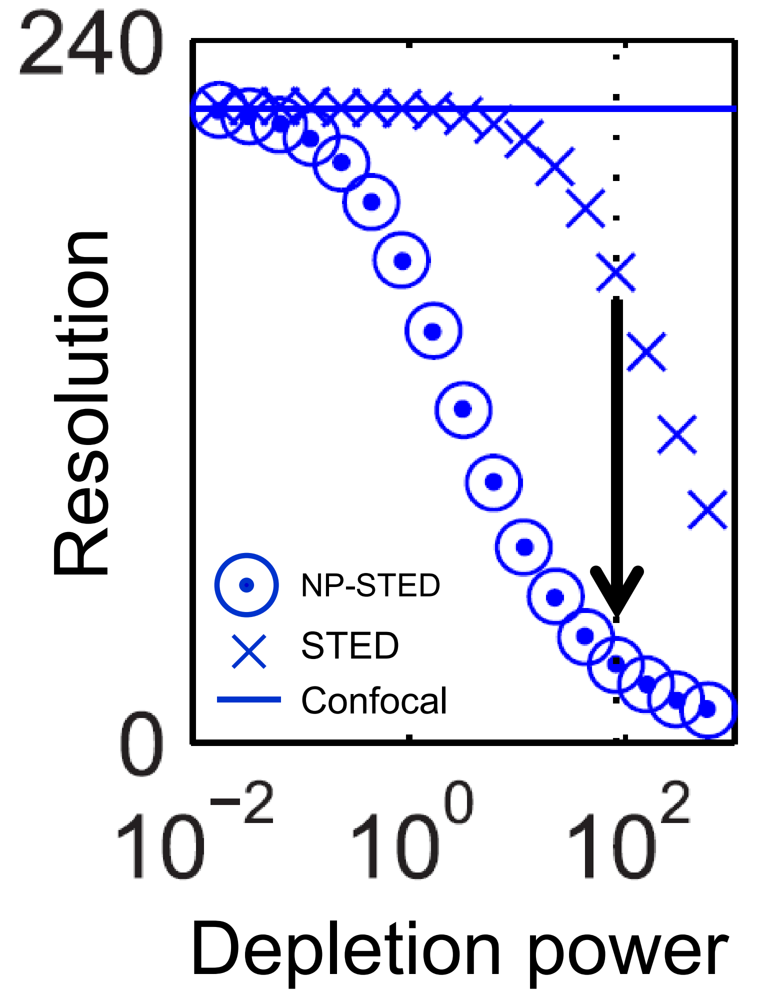
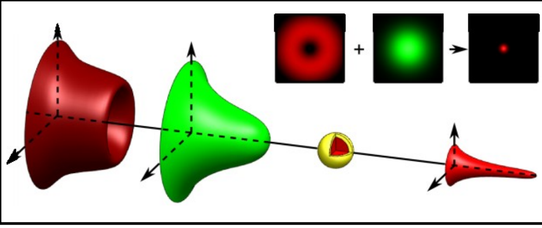


- At constant power, improvement of the resolution



Sivan et al., *ACS Nano* **6**, 5291 (2012)



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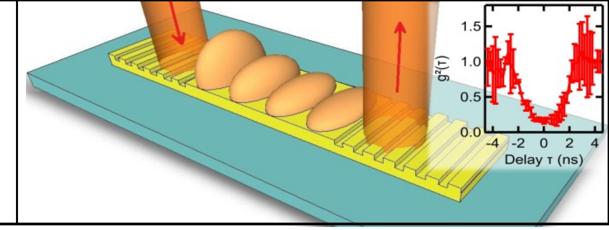
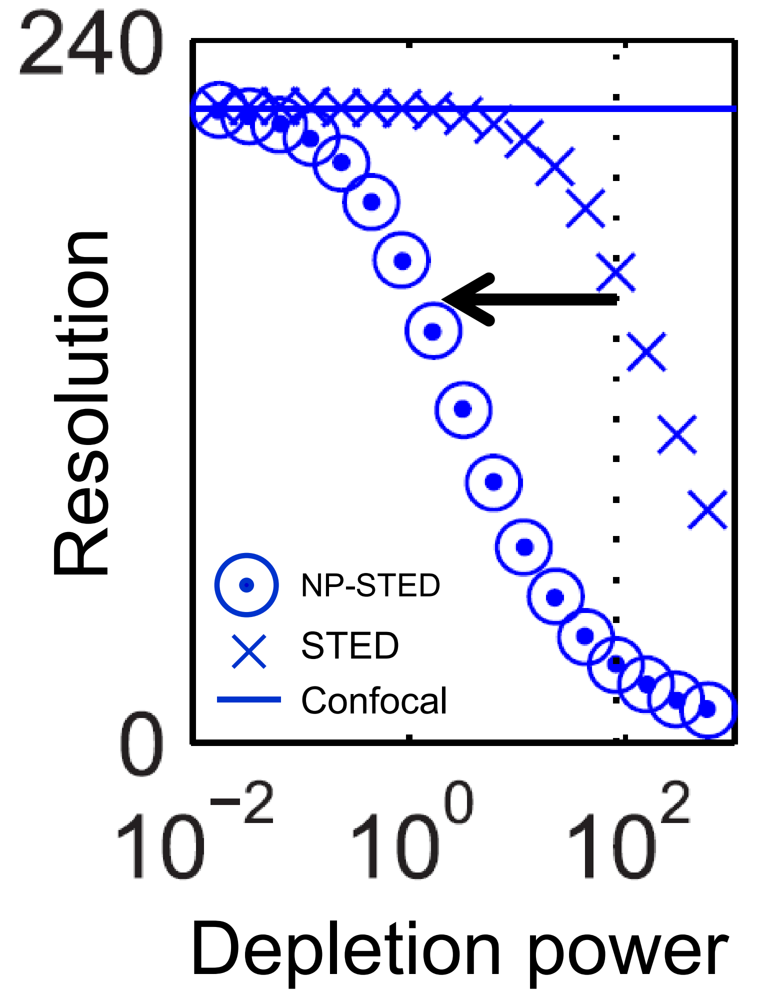


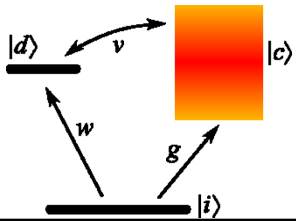
- At constant power, improvement of the resolution

- Reduction of the power needed to achieve a given resolution

➢ cheaper lasers, easier to implement



Sivan et al., *ACS Nano* **6**, 5291 (2012)



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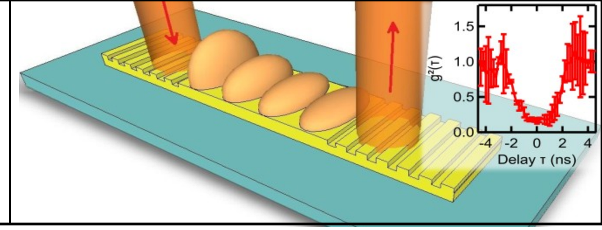

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Stefan A. Maier

Sonnefraud *et al.*, *Laser and Phot. Rev.* **6**, 277 (2012)

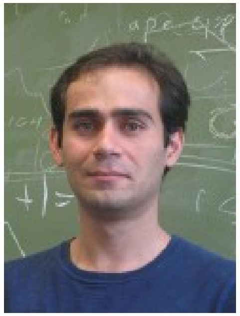
Hao *et al.*, *Nano Letters* **8**, 3983 (2008)

Hao *et al.*, *ACS Nano* **3**, 643 (2009)

Verellen *et al.*, *Nano Letters* **9**, 1663 (2009)

Sonnefraud *et al.*, *ACS Nano* **4**, 1664 (2010)

RICE

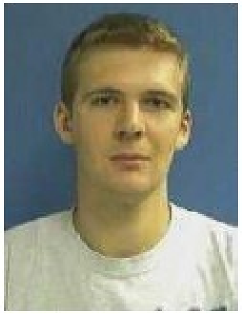


Heidar Sobhani

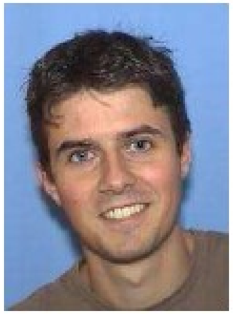
Peter Nordlander

& Feng Hao

imec

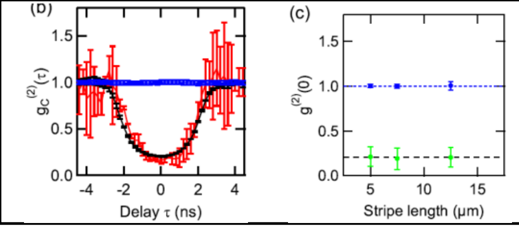


Niels Verellen



Pol van Dorpe

& Guy Vandenbosch,
Viktor V. Moshchalkov



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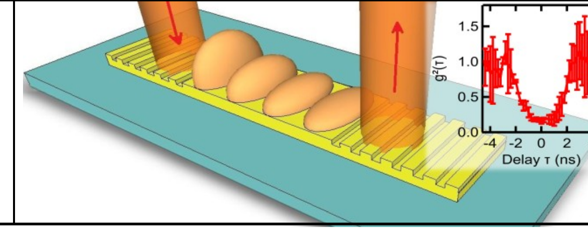
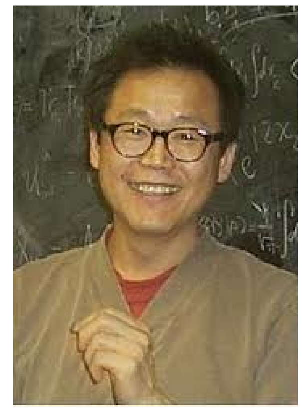


Giuliana Di Martino

Stéphane Kéna-Cohen

Mark Tame



Myungshik Kim

Stefan Maier

+ S. Ozdemir

Di Martino et al., *Nano Lett.* **12**, 2504 (2012)

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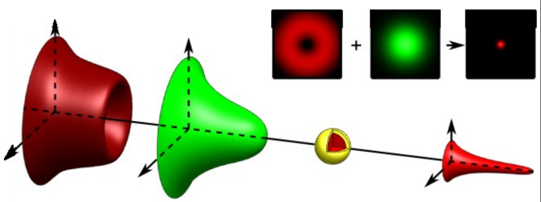

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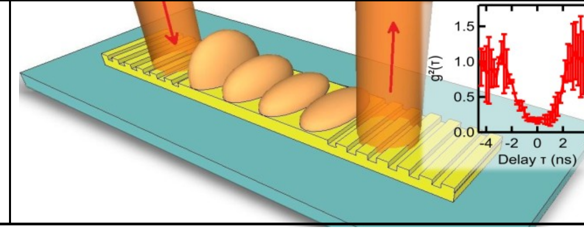

Yonatan Sivan

Stéphane Kéna-Cohen

John Pendry

Sivan et al., *ACS Nano* **6**, 5291 (2012)

Thanks!

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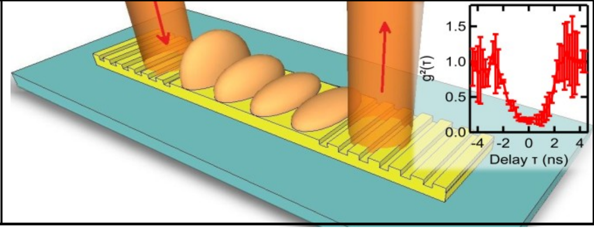
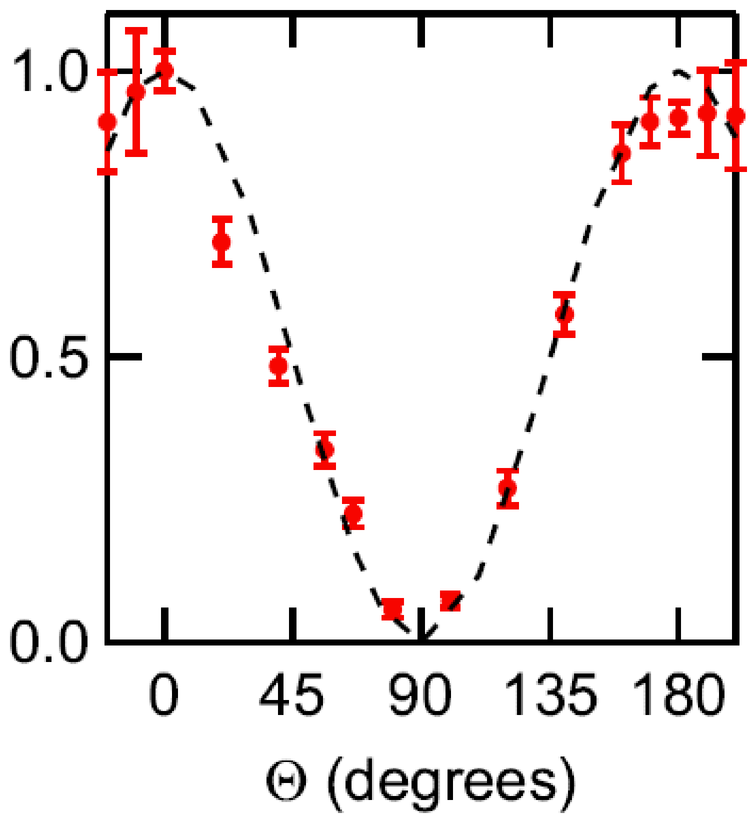
Polarisation dependence





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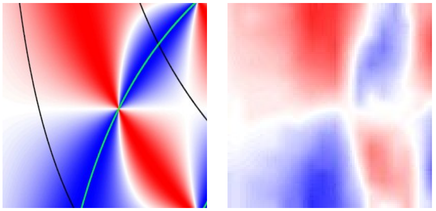
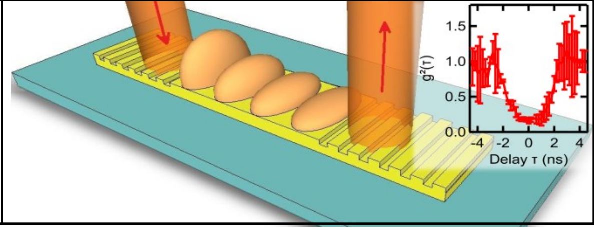
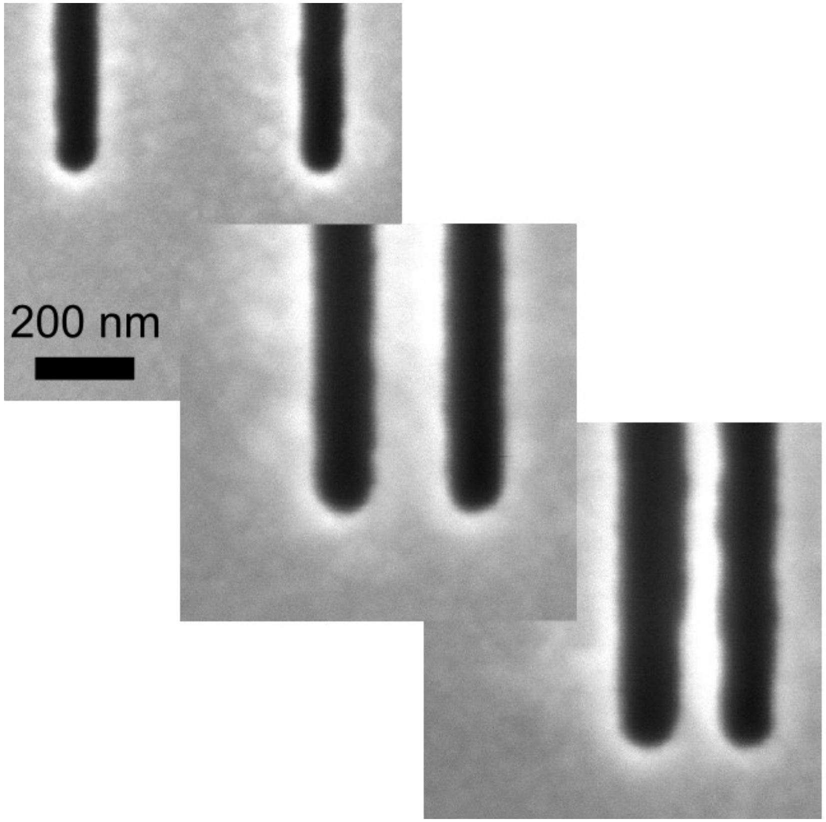
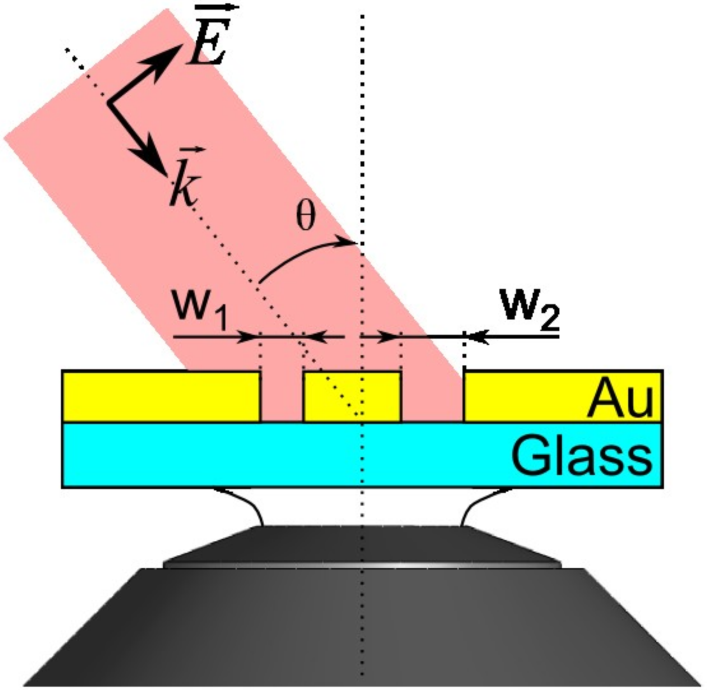


SPP launch – slits and directionality



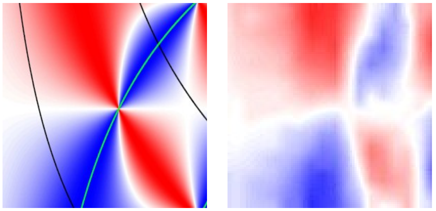




Use sub-wavelength **slits** in gold film to **excite SPP**

Observation in **leakage radiation microscopy**

Sonnefraud et al., Opt. Express **20**, 4893 (2012)



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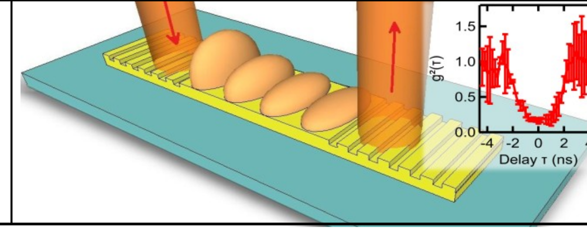
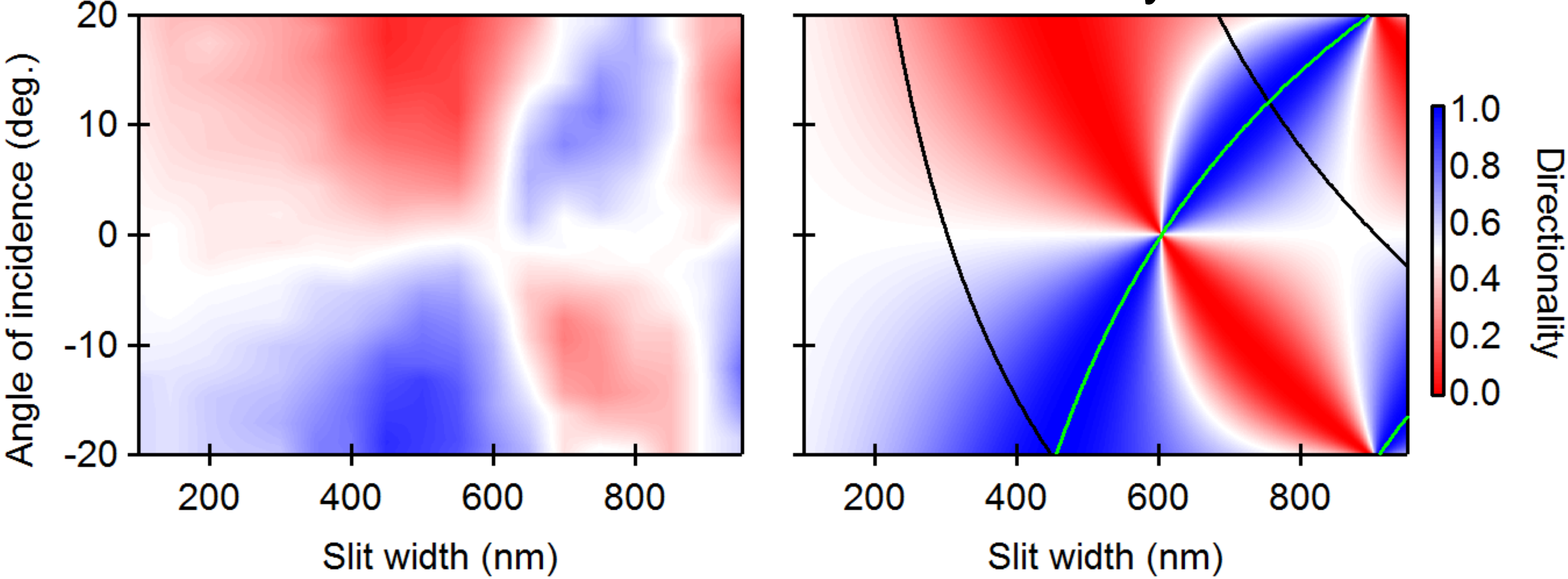


Experiment reproduced by a simple analytical model
Trade-off size coupler - directionality

Measurement | Theory



Sonnefraud et al., Opt. Express **20**, 4893 (2012)