Administrative issues

- Exams: online vs. offline, please read my message on Moodle and let me know!

- Material relevant for exam:
  - Lecture (until and including 04 Dec)
  - Your own presentation
  - Homework problems

On the menu today

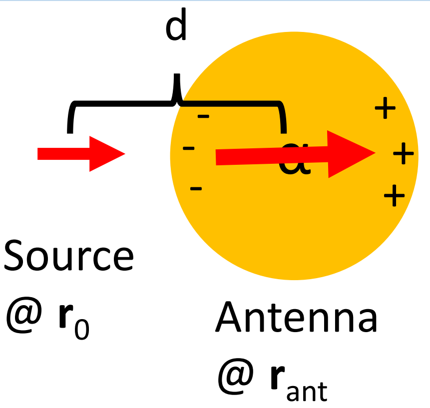
- A few more interesting aspects of optical antennas
- Photon statistics
- Optical forces

Optical antennas – a cleaner derivation

Calculate rate enhancement via power enhancement

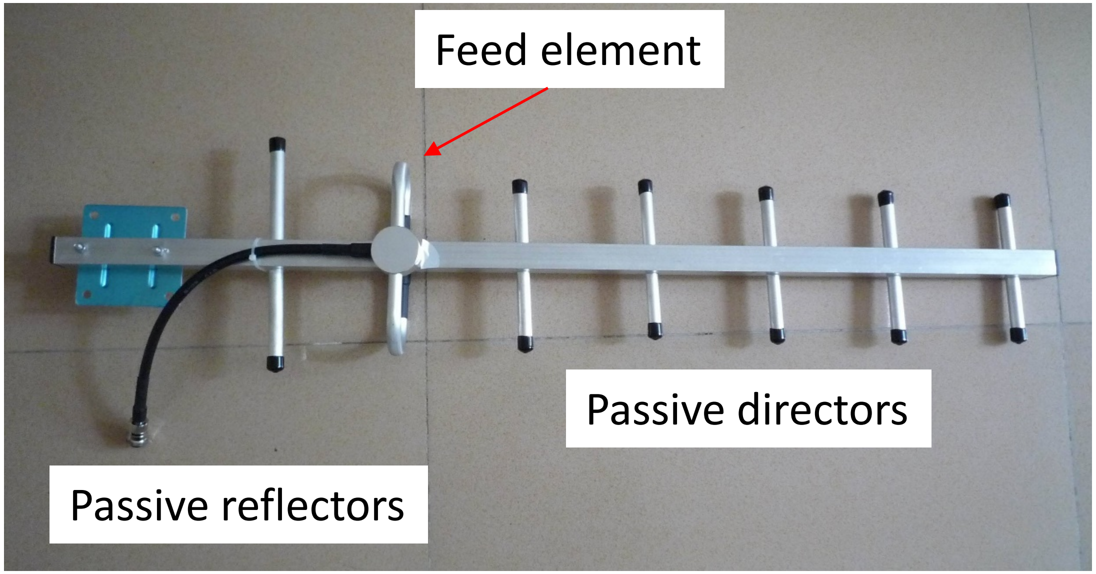
$$\langle P \rangle = \frac{\omega}{2} \mathrm{Im}\left[\boldsymbol{p}^* \cdot \boldsymbol{E}(\boldsymbol{r}_0)\right]$$

$$\underline{\overleftrightarrow{\boldsymbol{G}}} = \omega^2 \mu \mu_0 \overleftrightarrow{\boldsymbol{G}}$$



$$\frac{P}{P_0} = 1 + \frac{A}{d^6} \frac{\mathrm{Im}\,\alpha}{\mathrm{Im}\,\underline{G}_0}$$

From radio to optical antennas

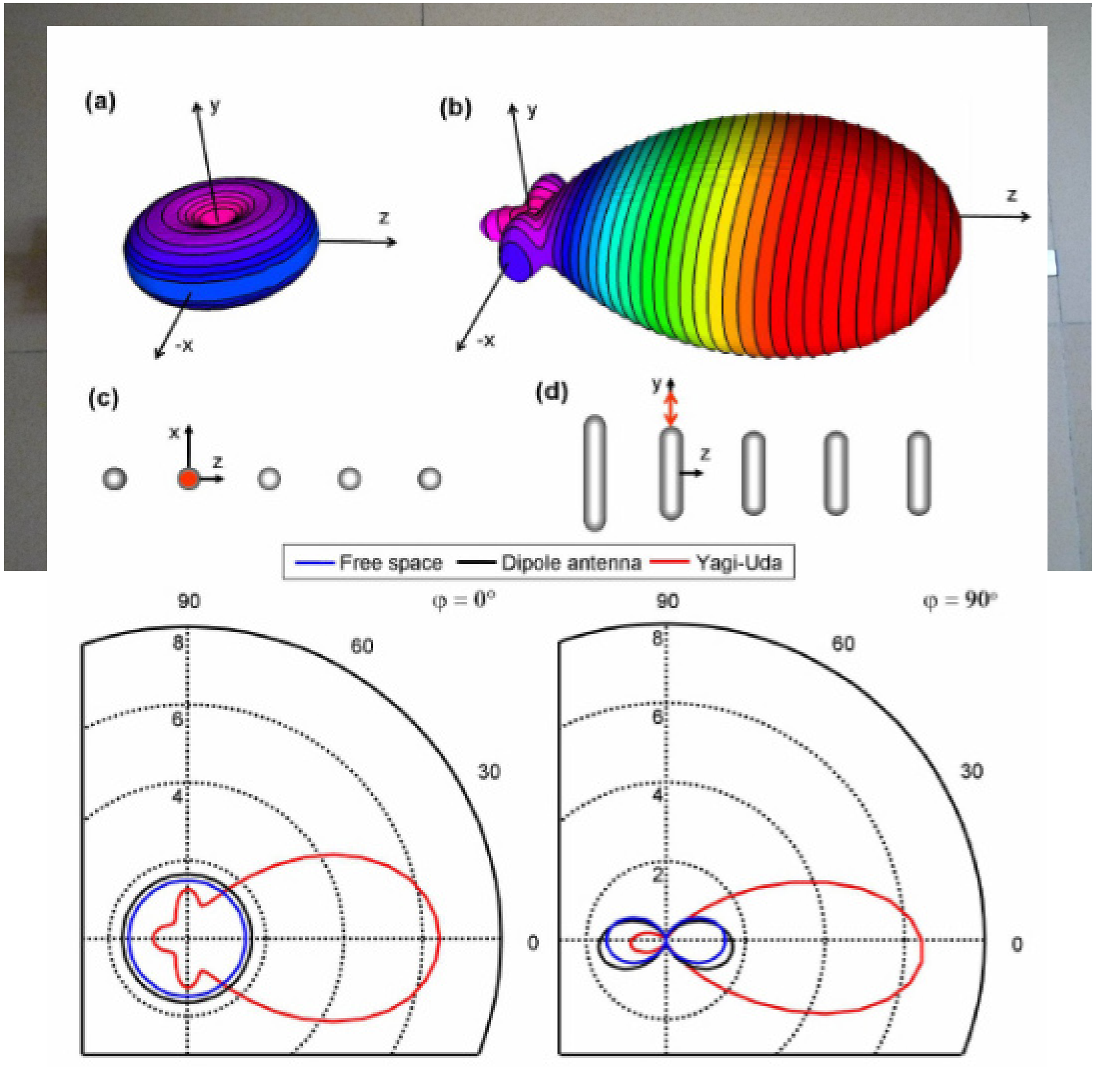


Yagi-Uda antenna (1926)

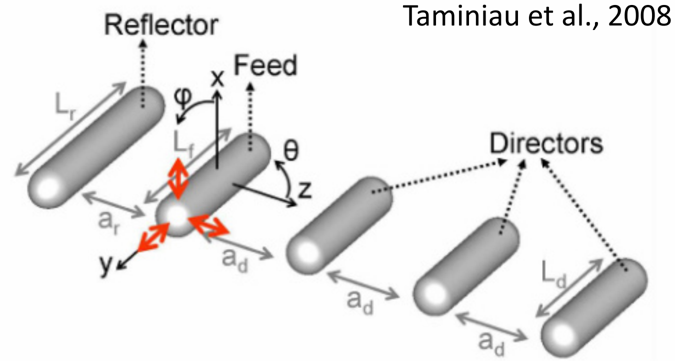
$$\mathbf{p}=\alpha\mathbf{E}$$

- Single active element
- Field of active element polarizes passive elements
- Passive elements generate fields and polarize each other (self-consistent solution)

Yagi-Uda antenna

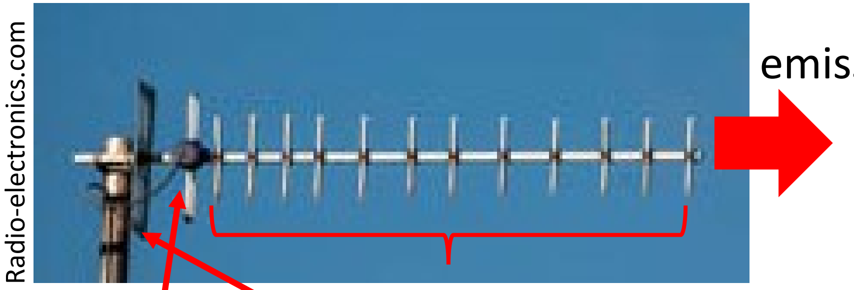


Taminiau et al., 2008

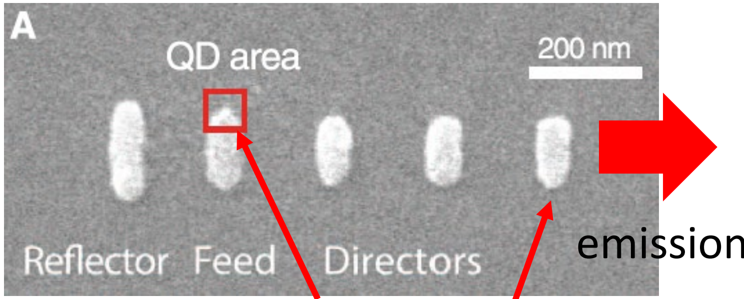


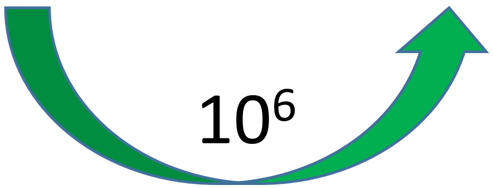
Optical antennas for directional photon emission

Yagi and Uda (1920s)



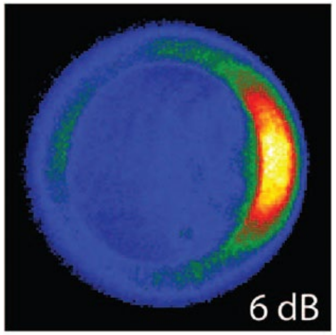
Curto et al., Science 329, 930 (2010)

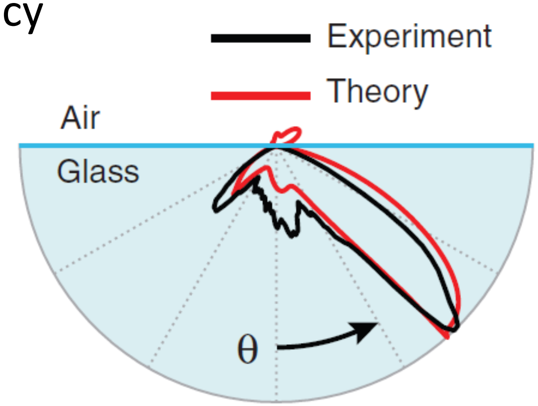




Scale down size, scale up frequency

- Optical antennas allow control of directionality of light emission for quantum emitters
- Antenna is photonic environment that offers a large density of states with specific k-vector

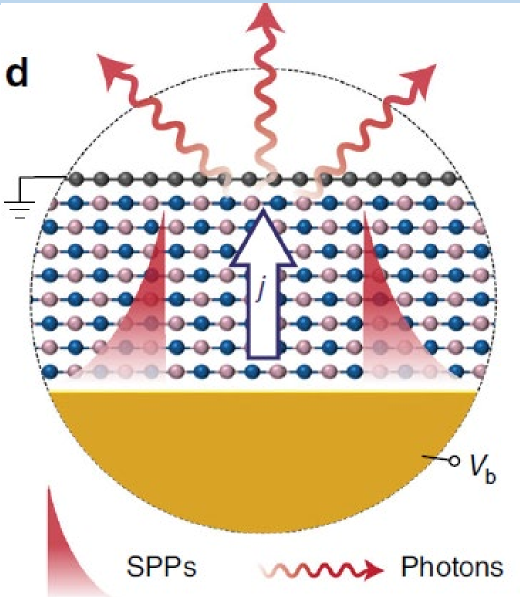


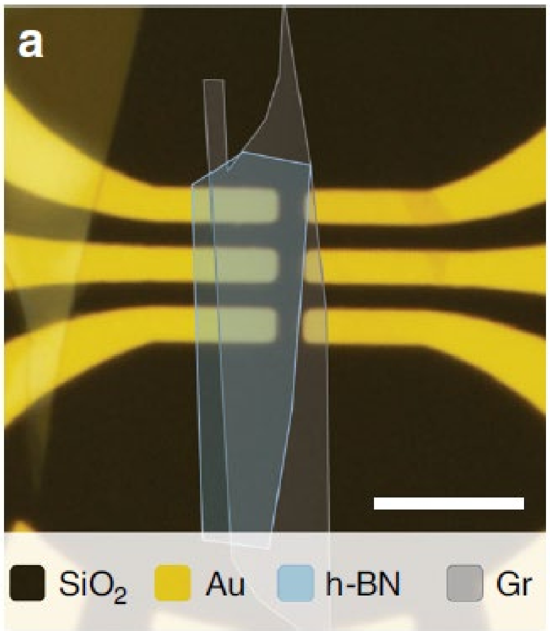


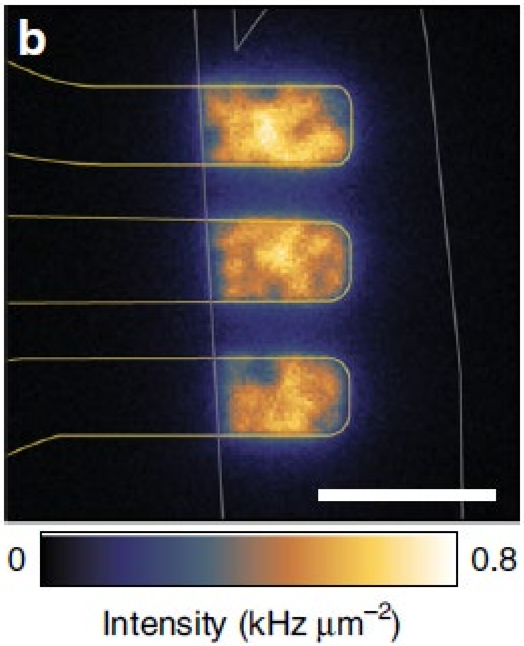
Electron tunneling as a light source

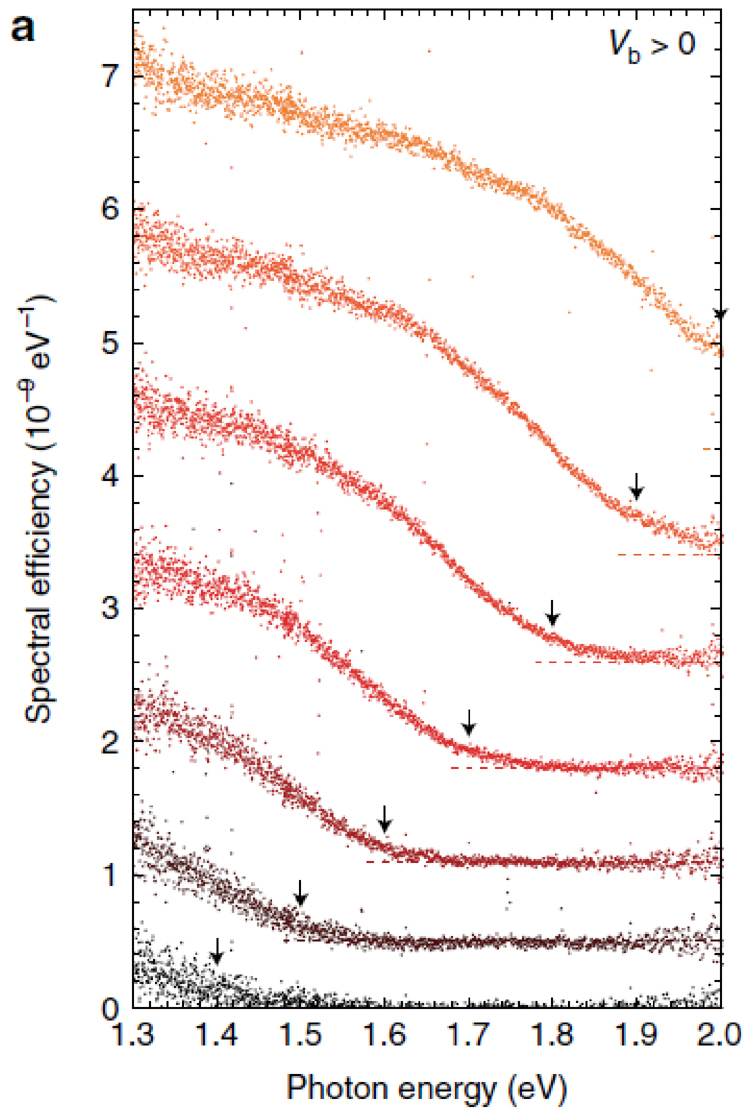
Electron tunneling as a light source

Parzefall et al., https://doi.org/10.1038/s41467-018-08266-8









Electrically driven optical antennas

Parzefall et al., https://doi.org/10.1038/s41467-018-08266-8

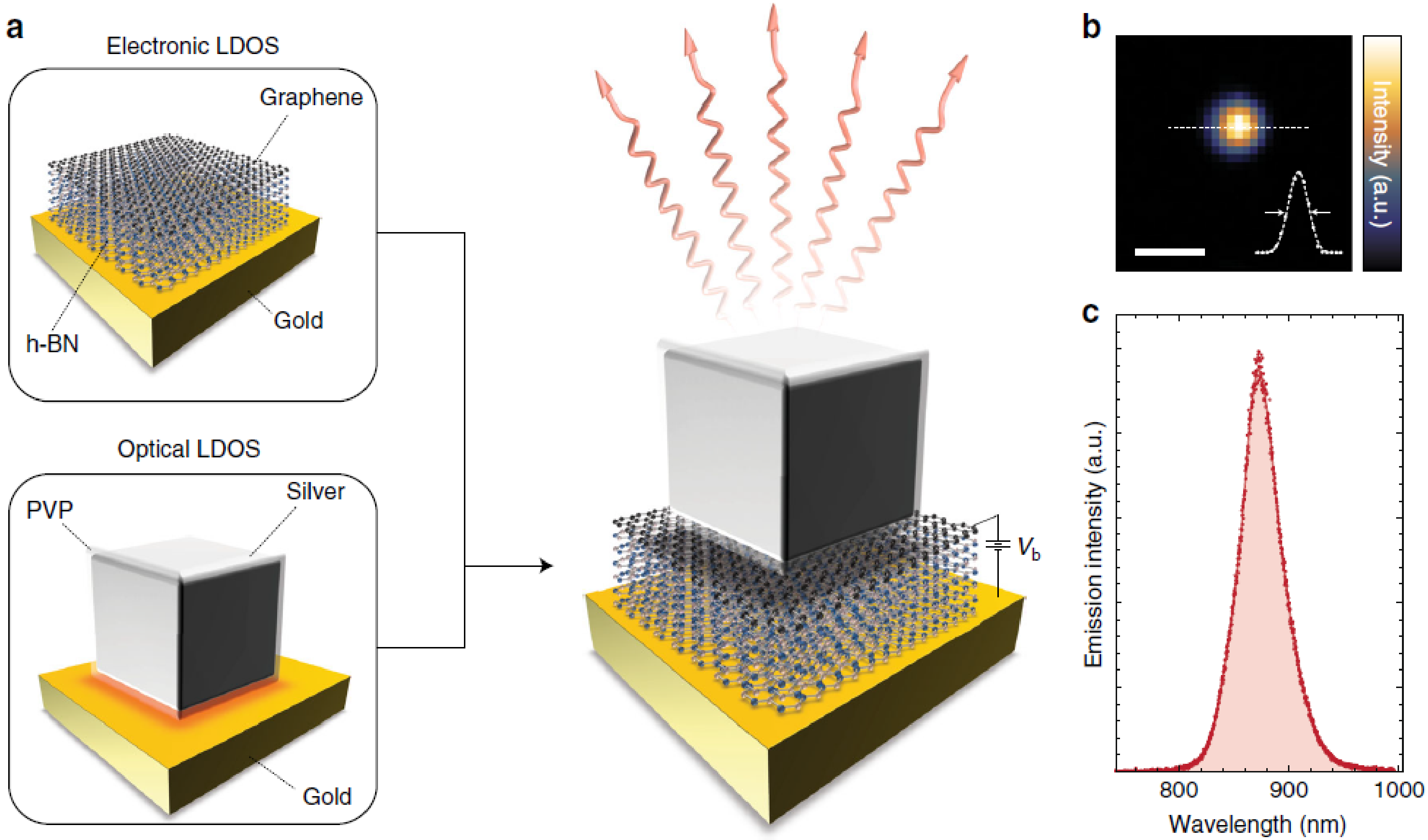


Fig. 1 Visualization of the vdWQT device concept. **a** Illustration (not to scale) of a gold-few-layer h-BN-graphene vdWQT device, integrated with a (silver, PVP-coated) nanocube antenna. In this device configuration, the electronic LDOS is controlled by the hybrid vdW heterostructure whereas the optical LDOS is governed by the nanocube antenna. Applying a voltage V_b across the insulating few-layer h-BN crystal results in antenna-mediated photon emission (wavy arrows) due to quantum tunneling. **b**, **c** Measured spatial (**b**) and spectral (**c**) photon distribution from a nanocube antenna coupled to a vdWQT device, demonstrating a diffraction-limited spot and a narrow emission spectrum. The inset in **b** shows a line-cut, featuring a line-width (FWHM) of ~460 nm, close to the expected value of $\lambda/(2NA)$ ~ 480 nm. Scale bar: 1 µm

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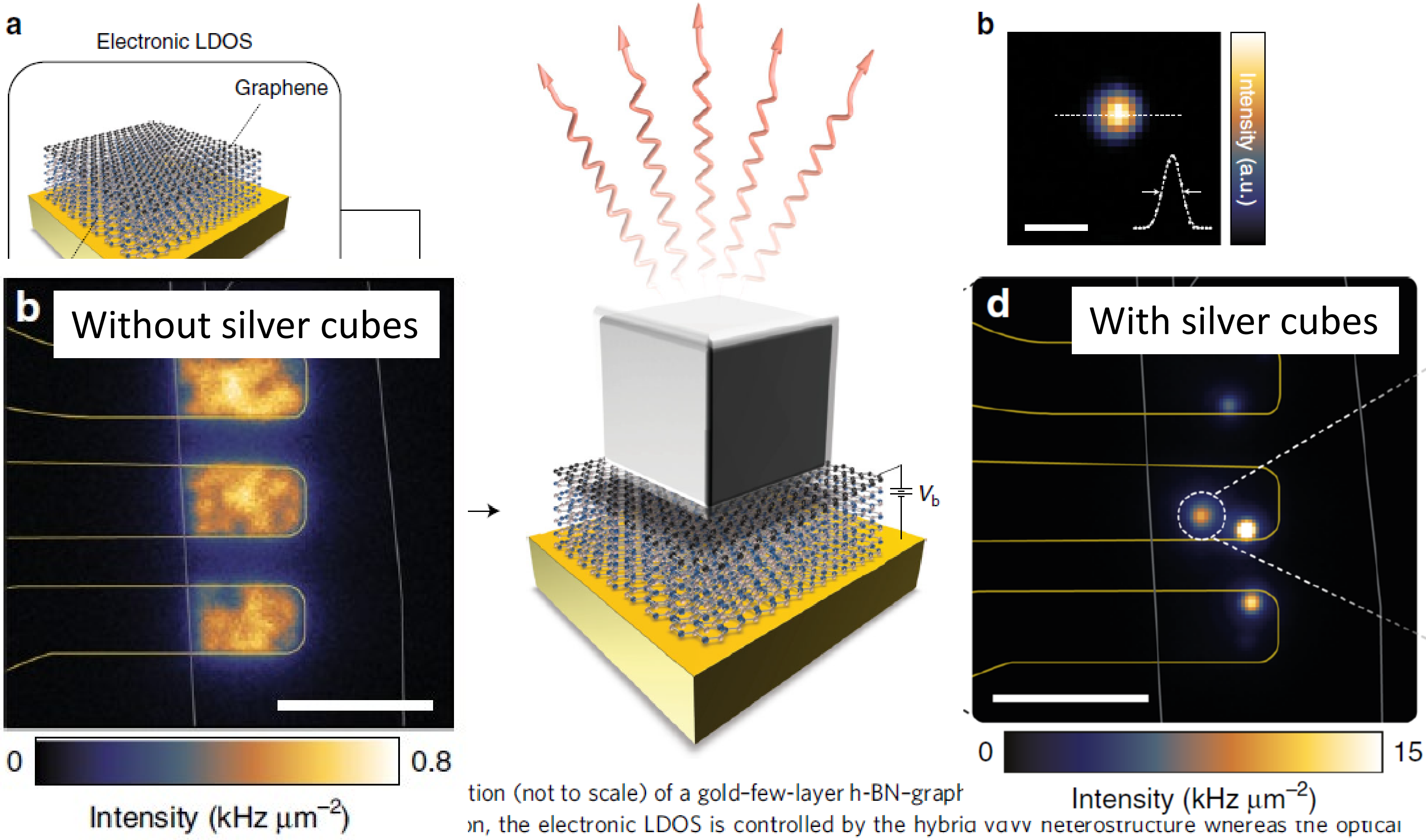


Fig. 1 Visua … tion (not to scale) of a gold-few-layer h-BN-grapl … PVP-coatec … on, the electronic LDOS is controlled by the hybrid vdW heterostructure whereas the optical LDOS is governed by the nanocube antenna. Applying a voltage V_b across the insulating few-layer h-BN crystal results in antenna-mediated photon emission (wavy arrows) due to quantum tunneling. **b**, **c** Measured spatial (**b**) and spectral (**c**) photon distribution from a nanocube antenna coupled to a vdWQT device, demonstrating a diffraction-limited spot and a narrow emission spectrum. The inset in **b** shows a line-cut, featuring a line-width (FWHM) of ~460 nm, close to the expected value of $\lambda/(2NA)$ ~ 480 nm. Scale bar: 1 μm

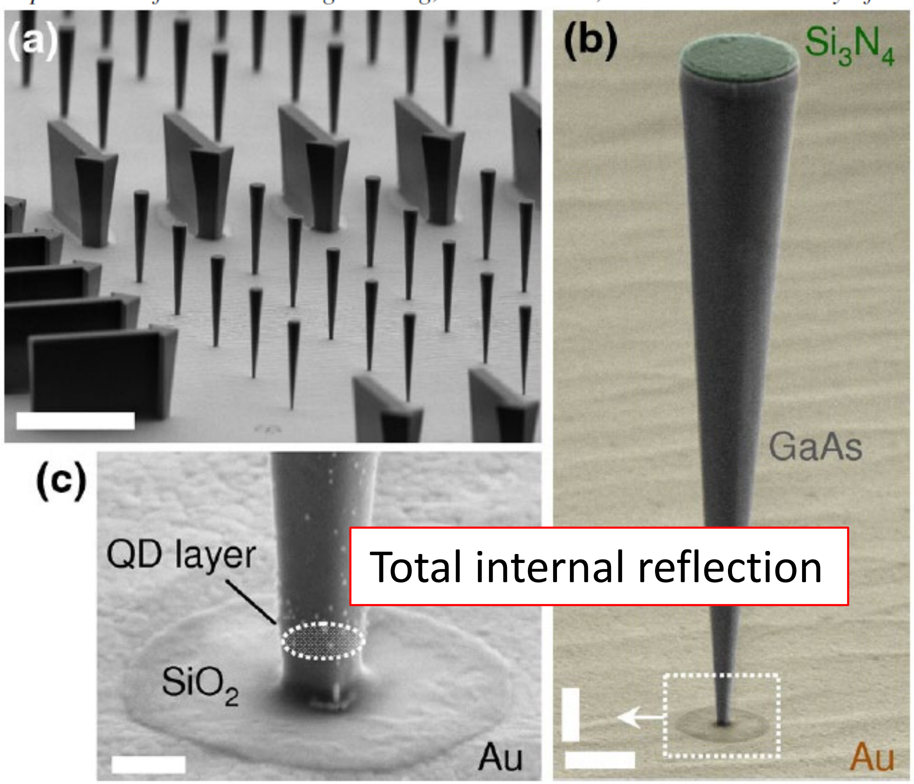
Antennas – resonators with engineered radiation loss

PRL **110,** 177402 (2013) PHYSICAL REVIEW LETTERS week ending 26 APRIL 2013

Dielectric GaAs Antenna Ensuring an Efficient Broadband Coupling between an InAs Quantum Dot and a Gaussian Optical Beam

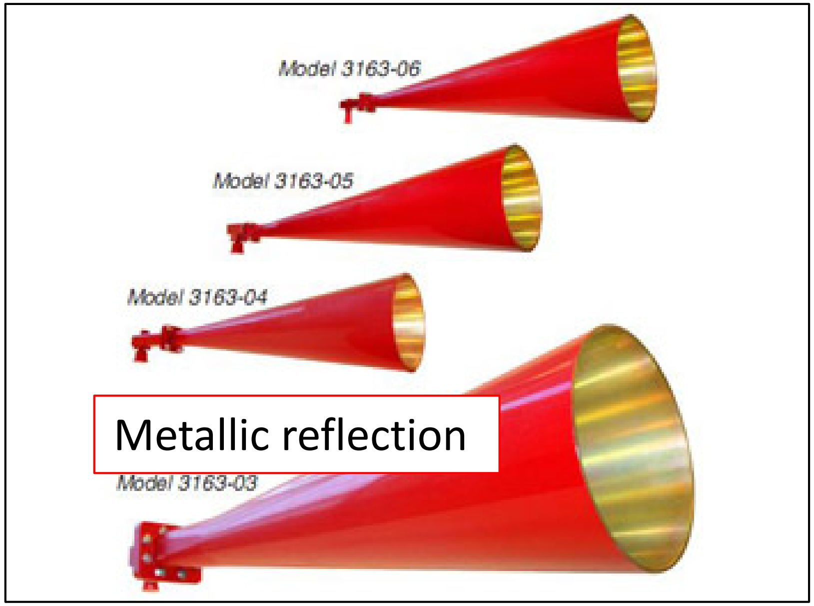
Mathieu Munsch, Nitin S. Malik, Emmanuel Dupuy, Adrien Delga, Joël Bleuse, Jean-Michel Gérard, and Julien Claudon*
CEA-CNRS-UJF Group, Nanophysique et Semiconducteurs, CEA, INAC, SP2M, F-38054 Grenoble, France

Niels Gregersen and Jesper Mørk
Department of Photonics Engineering, DTU Fotonik, Technical University of Denmark, Building 343, 2800 Kongens Lyngby, Denmark



Total internal reflection

In the µwave-regime:

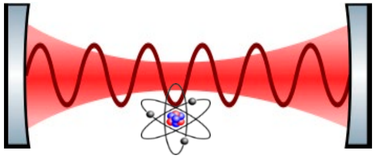


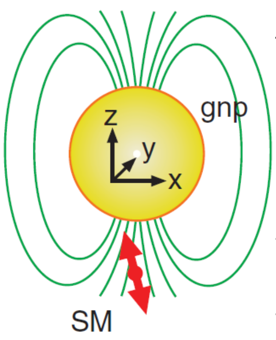
Metallic reflection

From resonators to antennas

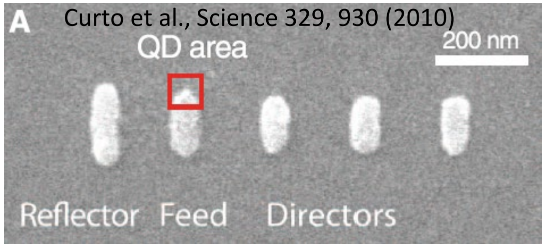
Near-field antennas
- Sub-λ-sized resonators
- Naturally high radiation loss
- Problematic Ohmic losses

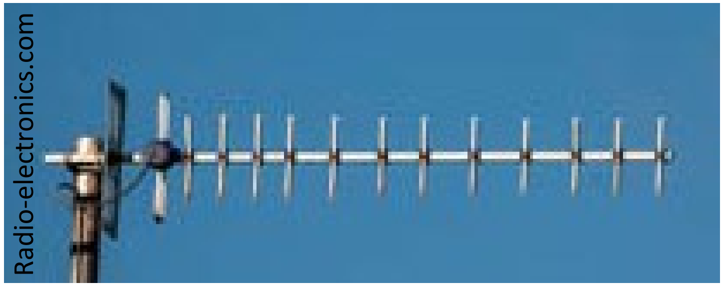
Cavity-based "antennas":
- λ-sized resonators
- Deliberately introduced radiation loss



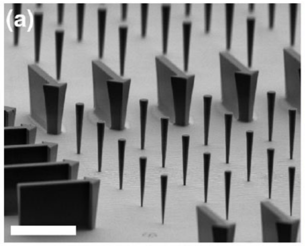


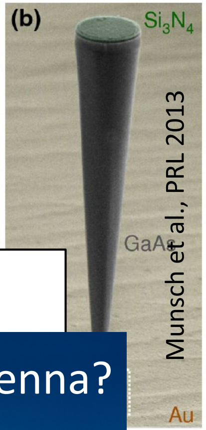
Kühn et al., PRL 97, 017402 (2006)



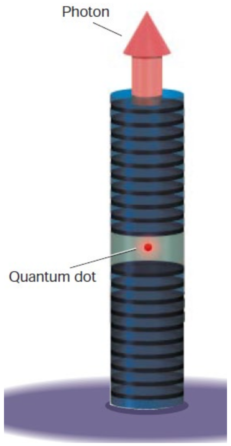


Radio-electronics.com

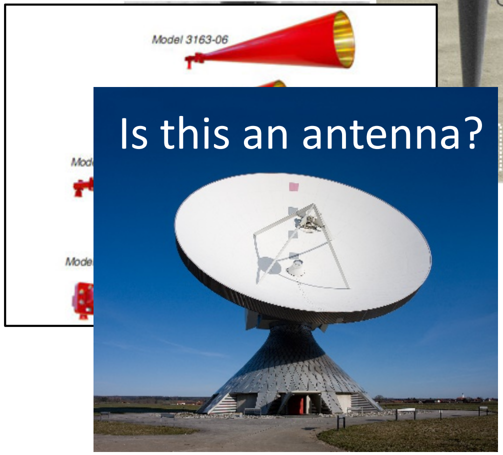




Munsch et al., PRL 2013



Vahala, Nature 424, 839



From resonators to antennas

Near-field antennas

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Cavity-based "antennas":

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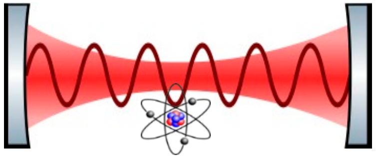
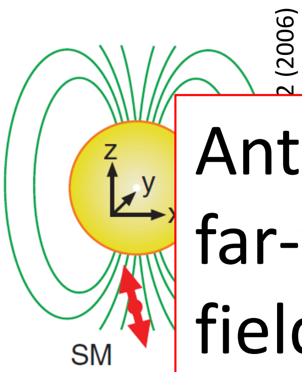
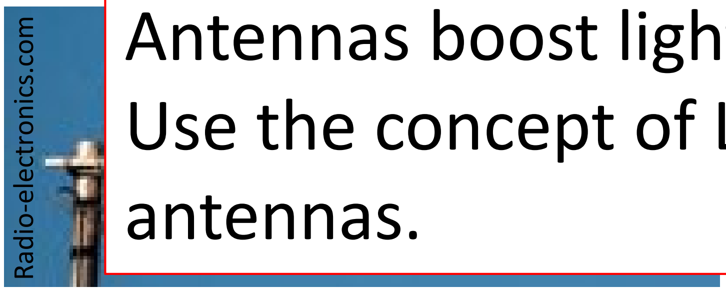
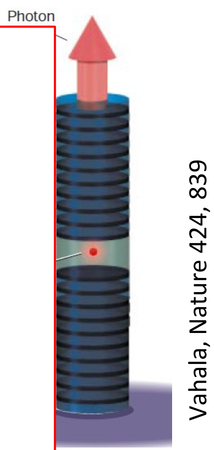




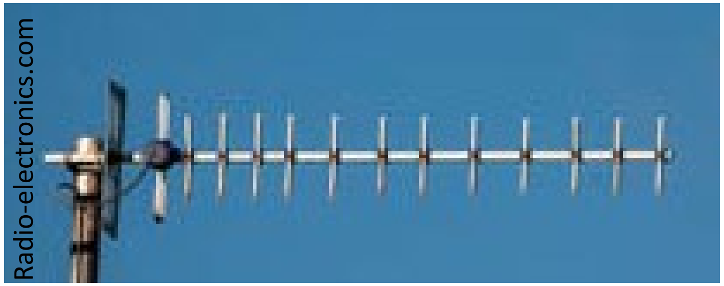


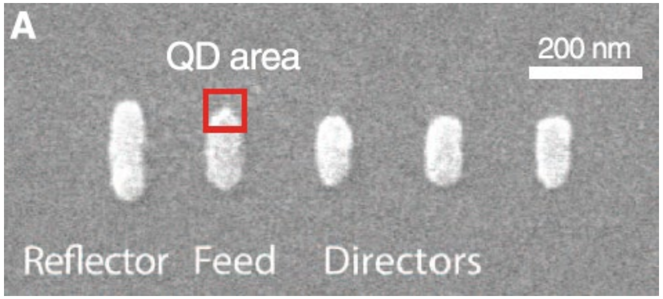


Antennas are devices which mediate between far-field (=propagating) radiation and localized fields.
Antennas boost light-matter interaction.
Use the concept of LDOS to discuss optical antennas.

Antennas – radio vs. optical

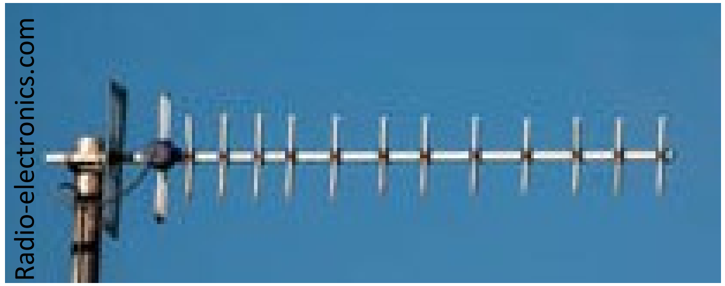
Curto et al., Science 329, 930 (2010)

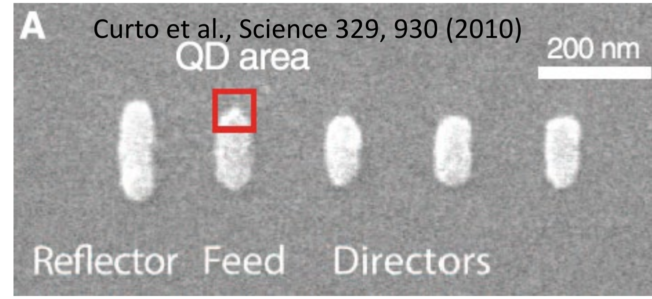




	Radio-antennas	Optical antennas
Antenna theory:	Maxwell	Maxwell
Resonance mechanisms:		
Sources:		

Antennas – radio vs. optical





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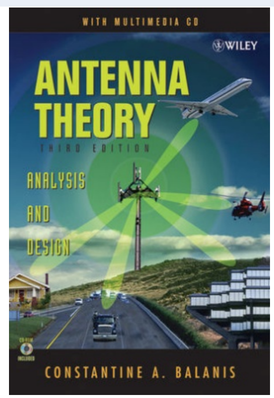
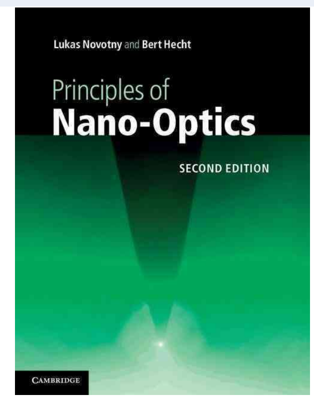
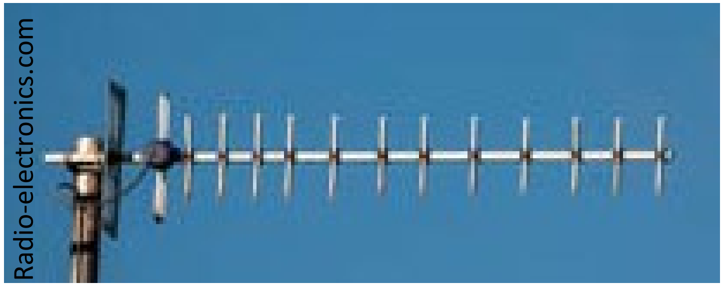
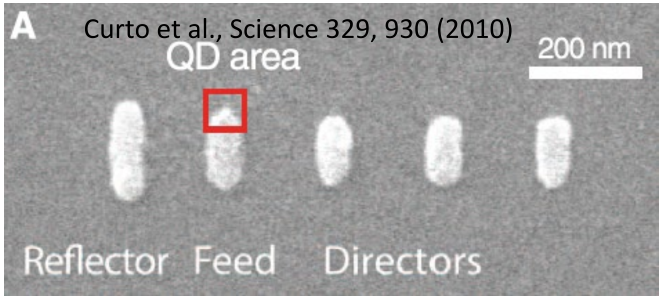




Antennas – radio vs. optical

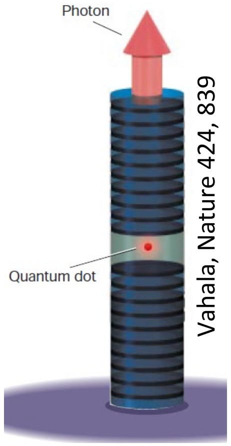




	Radio-antennas	Optical antennas
Antenna theory:	Maxwell	Maxwell
Resonance mechanisms:	Geometric resonances	Geometric resonances Material resonances
Sources:	Classical current source	Quantum emitter

- Nano-optics with optical antennas relies on classical antenna theory due to the scale invariance of Maxwell's equations.
- Difference 1: Frequency dependence of the material constants.
  At radio frequencies we have practically perfect metals.
  At optical frequencies metals are imperfect and show material resonances.
- Difference 2: Emitters in the optical regime show quantum behavior.

Summary – light matter interaction



Vahala, Nature 424, 839

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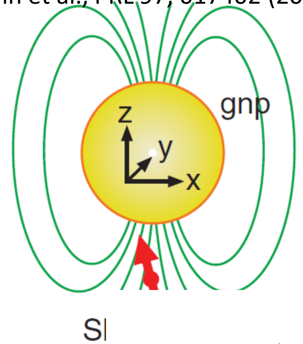

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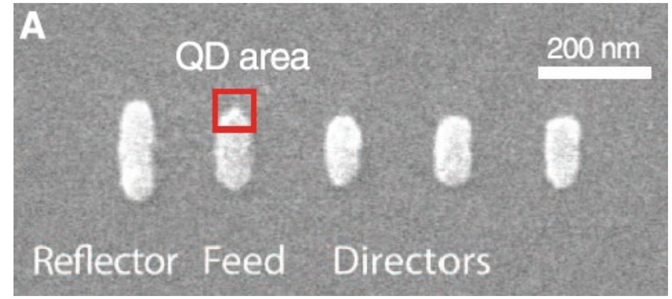
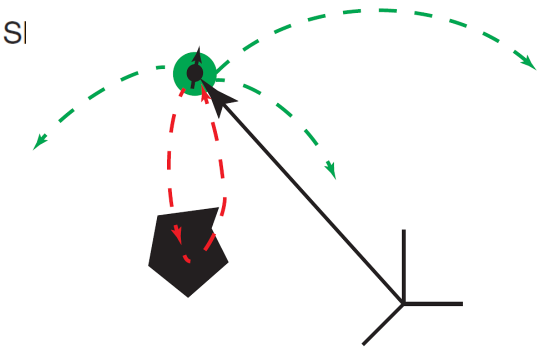


Quantum emitters are probes for their electromagnetic environment.

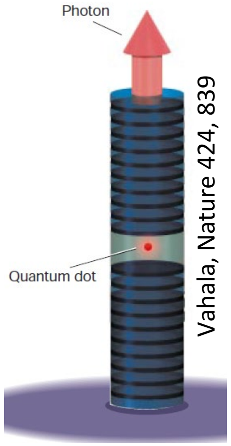


Quantum emission can be tailored via the emitter's electromagnetic environment.

Radiation carries information about

- The emitter
- The emitter's environment
- The emitter-environment interaction

Summary – light matter interaction



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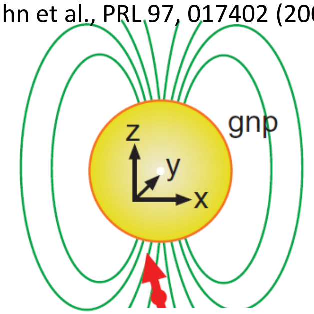

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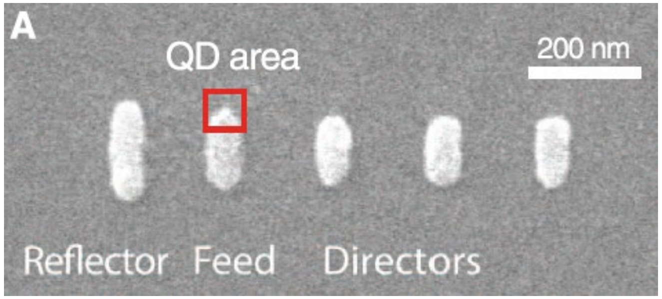

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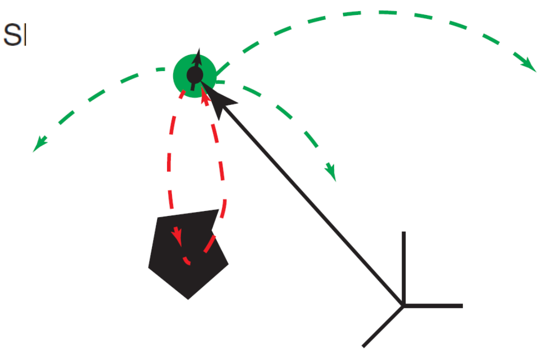
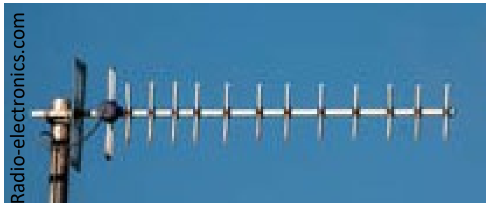
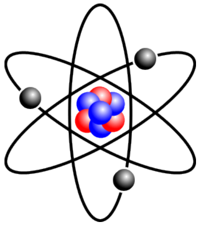


Quantum emission can be tailored via the emitter's electromagnetic environment.





kT

Ry

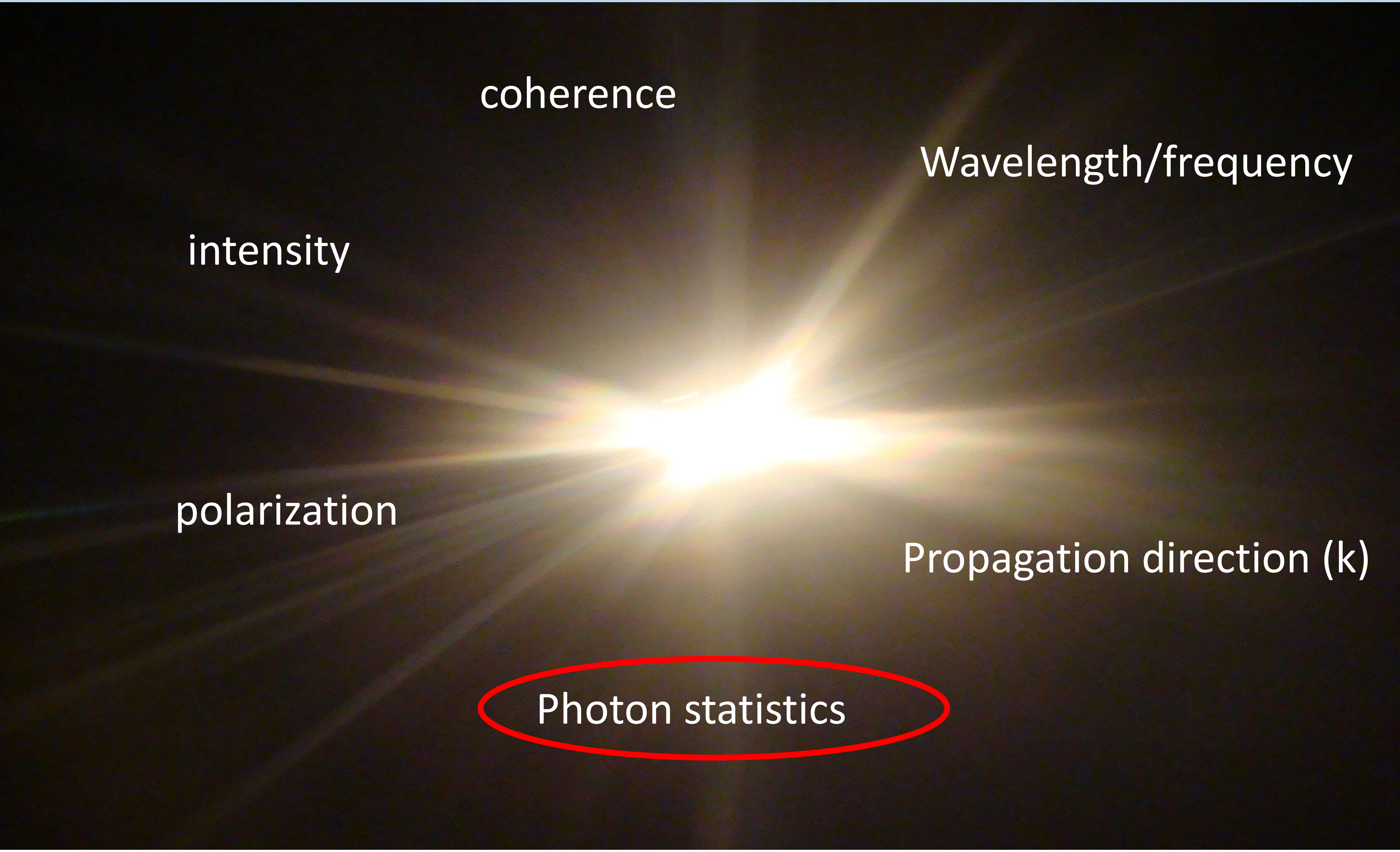
100 meV

1 eV

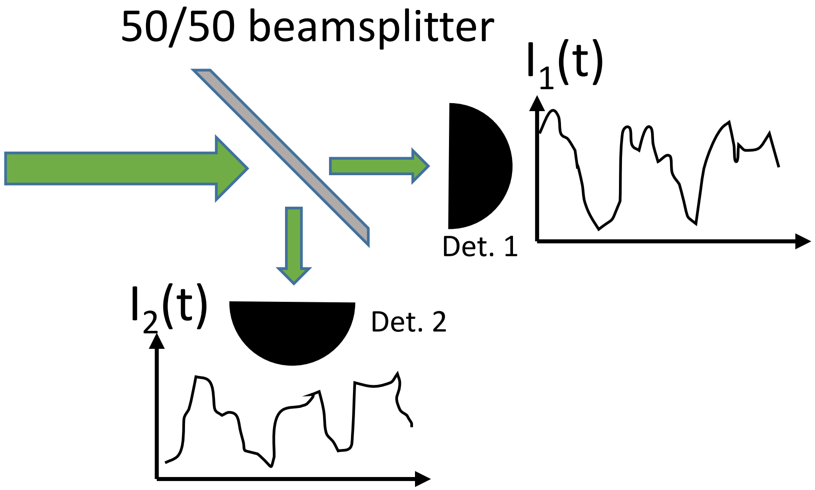
10 eV

Properties of “light”

Properties of “light”

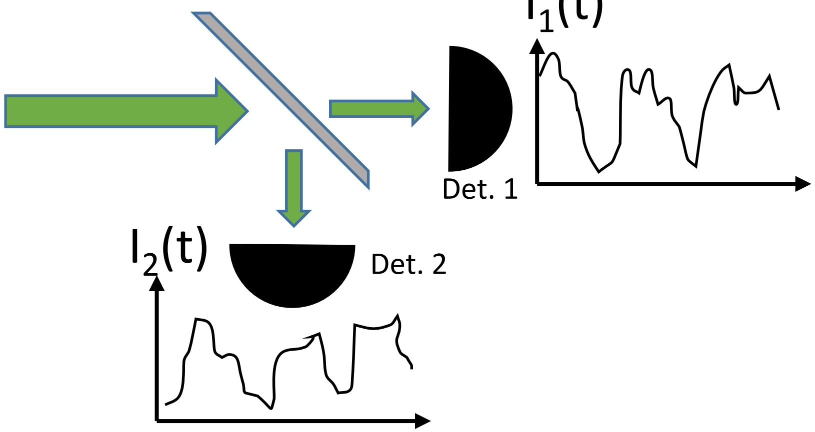


The Hanbury Brown-Twiss experiment



- Beam of light impinging on a 50/50 beamsplitter (BS)
- Record intensity I(t) in each arm after BS
- Calculate normalized cross correlation between signals I_1 and I_2

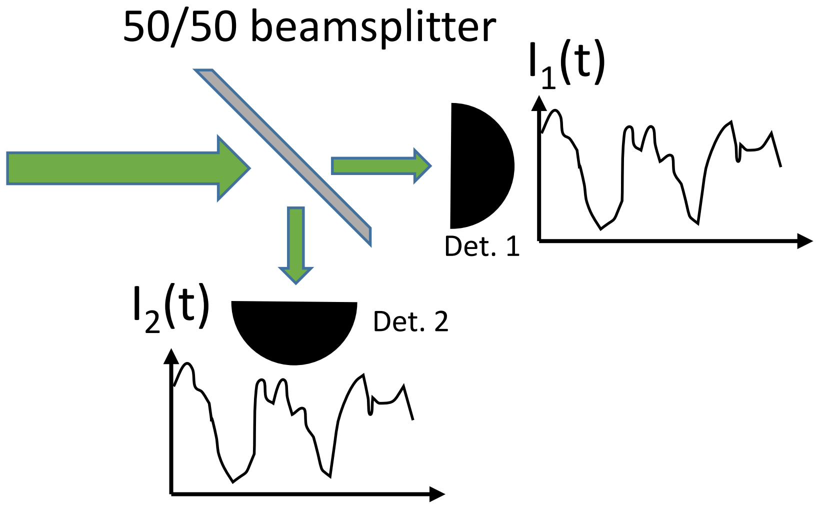
The second-order correlation function



$$g^{(2)}(\tau) = \frac{\langle I_1(t) I_2(t+\tau) \rangle}{\langle I_1(t) \rangle \langle I_2(t) \rangle}$$

- Beam of light impinging on a 50/50 beamsplitter (BS)
- Record intensity I(t) in each arm after BS
- Calculate normalized cross correlation between signals I_1 and I_2

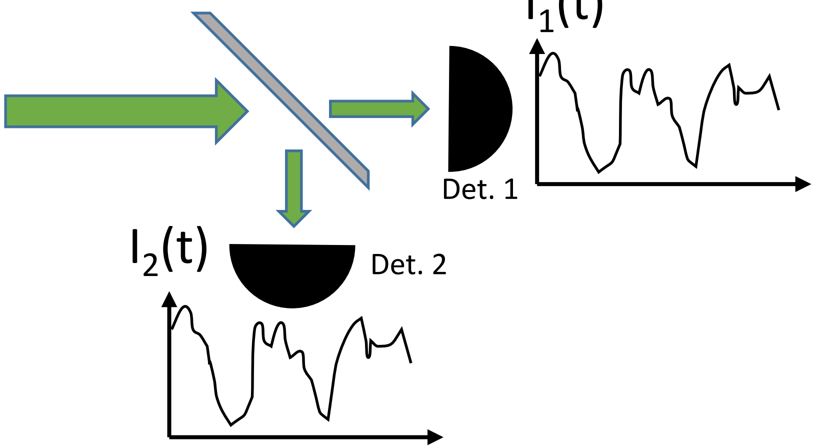
The classical case



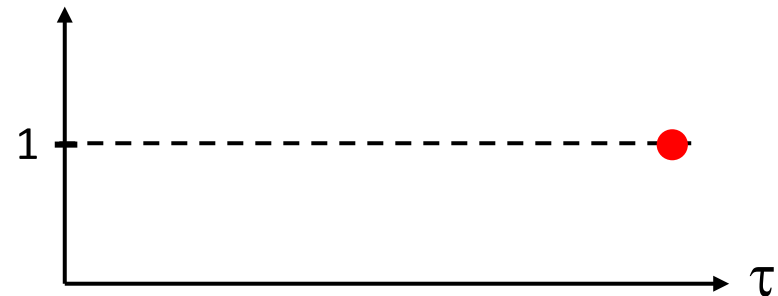
$$g^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle^2}$$

- Beam of light impinging on a 50/50 beamsplitter (BS)
- Record intensity I(t) in each arm after BS
- For a classical field $I_1(t) = I_2(t)$, so $g^{(2)}$ is intensity autocorrelation

Intensity autocorrelation - the classical case



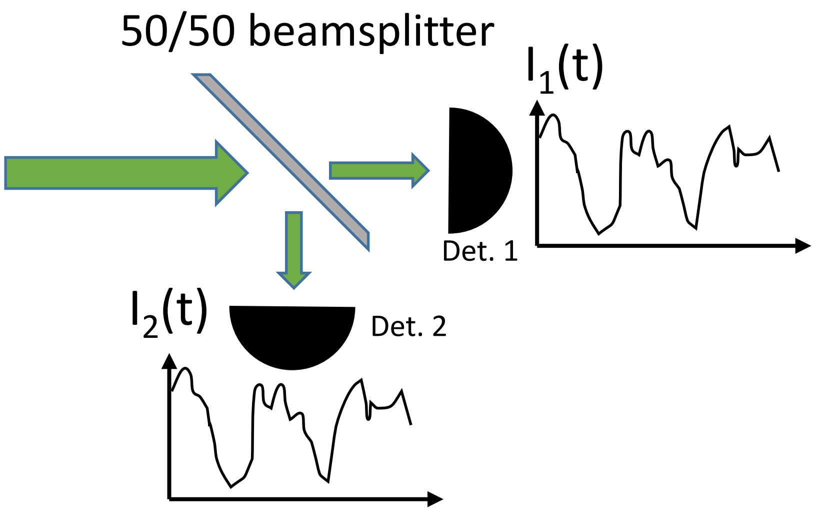
$$g^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle^2}$$



- Beam of light impinging on a 50/50 beamsplitter (BS)
- Record intensity I(t) in each arm after BS
- For a classical field $I_1(t) = I_2(t)$, so $g^{(2)}$ is intensity autocorrelation

[redacted]

Intensity autocorrelation - the classical case



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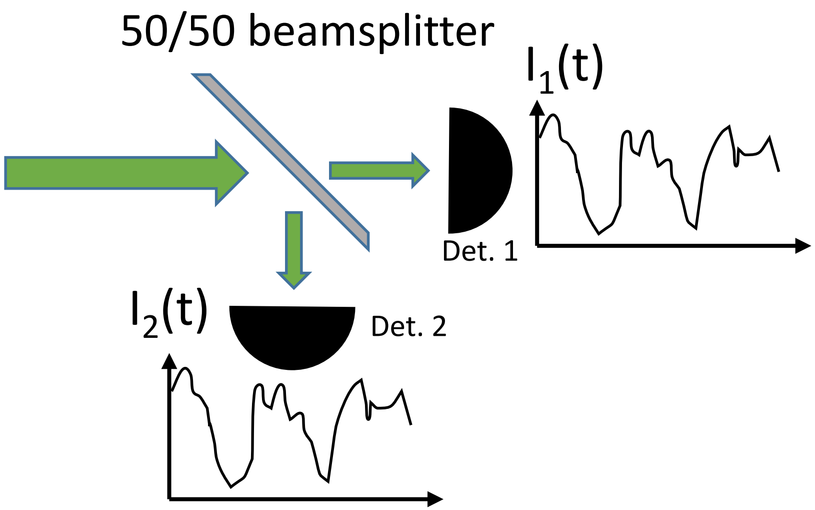
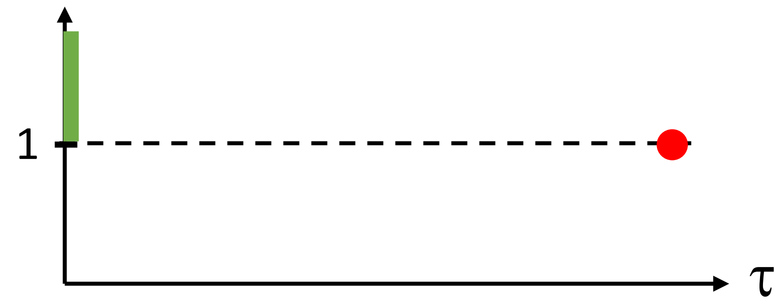
- Beam of light impinging on a 50/50 beamsplitter (BS)
- Record intensity I(t) in each arm after BS
- For a classical field $I_1(t) = I_2(t)$, so $g^{(2)}$ is intensity autocorrelation
- For long delay times $g^{(2)}(\tau \to \infty) = 1$

Intensity autocorrelation - the classical case

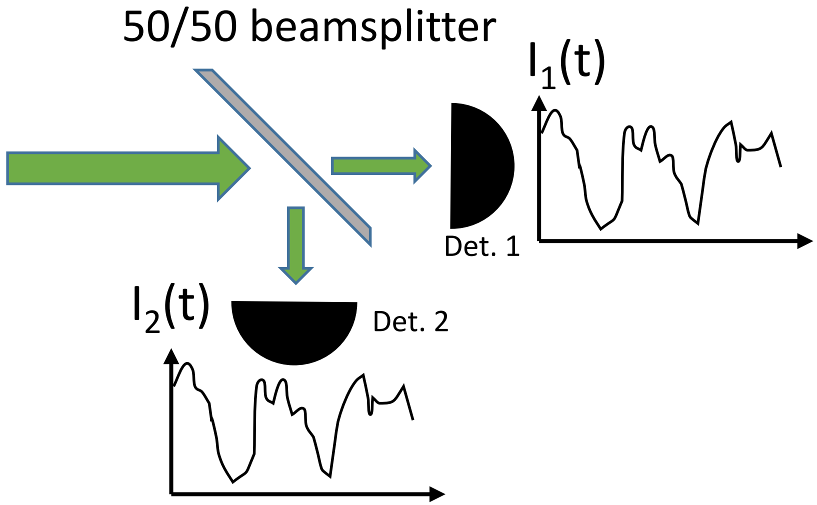


$$g^{(2)}(\tau) = \frac{\langle I(t) I(t+\tau) \rangle}{\langle I(t) \rangle^2}$$



- Beam of light impinging on a 50/50 beamsplitter (BS)
- Record intensity I(t) in each arm after BS
- For a classical field $I_1(t) = I_2(t)$, so $g^{(2)}$ is intensity autocorrelation
- For long delay times $g^{(2)}(\tau \to \infty) = 1$
- correlation at zero delay $g^{(2)}(\tau = 0) \geq 1$

Intensity autocorrelation - the classical case



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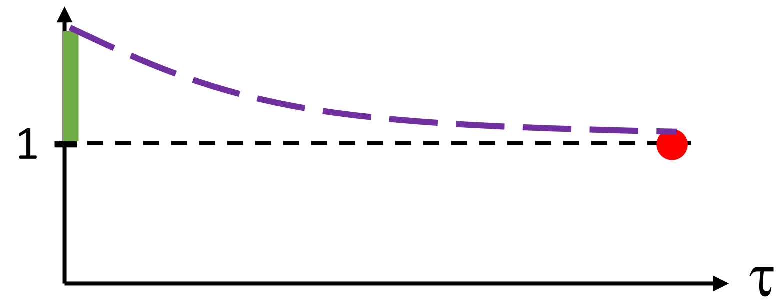

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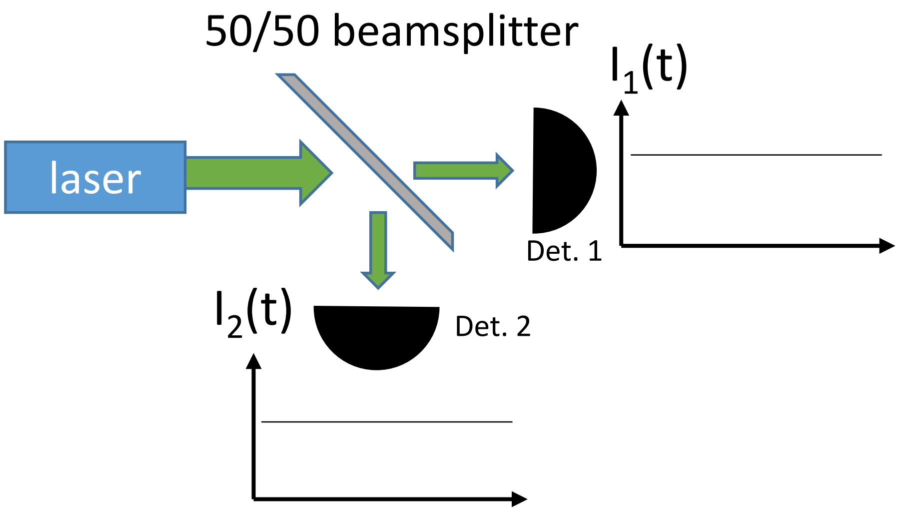
- global maximum at zero delay $g^{(2)}(0) \geq g^{(2)}(\tau)$

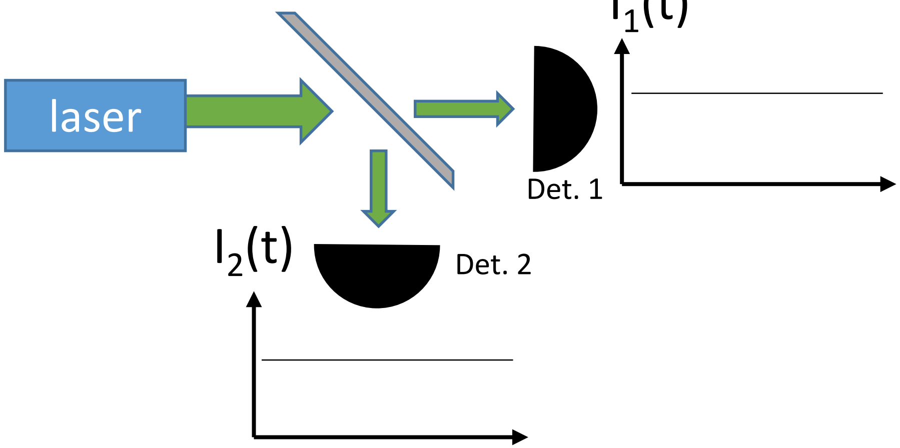
Intensity autocorrelation - the coherent case



$$g^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle^2}$$

- Perfectly monochromatic field $E(t) \propto \cos(\omega t)$
- Intensity is therefore $I(t) = \text{const.}$

Intensity autocorrelation - the coherent case



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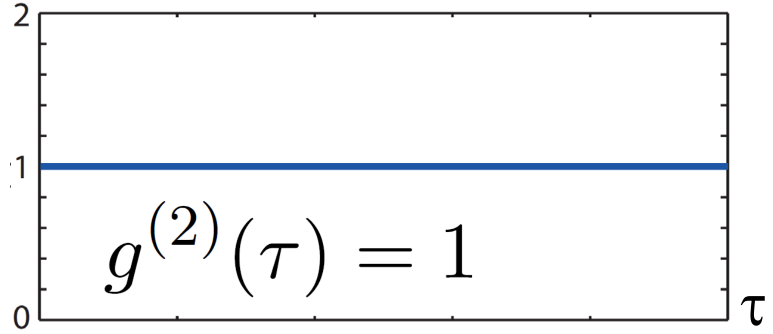

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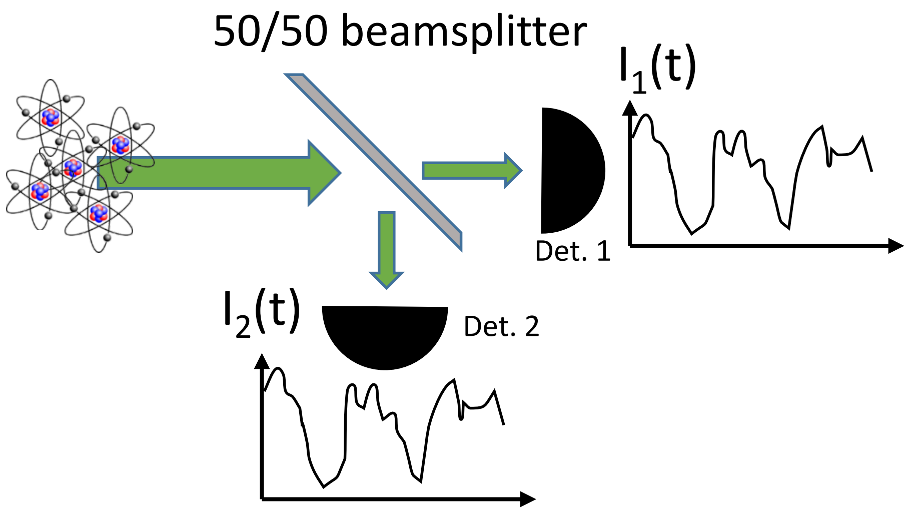
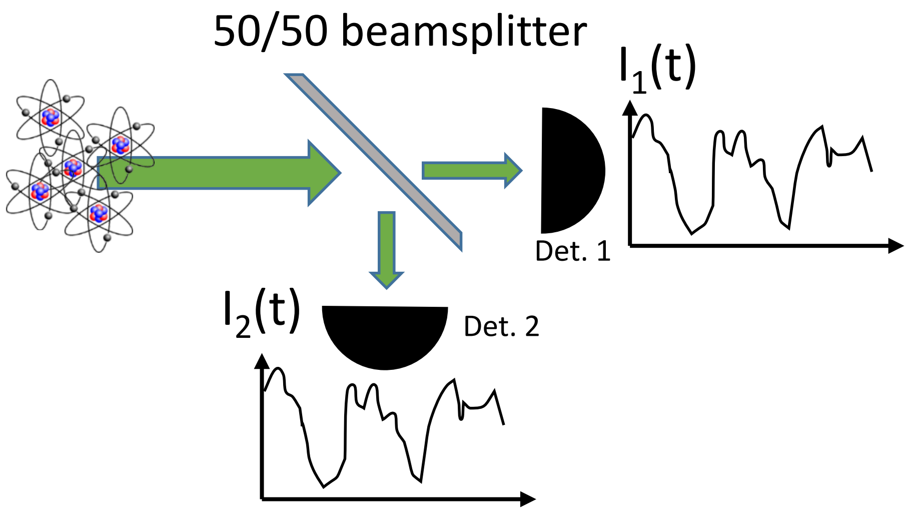


$$g^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle^2}$$

- Collection of sources
- Random phase ϕ_a

$$E(t) = E_0 \sum_{\text{atoms}} \exp\left[-\mathrm{i}\Omega_a t - \phi_a\right]$$

Intensity autocorrelation - the chaotic case



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- Collection of sources
- Random phase ϕ_a
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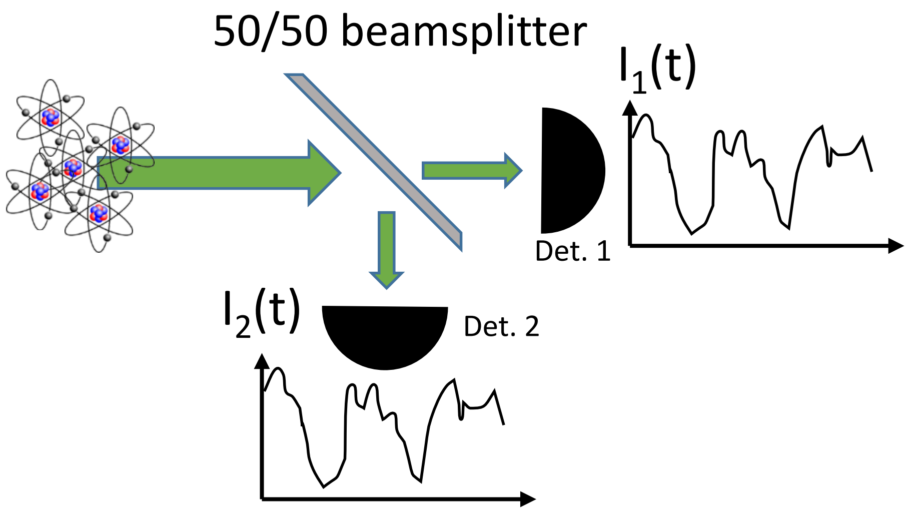
$$E(t) = E_0 \sum_{\text{atoms}} \exp\left[-\mathrm{i}\Omega_a t - \phi_a\right]$$

$$P(\Omega_a) \propto \exp\left[-(\Omega_0 - \Omega_a)^2 \tau_c^2\right]$$

Intensity autocorrelation - the chaotic case



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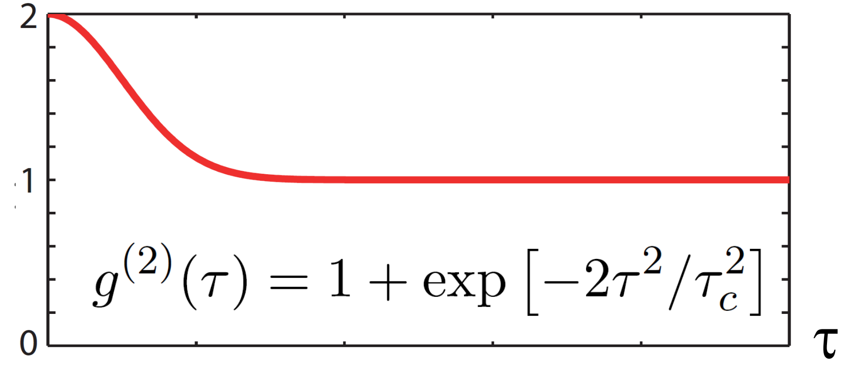

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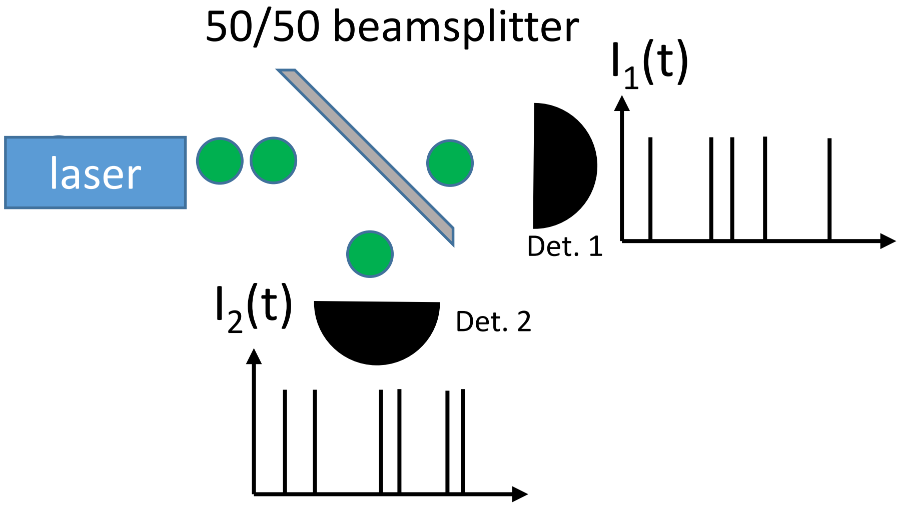
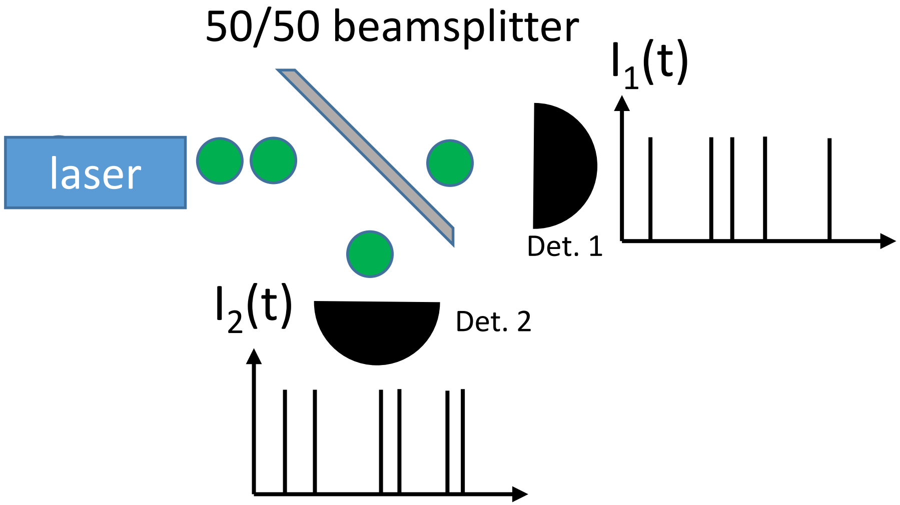
Intensity autocorrelation – counting photons



$$g^{(2)}(\tau) = \frac{\langle n_1(t) n_2(t+\tau) \rangle}{\langle n_1(t) \rangle \langle n_2(t) \rangle}$$

- $n_i(t)$ is the number of photons on detector i at time t
- Interpret $g^{(2)}(\tau)$ as the probability of detecting a photon on detector 2 at $t = \tau$ given that a photon was detected on detector 1 at $t=0$.

Counting photons – revisit coherent case



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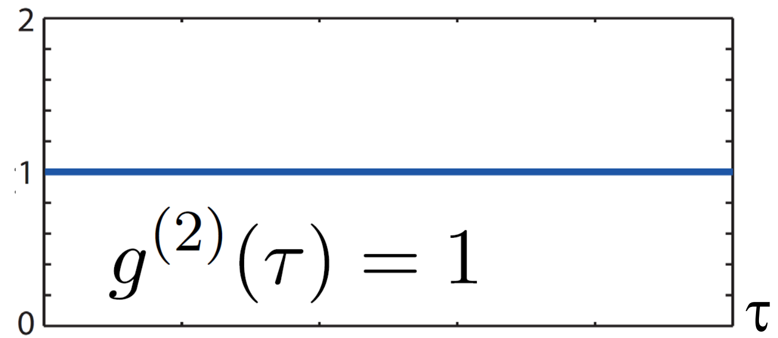

$$g^{(2)}(\tau) = 1$$

- $n_i(t)$ is the number of photons on detector i at time t
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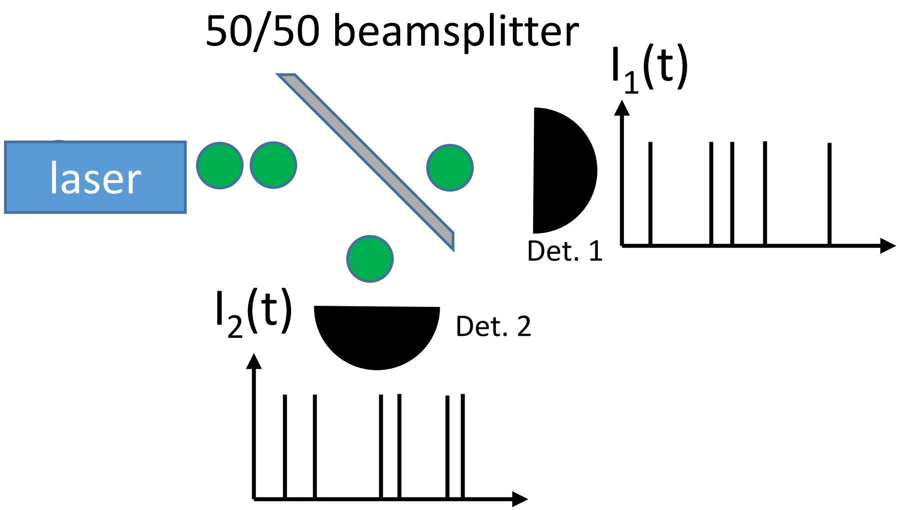
Counting photons – coherent case



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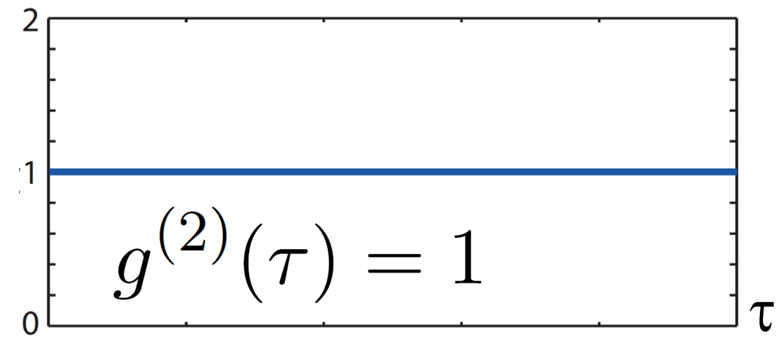
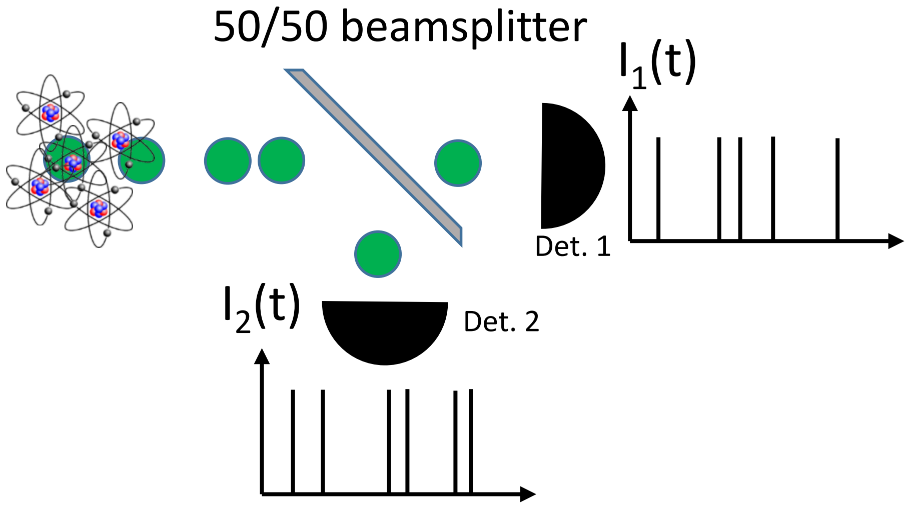


- $n_i(t)$ is the number of photons on detector i at time t
- Interpret $g^{(2)}(\tau)$ as the probability of detecting a photon on detector 2 at t= τ given that a photon was detected on detector 1 at t=0
- $g^{(2)}(\tau) = 1$ means that photons arrive with Poissonian distribution

$$P(n) = \frac{\langle n\rangle^n}{n!}\exp\left[-\langle n\rangle\right]$$

Counting photons – chaotic case



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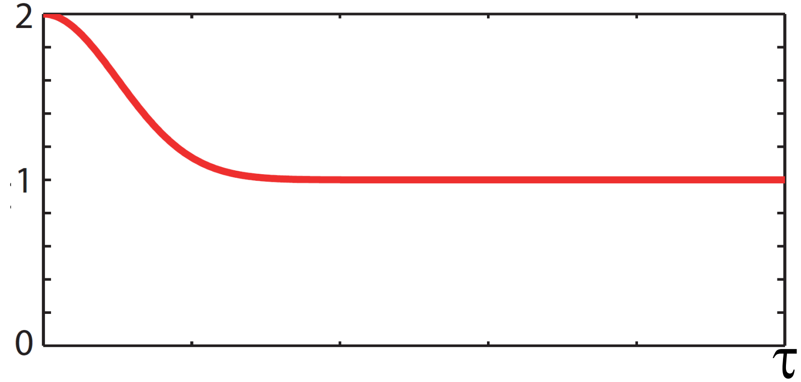

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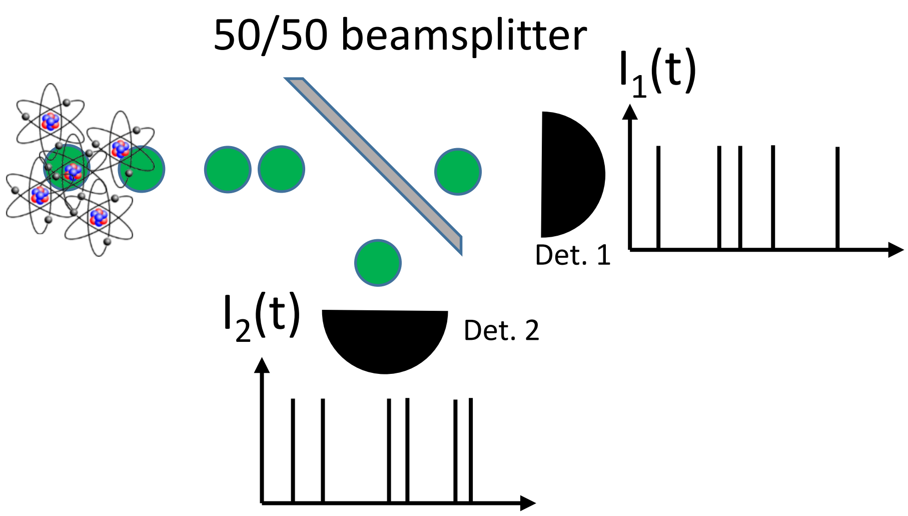
Counting photons – chaotic case



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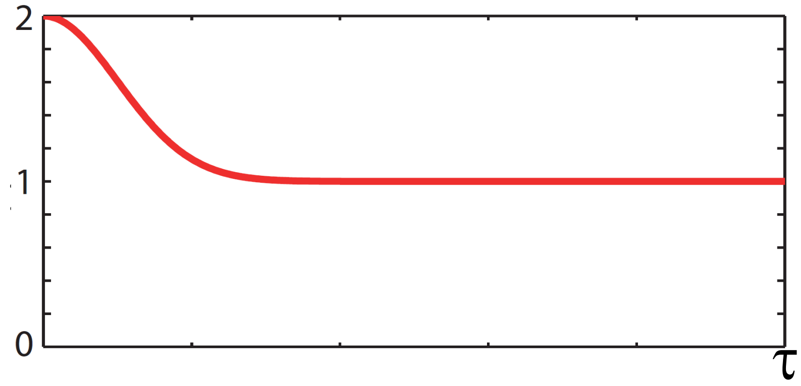

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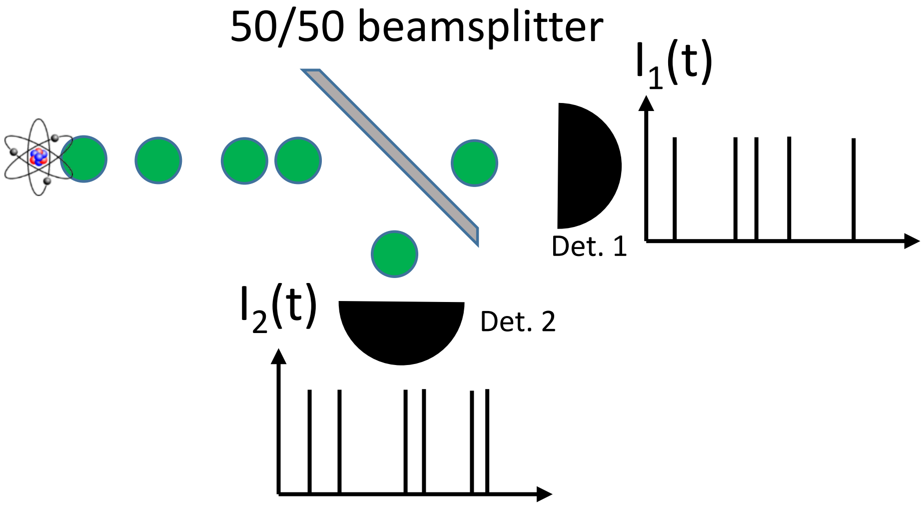
- Interpret $g^{(2)}(\tau)$ as the probability of detecting a photon on detector 2 at $t=\tau$ given that a photon was detected on detector 1 at $t=0$
- $g^{(2)}(\tau=0) > 0$ means that photons tend to arrive in bunches

Counting photons – a single quantum emitter



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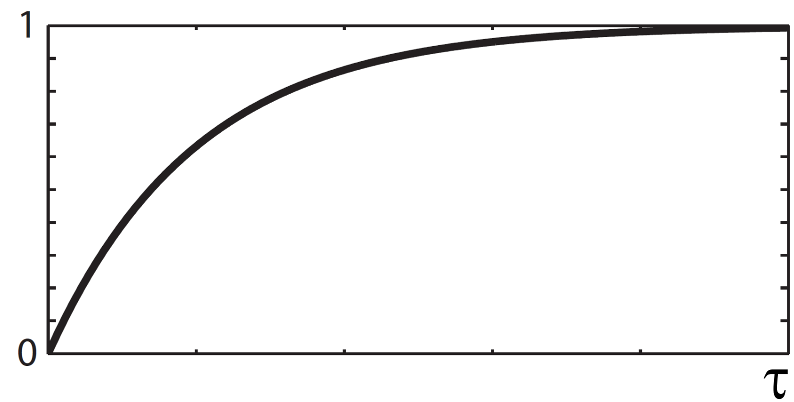
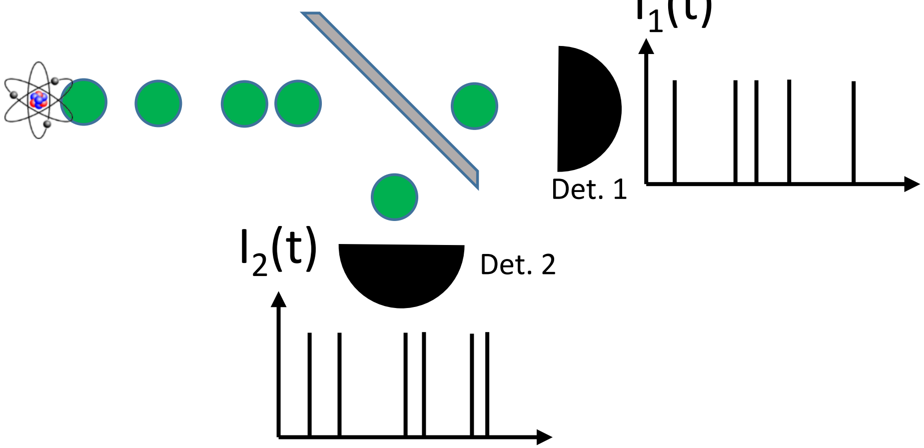


- Assume source is a single emitter
- Single emitter can only emit one photon at a time

Counting photons – a single quantum emitter



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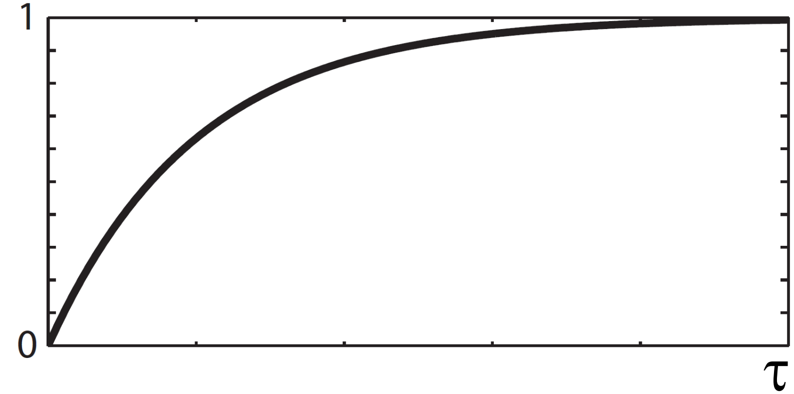

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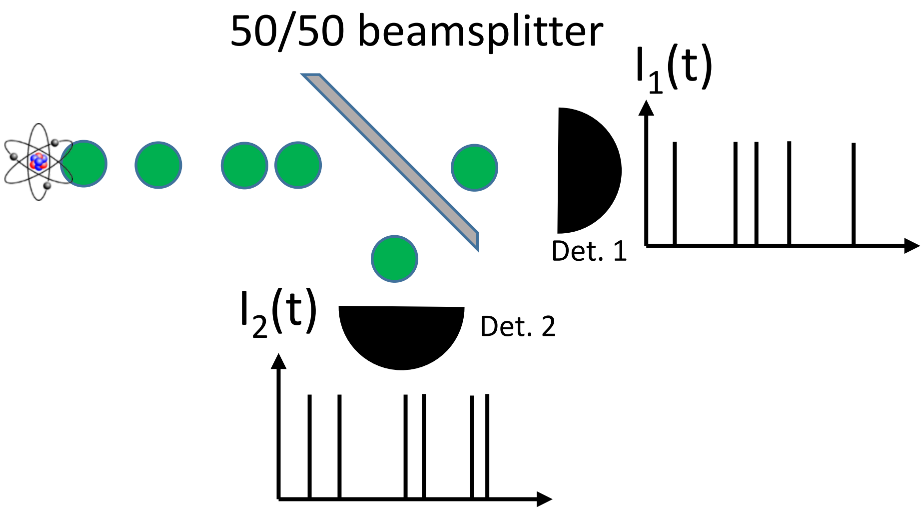
- If there is a photon on D1 there cannot be a photon on D2 → antibunching

Counting photons – a single quantum emitter



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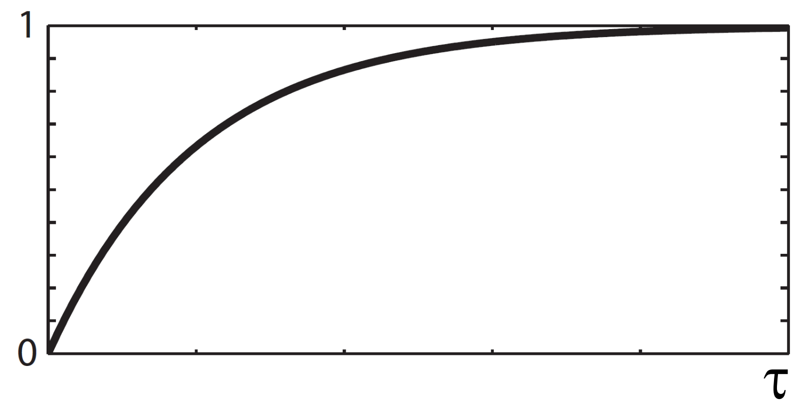

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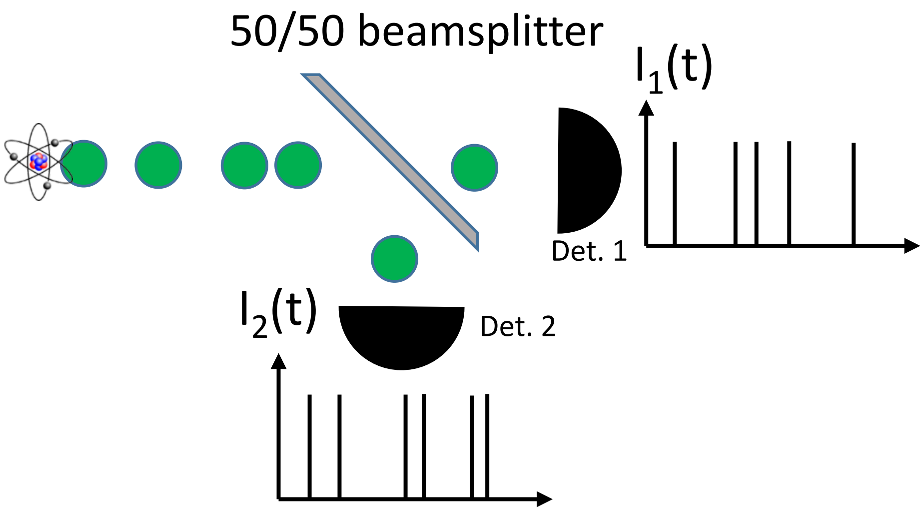

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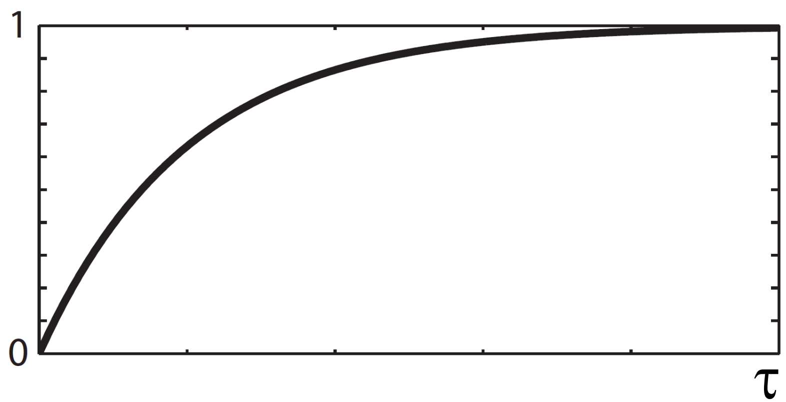

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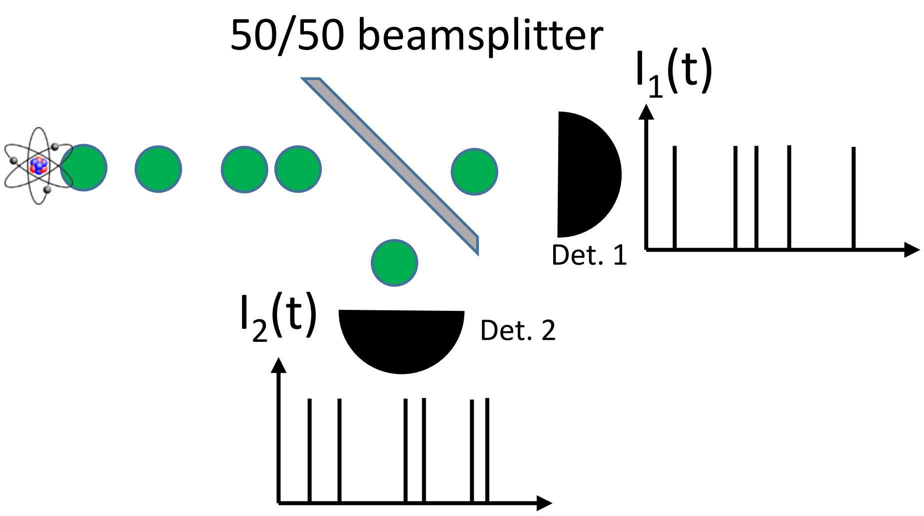
- $g^{(2)}(\tau=0) = 0$ is the signature of a single photon source

Counting photons – a single quantum emitter



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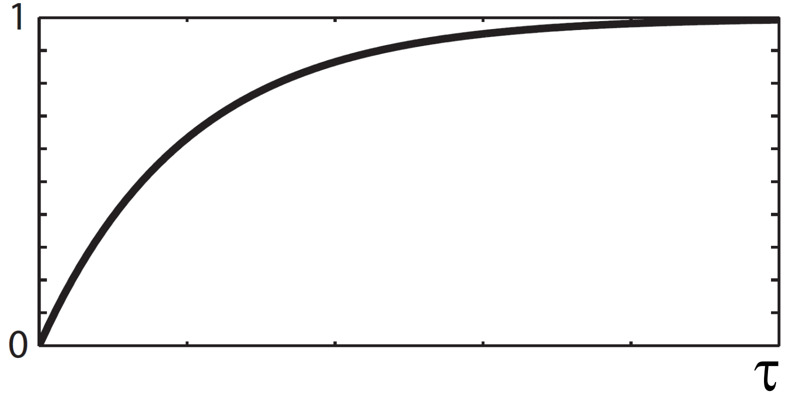

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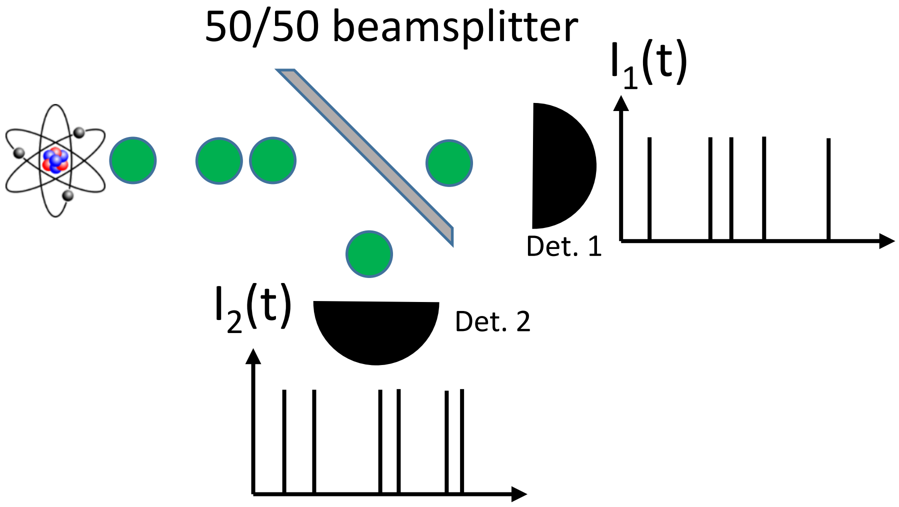
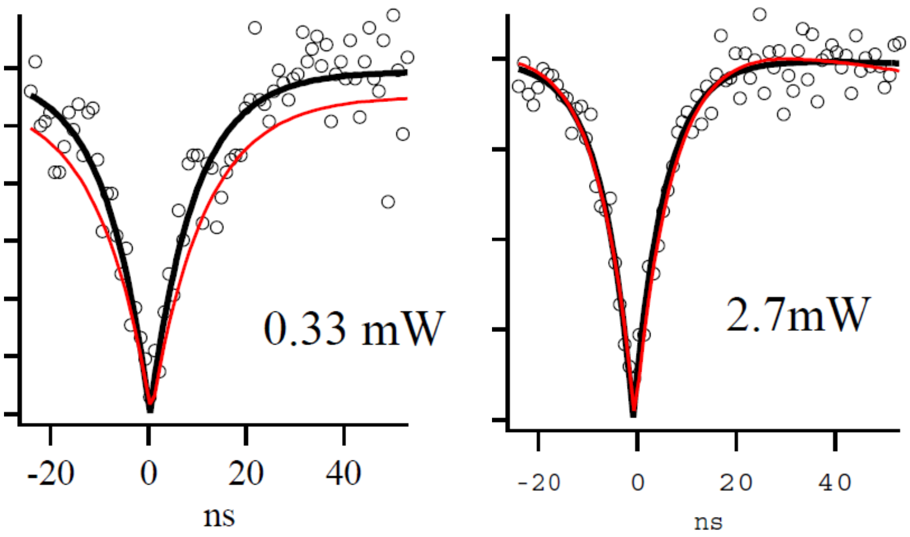
- Photon antibunching is at odds with classical electromagnetism
- $g^{(2)}(\tau=0) = 0$ is the signature of a single photon source
- What determines the rise time of $g^{(2)}(\tau)$?

Intensity correlation – counting single photons

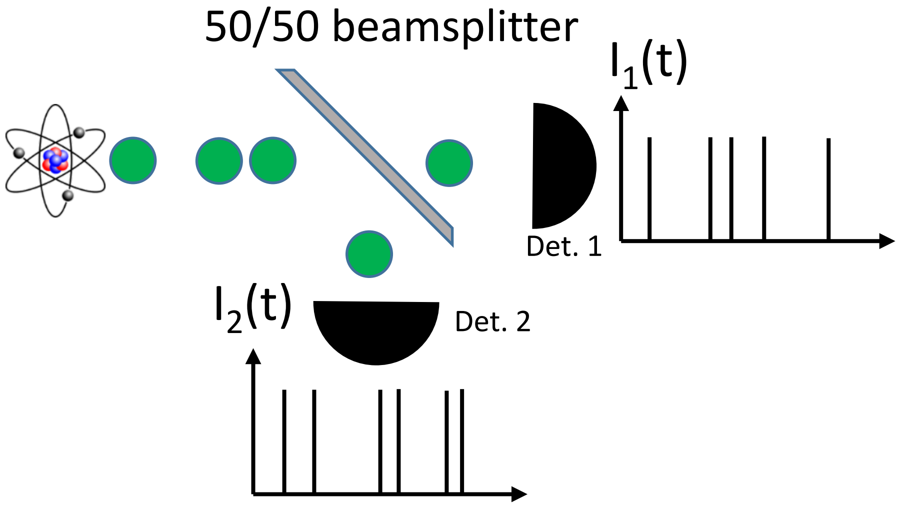


Beveratos, PhD thesis, Univ. Paris Sud (2002)



- How do you know your emitter is a single photon source?

Intensity correlation – counting single photons



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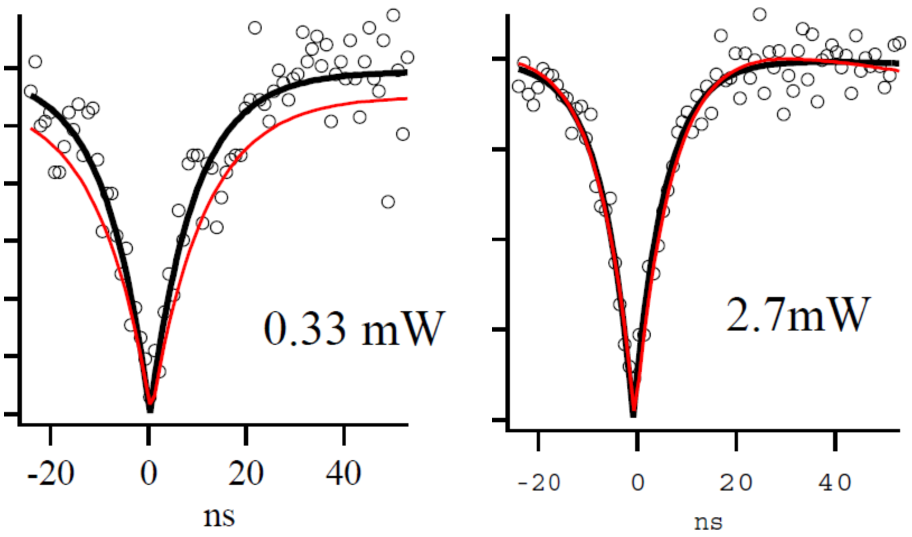
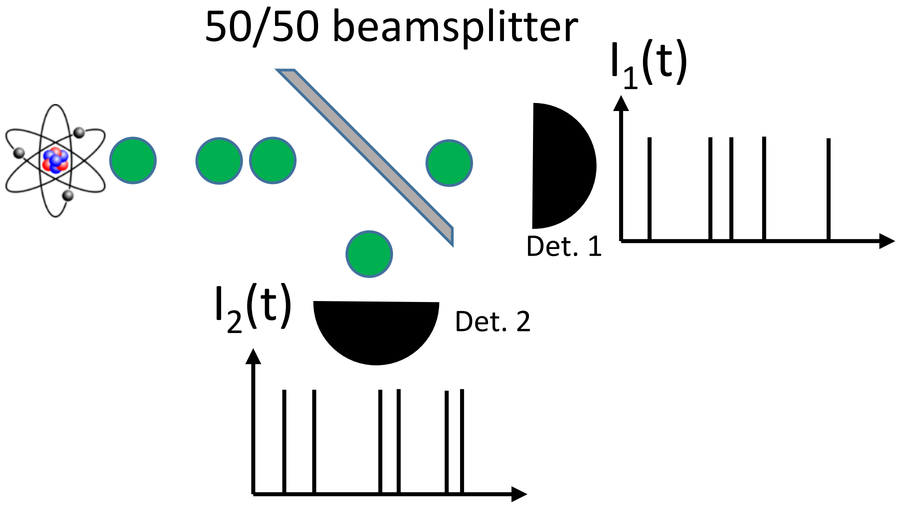


- How do you know your emitter is a single photon source?

For n emitters: $$g^2(0) = 1 - \frac{1}{n}$$

- How does the lifetime show up in the correlation function?

Intensity correlation – counting single photons



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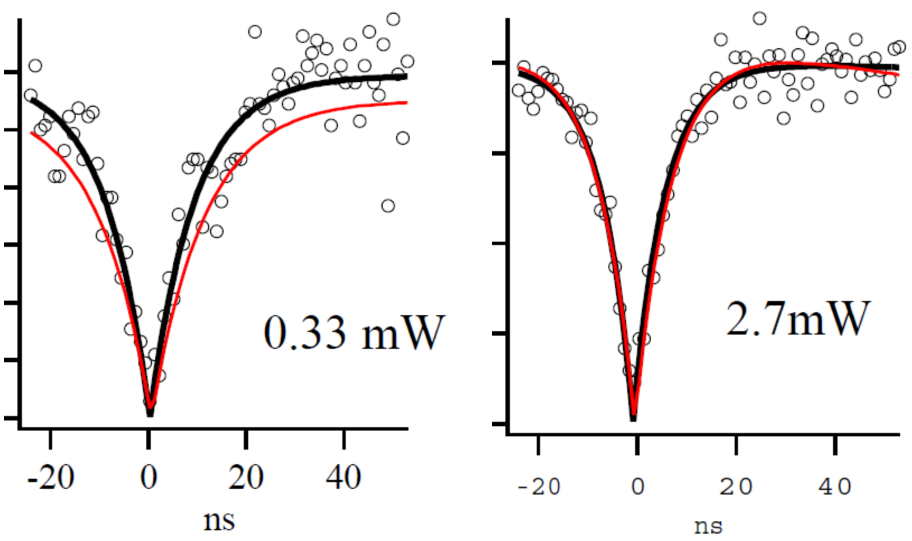


- How do you know your emitter is a single photon source?

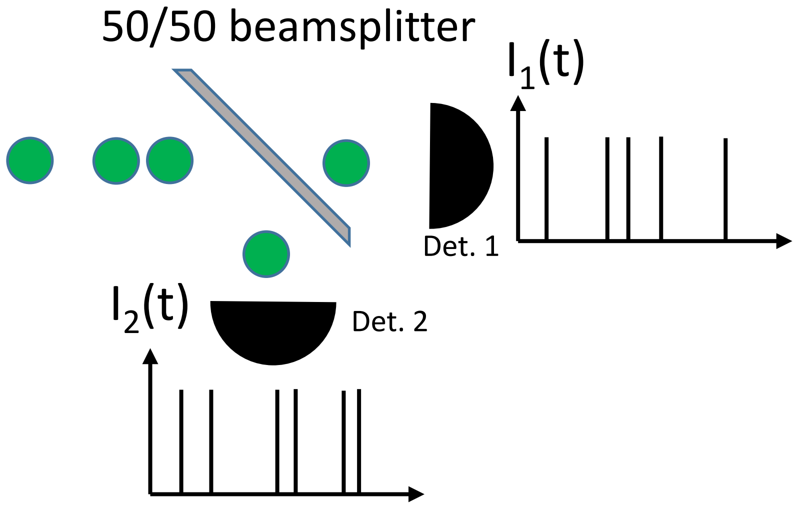
  For n emitters:

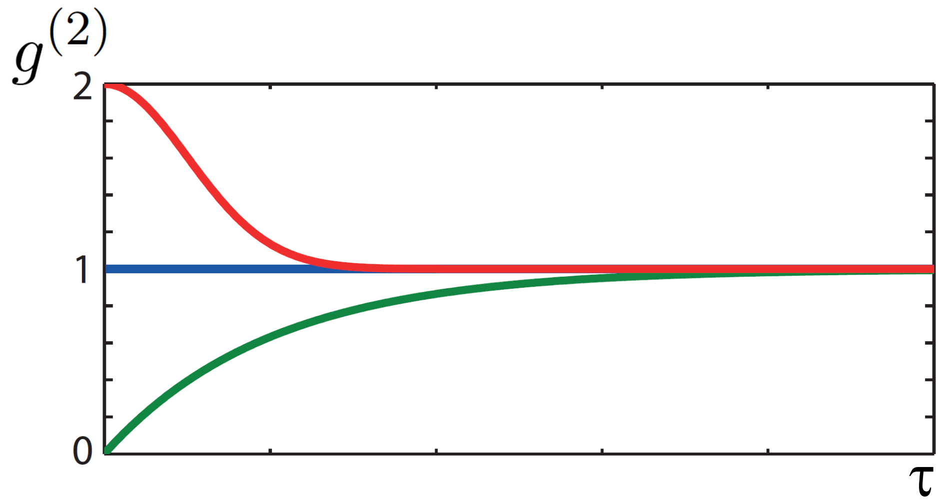
$$g^2(0) = 1 - \frac{1}{n}$$

- How does the lifetime show up in the correlation function?

  Rise time is lifetime in the case of weak pumping.

Intensity correlation – summary





- Second-order correlation function measures temporal intensity correlation
- Bunching: photons tend to “arrive together”, classically allowed/expected
- Antibunching: photons tend to “arrive alone”, classically forbidden

Properties of “light”