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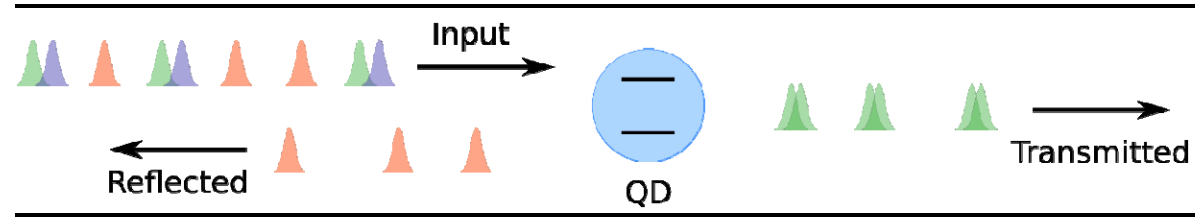
ITMO UNIVERSITY

# Управление статистикой ВЫХОДНОГО ИЗЛУЧЕНИЯ В ОДНОМОДОВОМ ВОЛНОВОДЕ С ИНКАПСУЛИРОВАННОЙ КВАНТОВОЙ ТОЧКОЙ

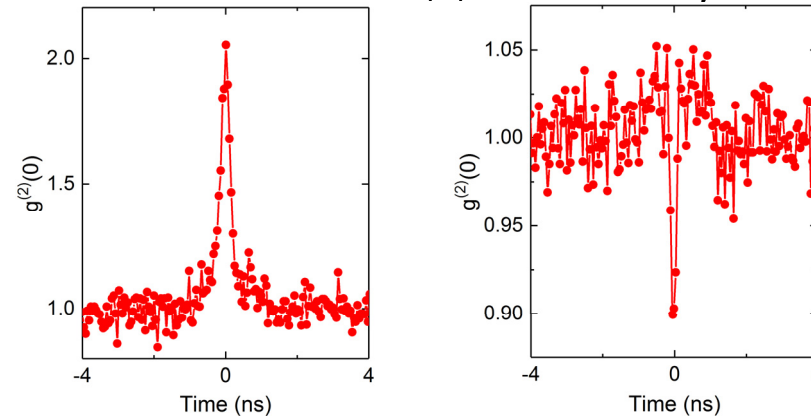
**И.В. Иорш**

# План доклада

- Введение
- Электрическая модуляция фотон-фотонных взаимодействий на чипе



- Управление статистикой выходного излучения



# Интегрированная квантовая фотоника

**Конечная цель:** Квантово-оптические логические операции на чипе для

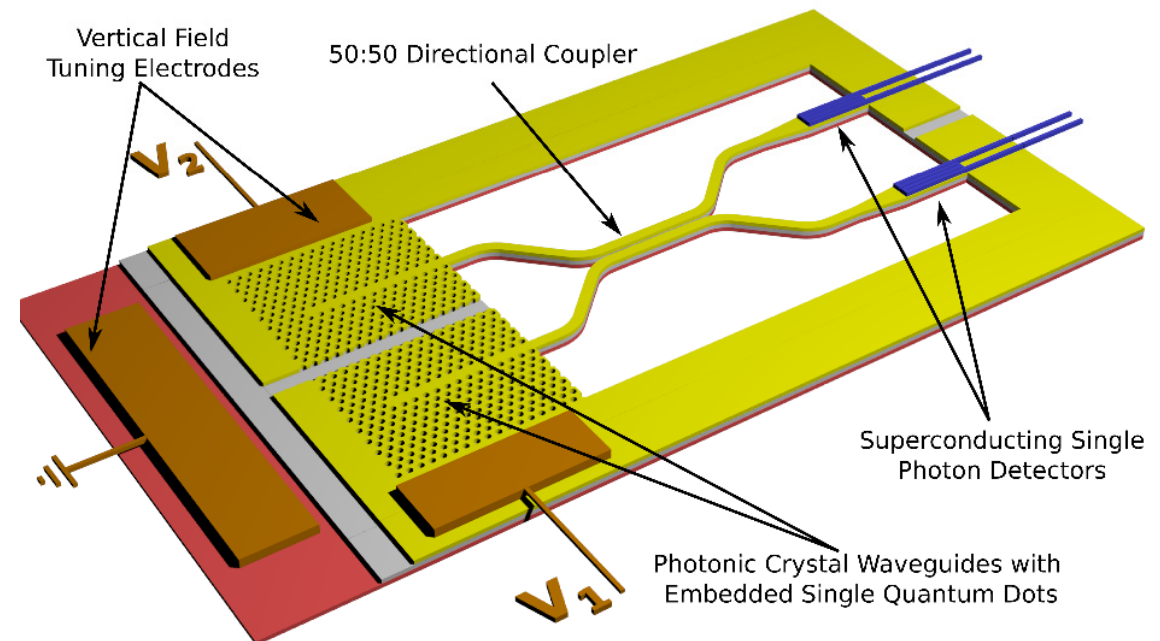
- моделирования
- метрологии
- Линейных оптических квантовых вычислений

**Проблема:** масштабирование

- Возможное решение: интегрированная на чипе нанофотоника

Платформы:

- Кремний
- SOI
- $\text{Si}_3\text{N}_4$
- Ниобат лития
- **Арсенид галлия**



# Фотон-фотонные взаимодействия на чипе

Фотоны идеальны для переноса квантовой информации

- Большое время когерентности
- **(очень) слабо взаимодействуют**

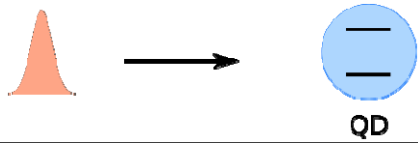
Но для квантово оптических вентилях необходимы **сильные фотон-фотонные взаимодействия**

Можно использовать нелинейные материалы ( например, Керровская нелинейность) но эффект обычно **очень слабый**

Возможное решение: использование квантовых точек

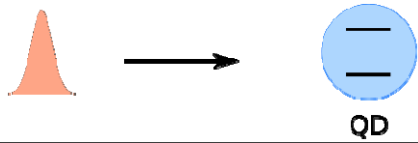
- КТ – квантовый элемент на мощностях нескольких фотонов

# Нелинейный отклик КТ (накачка одиночными фотонами)

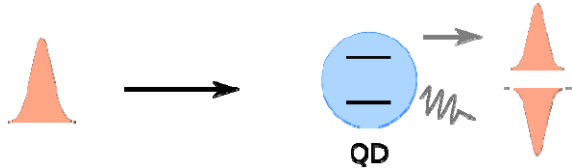


Одиночный фотон падает на КД

# Нелинейный отклик КТ (накачка одиночными фотонами)

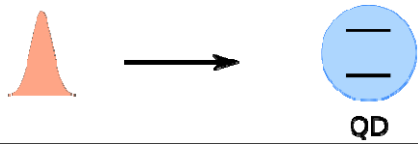


Одиночный фотон падает на КД

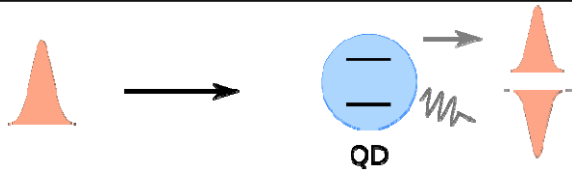


Рассеянный фотон набирает фазу  $\pi$

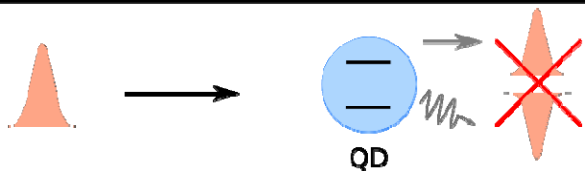
# Нелинейный отклик КТ (накачка одиночными фотонами)



Одиночный фотон падает на КД

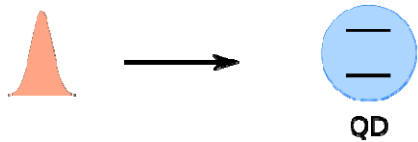


Рассеянный фотон набирает фазу  $\pi$

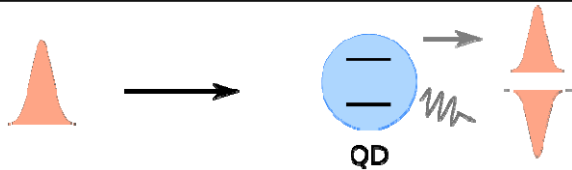


Деструктивная интерференция в прохождении  
(конструктивная в отражении)

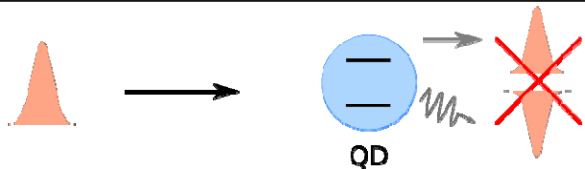
# Нелинейный отклик КТ (накачка одиночными фотонами)



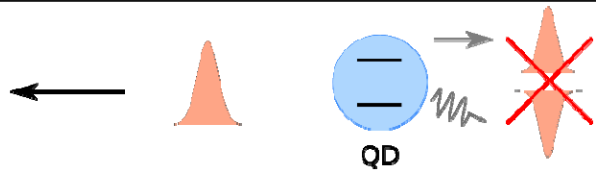
Одиночный фотон падает на КД



Рассеянный фотон набирает фазу  $\pi$



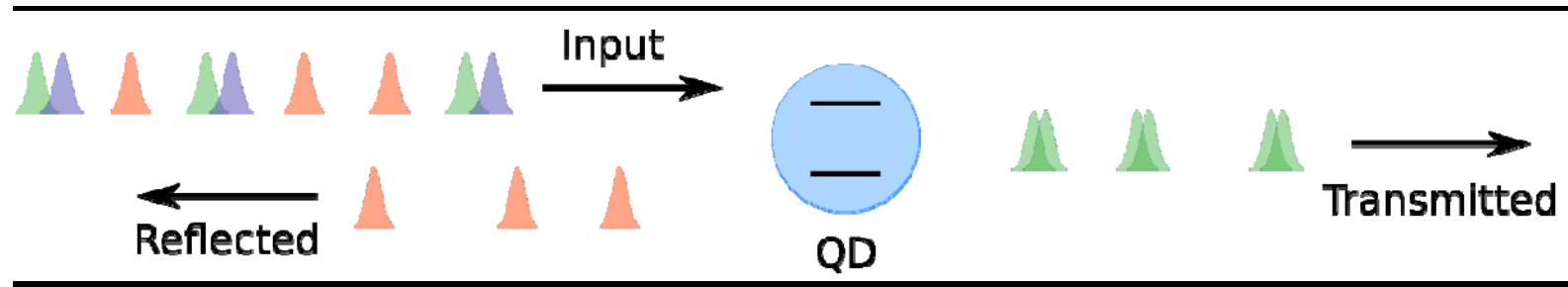
Деструктивная интерференция в прохождении  
(конструктивная в отражении)



Фотон отражается



# Нелинейный отклик КТ (накачка многими фотонами)



Рассеяние второго фотона зависит от рассеяния первого

➤ **Нелинейный процесс.**

Возможно формирование **двухфотонного связанного состояния**

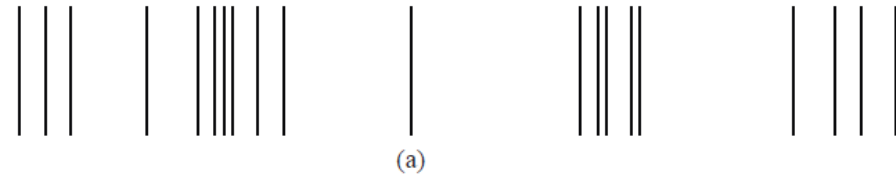
➤ Квантовое состояние, запутанное по частоте

Проходят в основном связанные состояния.

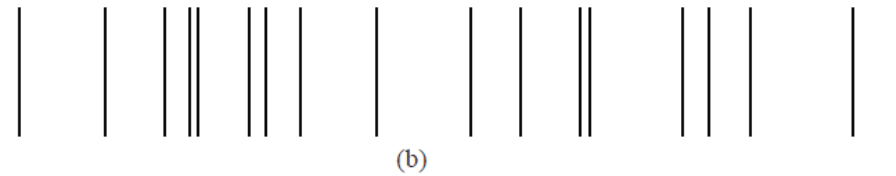
➤ Приводит к группировке **фотонов**

# Статистика фотонов

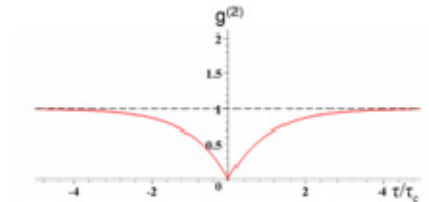
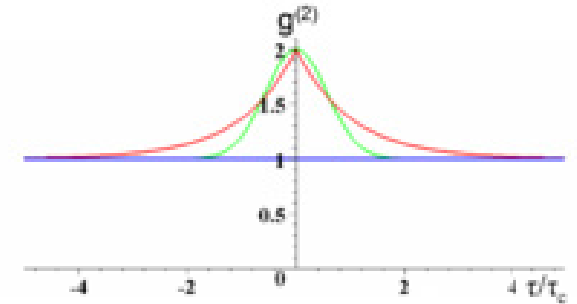
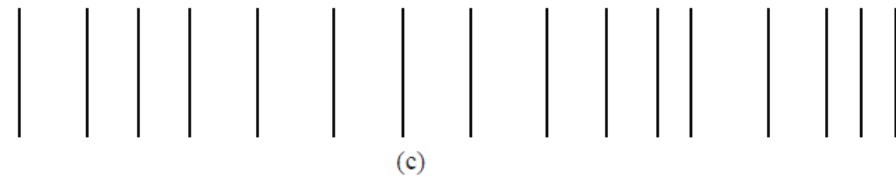
Тепловое излучение  
(группировка)



Когерентное излучение

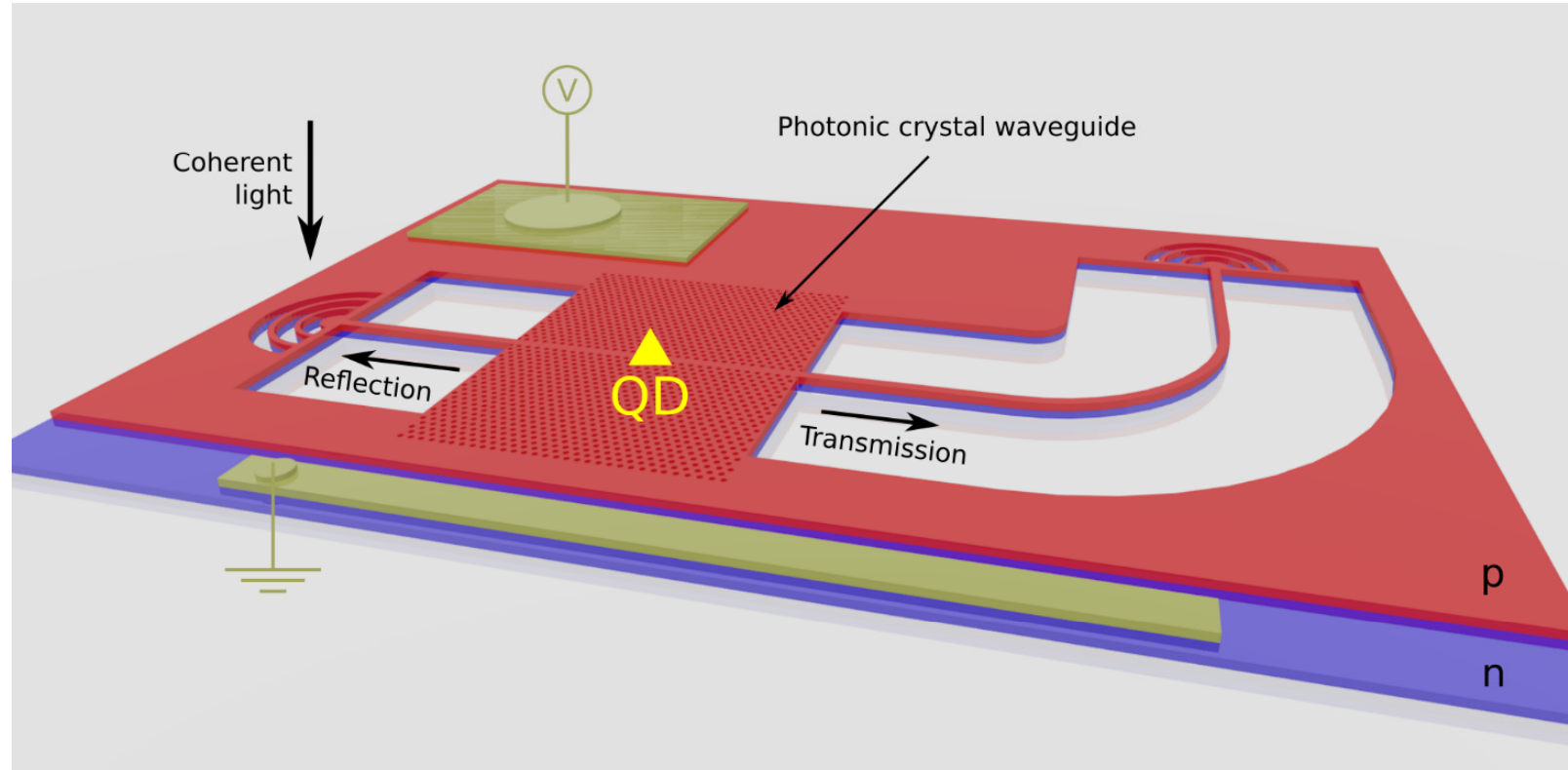


антигруппировка



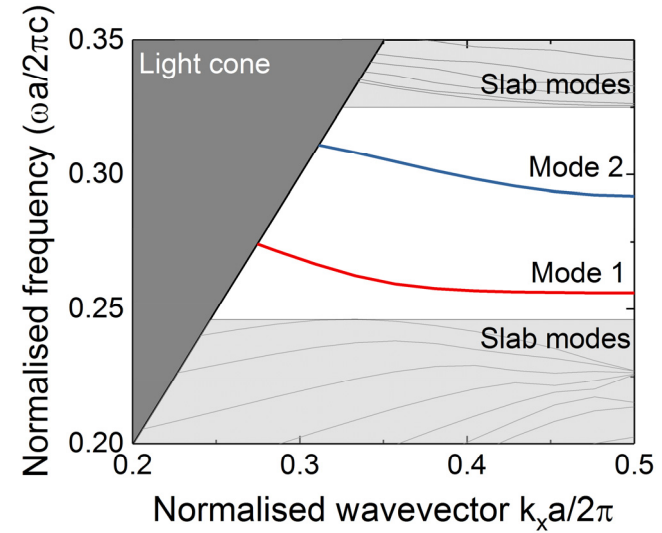
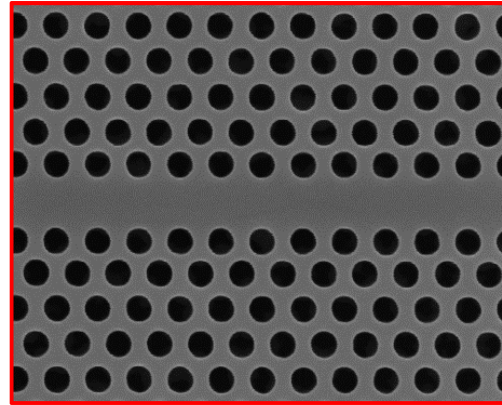
$$g_2(\tau) = \frac{\langle \alpha | c^\dagger(0) c^\dagger(\tau) c(\tau) c(0) | \alpha \rangle}{\langle \alpha | c^\dagger(\tau) c(0) | \alpha \rangle^2}$$

# Схема установки

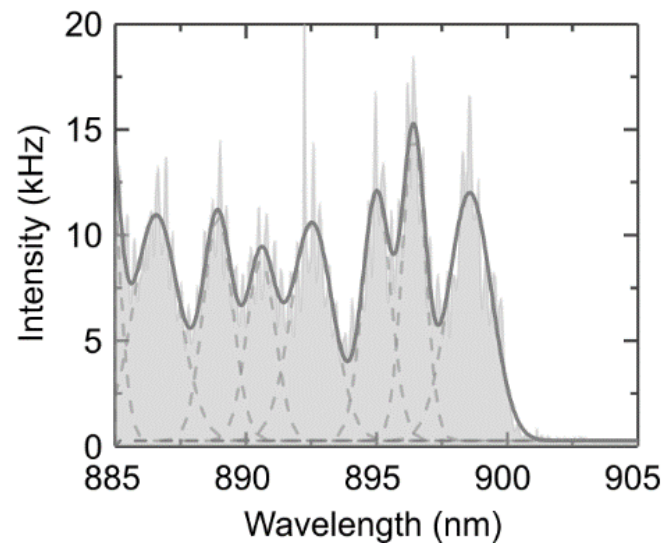


Platform: InGaAs QDs in 170nm GaAs *p-i-n* diode membrane

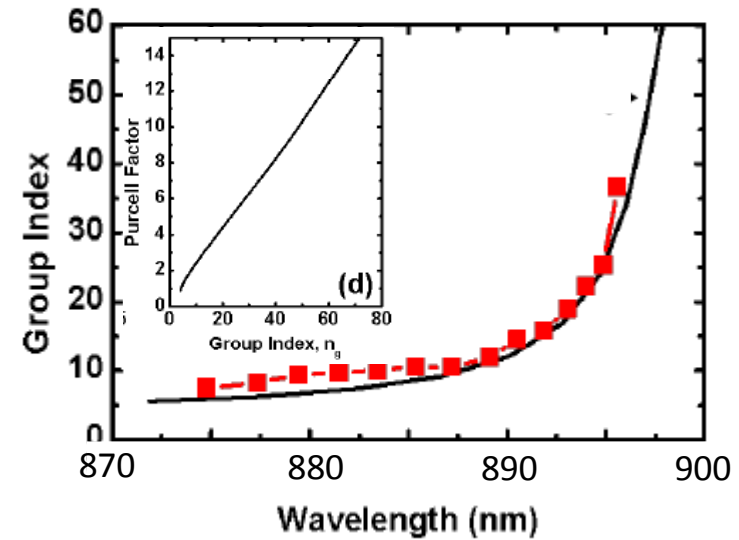
# Фотонно-кристаллический волновод



прохождение

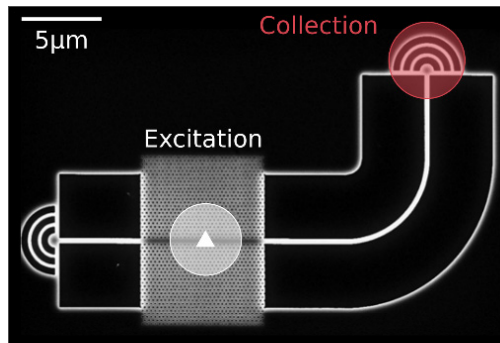


Эффект Парселла

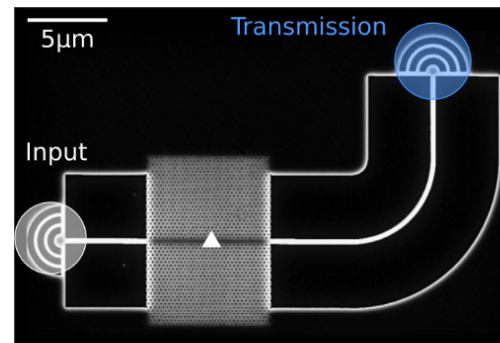


# Схема эксперимента

Резонансная  
Флуоресценция

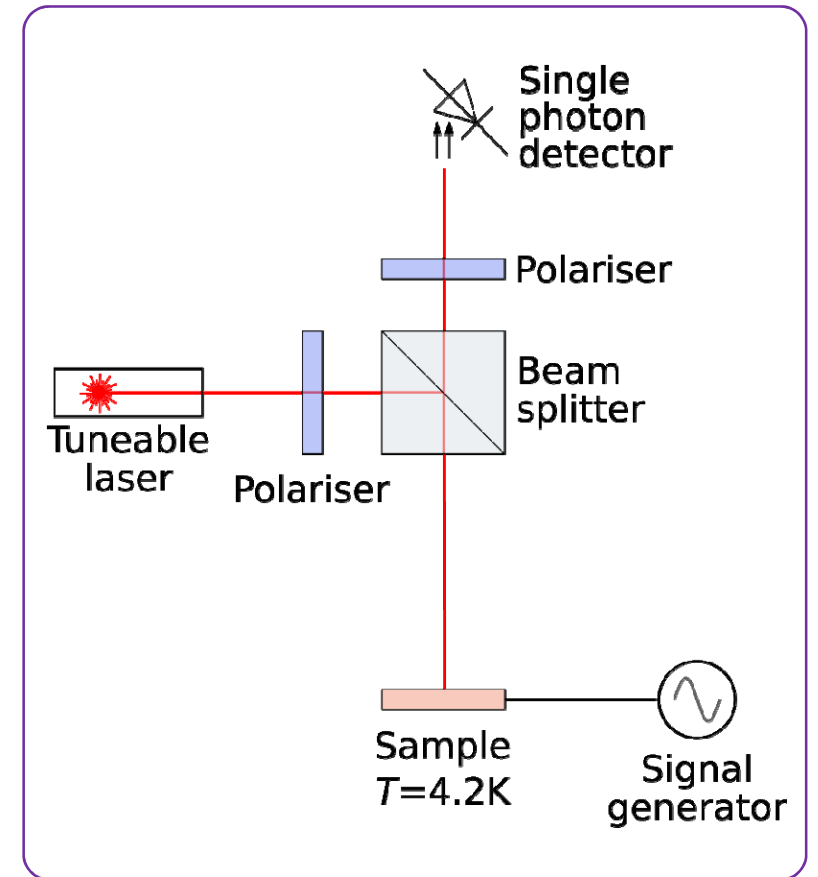


Резонансное  
прохождение

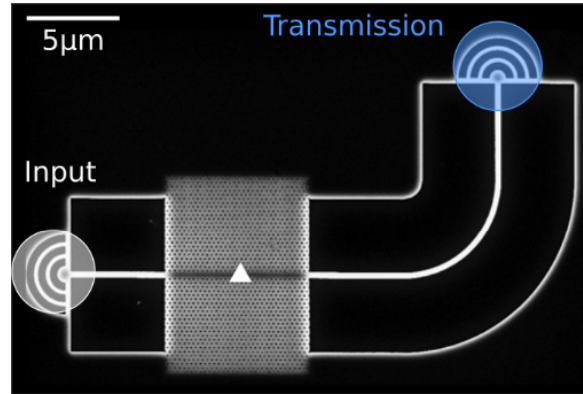


Низкие мощности

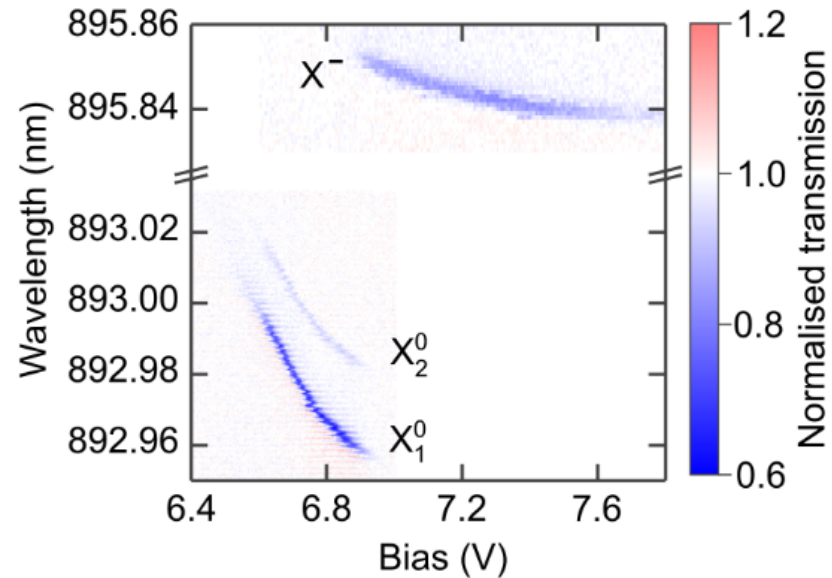
➤ Доминирует когерентное рассеяние



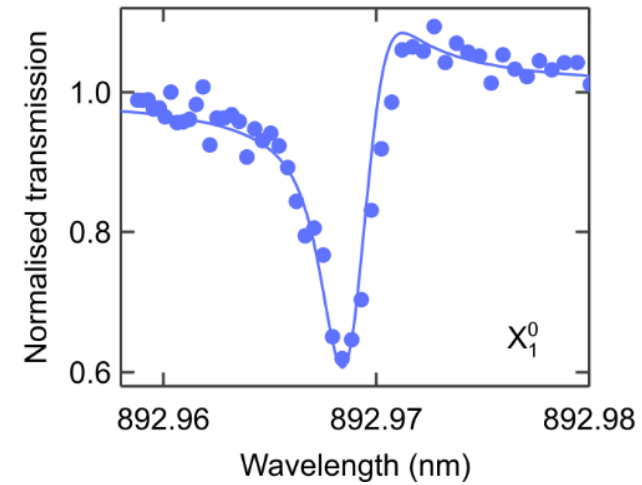
# Эксперименты по прохождению



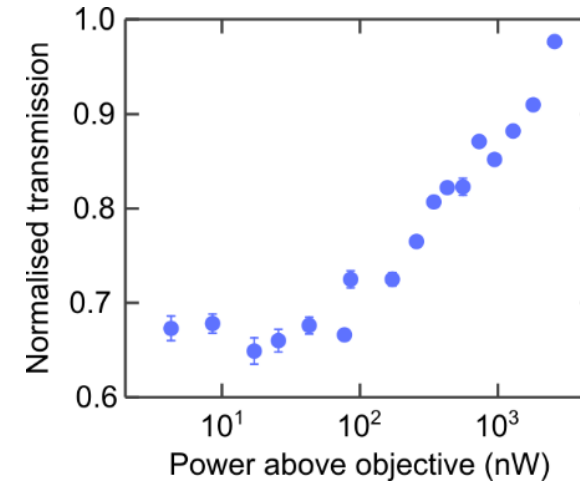
Suppression of transmitted laser by QD



Transmission minimum  $\sim 0.6$

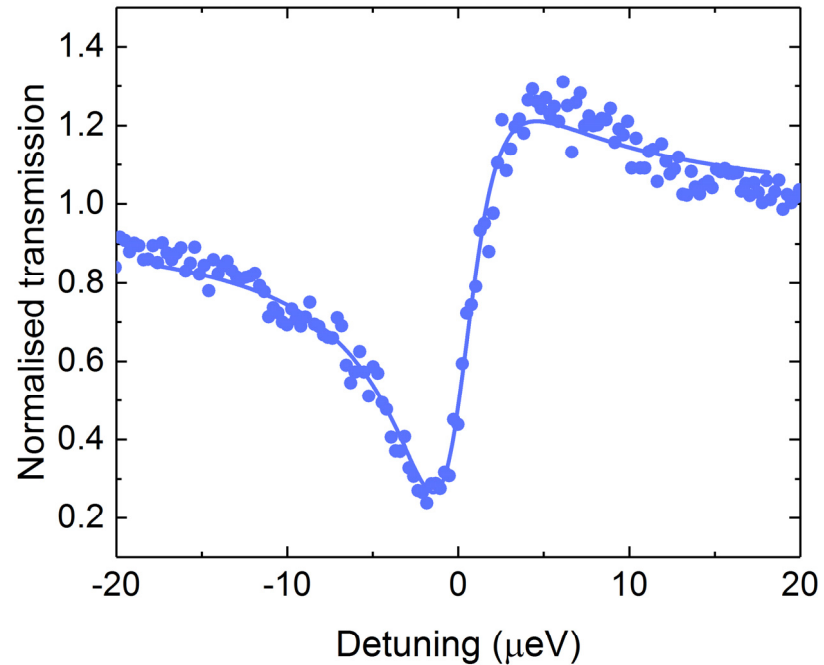


Higher power saturation –  
nonlinear effect



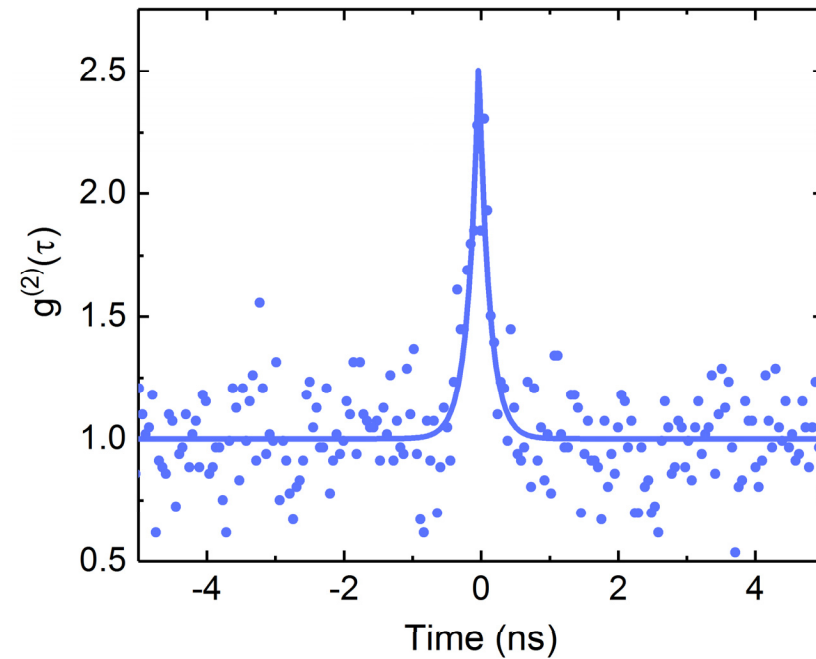
# Спектр прохождения и автокорреляционная функция

Transmission spectrum



Transmission minimum  $\sim 0.25$   
Measured linewidth:  $\sim 6\mu\text{eV}$   
Fourier limited linewidth:  
 $\sim 4.5\mu\text{eV}$

Transmission photon statistics



$$g^{(2)}(0) = 2.5 \pm 0.1$$

# Управление фотонной статистикой на чипе

So far, demonstrated bunching in transmission geometry.

Can the same system be used to generate single photons in transmission (generally more accessible than reflection)?

Input: a classical, coherent state  $|\alpha\rangle = \exp\left(-\frac{1}{2}|\alpha|^2\right) \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$

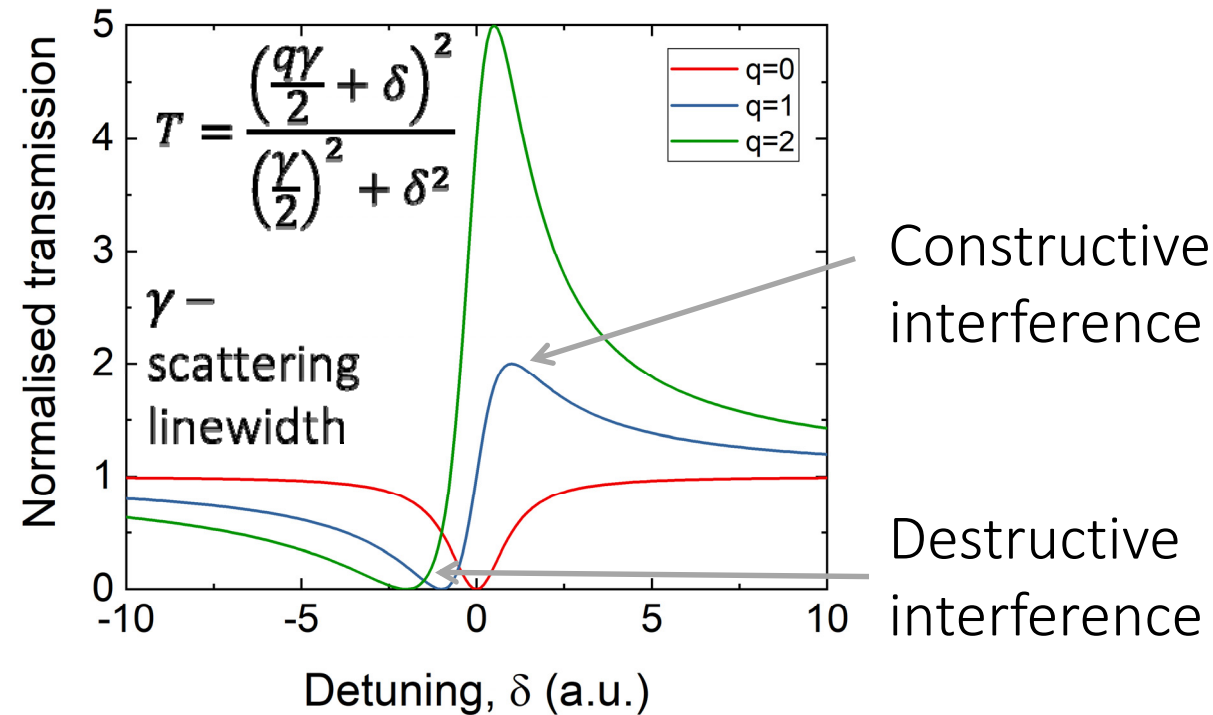
Can we selectively filter the  $n=1$  Fock state?

One possibility: Utilise interference between two scattering pathways – the Fano effect.



# Fano resonance

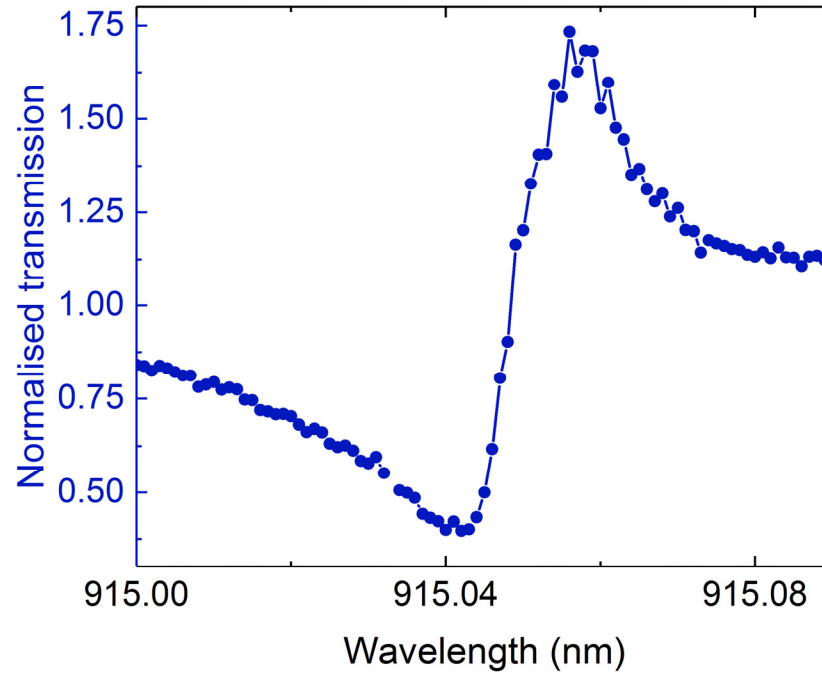
Fano resonances arise due to interference between a resonant scattering process and a background continuum – a very general phenomenon.



Particularly interesting for creating fast optical switches.

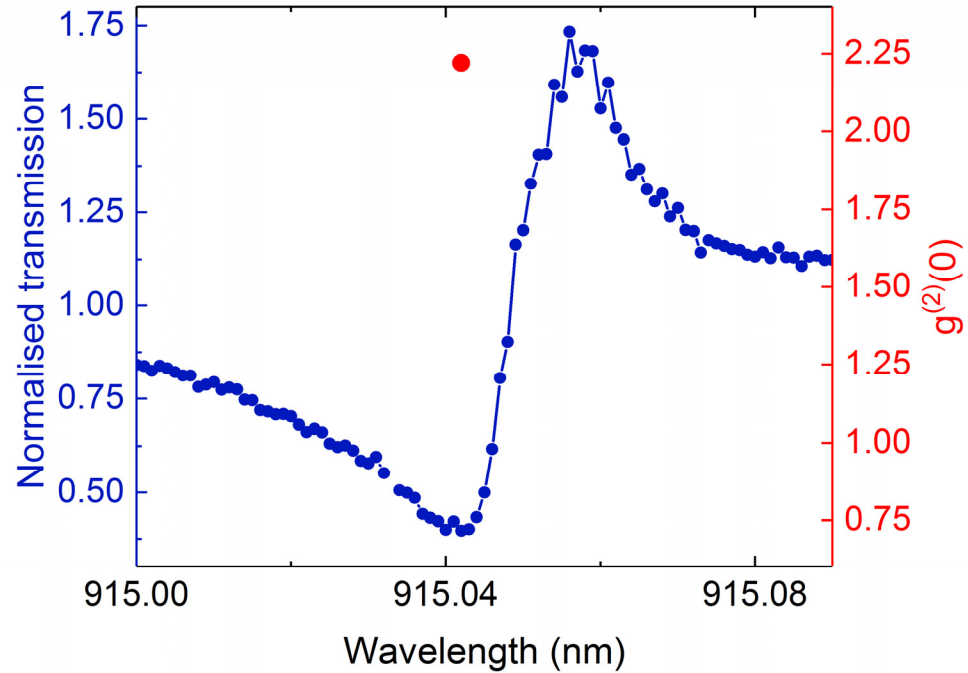
# Transmission and photon statistics

Clear Fano resonance observed in transmission.

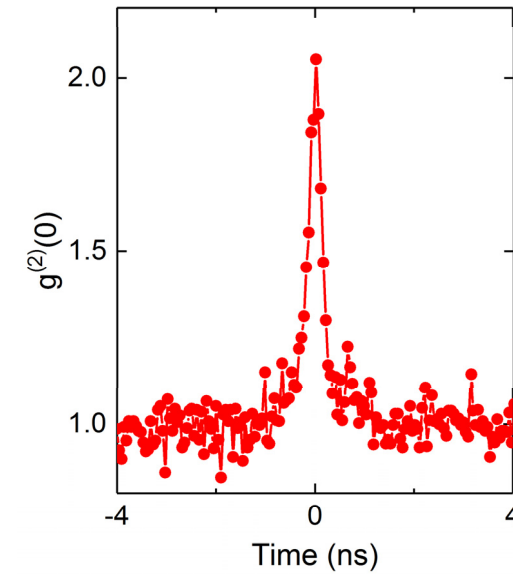


# Transmission and photon statistics

Clear Fano resonance observed in transmission.

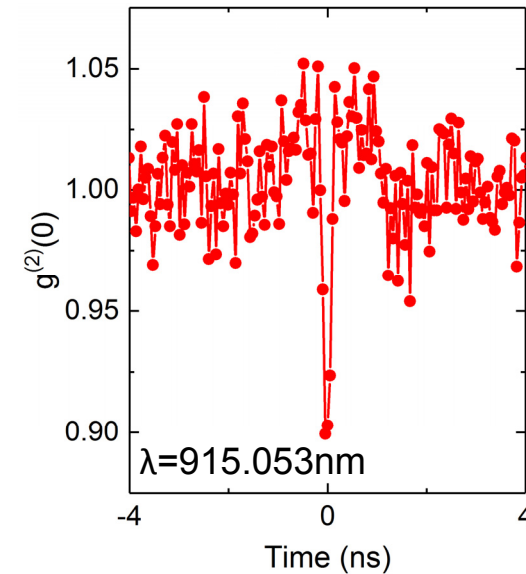
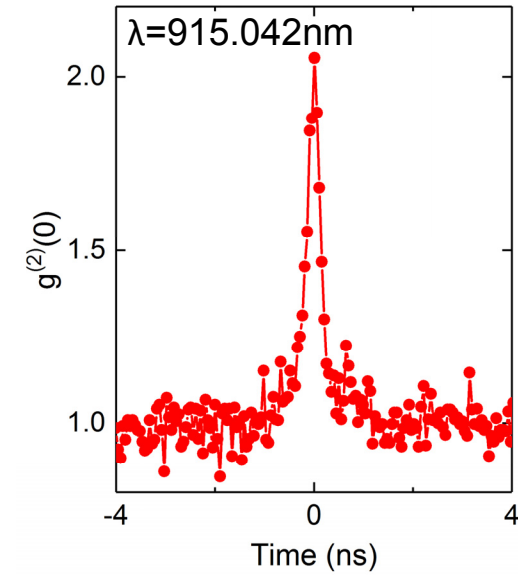
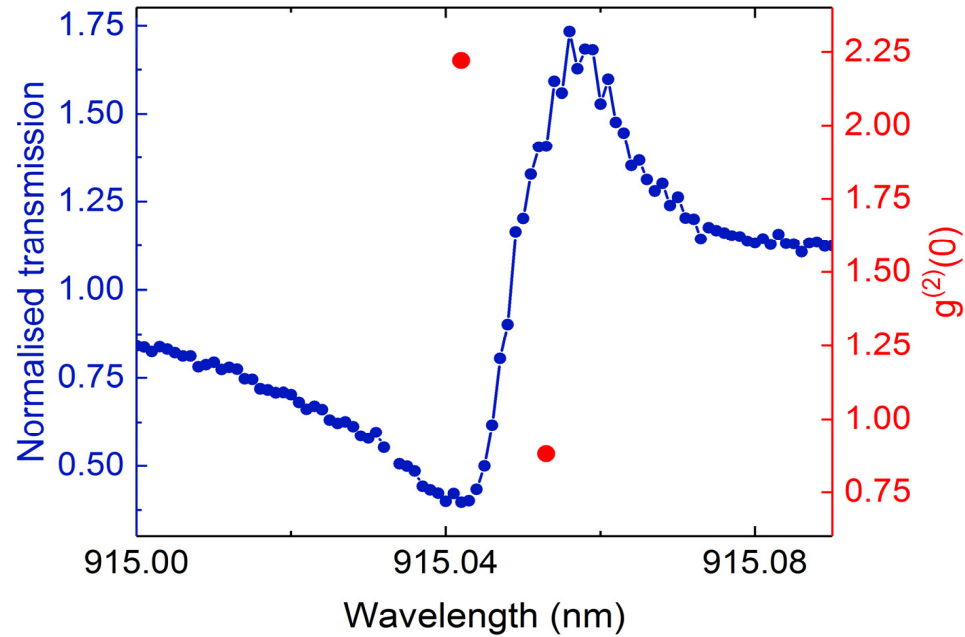


$\lambda=915.042\text{nm}$



# Transmission and photon statistics

Clear Fano resonance observed in transmission.



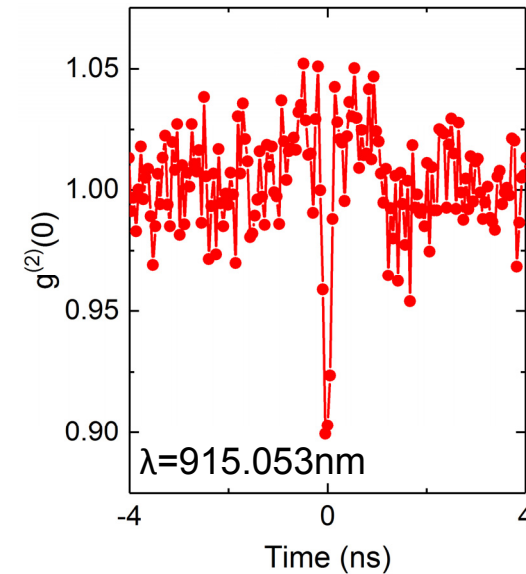
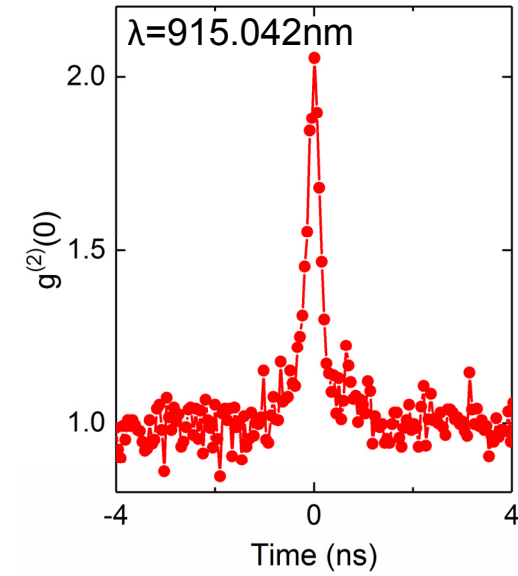
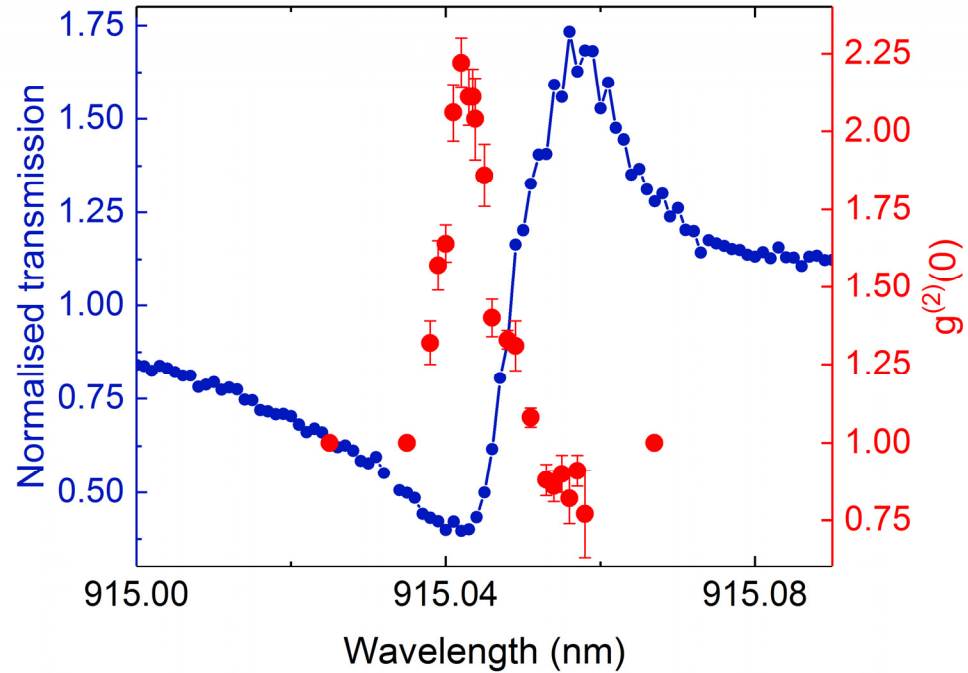
Classical coherent light:  $g^{(2)}(0)=1$

Bunched light:  $g^{(2)}(0)>1$

Antibunched light:  $g^{(2)}(0)<1$

# Transmission and photon statistics

Clear Fano resonance observed in transmission.



# Model: Input-output formalism

$$H = \int_{-\infty}^{\infty} d\omega \omega a_{\omega}^{\dagger} a_{\omega} + \frac{\Omega}{2} \sigma_z + V \int d\omega (\sigma_+ a_{\omega} + a_{\omega}^{\dagger} \sigma_-)$$

$$\begin{aligned} \dot{a}_{\omega} &= i[H, a] & a_{in}(t) &= \frac{1}{\sqrt{2\pi}} \int d\omega a_{\omega}(t_0) e^{i\omega(t-t_0)}, \quad t_0 \rightarrow -\infty \\ \dot{\sigma}_z &= i[H, \sigma_z] & a_{out}(t) &= \frac{1}{\sqrt{2\pi}} \int d\omega a_{\omega}(t_1) e^{-i\omega(t-t_1)}, \quad t_1 \rightarrow \infty \\ \dot{\sigma}_- &= i[H, \sigma_-] \end{aligned}$$

$$\begin{aligned} \dot{\sigma}_- &= -i\Omega\sigma_- - \pi V^2\sigma_- + i\sqrt{2\pi}V\sigma_z a_{in}, \\ \dot{\sigma}_z &= -2\pi V^2\sigma_z - 2\pi V^2 - i2\sqrt{2\pi}V(\sigma_+ a_{in} - a_{in}^{\dagger}\sigma_-), \\ a_{out} &= a_{in} - i\sqrt{2\pi}V\sigma_- \end{aligned}$$

$$a_{in}(t)|\alpha\rangle = \alpha e^{-i\omega t}|\alpha\rangle$$

$$g_1(t, t') = \langle |\alpha| a_{out}(t')^{\dagger} a_{out}(t) | \alpha \rangle$$

$$g_2(t, t') = \frac{\langle |\alpha| a_{out}(t)^{\dagger} a_{out}(t')^{\dagger} a_{out}(t') a_{out}(t) | \alpha \rangle}{g_1(t, t)g_1(t', t')}$$

$$2\pi V^2 = \gamma$$

**Measurable decay rate**

# What happens in a cavity?

$$\dot{\sigma}_- = -i\Omega\sigma_- - \frac{\gamma}{2}\sigma_- + i\sqrt{\gamma}\sigma_z a_{in},$$

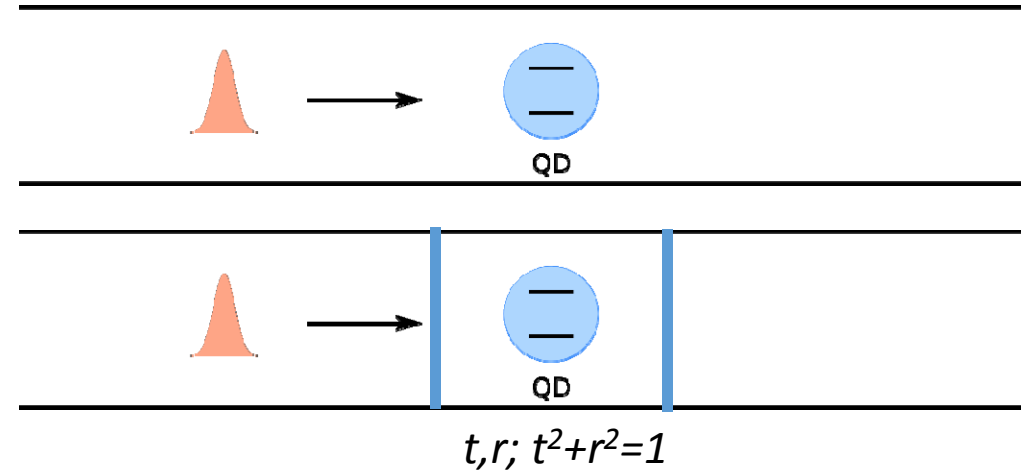
$$\dot{\sigma}_z = -\gamma\sigma_z - \gamma - i2\sqrt{\gamma}(\sigma_+ a_{in} - a_{in}^\dagger \sigma_-),$$

$$a_{out} = a_{in} - i\sqrt{\gamma}\sigma_-$$

$$\dot{\sigma}_- = -i\Omega\sigma_- - \frac{\gamma}{2}\sigma_- - d\sigma_z a_{in},$$

$$\dot{\sigma}_z = -\gamma\sigma_z - \gamma - (2d\sigma_+ a_{in} - 2d^* a_{in}^\dagger \sigma_-),$$

$$a_{out} = a_{in} + d\sigma_-$$



# What happens in a cavity?

$$\dot{\sigma}_- = -i\Omega\sigma_- - \frac{\gamma}{2}\sigma_- + i\sqrt{\gamma}\sigma_z a_{in},$$

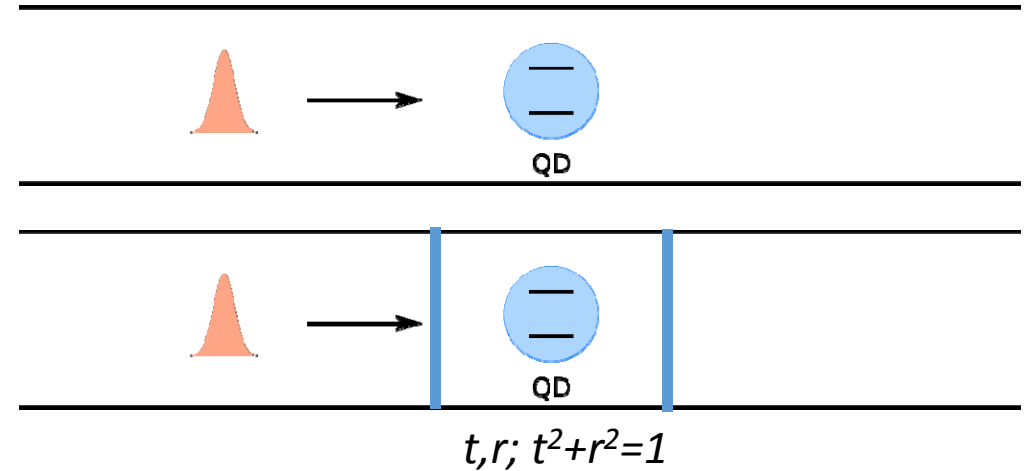
$$\dot{\sigma}_z = -\gamma\sigma_z - \gamma - i2\sqrt{\gamma}(\sigma_+ a_{in} - a_{in}^\dagger \sigma_-),$$

$$a_{out} = a_{in} - i\sqrt{\gamma}\sigma_-$$

$$\dot{\sigma}_- = -i\Omega\sigma_- - \frac{\gamma}{2}\sigma_- - d\sigma_z a_{in},$$

$$\dot{\sigma}_z = -\gamma\sigma_z - \gamma + (2d\sigma_+ a_{in} + 2d^* a_{in}^\dagger \sigma_-),$$

$$a_{out} = t a_{in} + d \sigma_-$$



Flux conservation+ time reversal symmetry:  
Relations between  $d$  and decay time

$$d = -ie^{i\varphi/2} \sqrt{\beta\gamma}$$

$$\varphi = \arctan(r / t)$$

Coupling acquires phase  $\rightarrow$  interference



# What happens in a cavity?

$$\dot{\sigma}_- = -i\Omega\sigma_- - \frac{\gamma}{2}\sigma_- + i\sqrt{\gamma}\sigma_z a_{in},$$

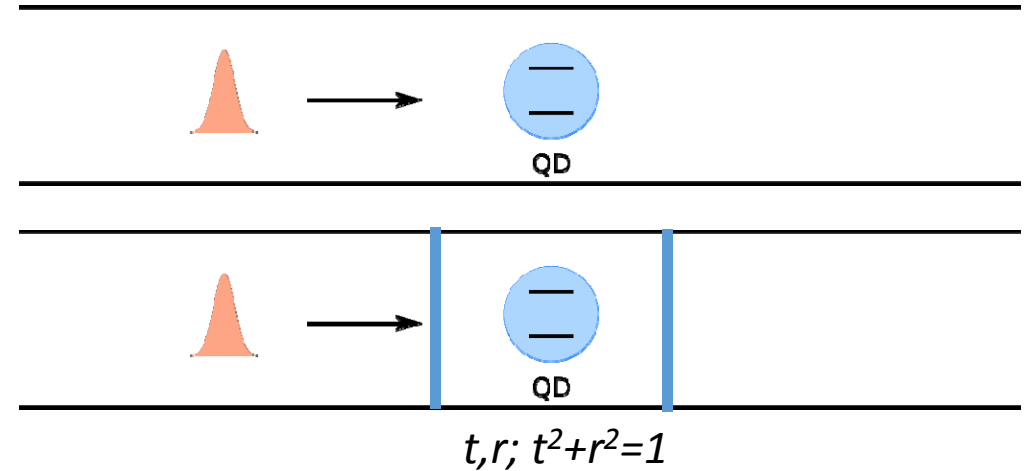
$$\dot{\sigma}_z = -\gamma\sigma_z - \gamma - i2\sqrt{\gamma}(\sigma_+ a_{in} - a_{in}^\dagger \sigma_-),$$

$$a_{out} = a_{in} - i\sqrt{\gamma}\sigma_-$$

$$\dot{\sigma}_- = -i\Omega\sigma_- - \frac{\gamma}{2}\sigma_- - d\sigma_z a_{in},$$

$$\dot{\sigma}_z = -\gamma\sigma_z - \gamma + (2d\sigma_+ a_{in} + 2d^* a_{in}^\dagger \sigma_-),$$

$$a_{out} = a_{in} + d\sigma_-$$



Flux conservation + time reversal symmetry:  
Relations between  $d$  and decay rate

$$d = -ie^{i\varphi/2} \sqrt{\beta\gamma}$$

$$\varphi = \arctan(r / t)$$

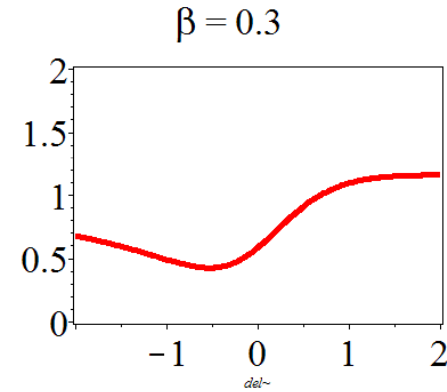
Probability to decay to the waveguide

Coupling acquires phase  $\rightarrow$  interference

# Normalized transmission and $g_2$

$$g_1 = \left[ 1 - \frac{2\beta(1 - \delta \tan \phi)}{1 + \delta^2 + \tilde{\alpha}} + \frac{\beta^2}{\cos^2 \phi (1 + \delta^2 + \tilde{\alpha})} \right],$$

$$\tilde{\alpha} = 2\beta |\alpha|^2 / \gamma; \delta = 2(\omega - \Omega) / \gamma$$



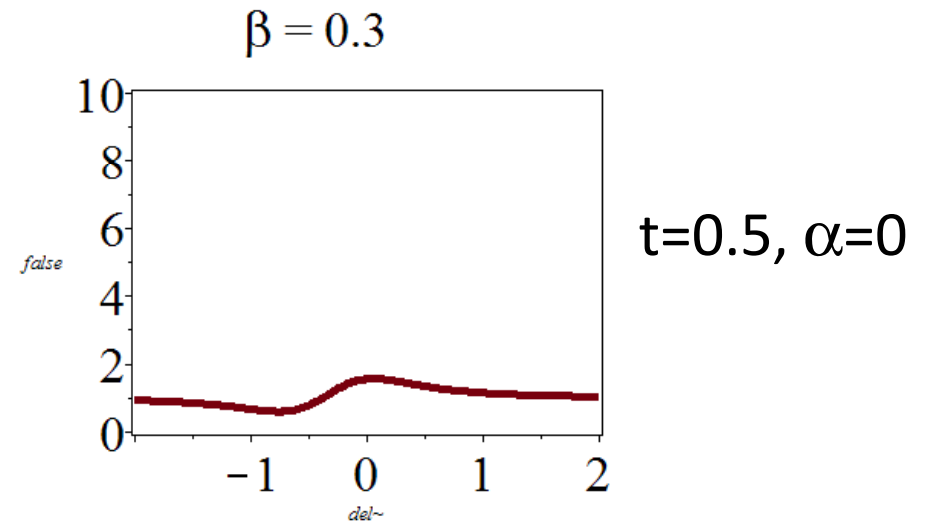
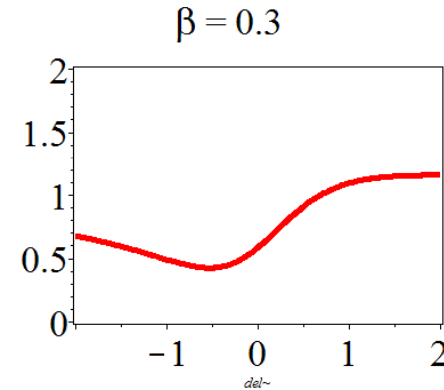
# Normalized transmission and g2

$$g_1 = \left[ 1 - \frac{2\beta(1 - \delta \tan \phi)}{1 + \delta^2 + \tilde{\alpha}} + \frac{\beta^2}{\cos^2 \phi (1 + \delta^2 + \tilde{\alpha})} \right],$$

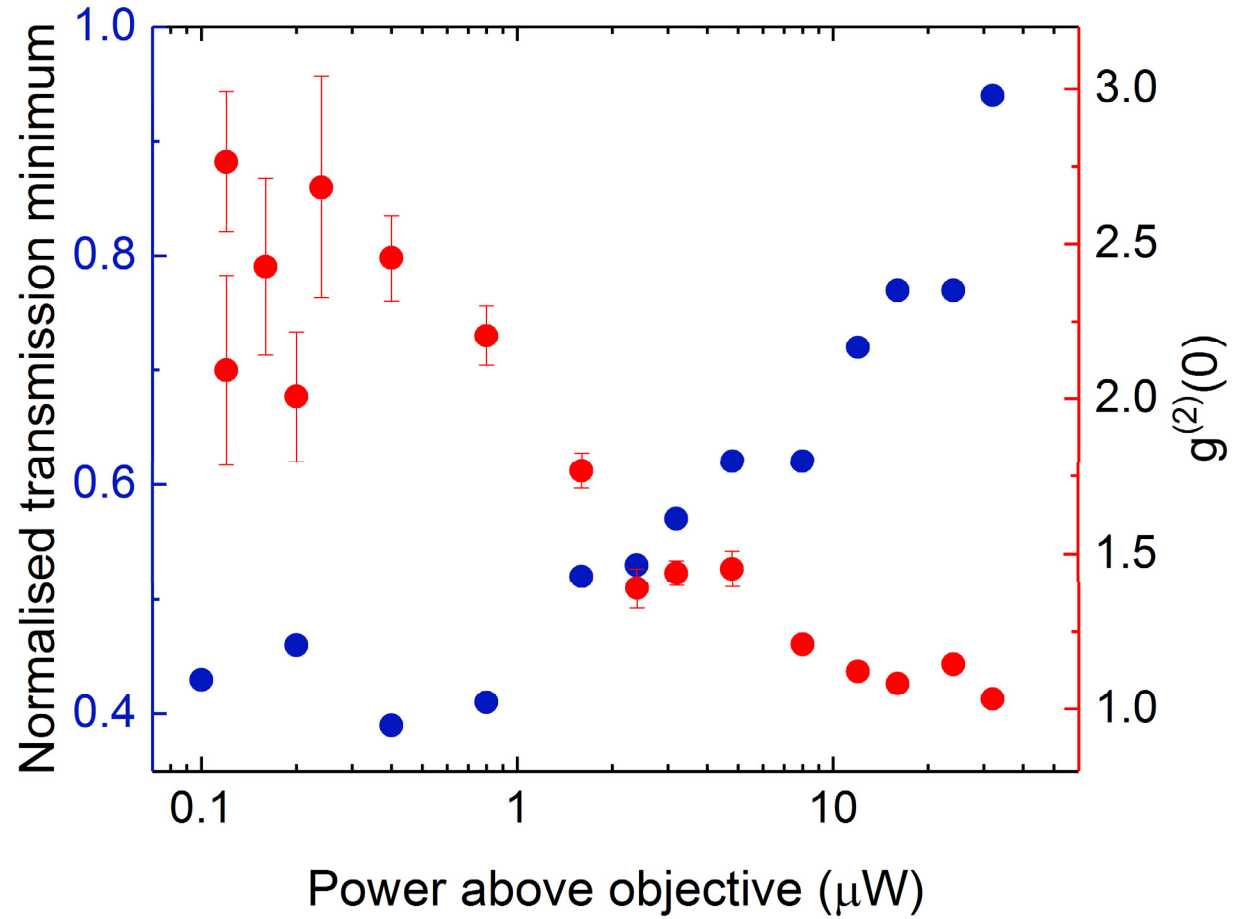
$$\tilde{\alpha} = 2\beta |\alpha|^2 / \gamma; \delta = 2(\omega - \Omega) / \gamma$$

$$g_2(0) = \frac{1}{g_1^2} \left[ 1 - \frac{4\beta(1 - \delta \tan \phi)}{1 + \delta^2 + \tilde{\alpha}} + \frac{4\beta^2}{\cos^2 \phi (1 + \delta^2 + \tilde{\alpha})} \right],$$

$$g_2(0) = \frac{g_1(2\beta)}{g_1(\beta)^2}$$



# Photon statistics power dependence

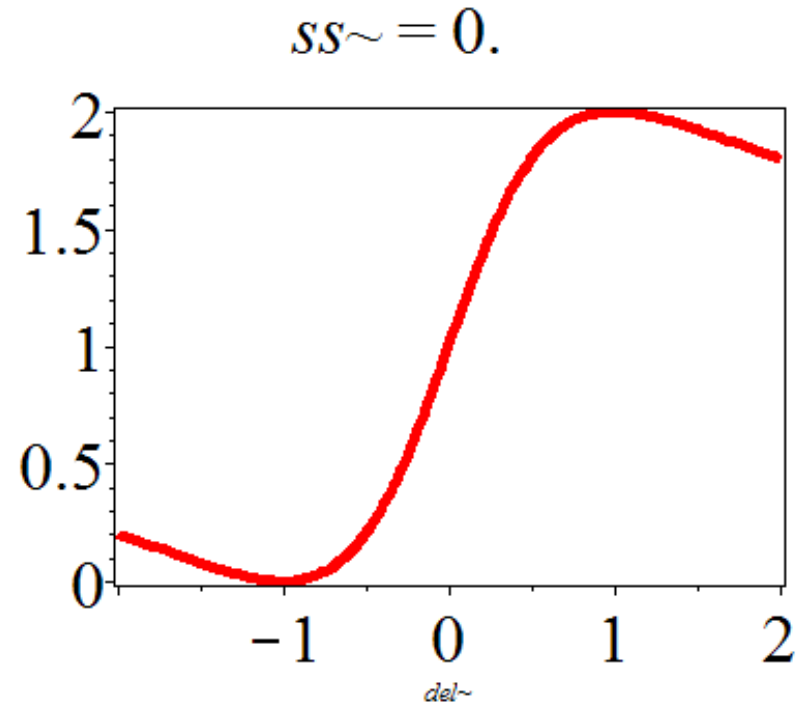


# Spectral wandering

Spectral position of quantum dot resonance “wanders” due to the thermal fluctuations. Measured is the convolution of the  $g_1$  or  $g_2$  with spectral wandering profile

$$\langle g_1 \rangle = \frac{1}{\sqrt{2\pi\sigma}} \int dz g_1(\delta + z) e^{-\frac{z^2}{\sigma^2}}$$

$$\langle g_2 \rangle = \frac{\langle g_1(2\beta) \rangle}{\langle g_1^2(\beta) \rangle}$$

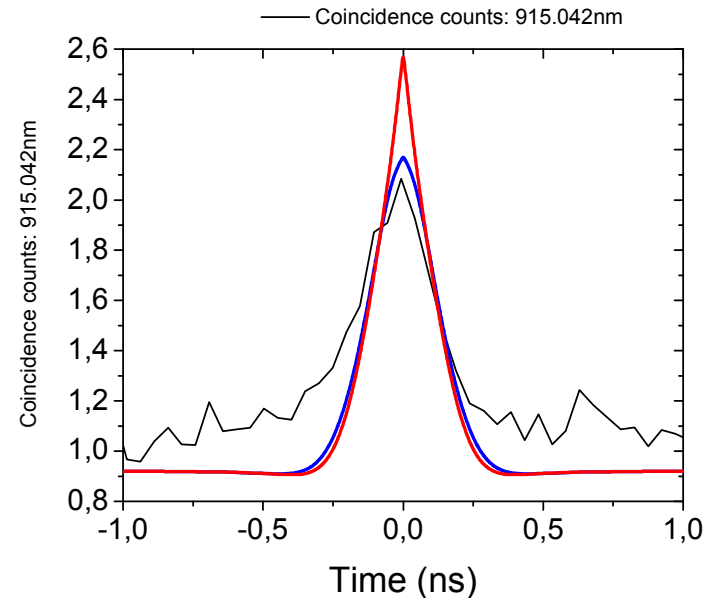
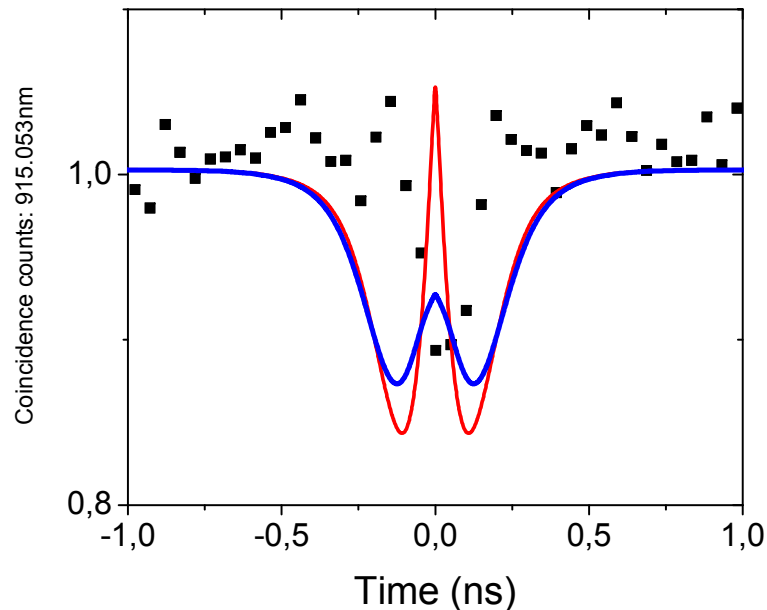


# Detector response time

Measured  $g_2(0)$  is the convolution of “real”  $g_2$  with the response function of the detector

$$g_2(0) |_{measured} = \frac{1}{\sqrt{2\pi}t_{resp}} \int d\tau g_2(\tau) e^{-\frac{\tau^2}{t_{resp}^2}}; \quad t_{resp} = 80 ps$$

$$g_2(\tau) = g_1^2 + W_2 e^{-2|\tau|} + (g_2(0) - g_1^2 - W_2) \cos(\delta\tau) e^{-\zeta|\tau|} + W_{as} \sin(\delta|\tau|) e^{-\zeta|\tau|},$$

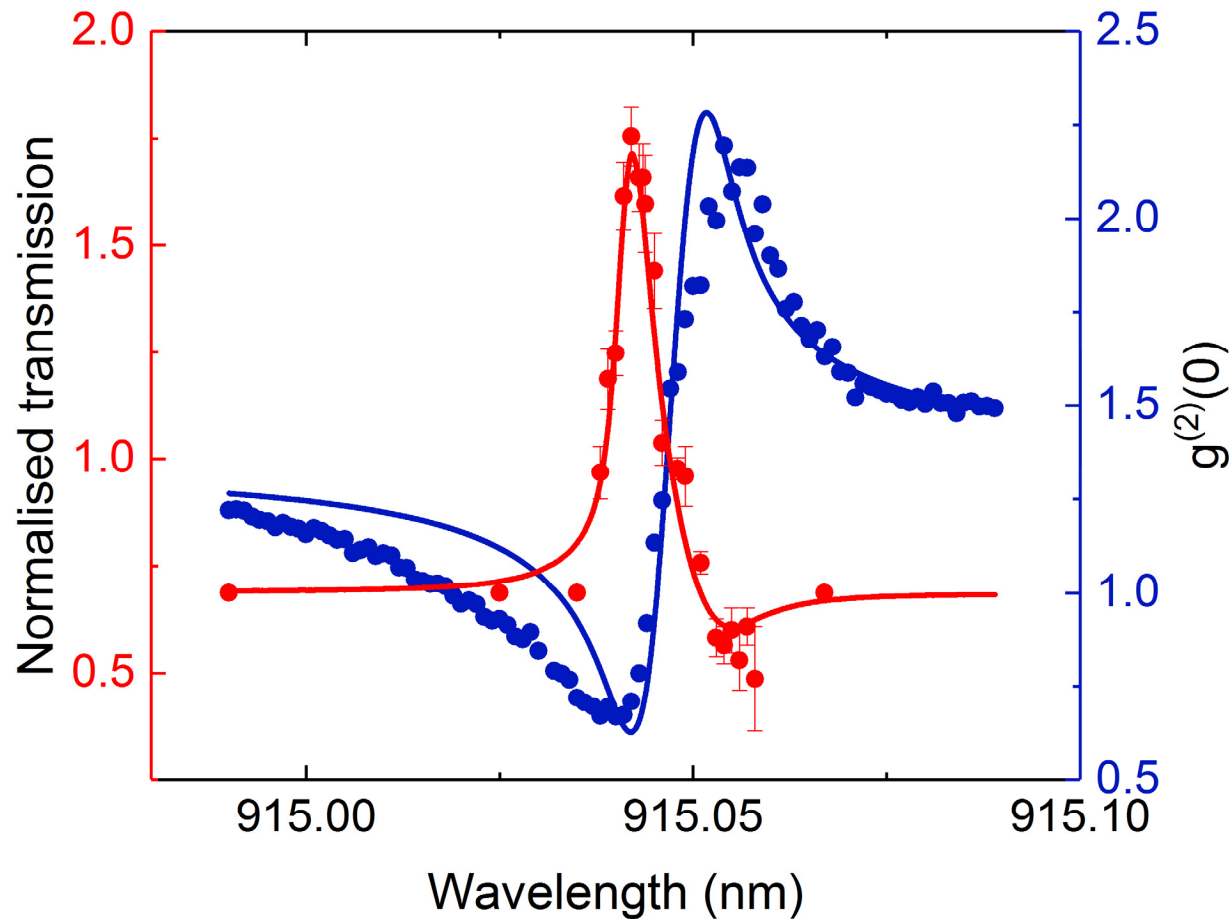


$$G^{(2)}(0) = |g^{(1)}|^2 + \frac{\beta^4}{\cos^4 \varphi (1 + \delta^2)^2} \quad \leftarrow \text{Two photon bound state}$$

$$+ \frac{2\beta^2}{\cos^4 \varphi (1 + \delta^2)^2} [\beta^2 - \cos^2 \varphi (1 - \delta^2 + 2\beta(1 - \delta \tan \varphi))$$

$$+ 2 \cos^4 \varphi (1 - \delta^2 - 2\delta \tan \varphi)] \quad \leftarrow \text{Interference term}$$

Two photon product state



Purcell-enhanced lifetime,  
 $\tau=110\text{ps}$

Pure dephasing time,  $\tau_{\text{de}}=2.1\text{ns}$

Waveguide coupling efficiency,  
 $\beta=0.95$

Spectral wandering,  $\sigma=12\mu\text{eV}$

Waveguide transmission,  $T=0.41$

## What limits the QD-photon interaction strength?

Parameter	Meaning	Effect
<b>Beta factor</b> , $\beta \sim 0.9$	QD-waveguide coupling strength	<b>Max transmission dip</b> $= (1 - \beta)^2$
<b>Spectral wandering</b> , $\sigma = 1.2 \mu\text{eV}$	Instability of charge environment	Decrease x10: $T_{\min}$ $\sim 0.03$
<b>Purcell effect</b> , $F_p \sim 1.7$	Effects intrinsic linewidth of QD	Increase x5: $T_{\min}$ $\sim 0.004$

With state-of-the-art parameters ( $\beta = 0.98$ ,  $\sigma = 0.3 \mu\text{eV}$ ,  $F_p \sim 5$ ),  
**minimum transmission  $\sim 0.02$**  (98% suppression).

**Record extinction measured for QD in single mode waveguide.**

**Very promising technique considering state of the art for QDs.**



# Motivation - controlled-phase quantum gate

Two-qubit gate – control and signal photon.

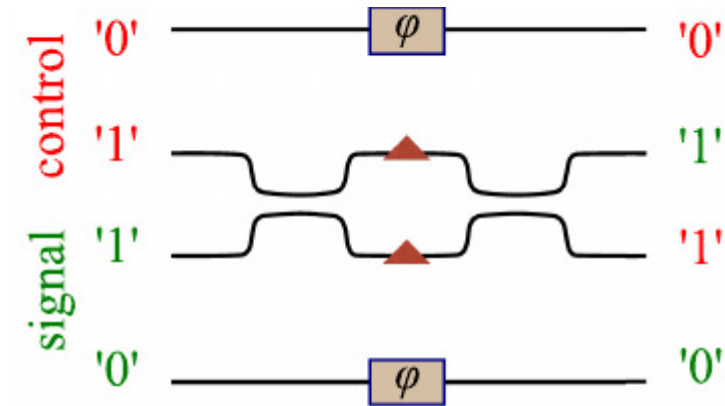
Single input photon transforms linearly.

Two photon input (one each in control and signal input arms) leads to Hong-Ou-Mandel bunching.

QD saturation means this input state transforms non-linearly.

Gate therefore performs operation:

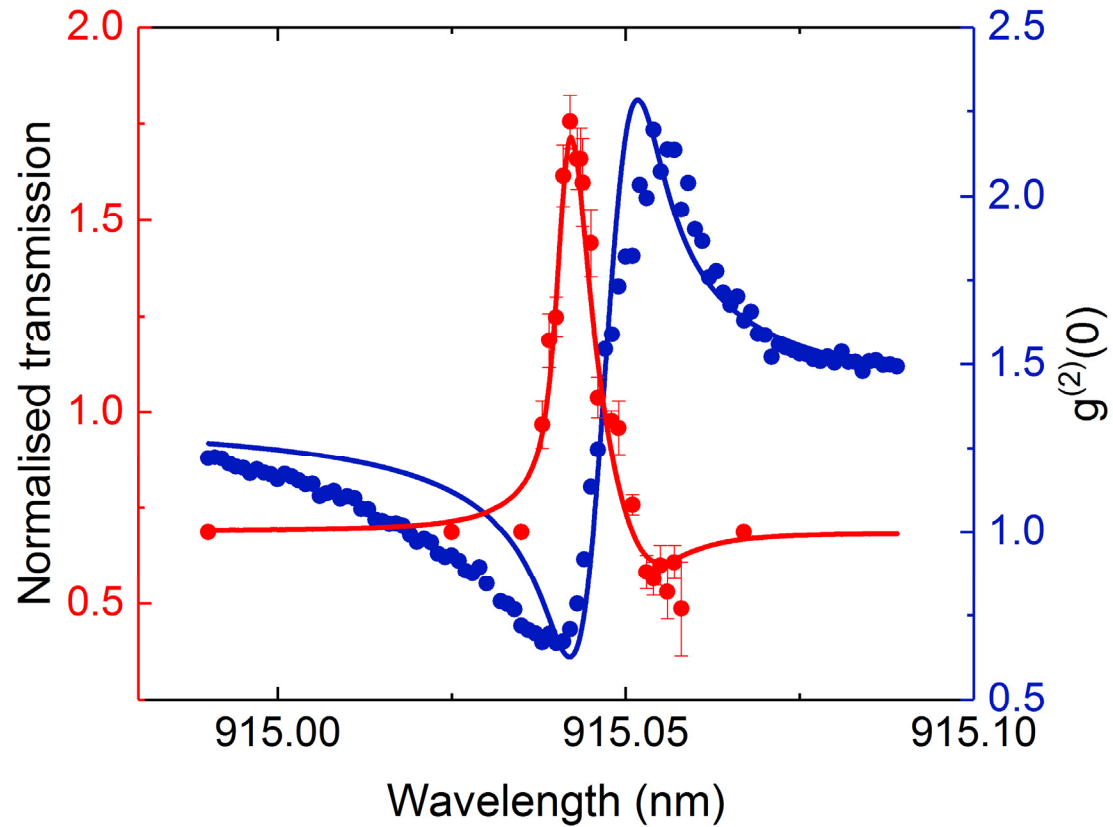
$$\begin{aligned}
 |'0_c'\rangle|'0_s'\rangle &\rightarrow |'0_c'\rangle|'0_s'\rangle \\
 |'0_c'\rangle|'1_s'\rangle &\rightarrow \exp[i\theta_s]|'0_c'\rangle|'1_s'\rangle \\
 |'1_c'\rangle|'0_s'\rangle &\rightarrow \exp[i\theta_c]|'1_c'\rangle|'0_s'\rangle \\
 |'1_c'\rangle|'1_s'\rangle &\rightarrow \exp[i\theta_c+i\theta_s+i\pi]|'1_c'\rangle|'1_s'\rangle
 \end{aligned}$$



Phys. Rev. A (2017) **95**,  
062304

# Summary

Tuning photon statistics on-chip



- Used Fano interference to 'target' specific Fock state of classical coherent source
- Bunching or antibunching generated by the same QD
- Measured record bunching for a QD in a waveguide

# Acknowledgements

## Fabrication and experiment

- Andrew Foster
- Daniel Hallett
- Ben Royal

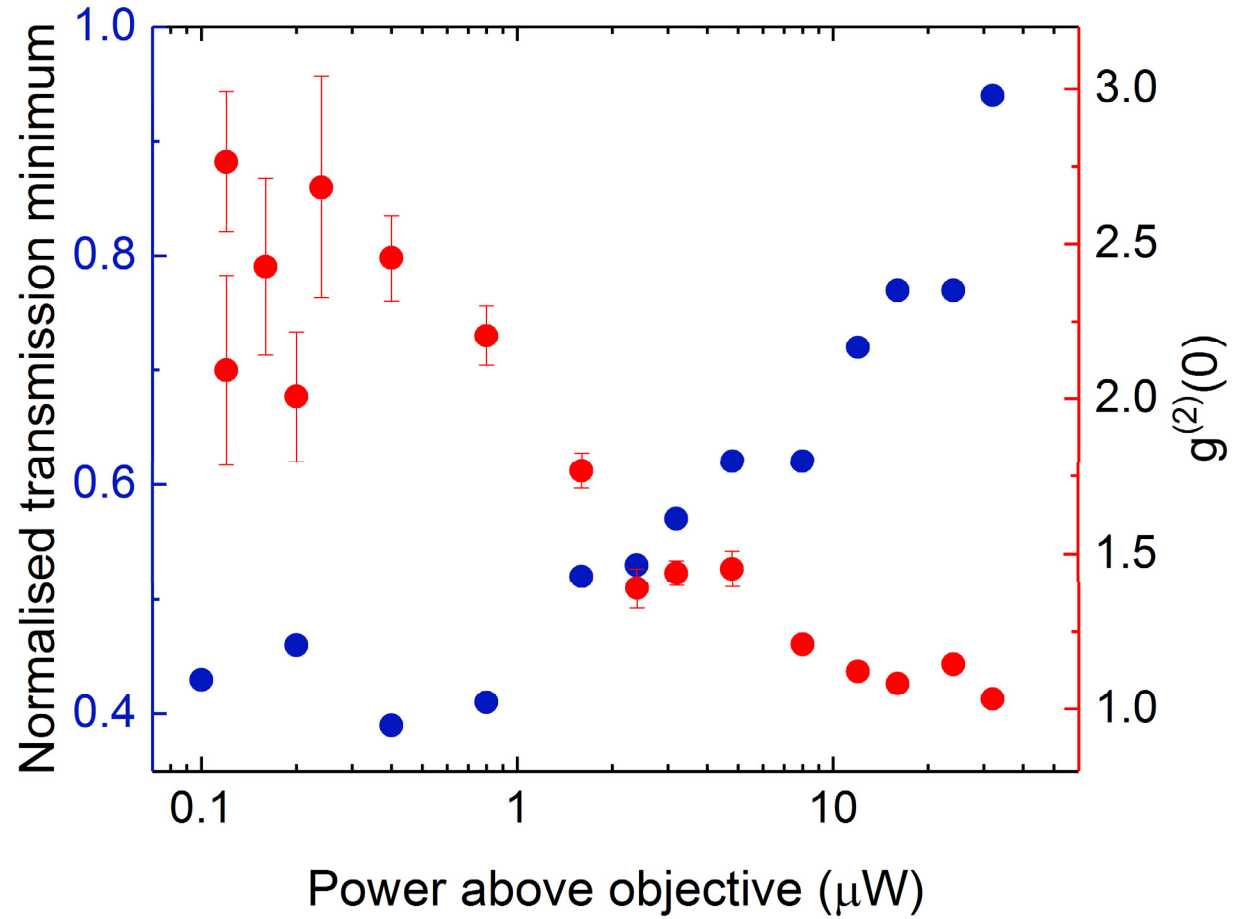


## Modelling

- Daniil Kornovan

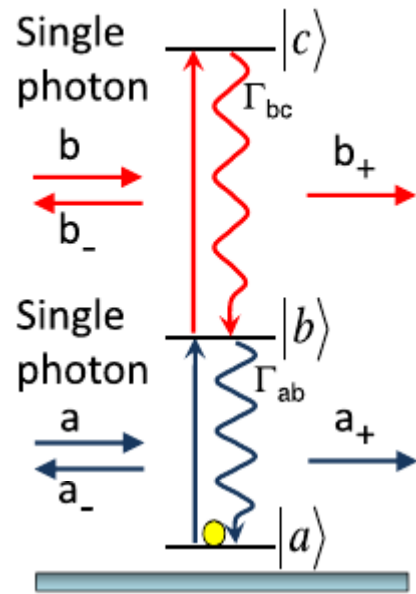


# Photon statistics power dependence



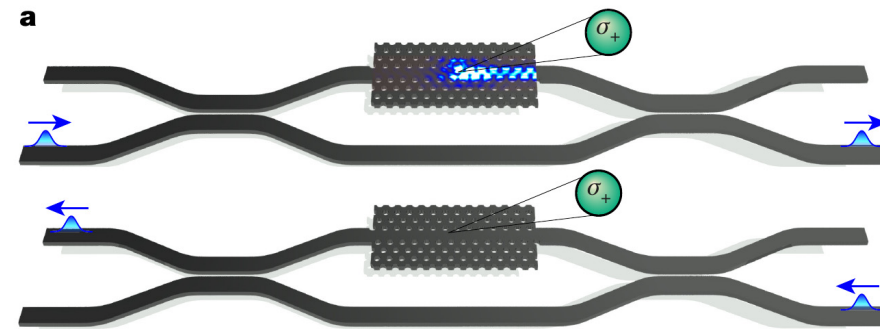
# Motivation: QD-photon interactions

Switching using a single control photon



P. Kolchin *et al.* Phys. Rev. Lett. (2011) **106**, 113601

Single photon optical circulator



P. Lodahl *et al.* Nature (2017) **531**, 473

# Still not a good fit!!

Measured lifetime – 190 ps!  
Fitting results in 110 ps! Why?

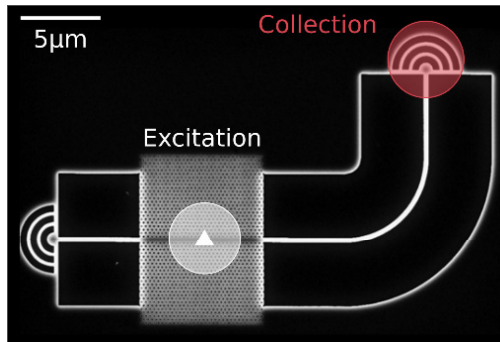
Question to ask for a theoretician: “What exactly do they measure?”

# Still not a good fit!!

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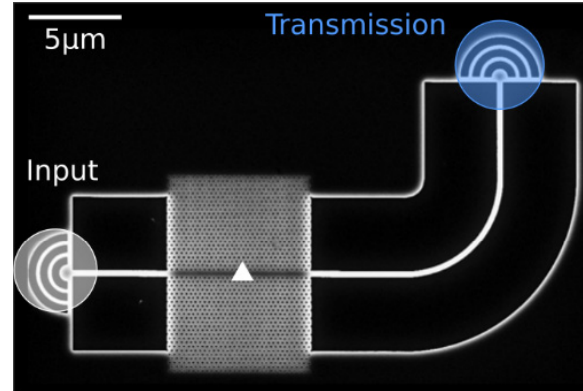
Question to ask for a theoretician: “What exactly do they measure?”

Lifetime measurements:  
excitation from the top



Lateral dipole

g2 measurements:  
Excitation by a waveguide mode



Tilted dipole

Different Purcell  $F$  factors for different  
Dipole orientations

$$\frac{F_{\text{tilted}}}{F_{\text{lateral}}} \approx 1.6, \text{ lifetime} - 119 \text{ ps}$$