



НАЦИОНАЛЬНЫЙ ИССЛЕДОВАТЕЛЬСКИЙ  
УНИВЕРСИТЕТ



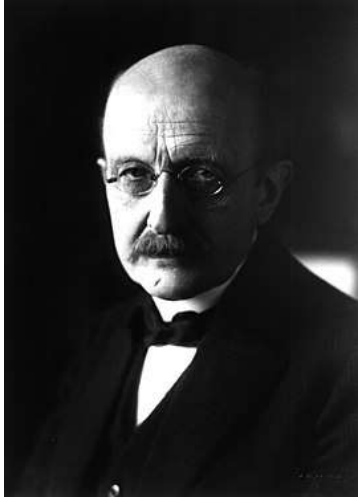
# Статистика излучения и экспериментальные методы ее определения

Антон Гритченко

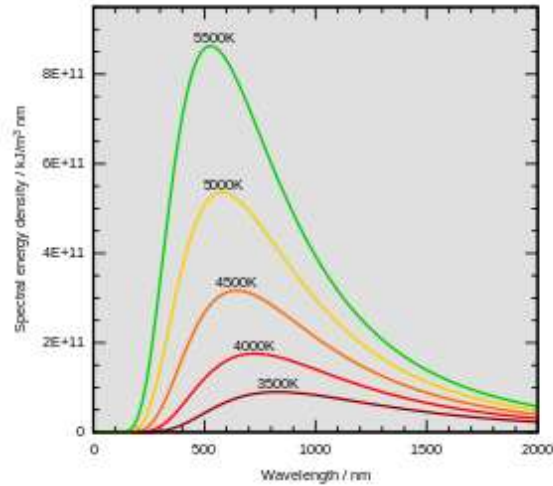
Семинар НУГ «Квантовая оптика и нанофотоника»

ИСАН, Троицк, 28.02.2019г.

# Важность измерения статистики света



Распределение Планка

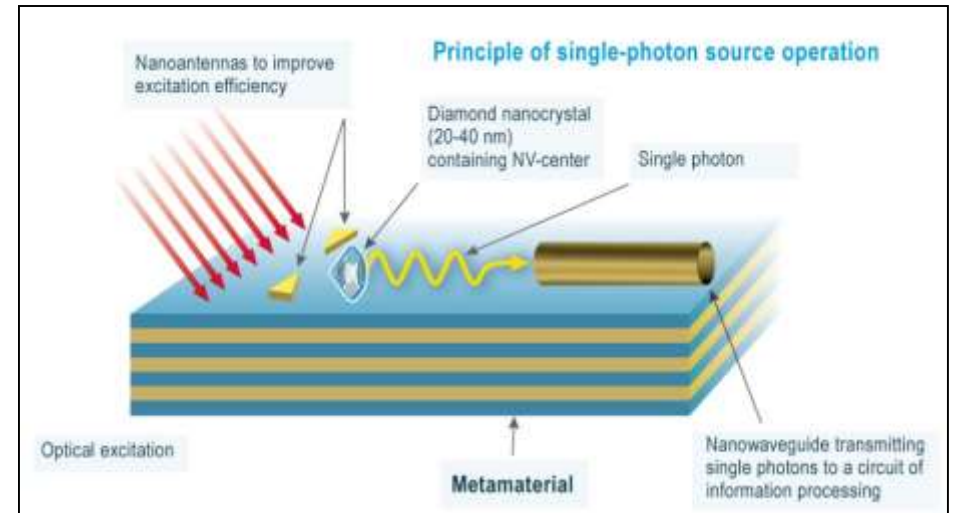
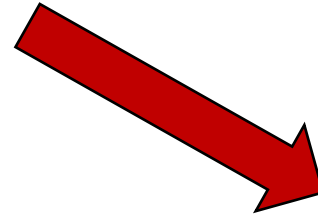


Источник хаотического излучения (лампочка)

М. Планк, 1900



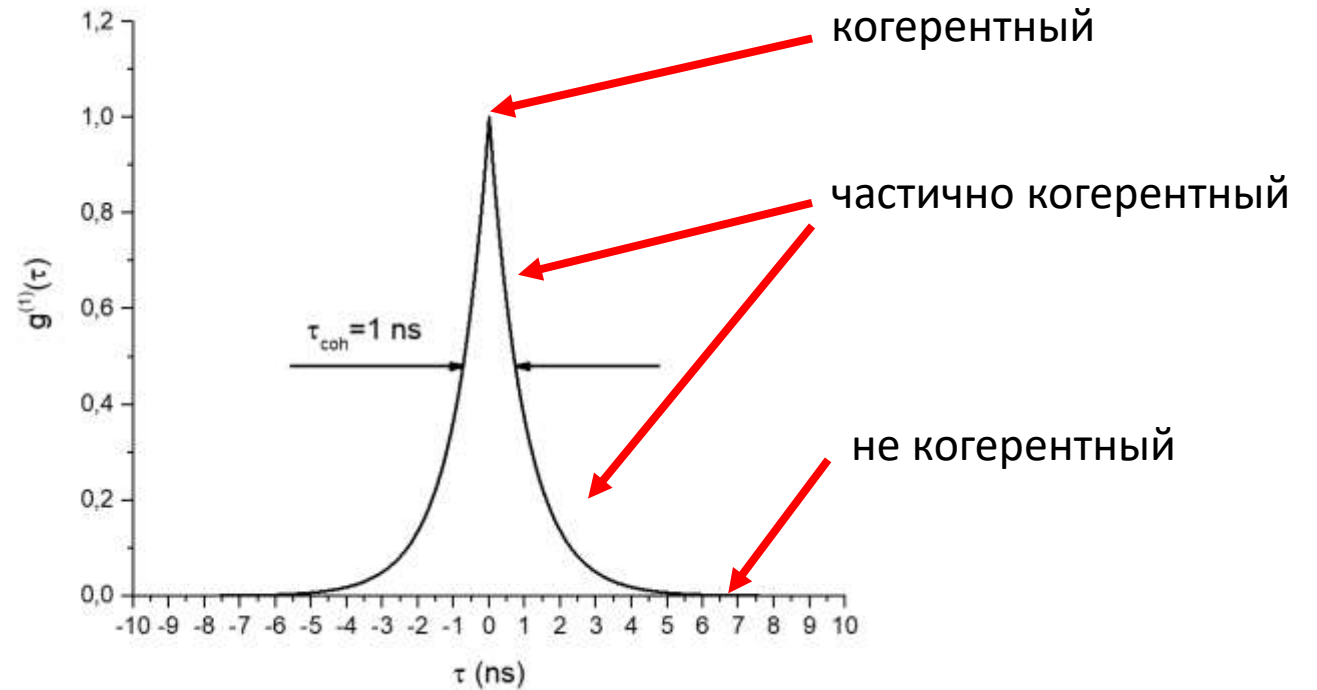
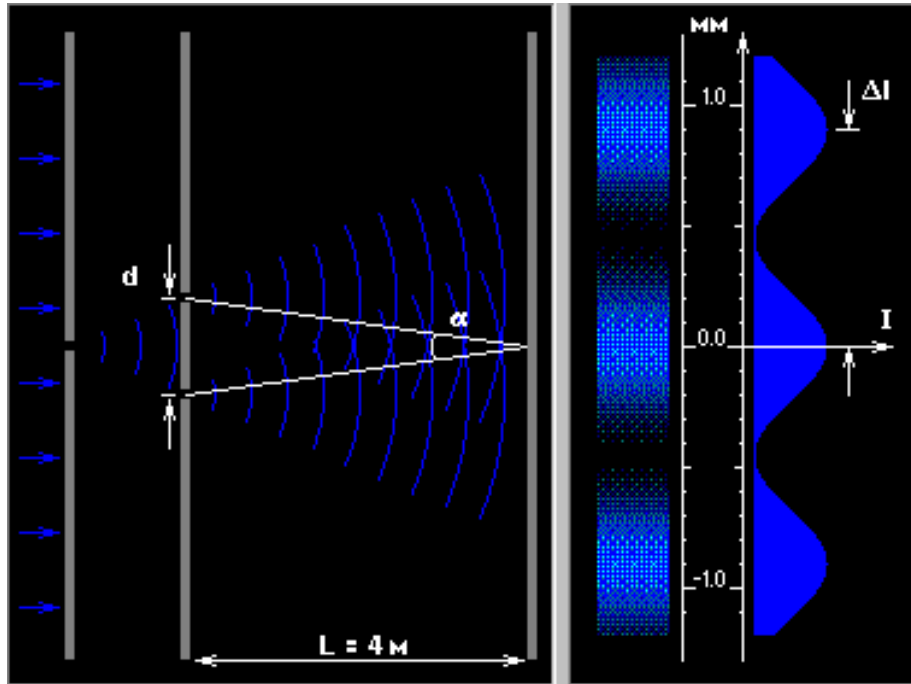
Лазер на красителе



Однофотонные источники

# Интерференция и когерентность света

Опыт Юнга

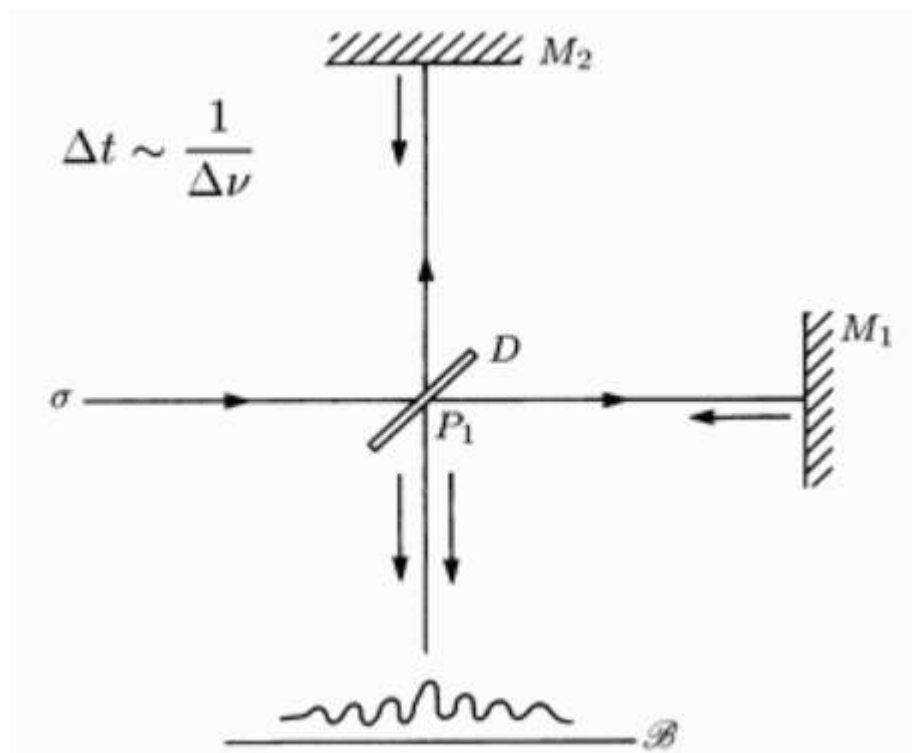


$$g^{(1)}(r_1, t_1, r_2, t_2) = \frac{|\langle E^*(r_1, t_1)E(r_2, t_2) \rangle|}{(\langle |E(r_1, t_1)|^2 \rangle \langle |E(r_2, t_2)|^2 \rangle)^{\frac{1}{2}}} - \text{функция когерентности первого порядка}$$

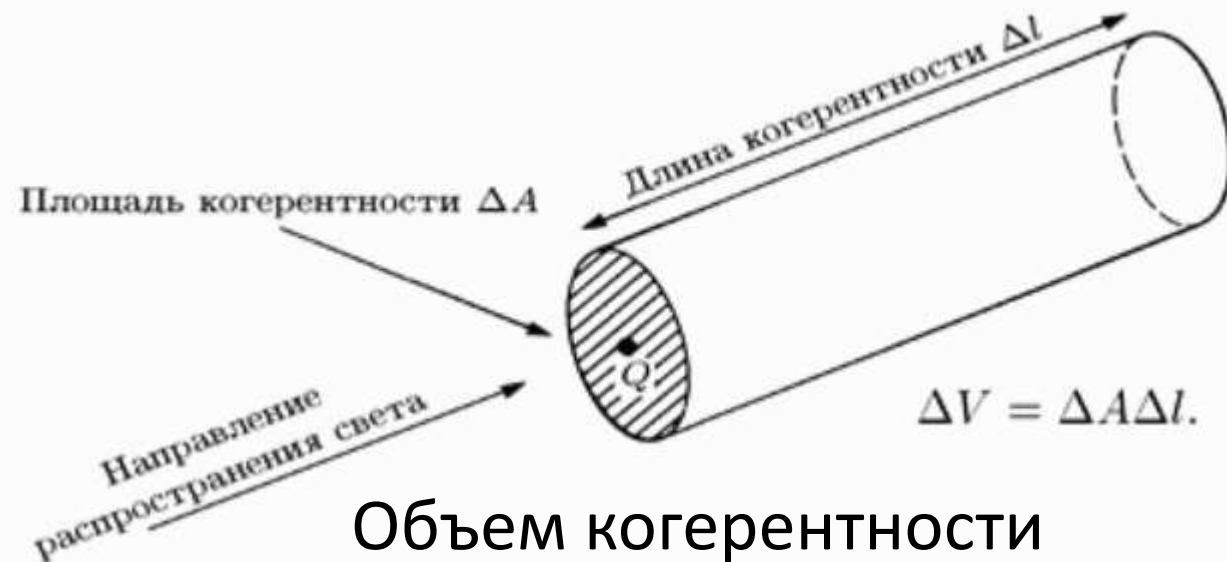
$$\langle E^*(r_1, t_1)E(r_2, t_2) \rangle = \lim_{T \rightarrow \infty} \left\{ \frac{1}{T} \int_0^T E^*(r_1, t_1)E(r_2, t_2) dt_1 \right\}$$

$$\bar{I}(r) = \frac{1}{2} \epsilon_0 c \{ |u_1|^2 \langle |E(r_1, t_1)|^2 \rangle + |u_2|^2 \langle |E(r_2, t_2)|^2 \rangle + 2u_1^* u_2 \text{Re} \langle E^*(r_1, t_1)E(r_2, t_2) \rangle \}$$

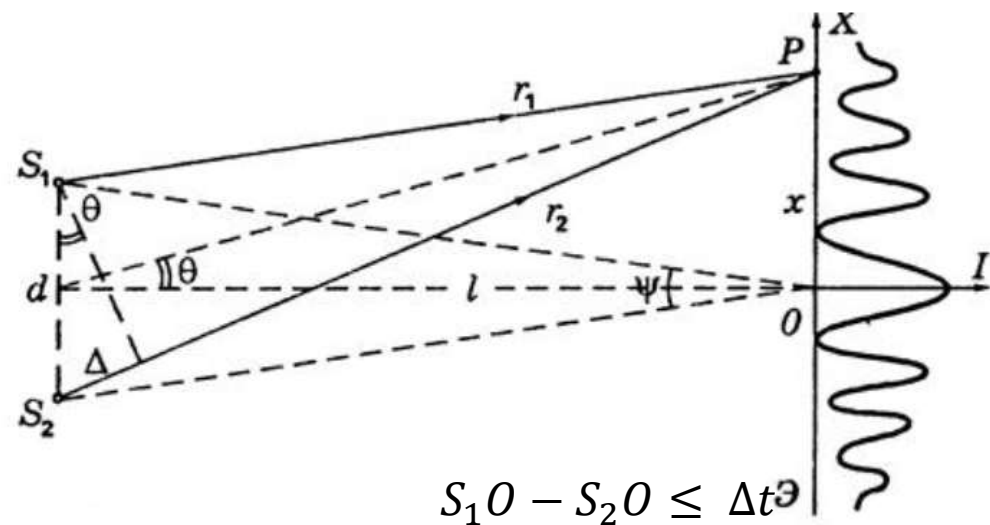
# Когерентность света



Временная когерентность



Объем когерентности



Пространственная когерентность

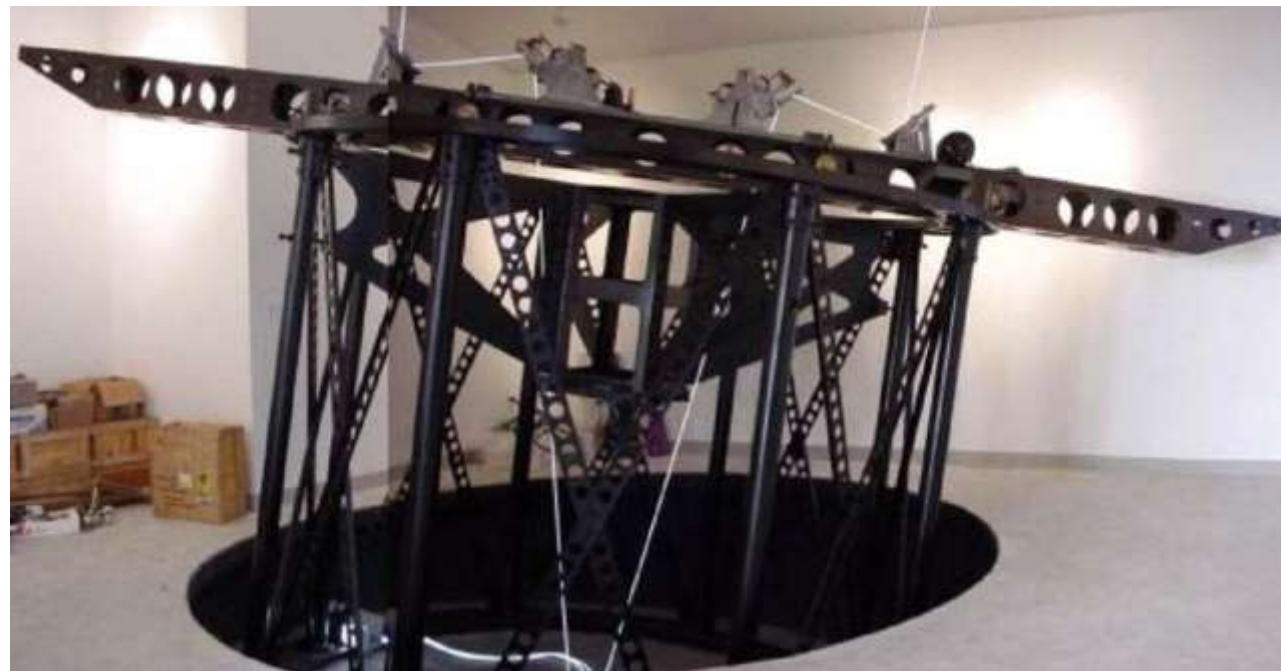
# Звездный интерферометр Майкельсона



А. Майкельсон



И. Физо

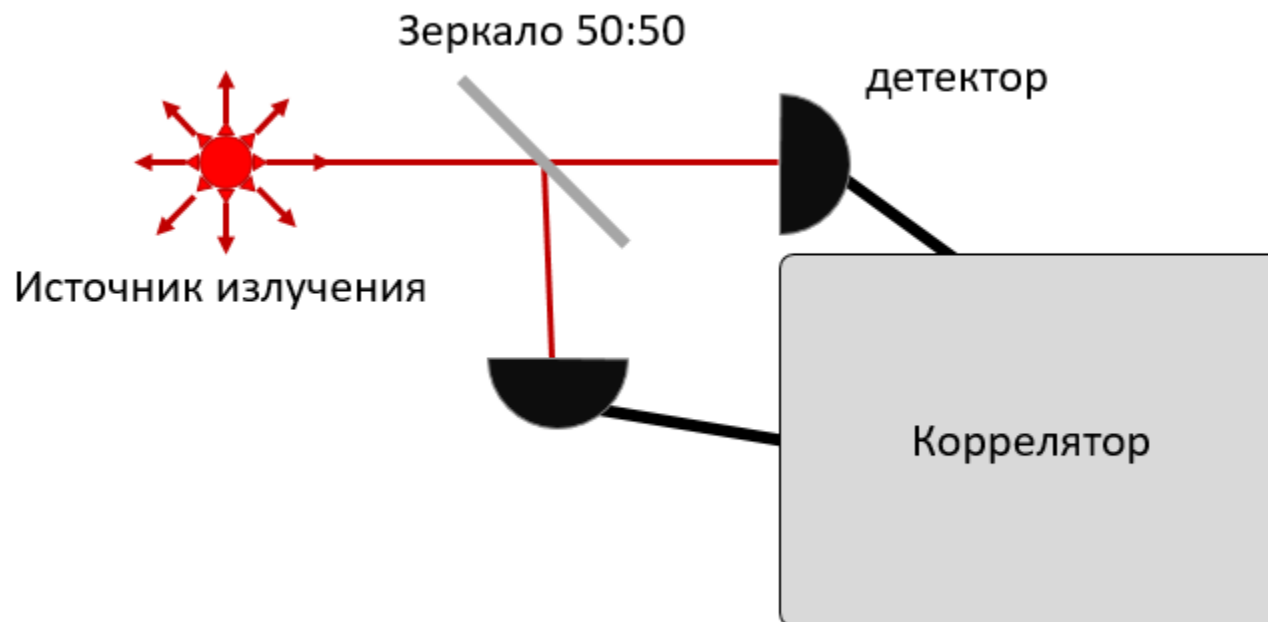


A. A. Michelson and F. G. Pease, *Astrophysical J.* 51, p249 (1920)

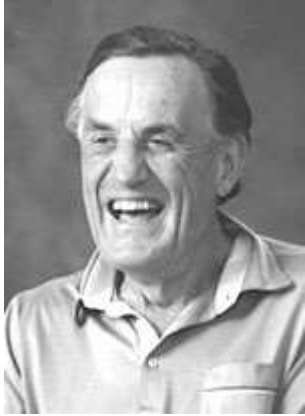
# Когерентность второго порядка

$$g^{(2)}(r_1, t_1, r_2, t_2; r_2, t_2, r_1, t_1) = \frac{\langle E^*(r_1, t_1)E^*(r_2, t_2)E(r_1, t_1)E(r_2, t_2) \rangle}{\langle |E(r_1, t_1)|^2 \rangle \langle |E(r_2, t_2)|^2 \rangle}$$

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



# Интерферометр Хэнбери-Брауна и Твисса



R. Hanbury-Brown



R. Q. Twiss

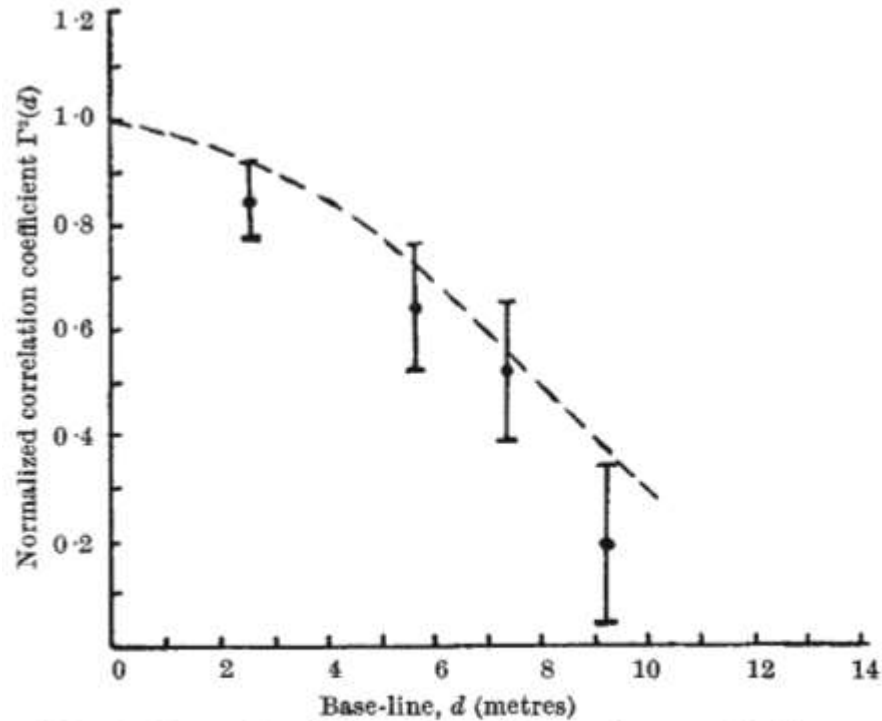


Fig. 2. Comparison between the values of the normalized correlation coefficient  $\Gamma^2(d)$  observed from Sirius and the theoretical values for a star of angular diameter  $0.0063''$ . The errors shown are the probable errors of the observations

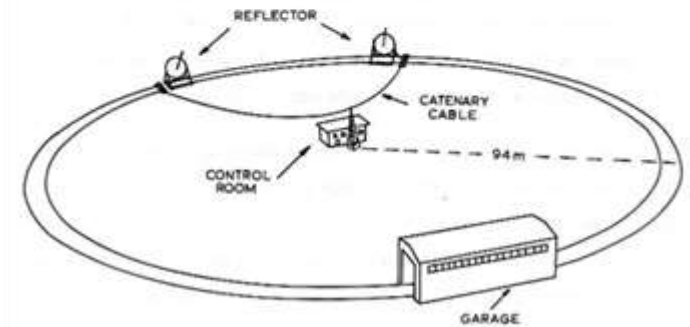
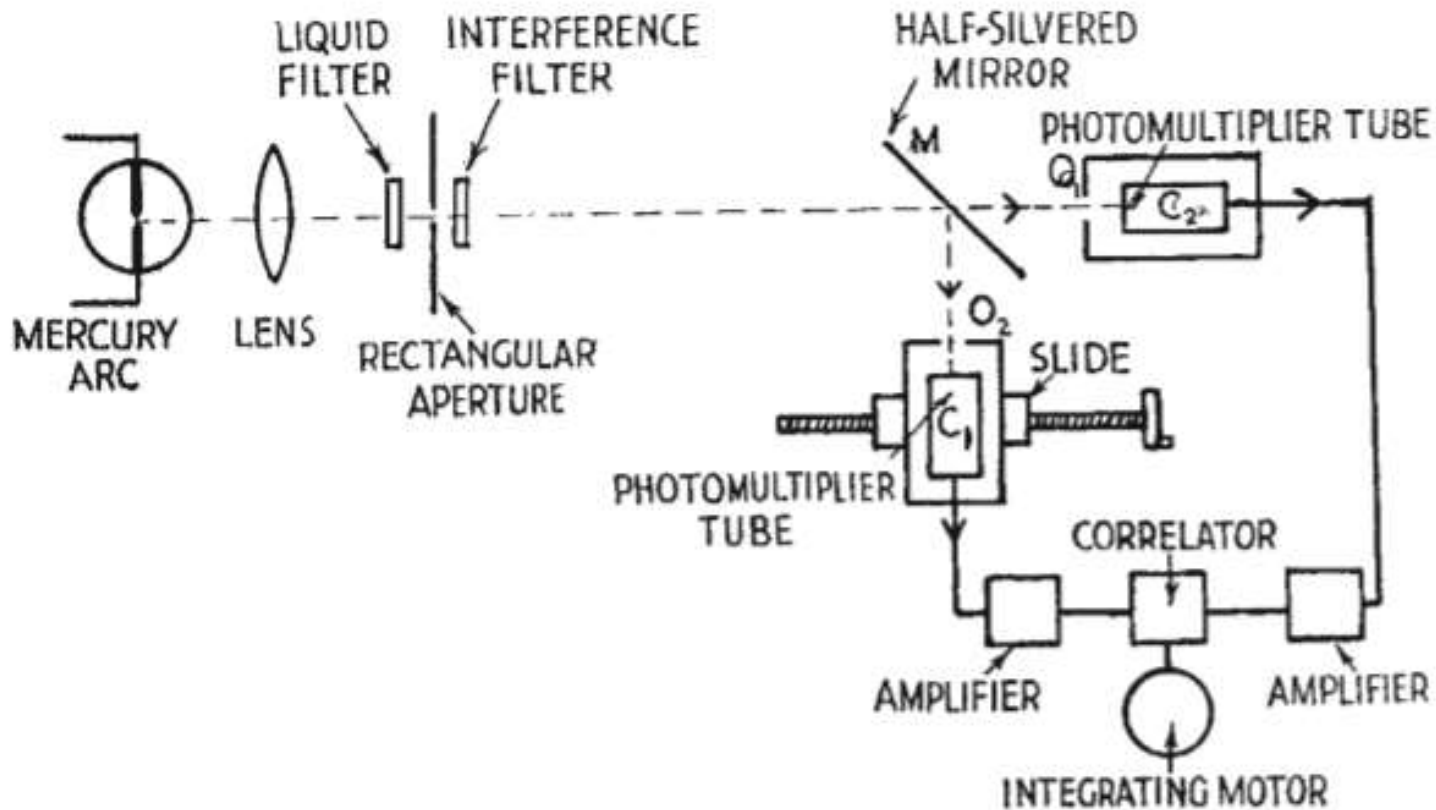


Figure 1. Aerial photo and illustration of the original HBT apparatus. They have been extracted from Ref.[1].



# Корреляции фотонов и когерентность



	Cathodes superimposed ( $d = 0$ )		Cathodes separated ( $d = 2a = 1.8 \text{ cm.}$ )	
	Experimental ratio of correlation to r.m.s. deviation $S_e(0)/N_e$	Theoretical ratio of correlation to r.m.s. deviation $S(0)/N$	Experimental ratio of correlation to r.m.s. deviation $S_e(d)/N_e$	Theoretical ratio of correlation to r.m.s. deviation $S(d)/N$
1	+ 7.4	+ 8.4	- 0.4	2 0
2	+ 6.6	+ 8.0	+ 0.5	2 0
3	+ 7.6	+ 8.4	+ 1.7	2 0
4	+ 4.2	+ 5.2	- 0.3	2 0


Fig. 2. Simplified diagram of the apparatus

$$S(0) = A \cdot T \cdot b_v \cdot f\left(\frac{a_1 \theta_1 \pi}{\lambda_0}\right) \cdot f\left(\frac{a_2 \theta_2 \pi}{\lambda_0}\right) \int \alpha^2(\nu) \cdot n_0^2(\nu) \cdot d\nu$$




# Переход от классических величин к КВАНТОВЫМ

$$g^{(2)}(r_1, t_1, r_2, t_2; r_2, t_2, r_1, t_1) = \frac{\langle E^*(r_1, t_1)E^*(r_2, t_2)E(r_1, t_1)E(r_2, t_2) \rangle}{\langle |E(r_1, t_1)|^2 \rangle \langle |E(r_2, t_2)|^2 \rangle}$$


$$\mathbf{E}(\mathbf{r}) = i \sum_{\mathbf{k}, \mu} \sqrt{\frac{\hbar \omega}{2V \epsilon_0}} \left\{ \mathbf{e}^{(\mu)} a^{(\mu)}(\mathbf{k}) e^{i\mathbf{k} \cdot \mathbf{r}} - \bar{\mathbf{e}}^{(\mu)} a^{\dagger(\mu)}(\mathbf{k}) e^{-i\mathbf{k} \cdot \mathbf{r}} \right\}$$

$$n = a^{\dagger} a$$

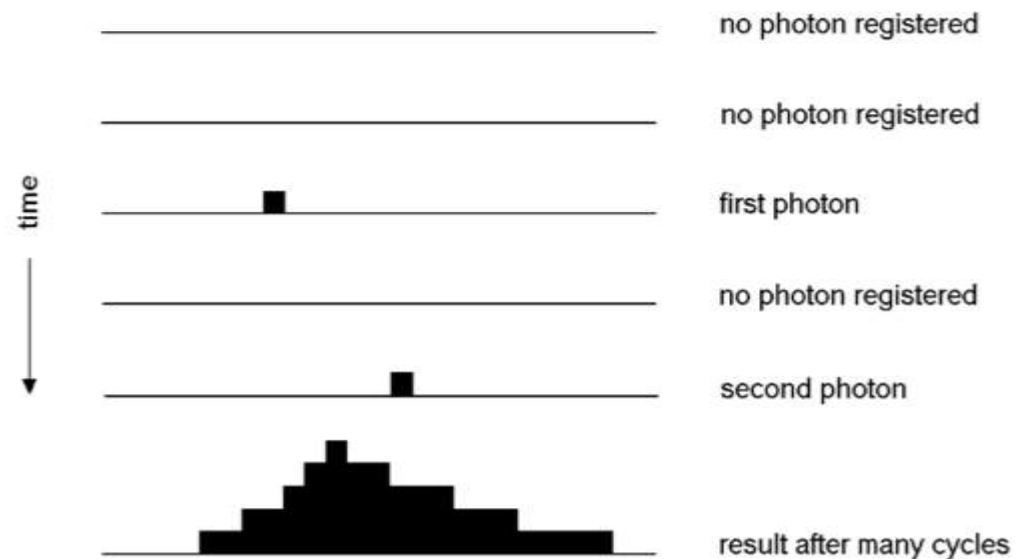
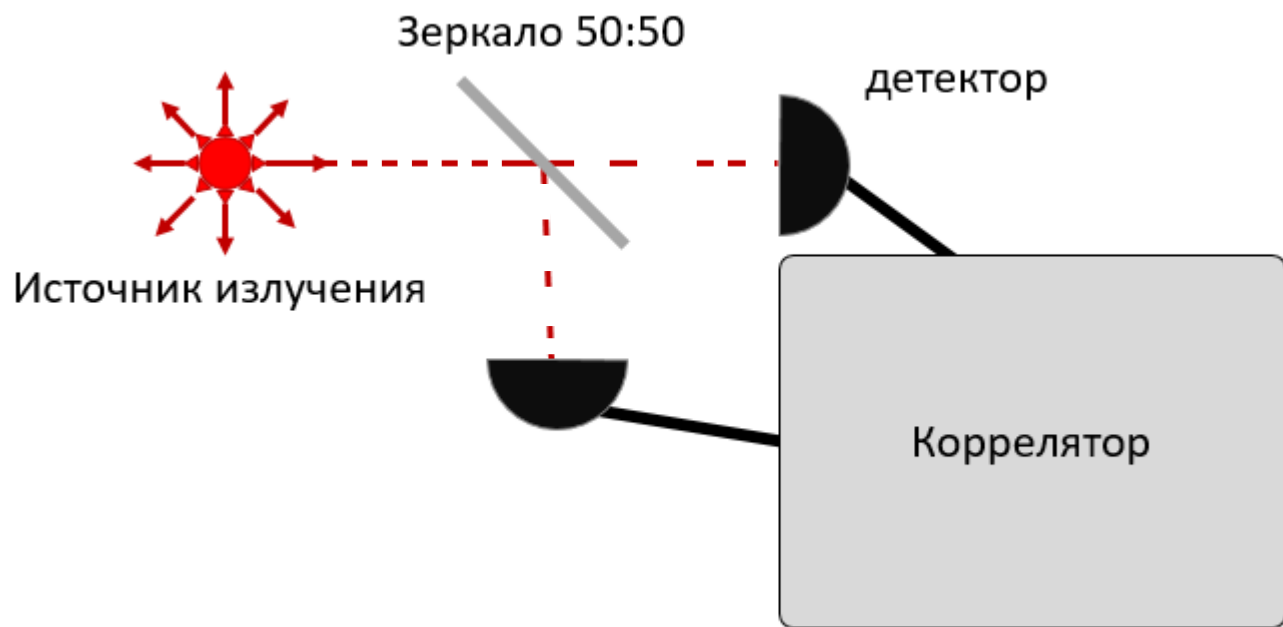

$$g^{(2)}(\tau) = \frac{\langle n_1(t) n_2(t + \tau) \rangle}{\langle n_1(t) \rangle \langle n_2(t + \tau) \rangle}$$

# Схема старт-стоп

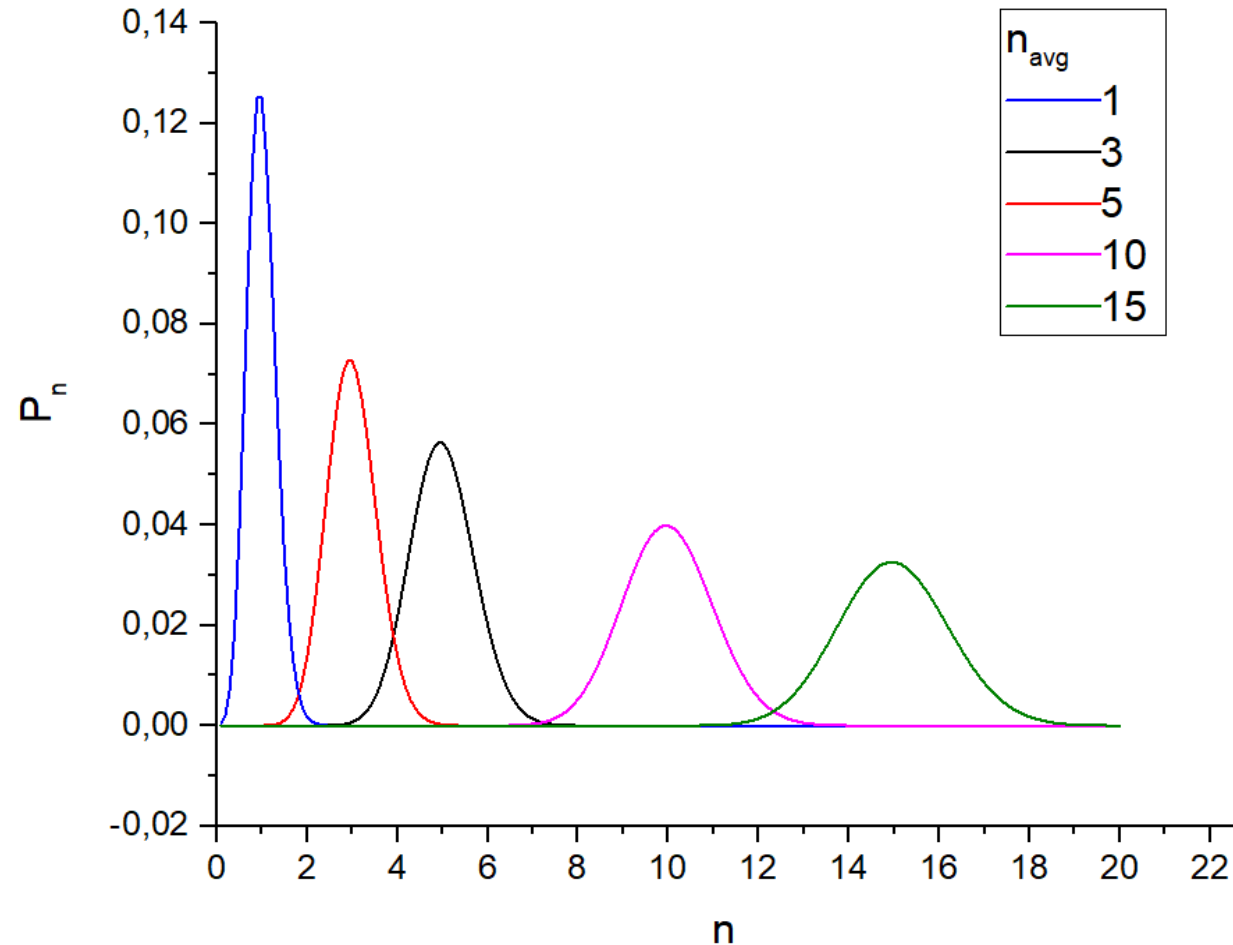
$$g^{(2)}(\tau) = \frac{\langle I(t)I(t + \tau) \rangle}{\langle I(t) \rangle \langle I(t + \tau) \rangle}$$



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



# Пуассоновская статистика излучения (лазерные источники)

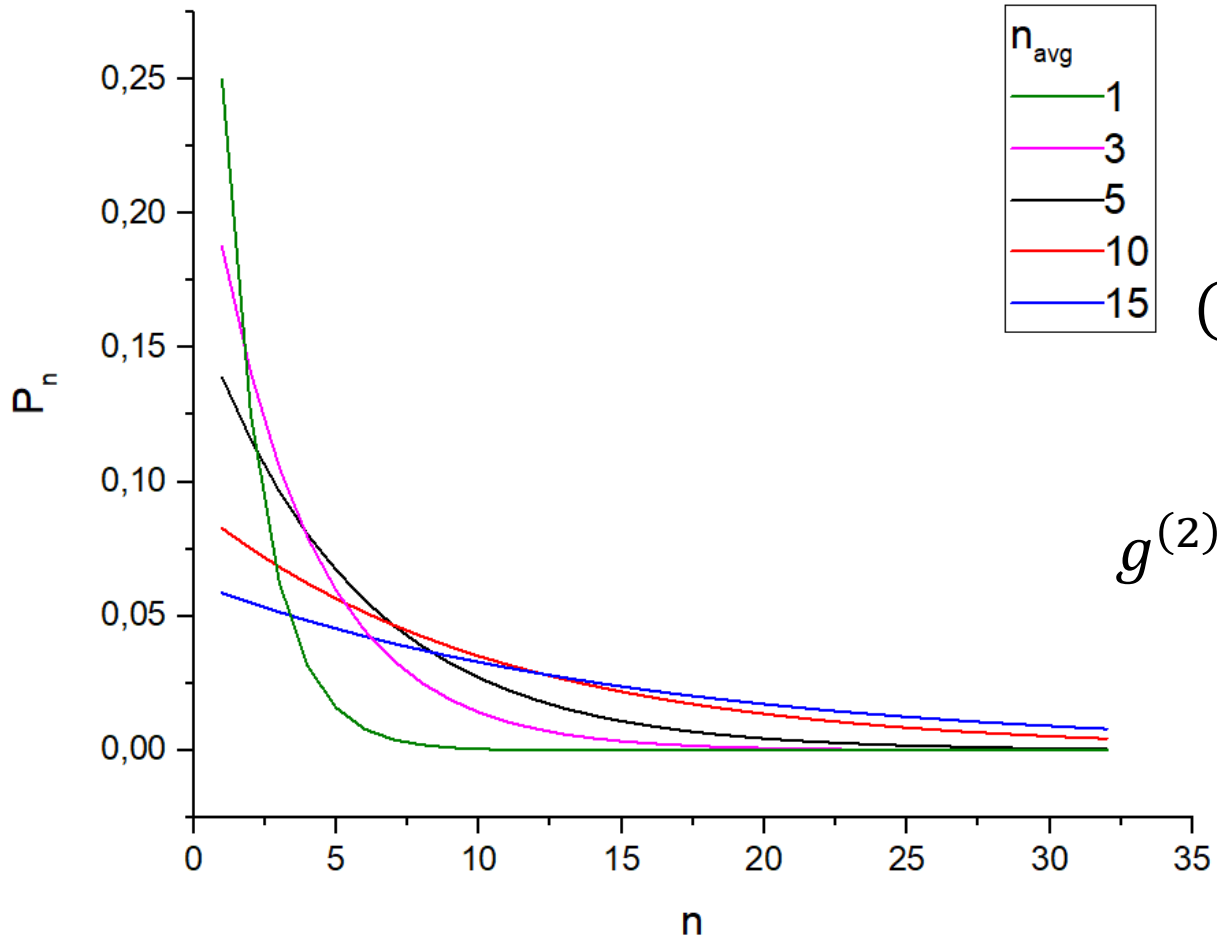


$$P_n(T) = \frac{\bar{n}^n}{n!} \exp[-\bar{n}]$$

$$(\Delta n)^2 = \bar{n}$$

$$g^{(2)} = \frac{\langle n_1 n_2 \rangle}{\bar{n}^2} = 1$$

# Хаотический источник (статистика Бозе)



$$P_n = \frac{\bar{n}^n}{(1 + \bar{n})^{1+n}}$$

$$(\Delta n)^2 = \bar{n} + \frac{\bar{n}^2}{2\gamma^2 T^2} - \{ \exp(-2\gamma T) - 1 + 2\gamma T \}$$

$$g^{(2)} = \frac{\langle n_1 n_2 \rangle}{\bar{n}^2} = 1 + (g^{(1)})^2 = 1 + \exp\left(-\frac{2|\tau|}{\tau_{coh}}\right)$$

$$\tau_{coh} \sim \frac{1}{\pi \Delta \nu}$$

# Время когерентности для различных источников

Источник	Ширина спектра	Время когерентности
Диодный лазер	1 МГц	1 мкс
Солнце	400 нм	5 фс
Светодиод	20 нм	100 фс
Rb (T=300K)	500 МГц	2 ns
Rb cooled	6 МГц	0,16 мкс

# Детекторы для измерения статистики

## Лавинные фотодиоды



**Single Photon Timing Resolution**  
 TTL Counting Output  
 NIM Timing Output (additional internal circuit board required)

	Typ	Max	
	35	250 50	ps (FWHM)

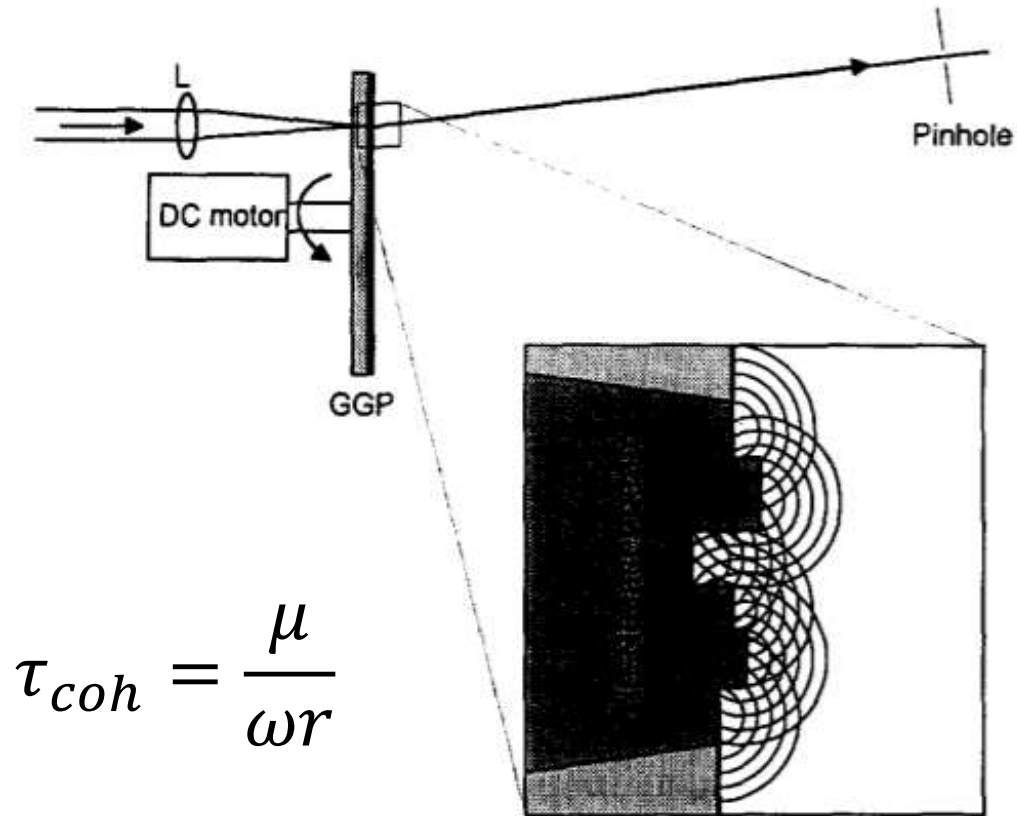


## ФЭУ

MCP-PMT Type No.	Rise Time	Fall Time	Transit Time	IRF (FWHM)
R3809U-50 (6 $\mu$ m, 2-stage MCP)	150ps	360ps	400ps	45ps
R5916U-50 (6 $\mu$ m, 2-stage MCP)	180ps	700ps	350ps	95ps
R7024U (6 $\mu$ m, 2-stage MCP)	110ps	120ps	400ps	–

Figure 10-3: External view of an MCP-PMT

# Эксперимент с матированной пластиной (псевдотепловой источник)



$$\tau_{coh} = \frac{\mu}{\omega r}$$

Постоянная сбивка фазы приводит к статистике излучения, схожей с тепловой

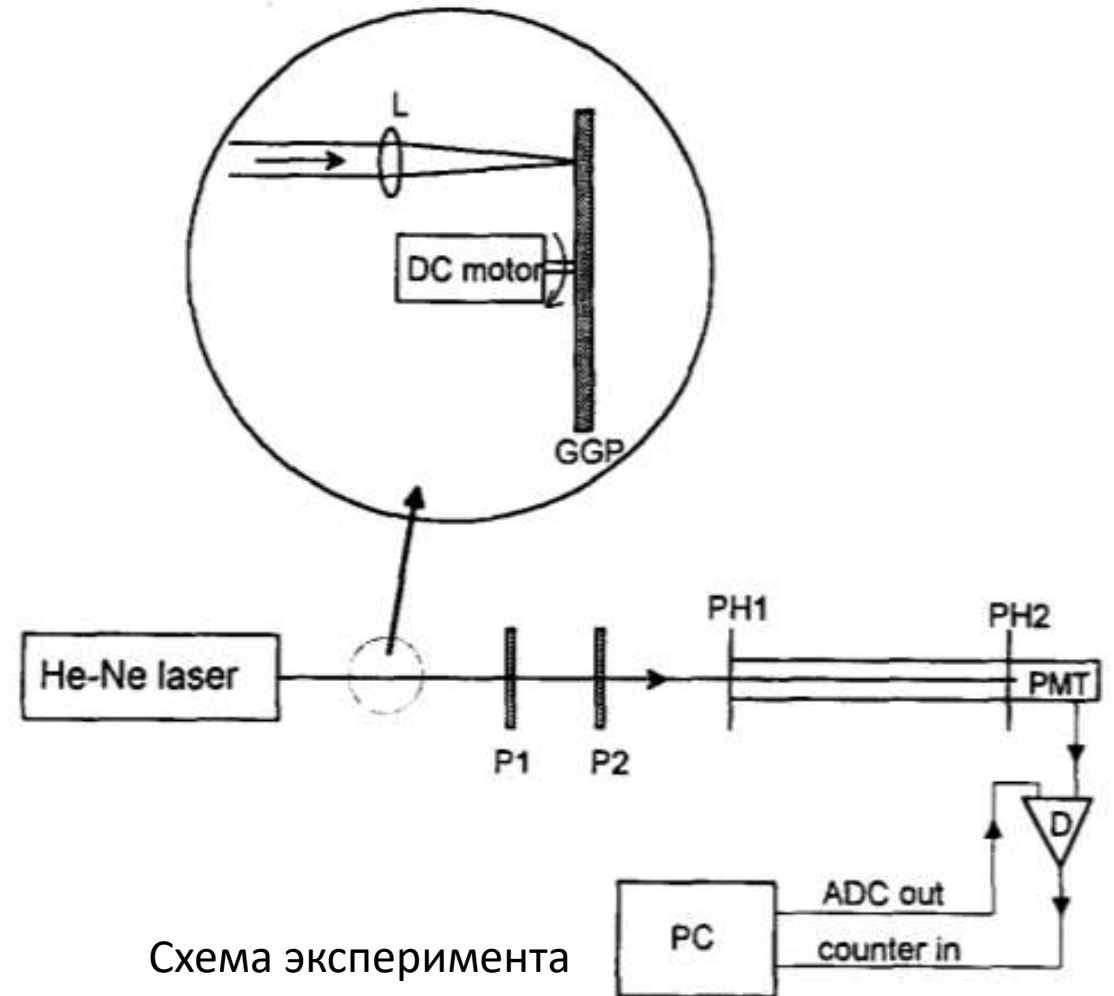


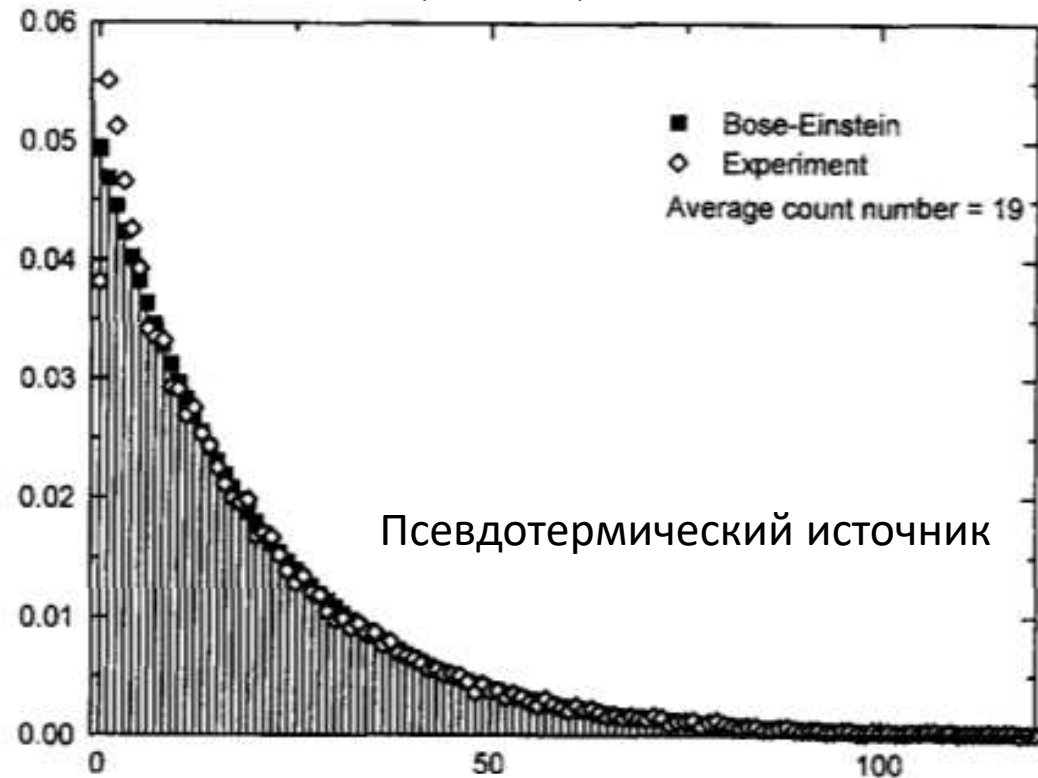
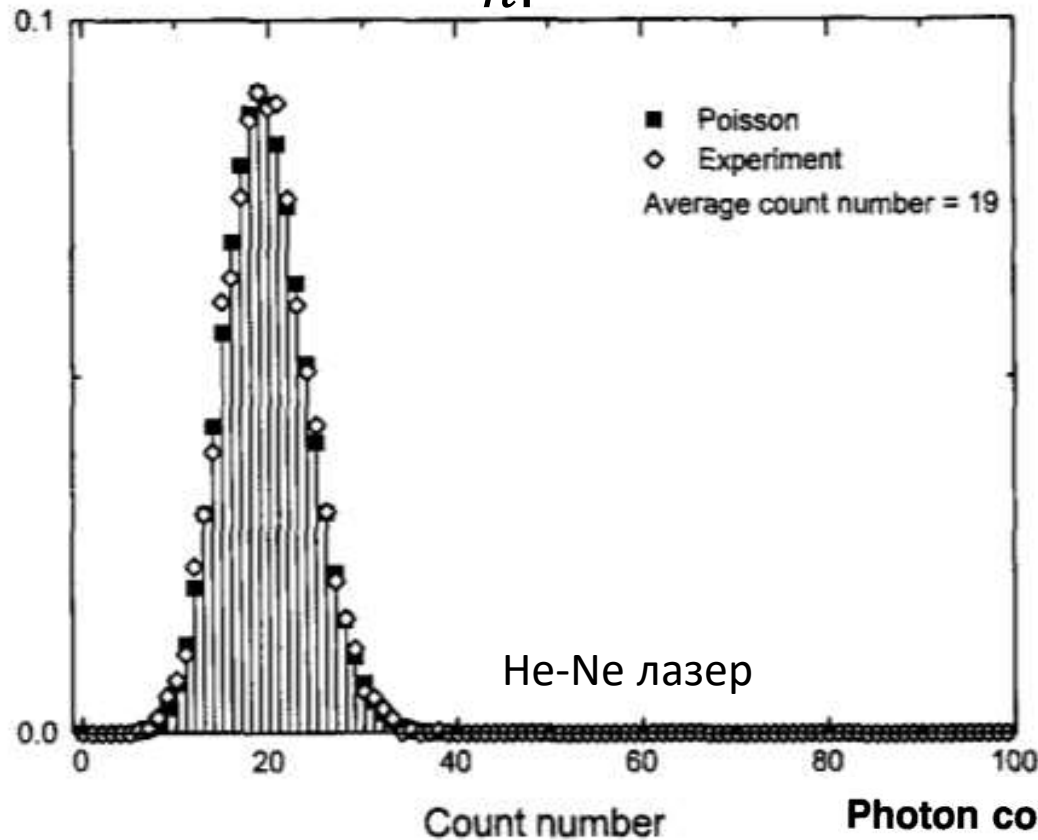
Схема эксперимента



# Эксперимент с матированной пластиной (псевдотермальным источником)

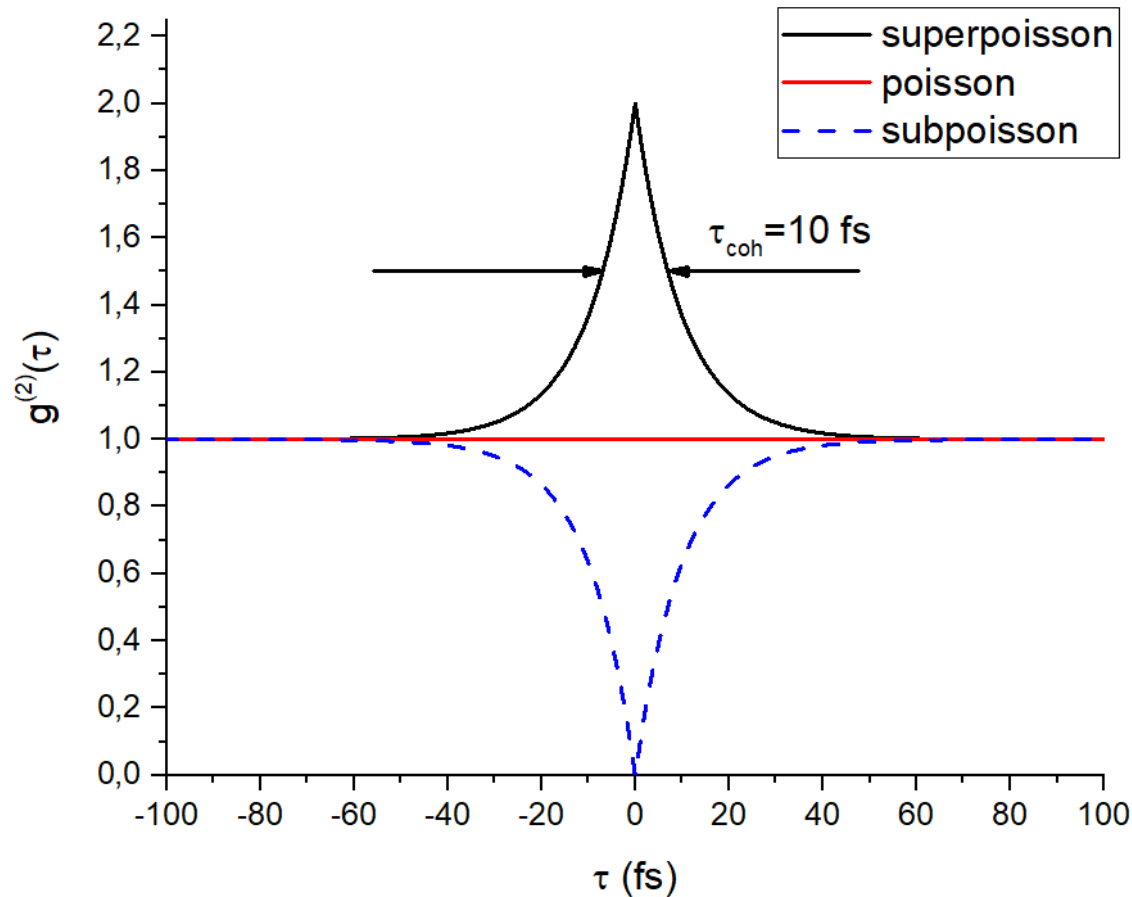
$$P_n(T) = \frac{\bar{n}^n}{n!} \exp[-\bar{n}]$$

$$P_n = \frac{\bar{n}^n}{(1 + \bar{n})^{1+n}}$$



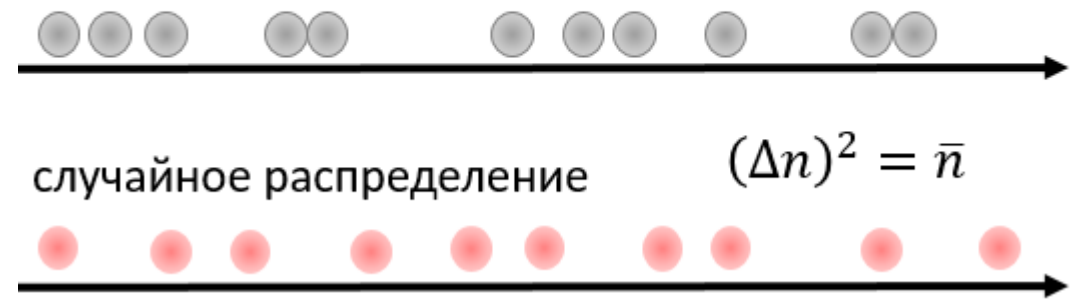
Photon counting statistics—Undergraduate experiment

# Статистика классического света

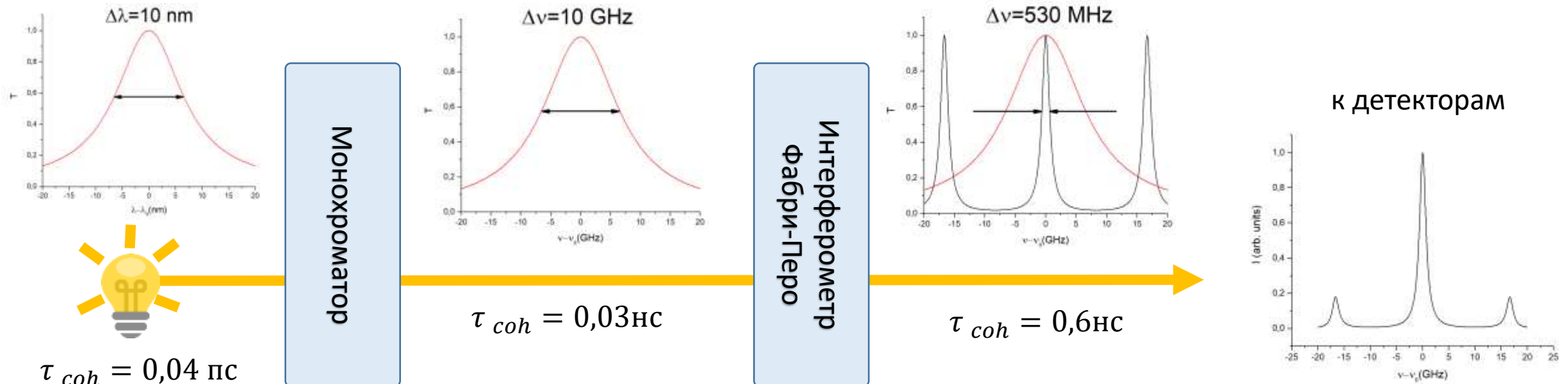


$$(\Delta n)^2 = \bar{n} + \frac{\bar{n}^2}{2\gamma^2 T^2} - \{ \exp(-2\gamma T) - 1 + 2\gamma T \}$$

Группировка

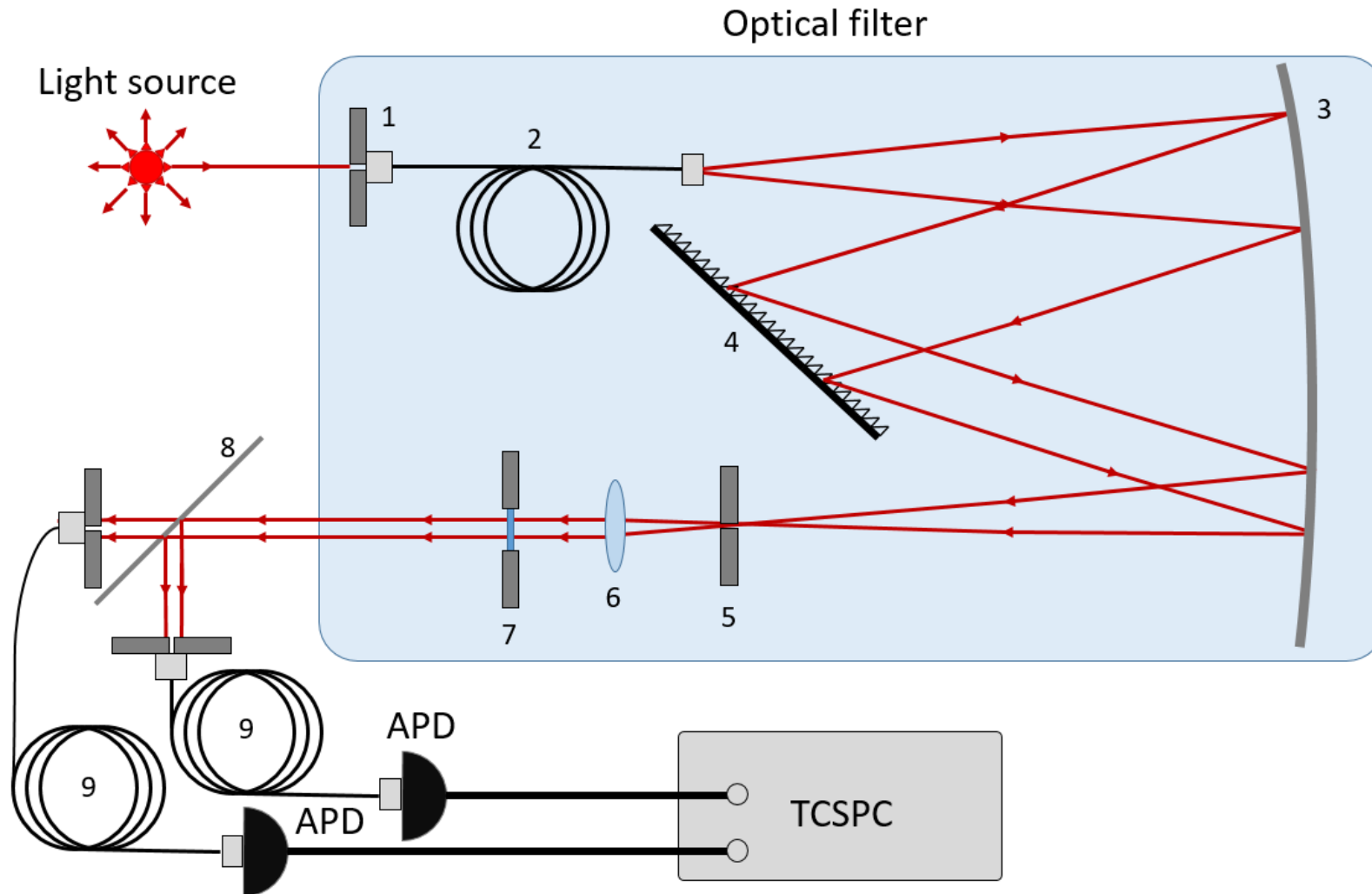


# Измерение статистики света от источника теплового излучения

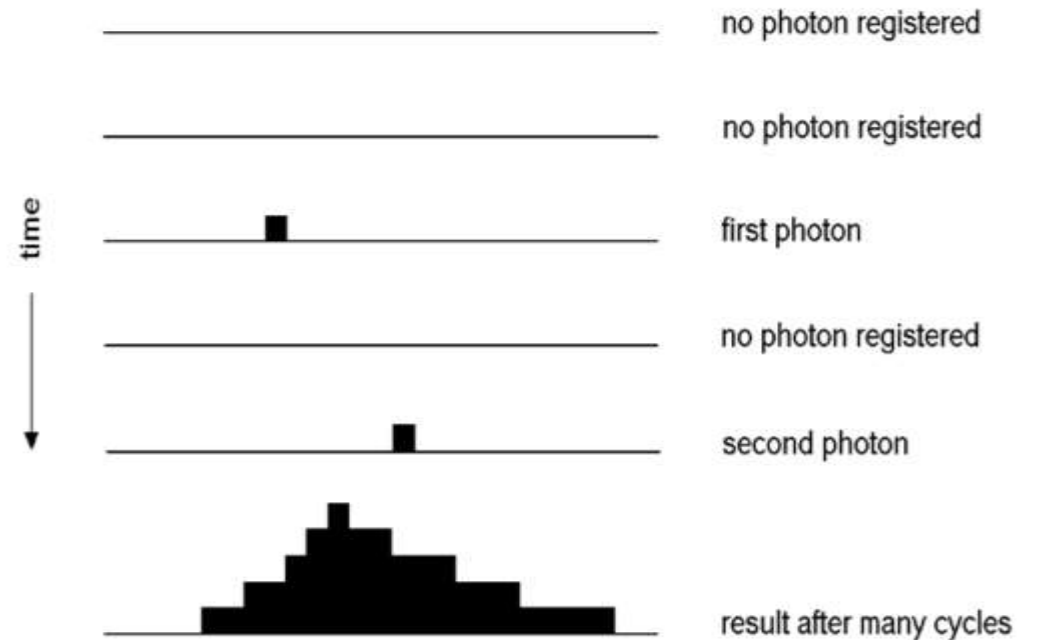
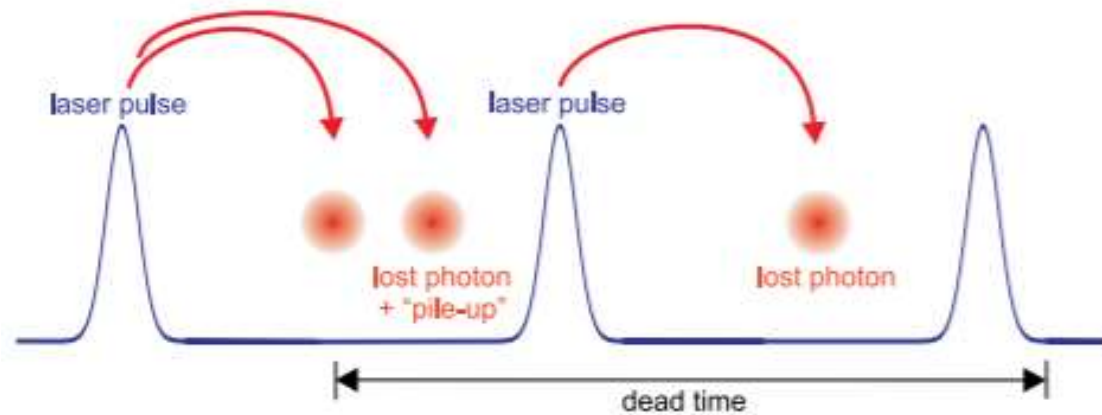


$$\tau_{coh} \sim \frac{1}{\pi \Delta\nu}$$

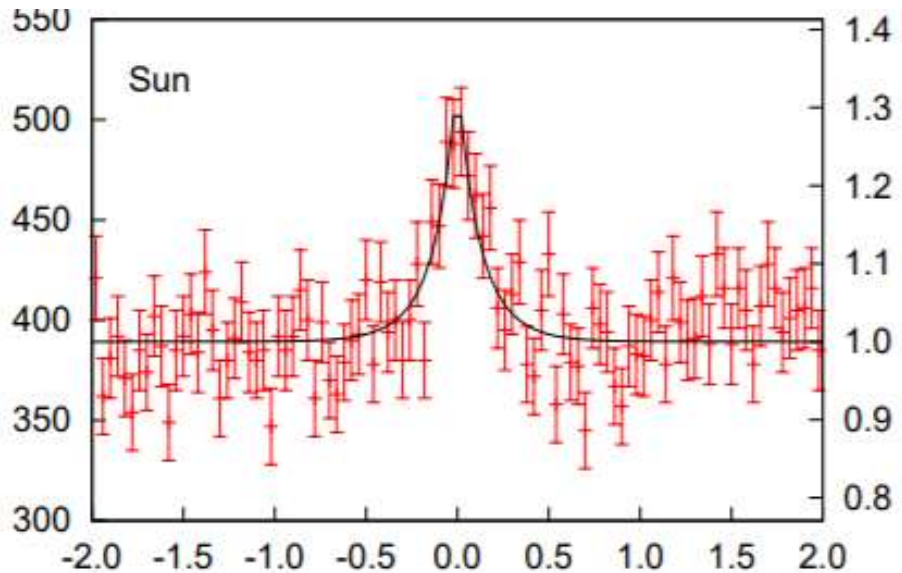
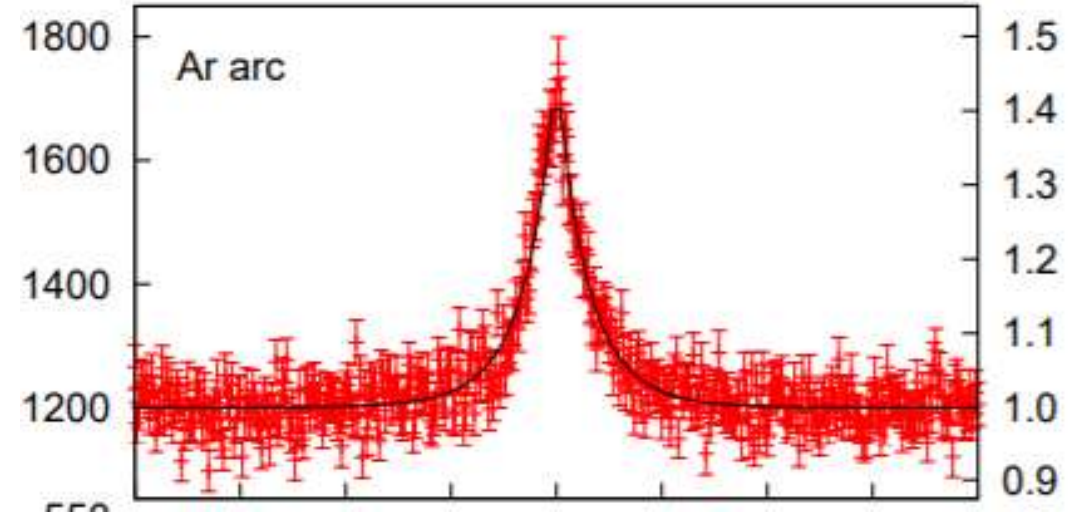
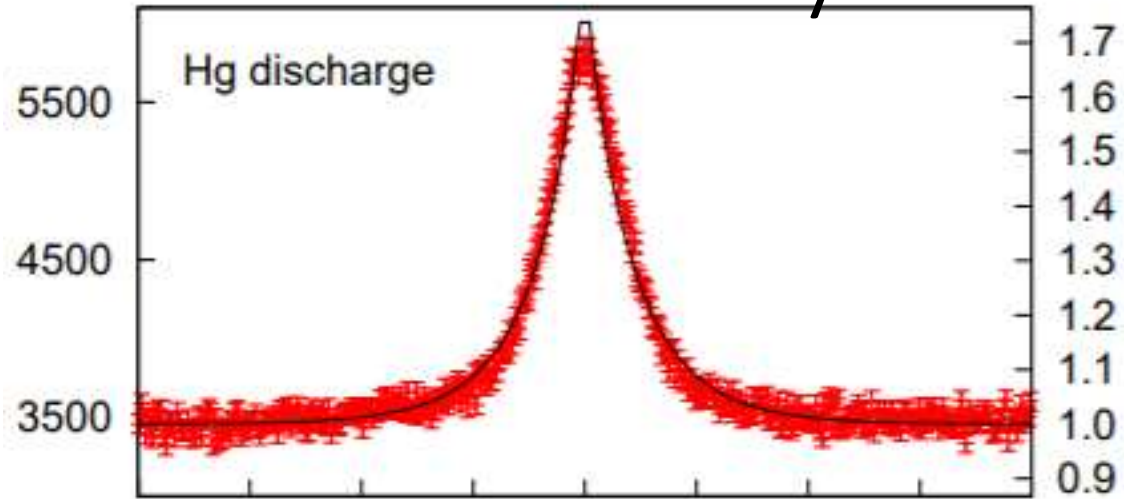
# Измерение статистики света от источника теплового излучения



# Измерение статистики света от источника теплового излучения



# Измерение статистики света от источника теплового излучения

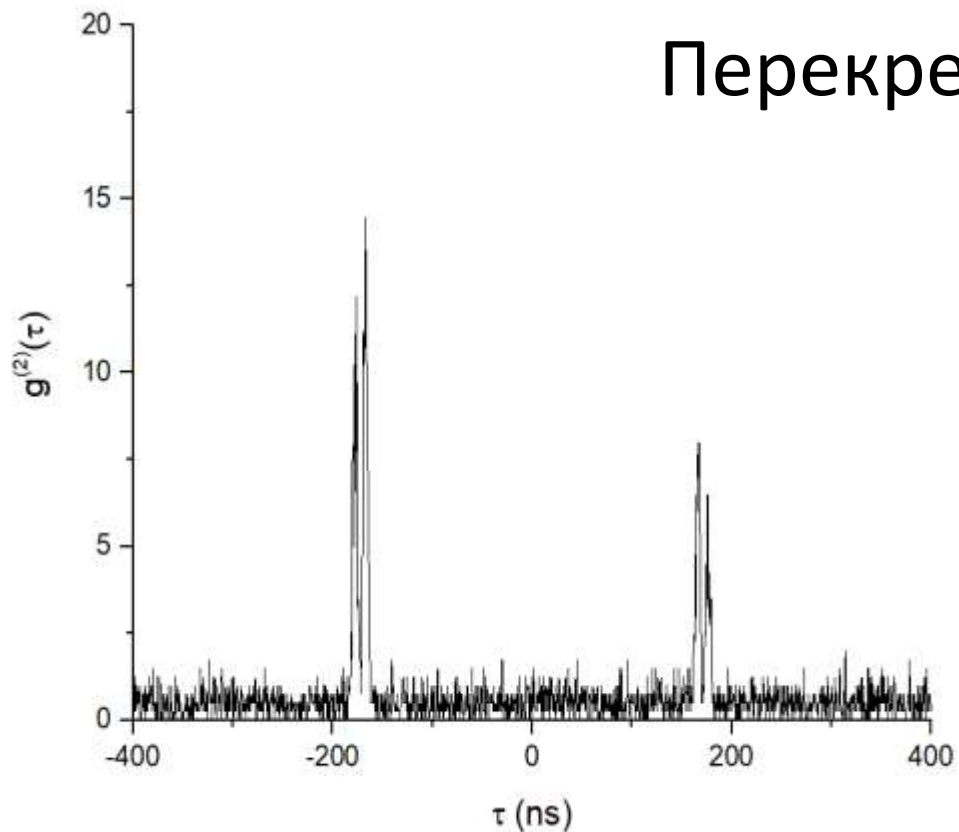


MEASURING TEMPORAL PHOTON BUNCHING IN BLACKBODY RADIATION

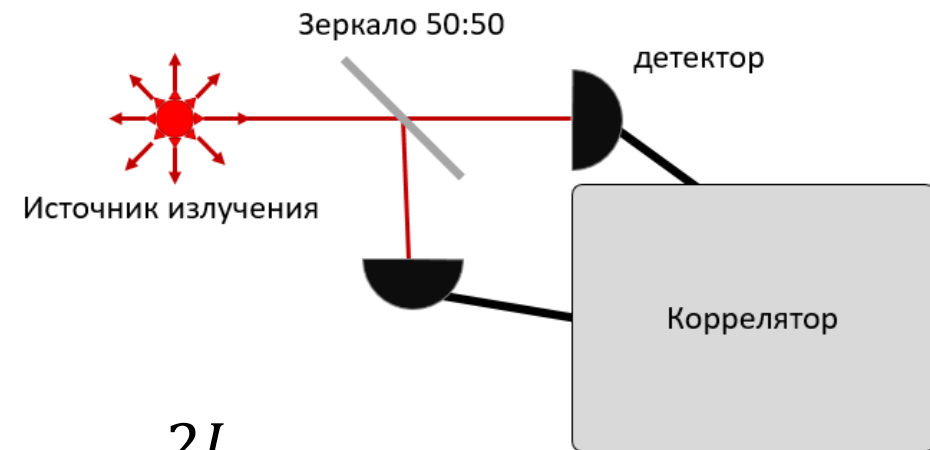
P. K. TAN<sup>1,2,\*</sup>, G. H. YEO<sup>2</sup>, H. S. POH<sup>1</sup>, A. H. CHAN<sup>2</sup>, AND C. KURTSIEFER<sup>1,2,+</sup>

*Draft version April 7, 2014*

# Артефакты при измерении $g^2$ функции



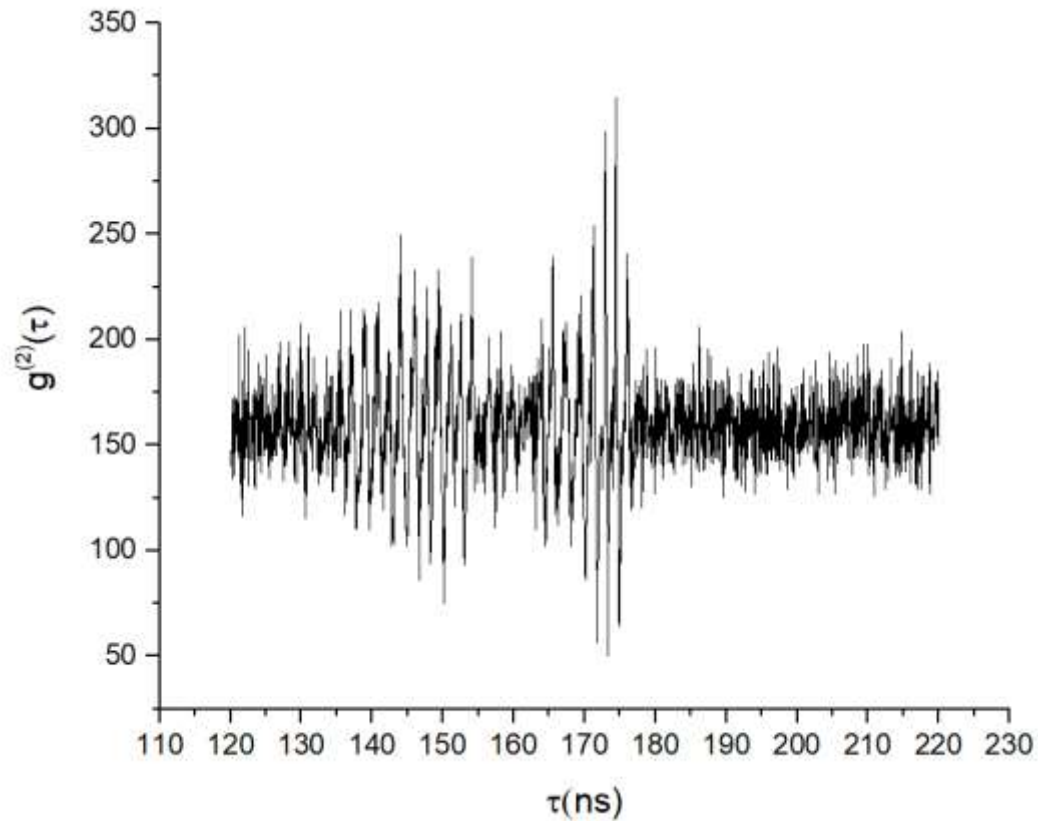
## Перекрестные оптические помехи (crosstalk)



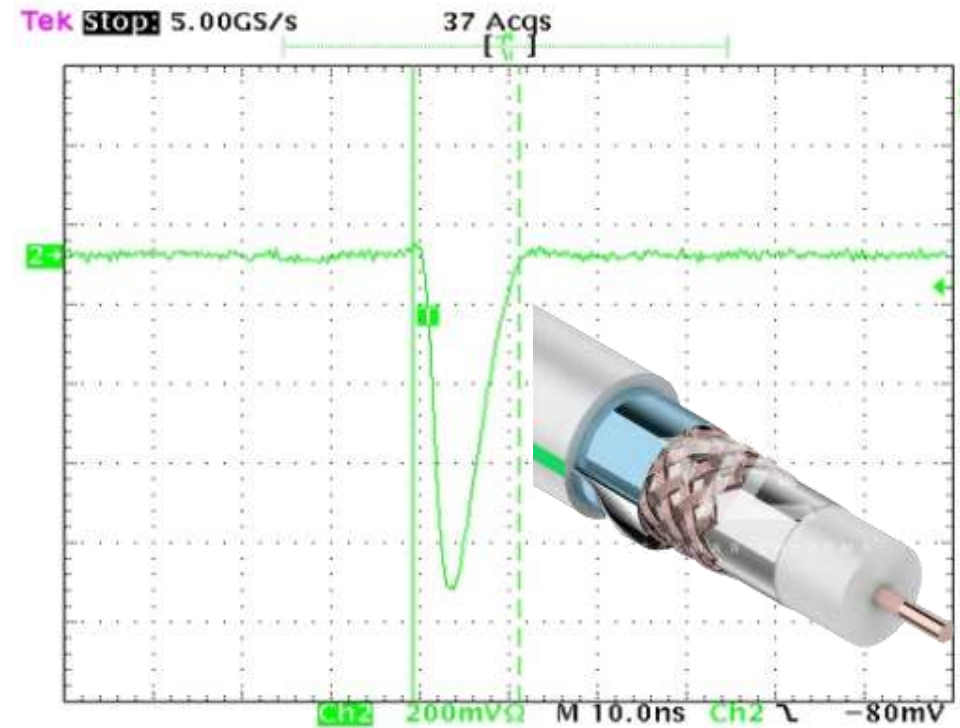
$$\Delta\tau = \frac{2L}{c}$$



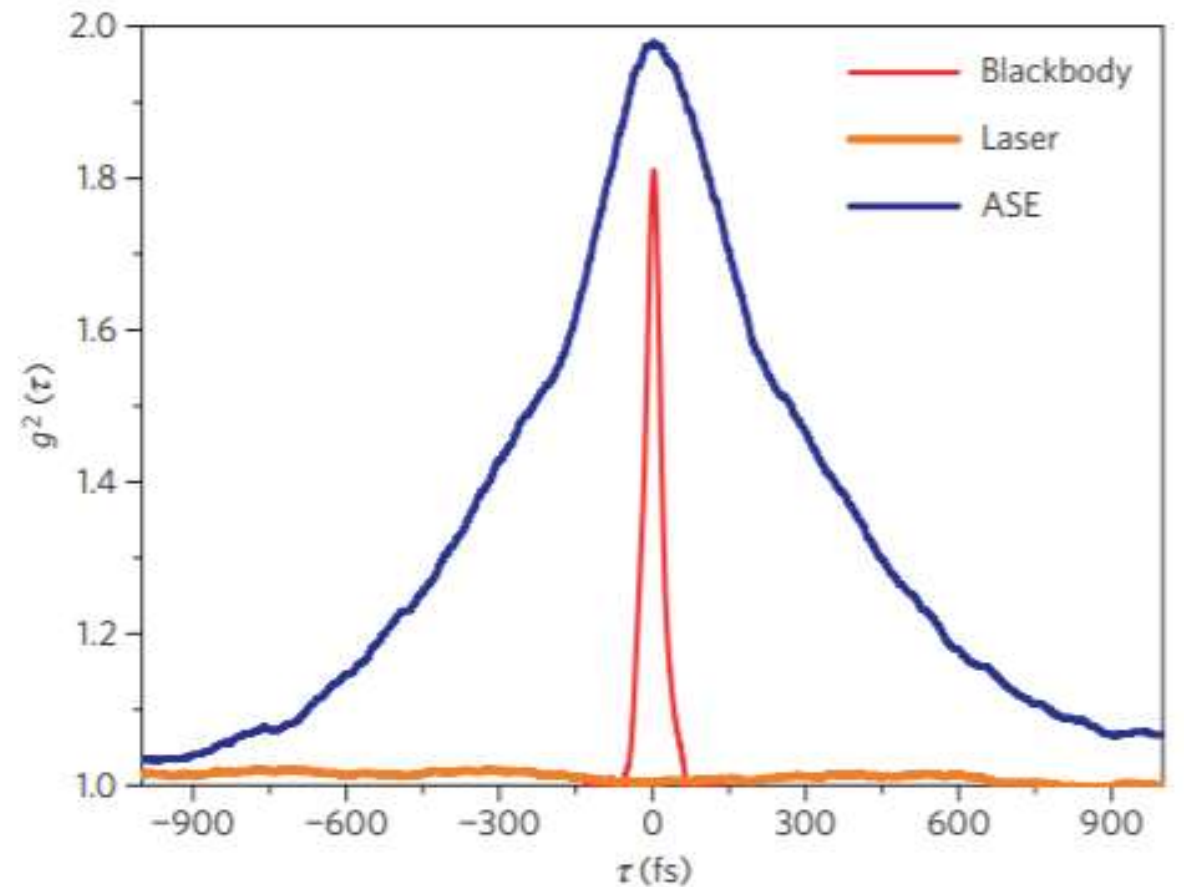
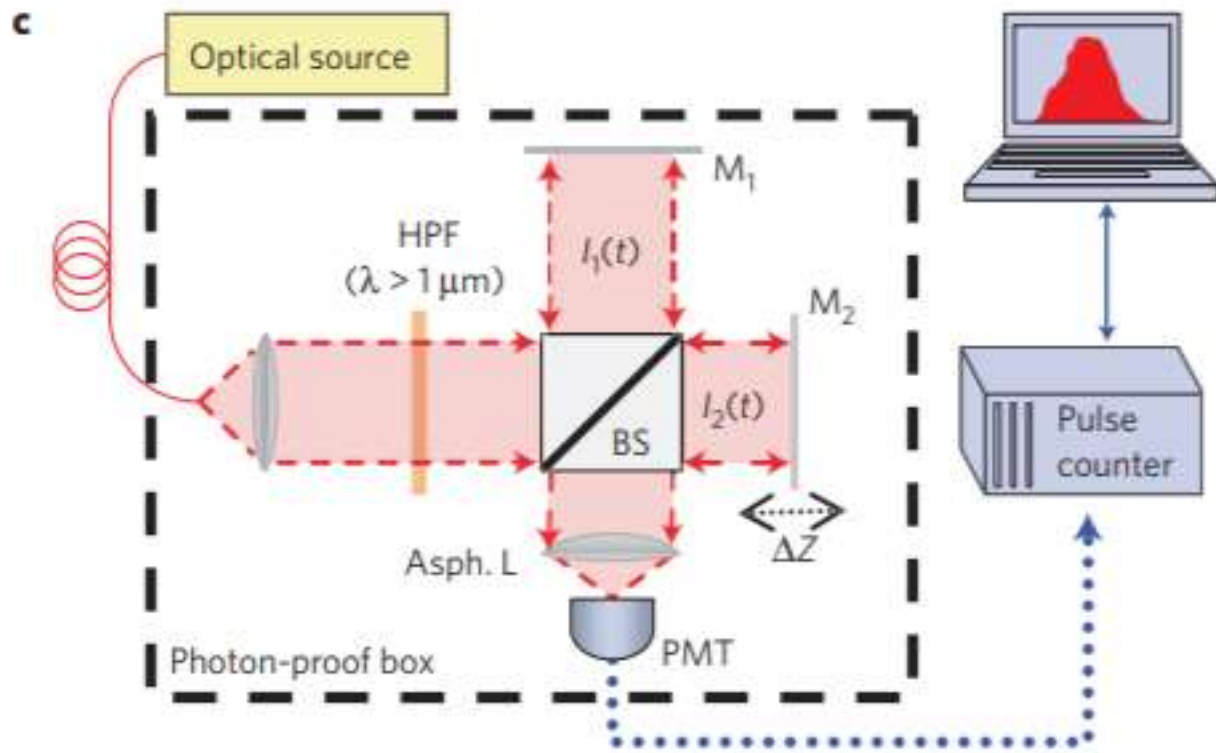
# Артефакты при измерении $g^2$ функции



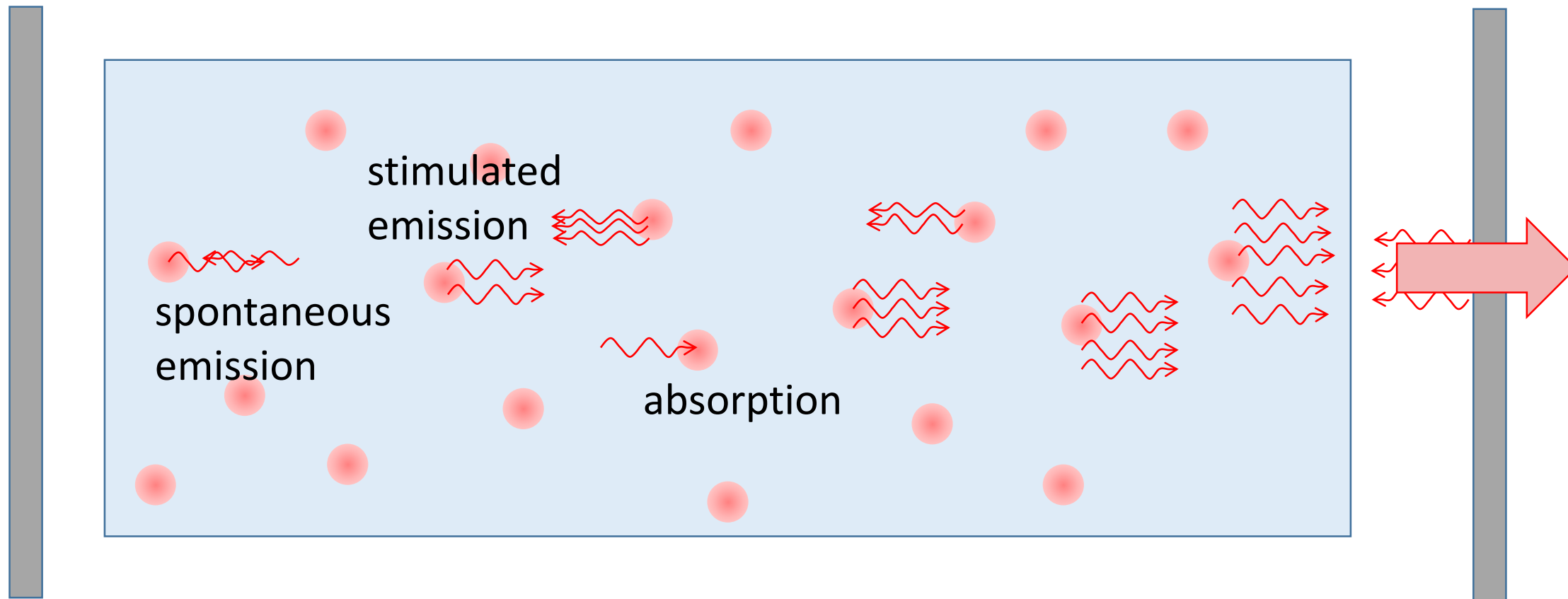
Перекрестные  
электрические помехи



# Измерение статистики при помощи двухфотонного процесса в ФЭУ



# Для чего необходимо измерять статистику?



# Для чего необходимо измерять статистику?

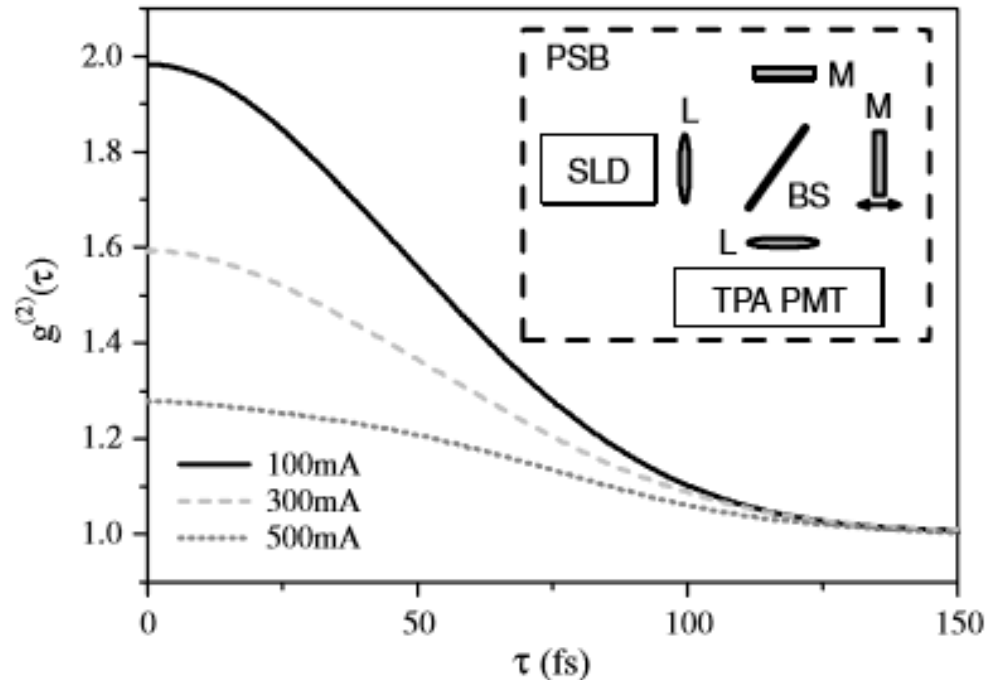
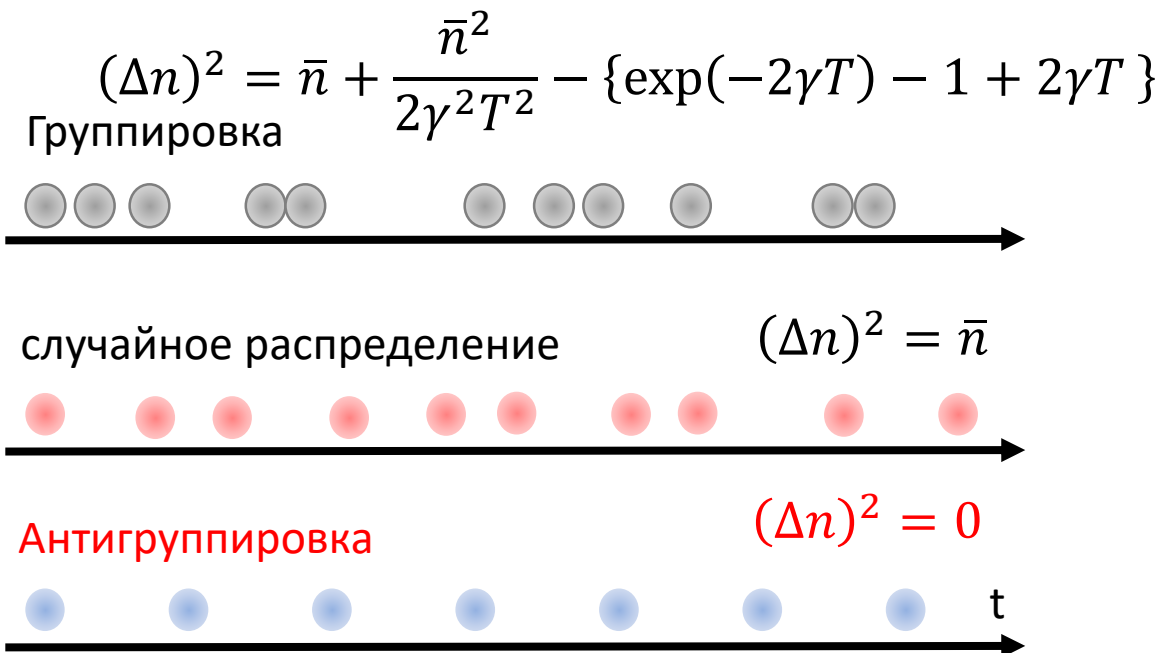
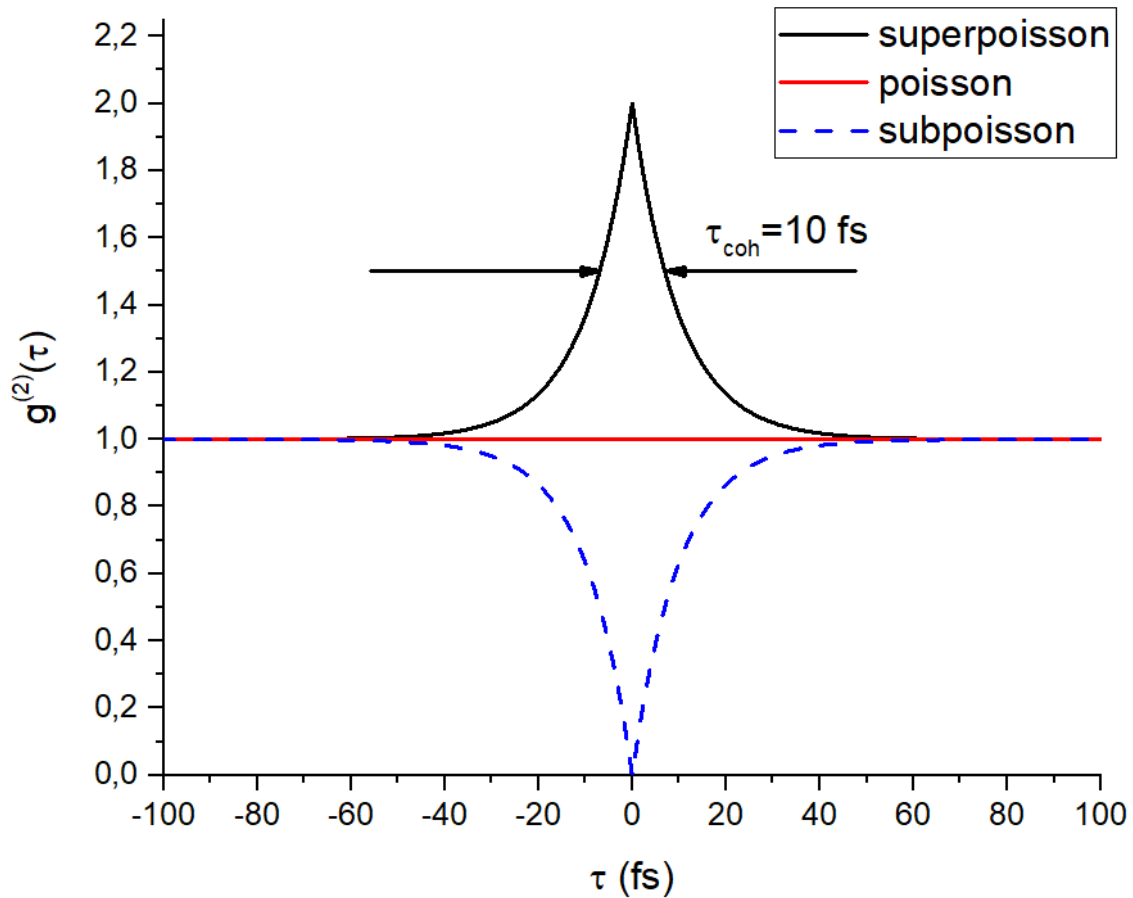


Fig. 2. Second-order correlation function  $g^{(2)}(\tau)$  for various pump currents. (inset) Experimental setup with photon-shielded box, PSB; superluminescent diode, SLD; aspheric lenses, L; beam splitter, BS; mirrors, M; photomultiplier operating in TPA mode, TPA PMT.

## Unifying intensity noise and second-order coherence properties of amplified spontaneous emission sources

Martin Blazek,<sup>1,\*</sup> Sébastien Hartmann,<sup>1</sup> Andreas Molitor,<sup>1</sup> and Wolfgang Elsaesser<sup>1,2</sup>

# Субпуассоновская статистика света

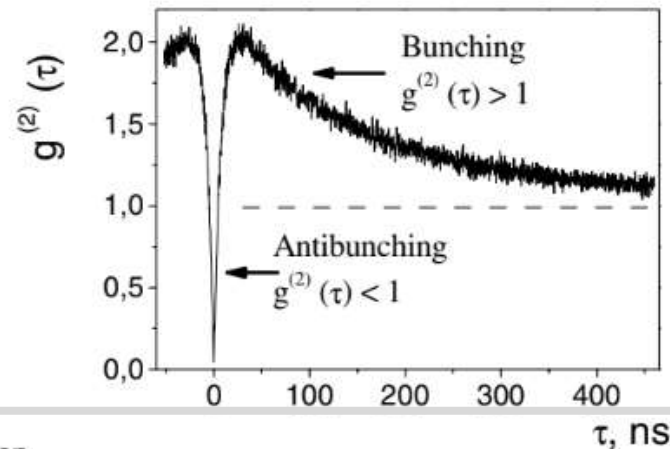
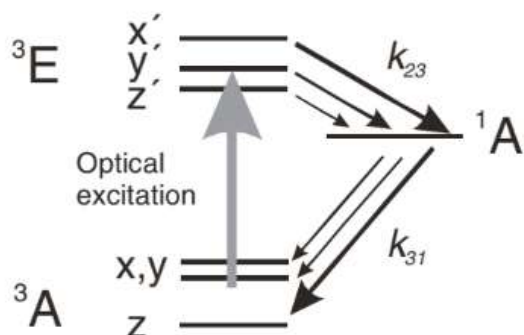
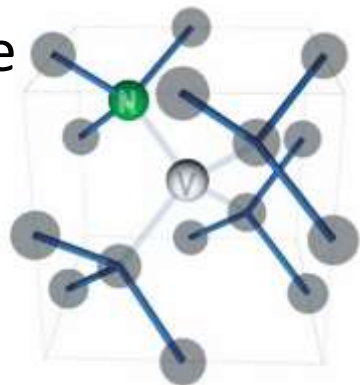


# Однофотонные источники

## Дислокации в кристалле

Single defect centres in diamond: A review

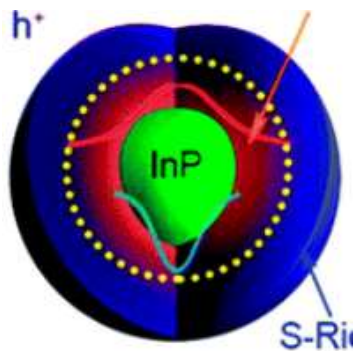
F. Jelezko and J. Wrachtrup\*



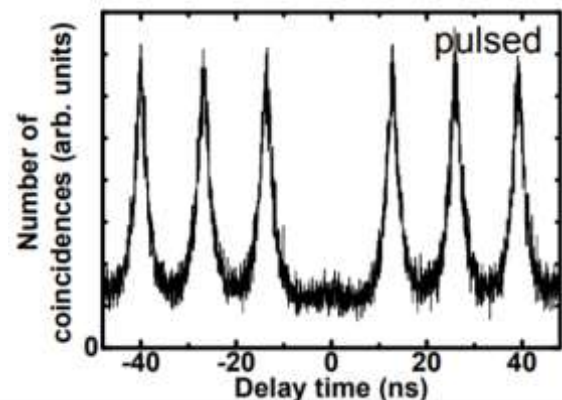
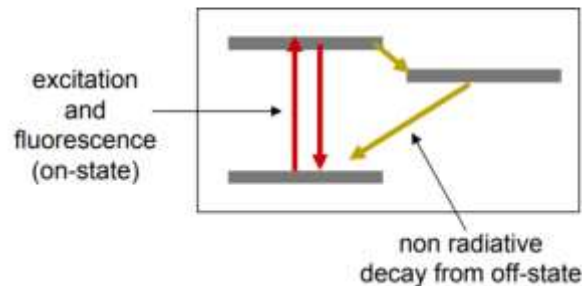
## Квантовые точки

Generating visible single photons on demand with single InP quantum dots

V. Zaitsev<sup>1</sup> and T. Aichele  
 Nano-Optics, Physics Department, Humboldt University, D-10077 Berlin, Germany  
 W. Sefert and J. Persson  
 Solid State Physics, Box 118, Lund University, SE-22009 Lund, Sweden  
 © Beron  
 Nano-Optics, Physics Department, Humboldt University, D-10077 Berlin, Germany



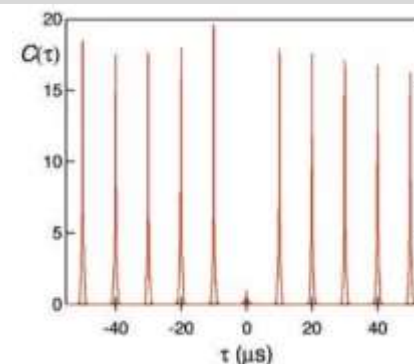
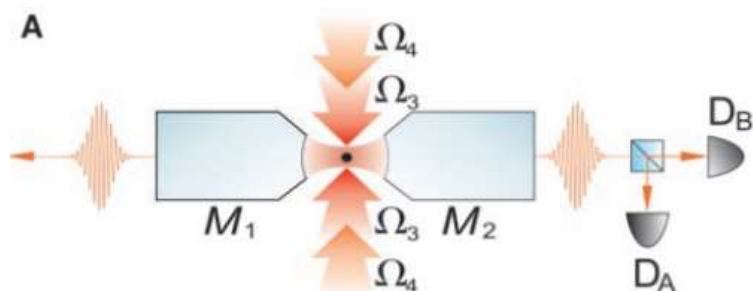
Spontaneous transition between on- and off states.



## Локализованные атомы

Deterministic Generation of Single Photons from One Atom Trapped in a Cavity

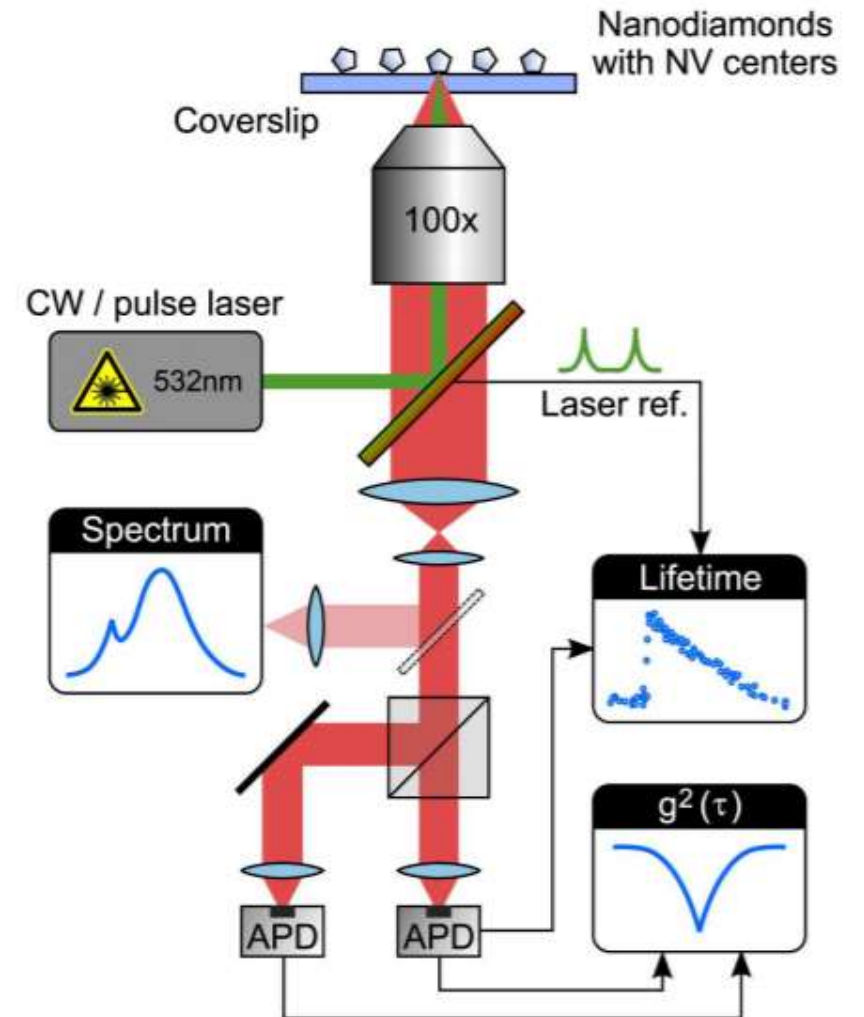
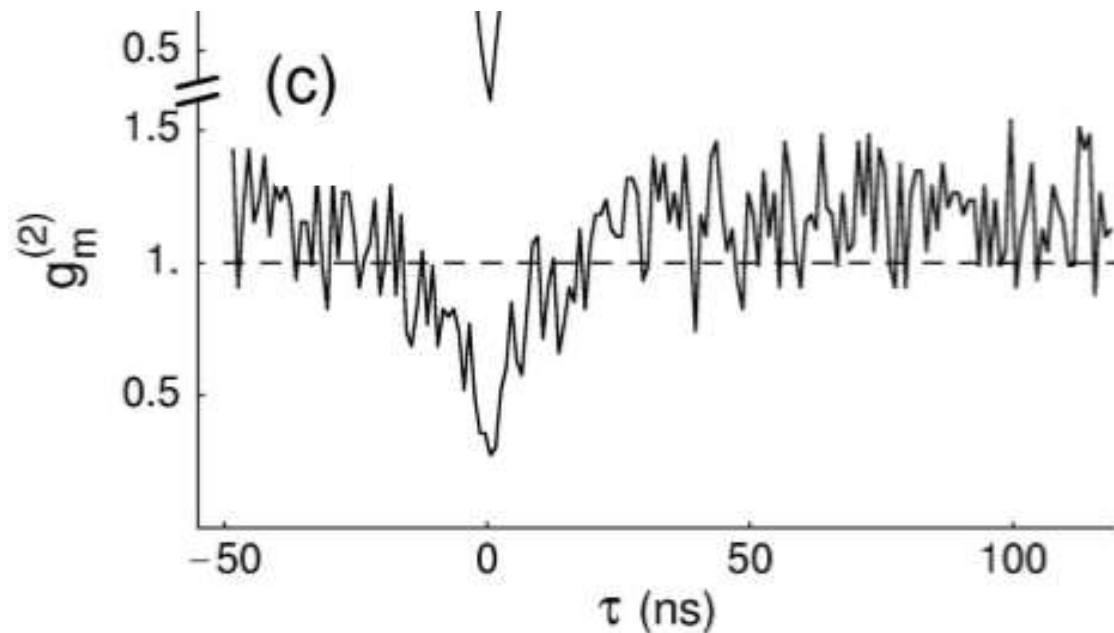
J. McKeever, A. Boca, A. D. Boozer, R. Miller, J. R. Buck, A. Kuzmich, H. J. Kimble\*





# Некоторые особенности измерения статистики однофотонных источников

$$g^{(2)}(0) = \frac{\langle n | \hat{a}^\dagger \hat{a}^\dagger \hat{a} \hat{a} | n \rangle}{\langle n | \hat{a}^\dagger \hat{a} | n \rangle \langle n | \hat{a}^\dagger \hat{a} | n \rangle} = \frac{n(n-1)}{n^2} = 1 - \frac{1}{n}$$





# Новые задачи

## Fundamental limitations in spontaneous emission rate of single-photon sources

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The rate of single-photon generation by quantum emitters (QEs) can be enhanced by placing a QE inside a resonant structure. This structure can represent an all-dielectric micro-resonator or waveguide and thus be characterized by ultra-low loss and dimensions on the order of wavelength. Or it can be a metal nanostructure supporting localized or propagating surface plasmon-polariton modes that are of sub-wavelength dimensions, but suffer from strong absorption. In this work, we develop a physically transparent analytical model of single-photon emission in resonant structures and show unambiguously that, notwithstanding the inherently high loss, the external emission rate can be enhanced with plasmonic nanostructures by **two orders of magnitude compared to all-dielectric structures**. Our analysis provides guidelines for developments of new plasmonic configurations and materials to be exploited in quantum plasmonics. © 2016 Optical Society of America

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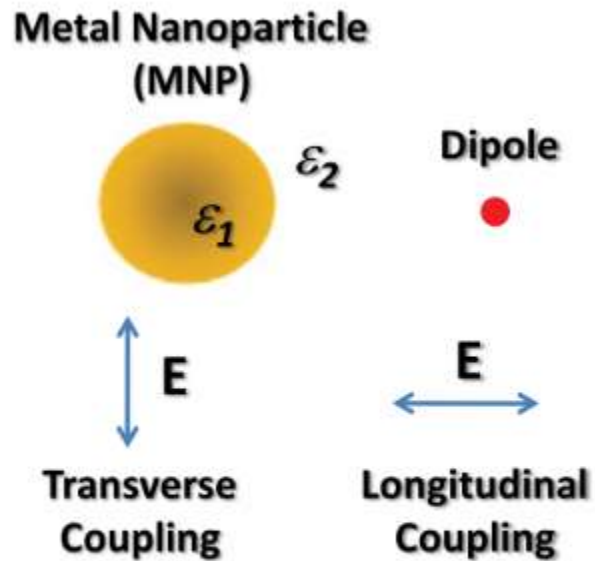


FIG. 1. (Color online) Schematic of the dipole-MNP system. We refer to two different incident field orientations, longitudinal and transverse.

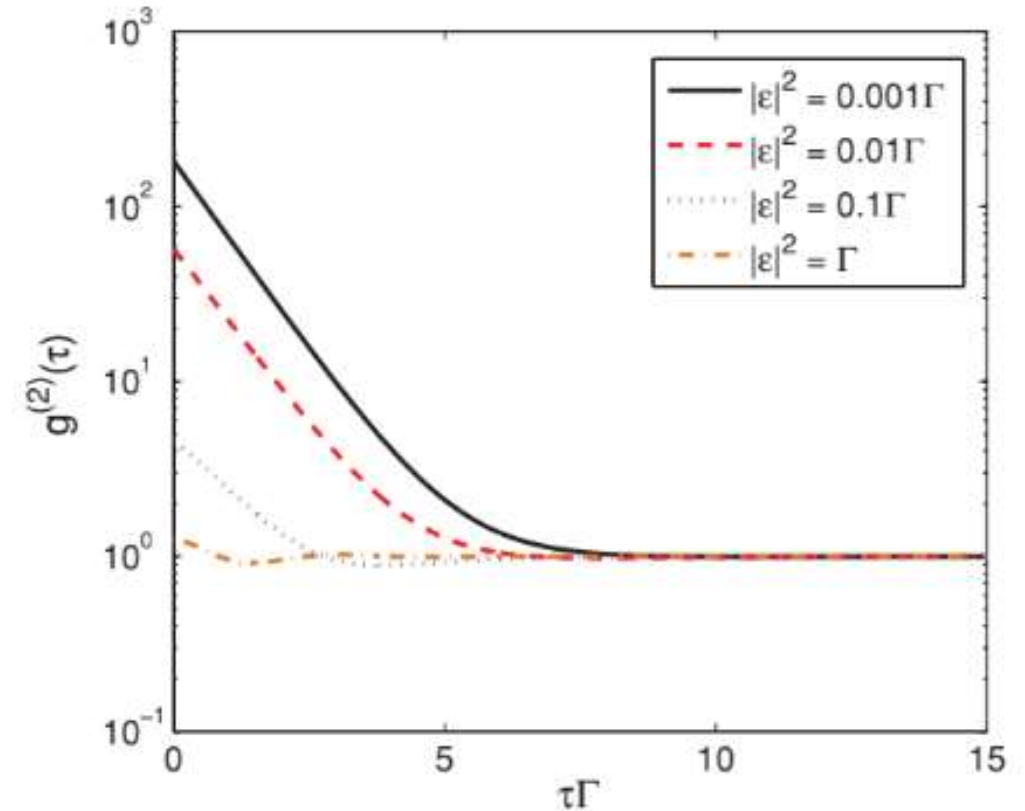


FIG. 10. (Color online) Second-order correlation function for four different pumping intensity values.

## Cavity QED treatment of interactions between a metal nanoparticle and a dipole emitter

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