НАЦИОНАЛЬНЫЙ ИССЛЕДОВАТЕЛЬСКИЙ УНИВЕРСИТЕТ

Факультет физики, кафедра квантовой оптики и нанофотоники ИСАН

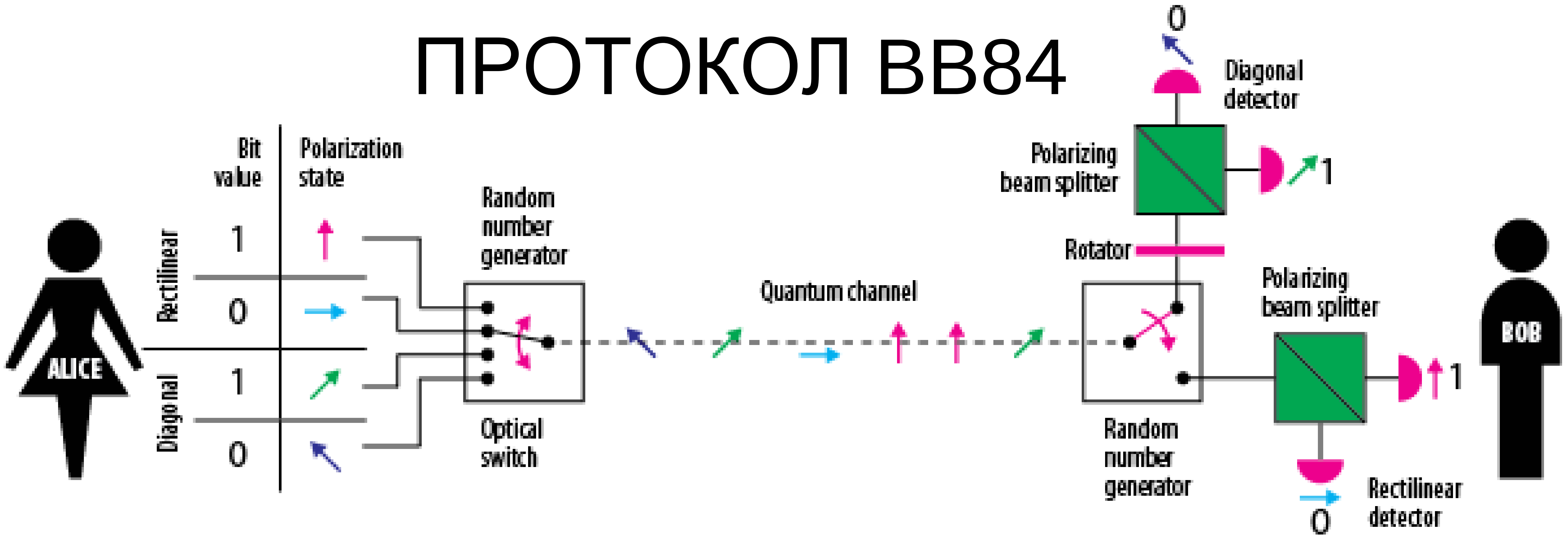
NV ЦЕНТРЫ В НАНОАЛМАЗАХ, СВЯЗАННЫЕ С ПЛАНАРНЫМ ВОЛНОВОДОМ

Семинар НУГ

Антон Гритченко,
Москва, Троицк, 2019

QUANTUM KEY DISTRIBUTION

ПРОТОКОЛ BB84

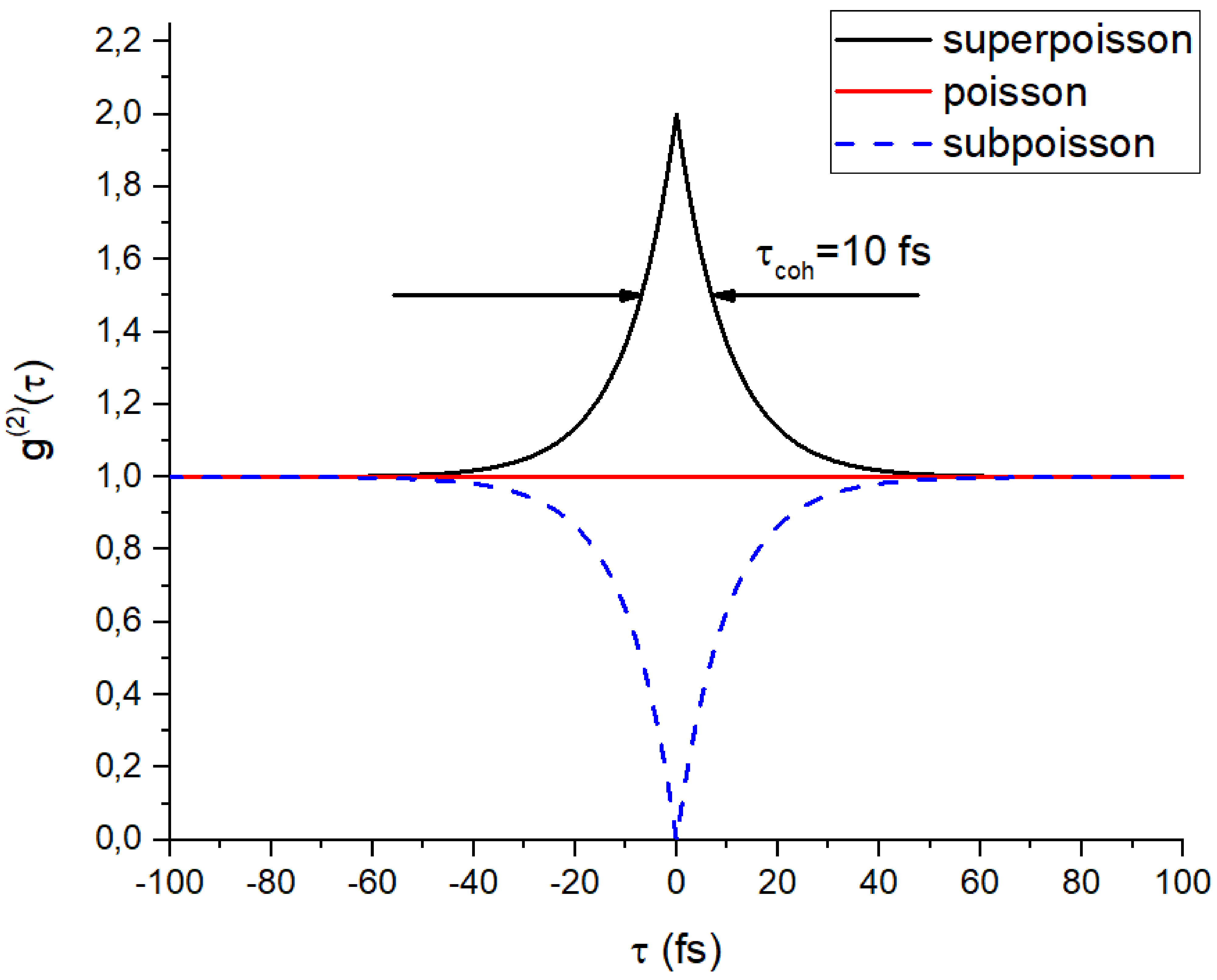


		1	2	3	4	5	6	7	8
Quantum transmission & detection	ALICE sends photons	↖	↗	→	↑	↑	↗	↖	↑
	ALICE's random bits	0	1	0	1	1	1	0	1
	BOB's detection events	↑	↗	↖	↑	↗	↗	↖	↖
	BOB's detected bit values	1	1	0	1	1	1	0	0
Public discussion (i.e., sifting)	BOB tells ALICE the basis choices he made	Rect	Diag	Diag	Rect	Diag	Diag	Diag	Diag
	ALICE tells BOB which bits to keep		✔		✔		✔	✔	
	ALICE and BOB's shared sifted key	–	1	–	1	–	1	0	–

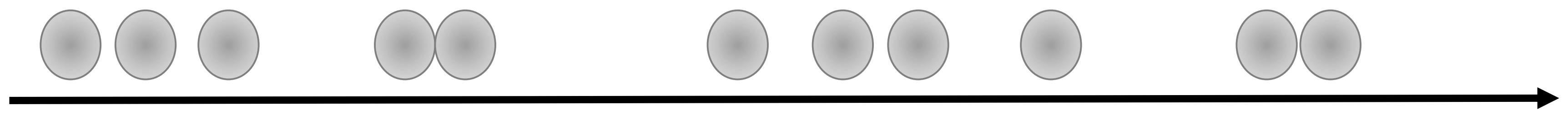
Photon number splitting attack – способ «украсть» ключ в случае, если источник не однофотонный

СТАТИСТИКА ИЗЛУЧЕНИЯ

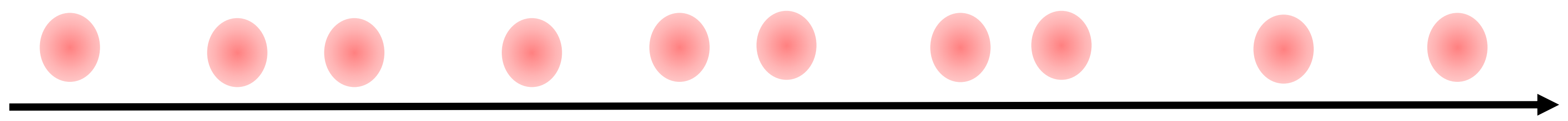
$$g^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle\langle I(t+\tau)\rangle}$$



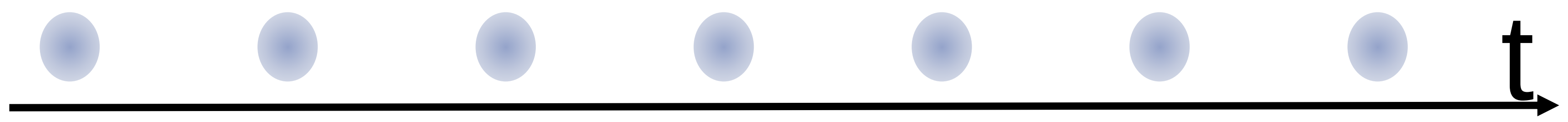
Группировка $(\Delta n)^2 = \bar{n} + \frac{\bar{n}^2}{2\gamma^2 T^2} - \{\exp(-2\gamma T) - 1 + 2\gamma T\}$



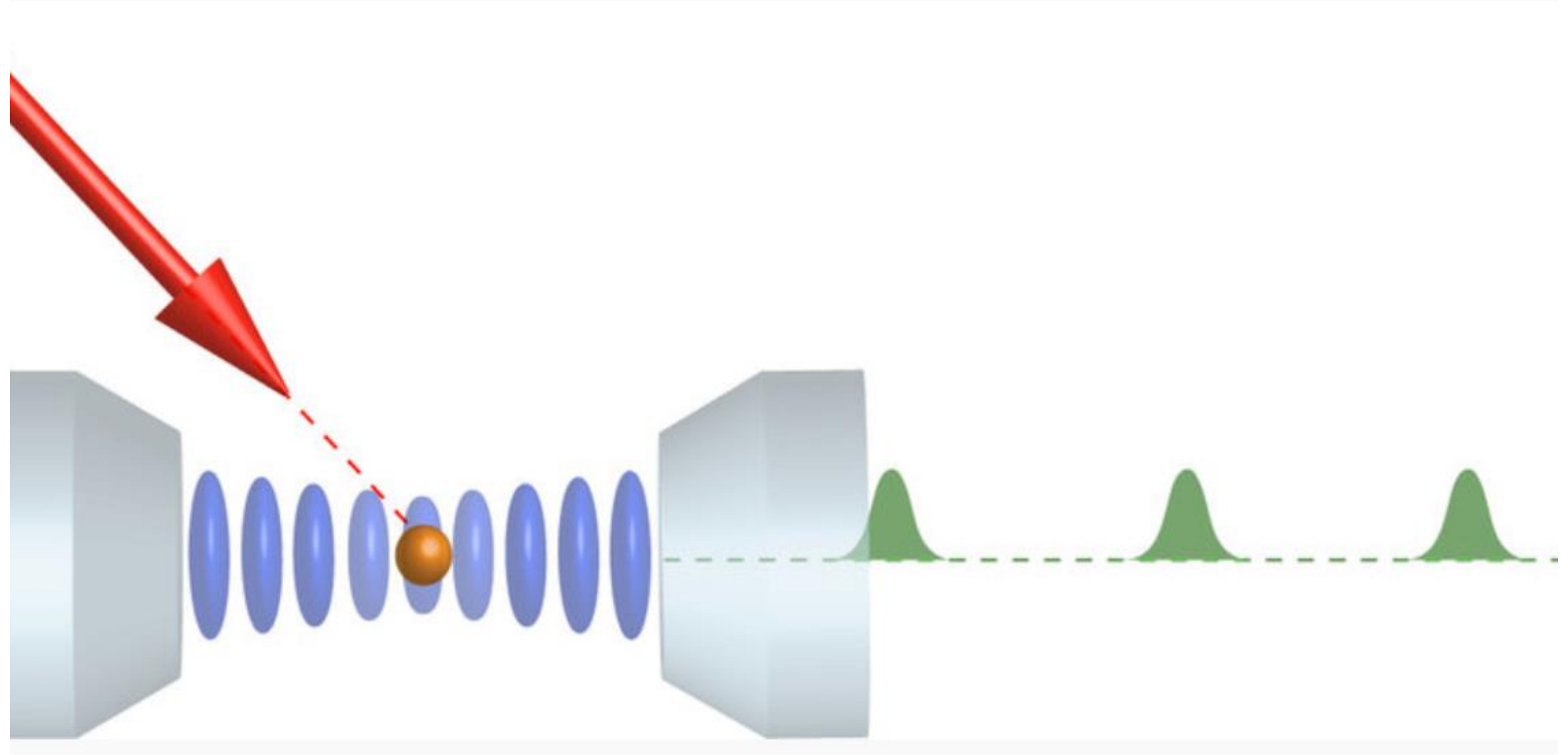
Случайное распределение $(\Delta n)^2 = \bar{n}$



Антигруппировка $(\Delta n)^2 = 0$



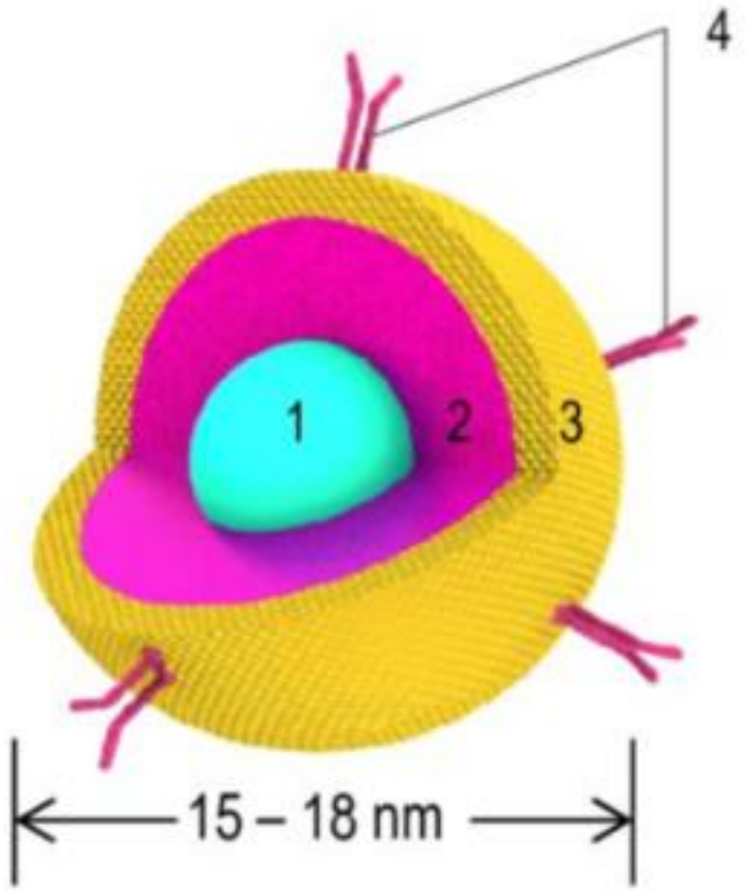
ПРИМЕРЫ ИСТОЧНИКОВ ОДИНОЧНЫХ ФОТОНОВ

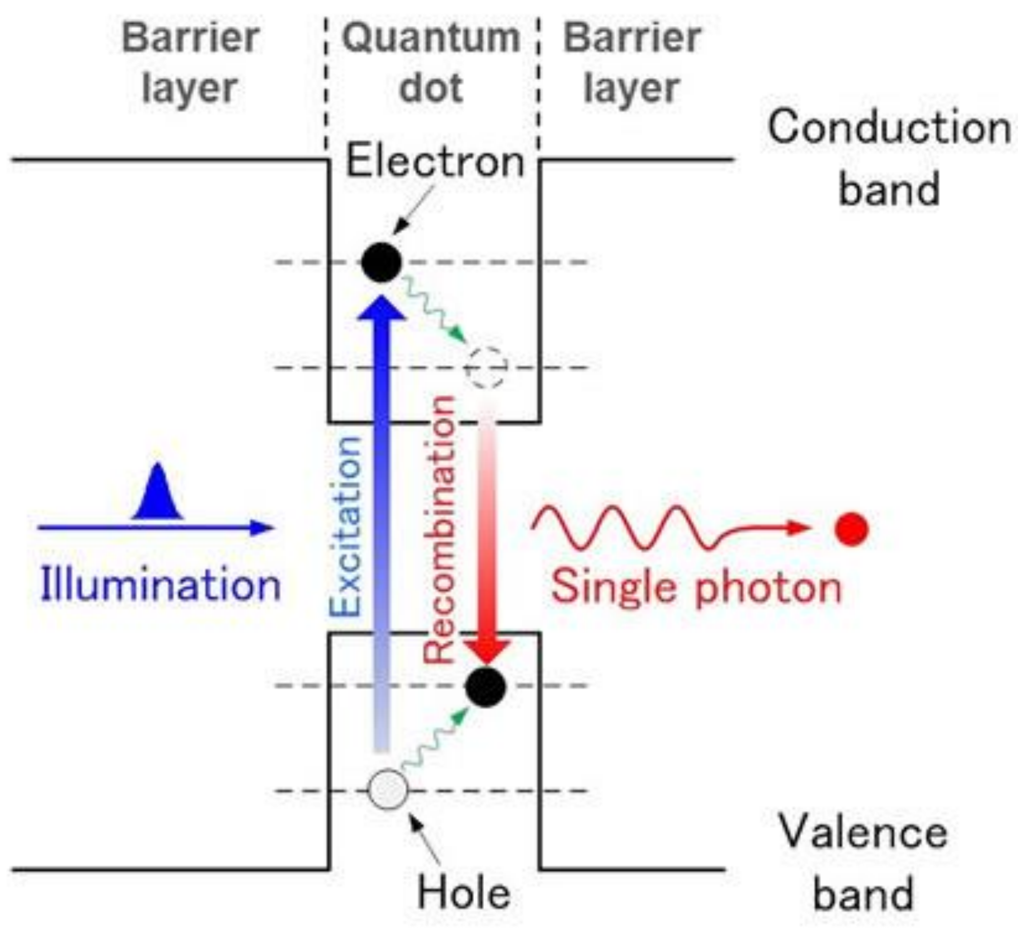


Одиночные атомы и ионы

Pure single photons from a trapped atom source

D B Higginbottom[1,2], L Slodička[3], G Araneda[2], L Lachman[3], R Filip[3], M Hennrich[2] and R Blatt[2,4]



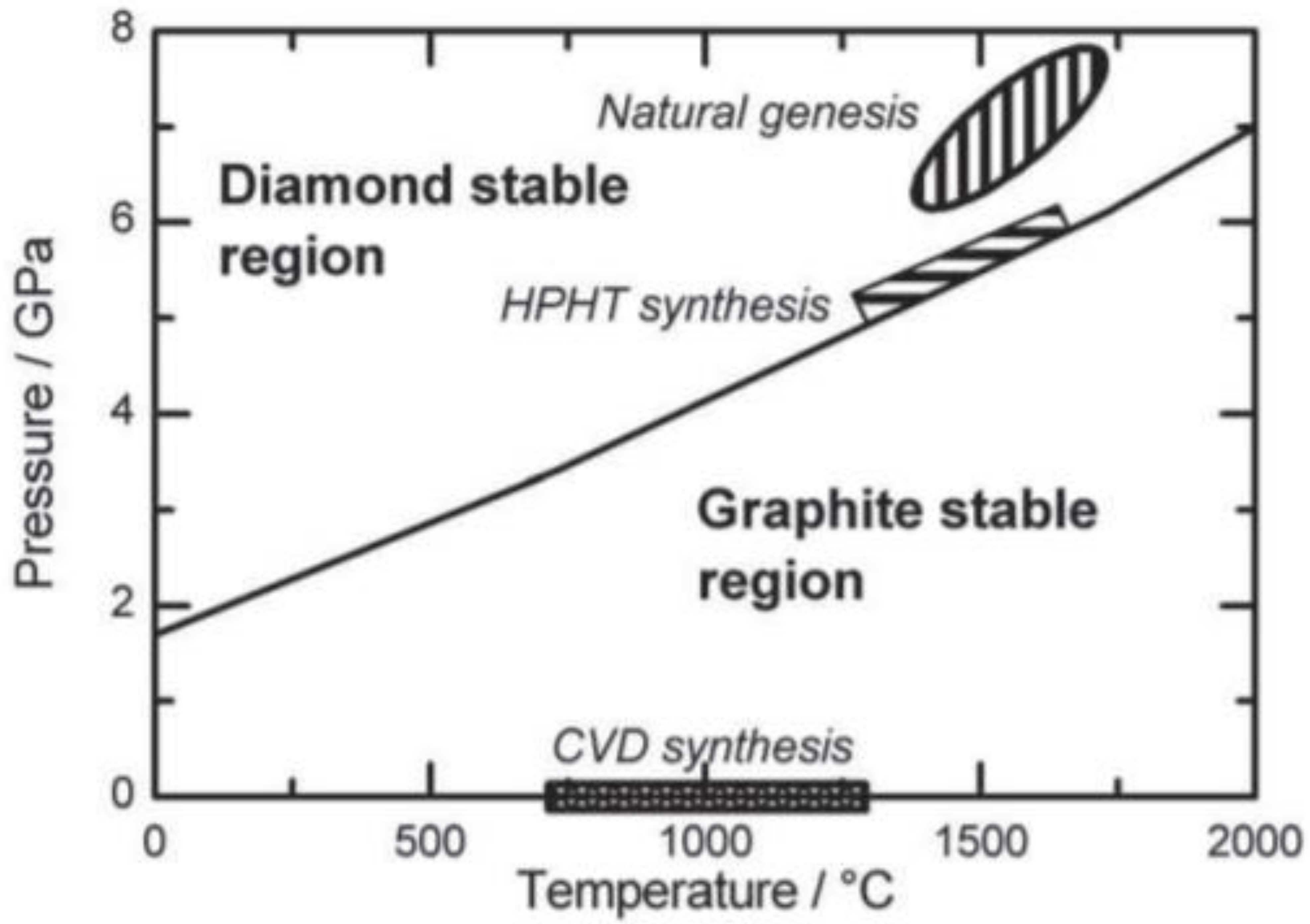


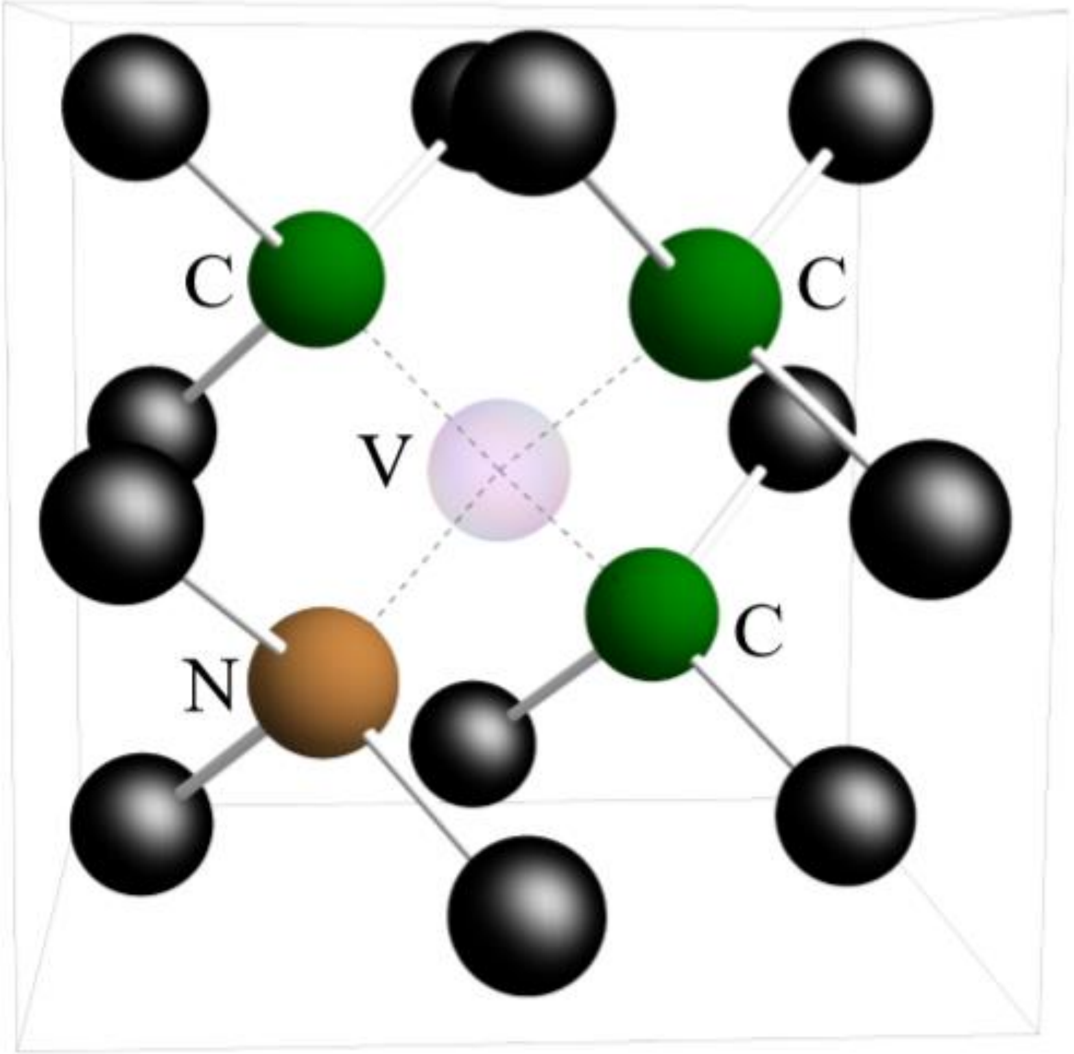
Квантовые точки

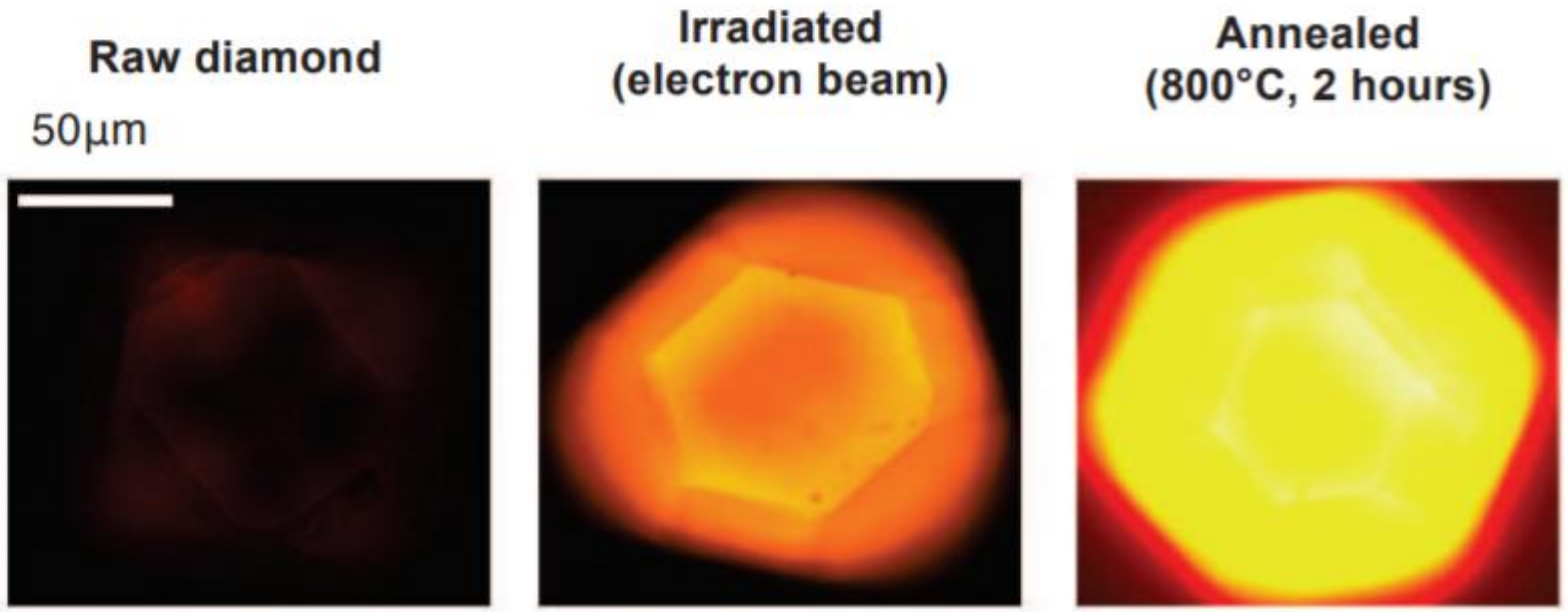
High-performance semiconductor quantum-dot single-photon sources

Pascale Senellart, Glenn Solomon & Andrew White

NV ЦЕНТРЫ

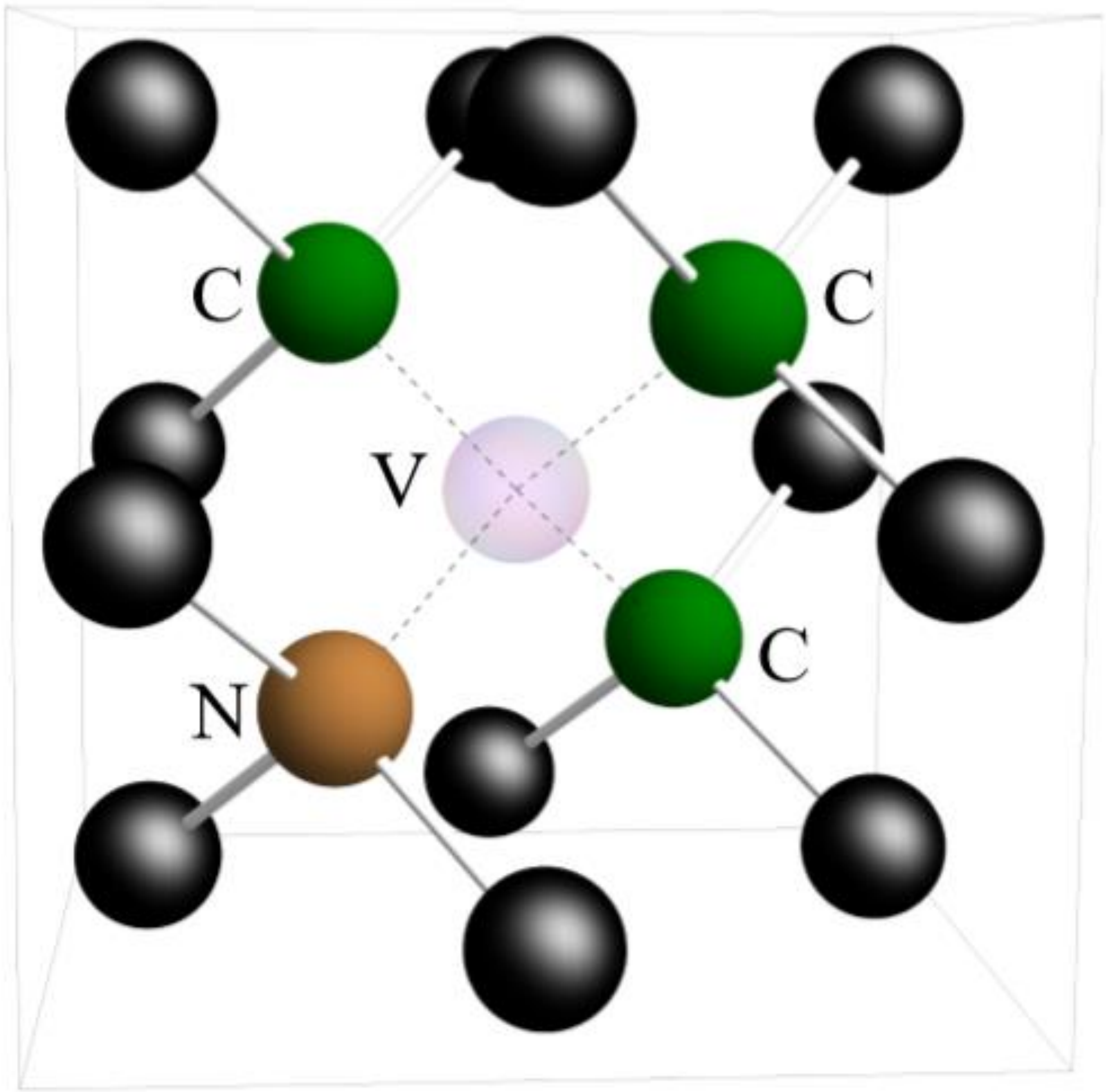


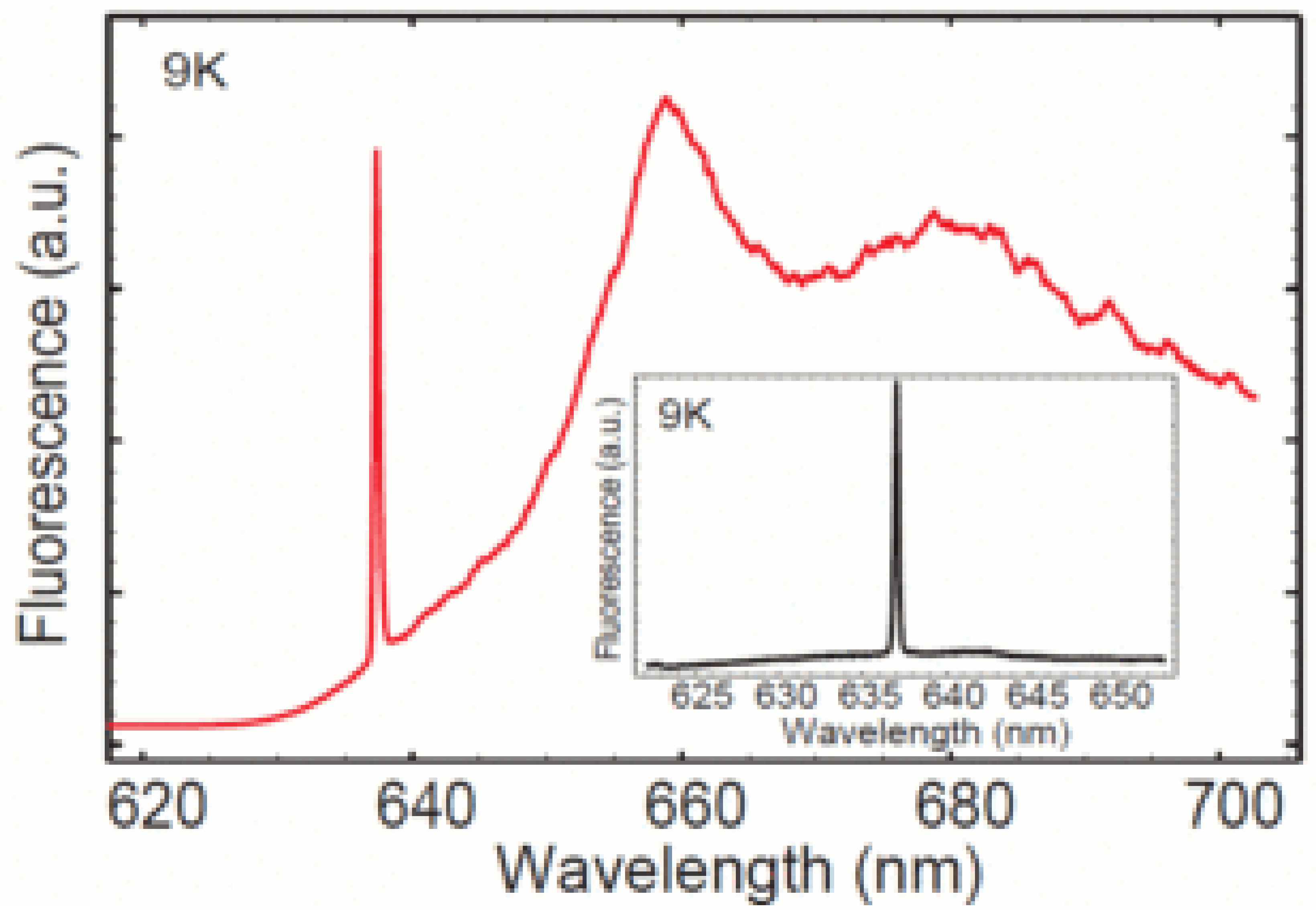


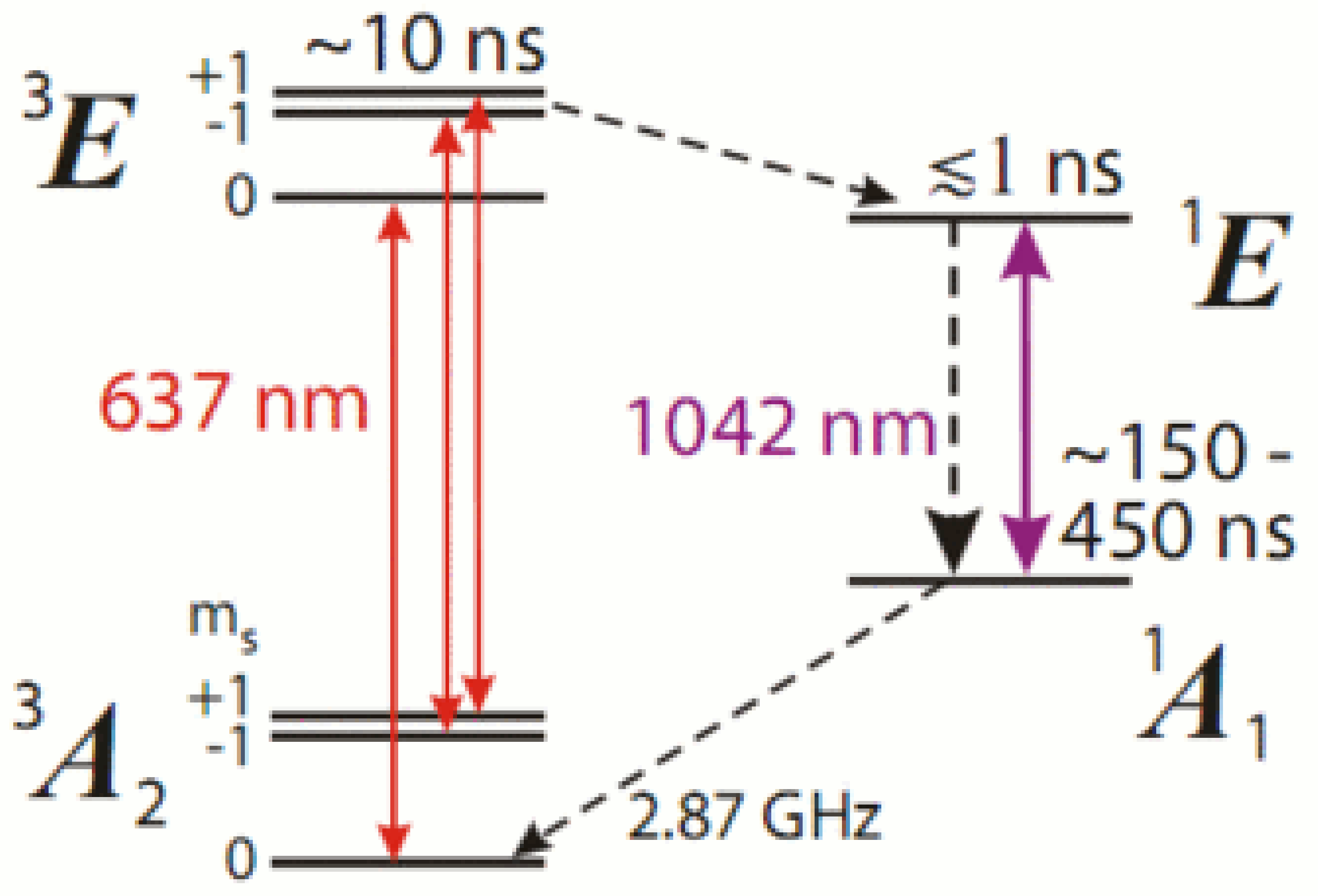


Процесс создания NV центров в алмазе

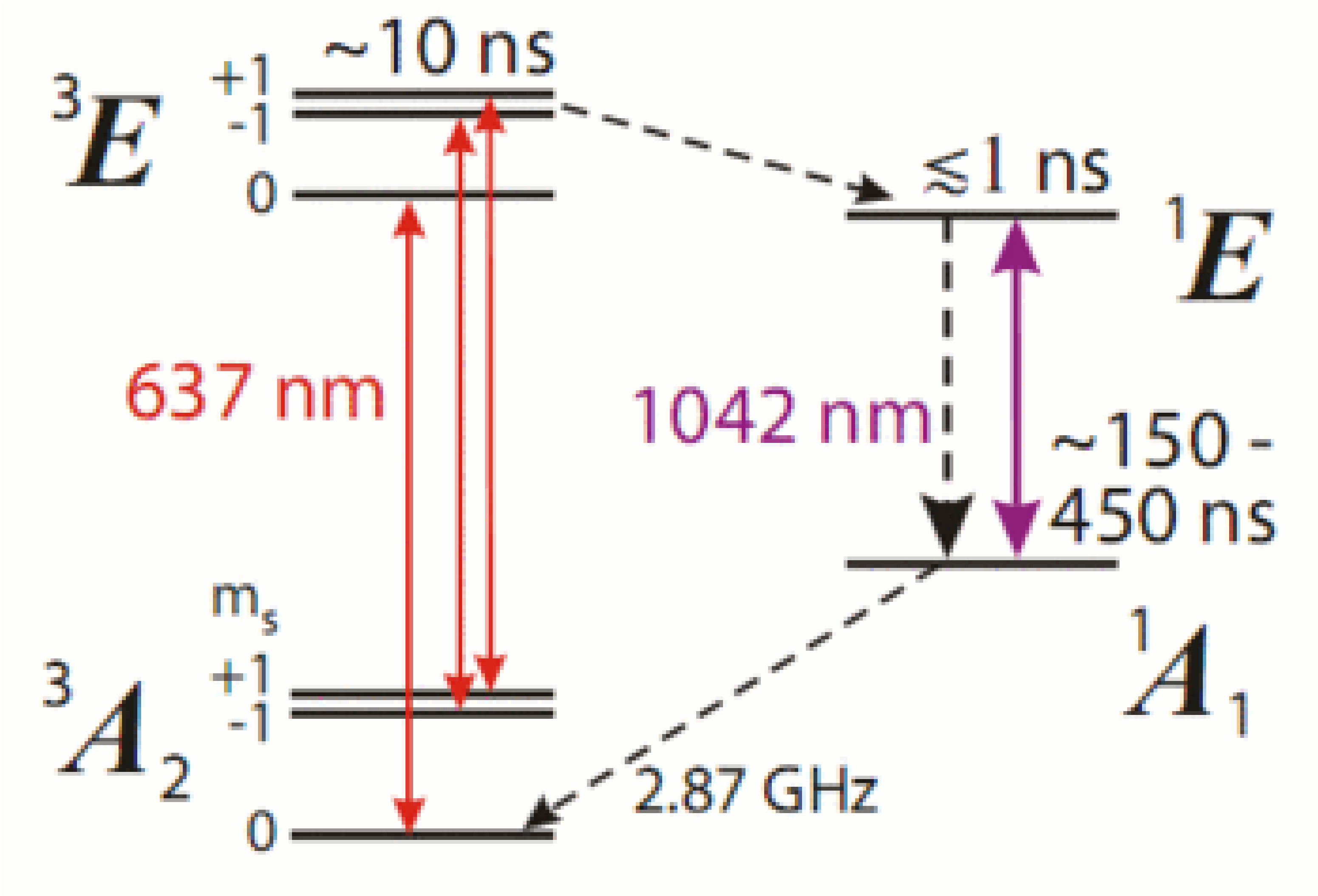
NV ЦЕНТРЫ


C
C
V
C
N


9K
Fluorescence (a.u.)
620
640
660
680
700
Wavelength (nm)
625 630 635 640 645 650


~10 ns
3E
+1
-1
0
≲1 ns
1E
637 nm
1042 nm
~150 -
450 ns
ms
3A2
1A1
2.87 GHz

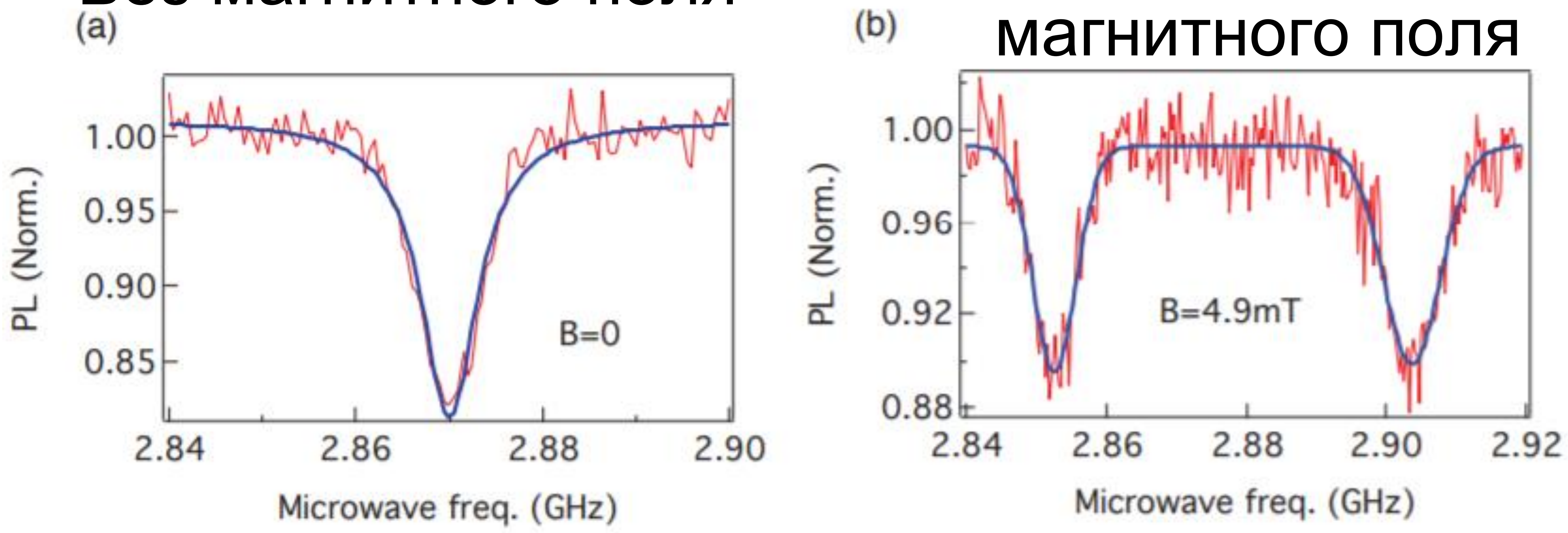
OPTICALLY DETECTABLE MAGNETIC RESONANCE (ODMR)

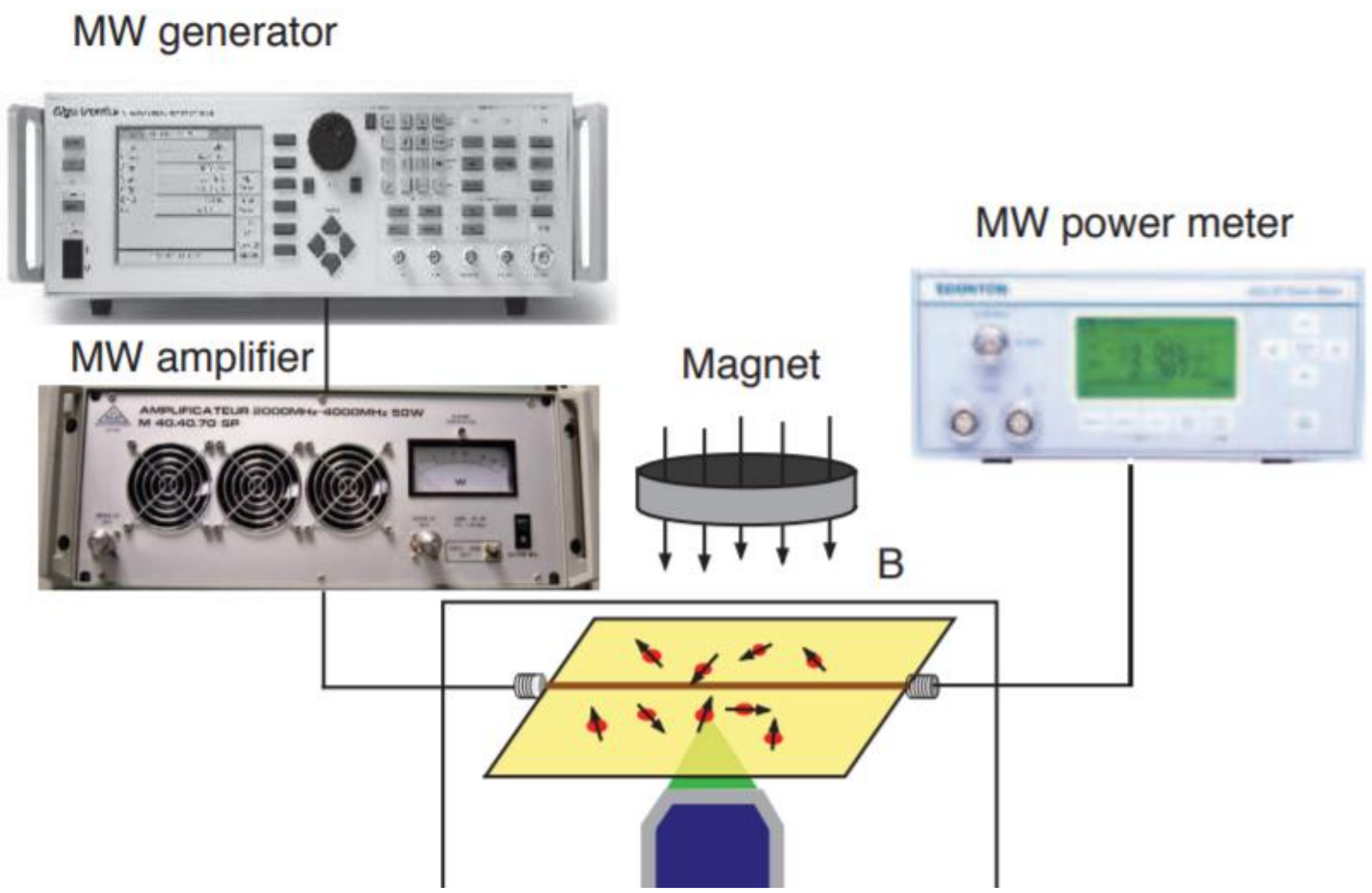


$$H = H_{ZF} + H_{eZeeman} + H_{hf} + H_Q + H_{nZeeman}$$
$$= \mathbf{S} \cdot \mathrm{D} \cdot \mathbf{S} + g_e \mu_B \mathbf{B} \cdot \mathbf{S} + \sum_k [\mathbf{S} \cdot A_k \cdot \mathbf{I}_k + \mathbf{I}_k \cdot P \cdot \mathbf{I}_k - g_{n,k} \mu_n \mathbf{B} \cdot \mathbf{I}_k]$$

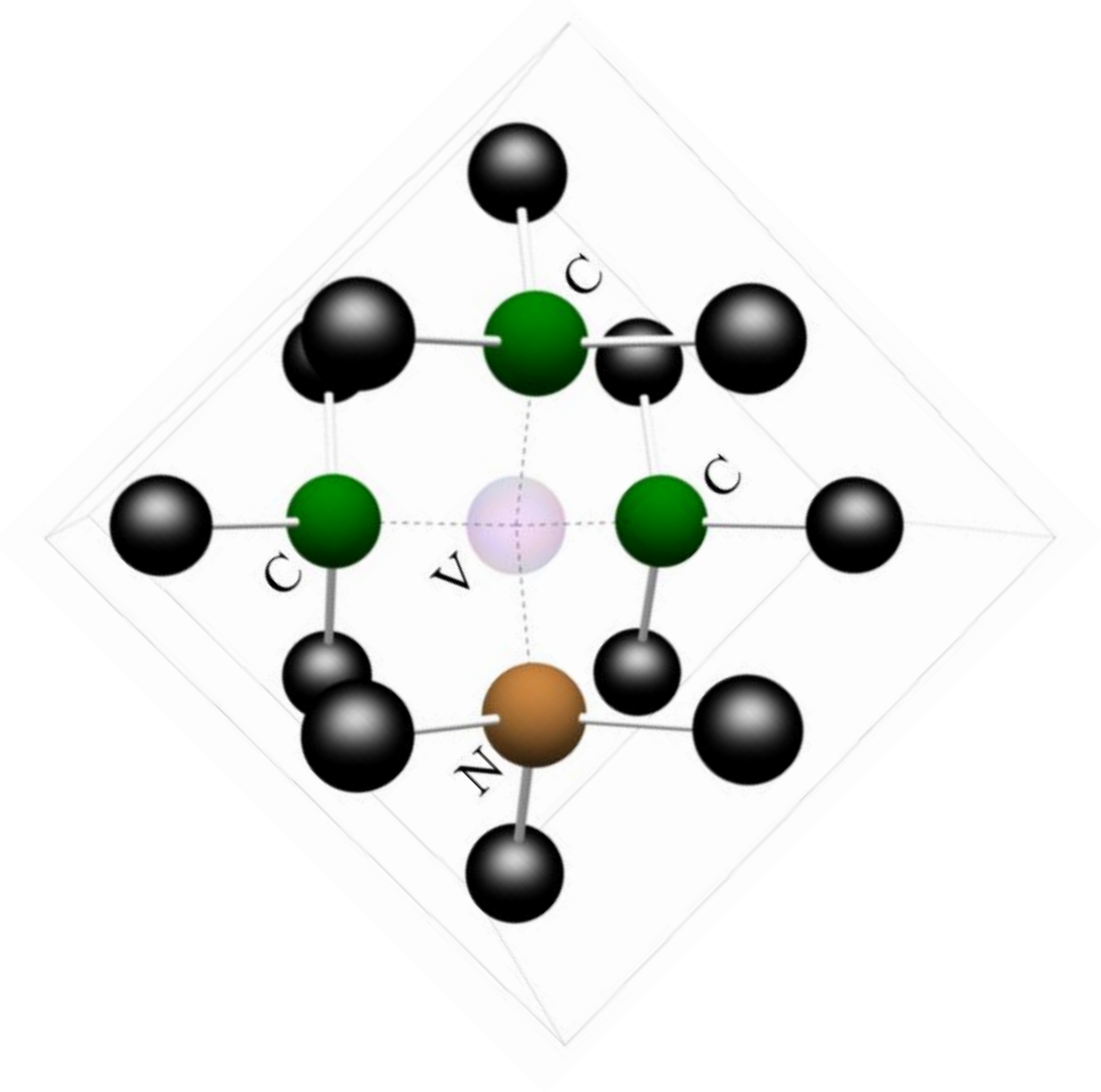
Без магнитного поля

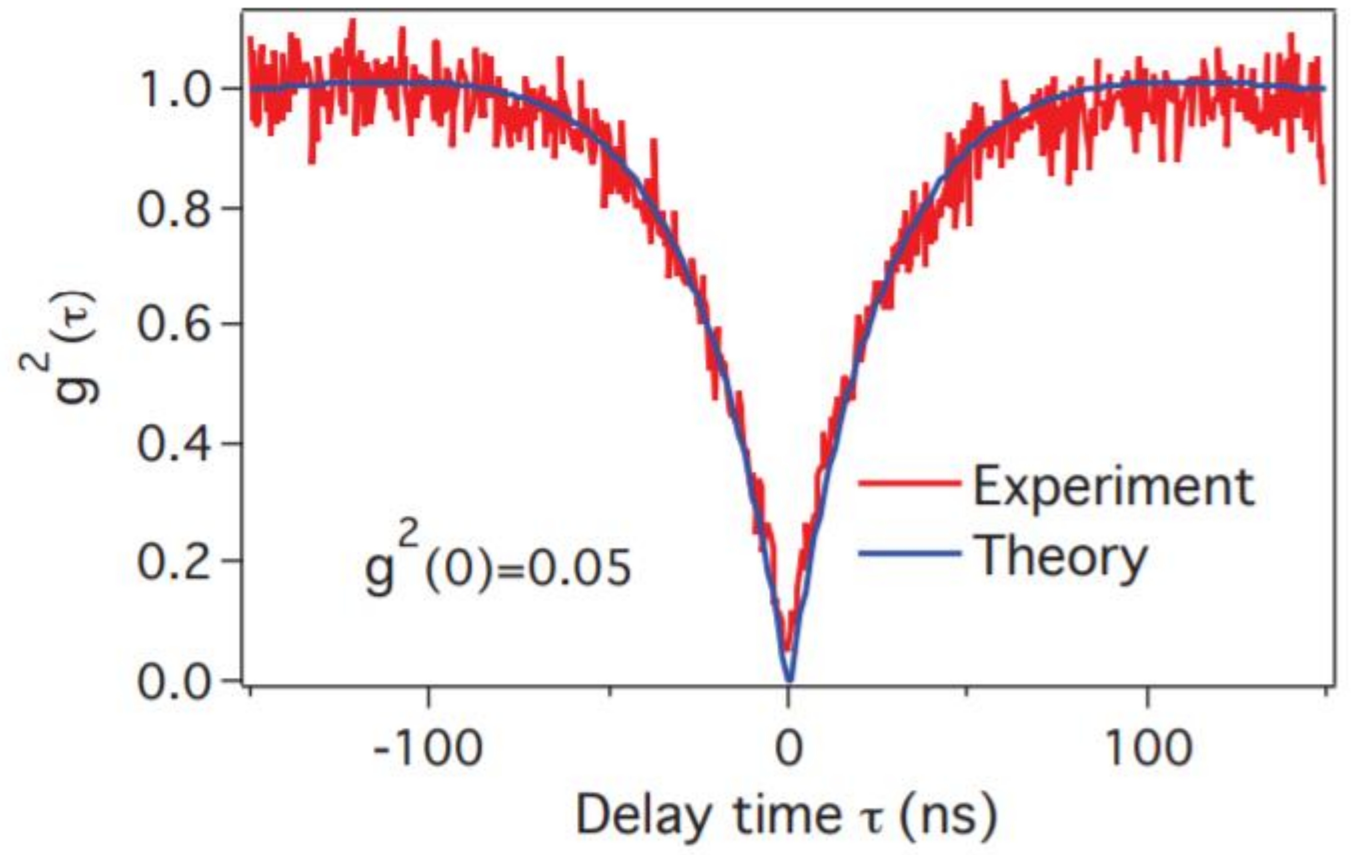
В присутствии магнитного поля

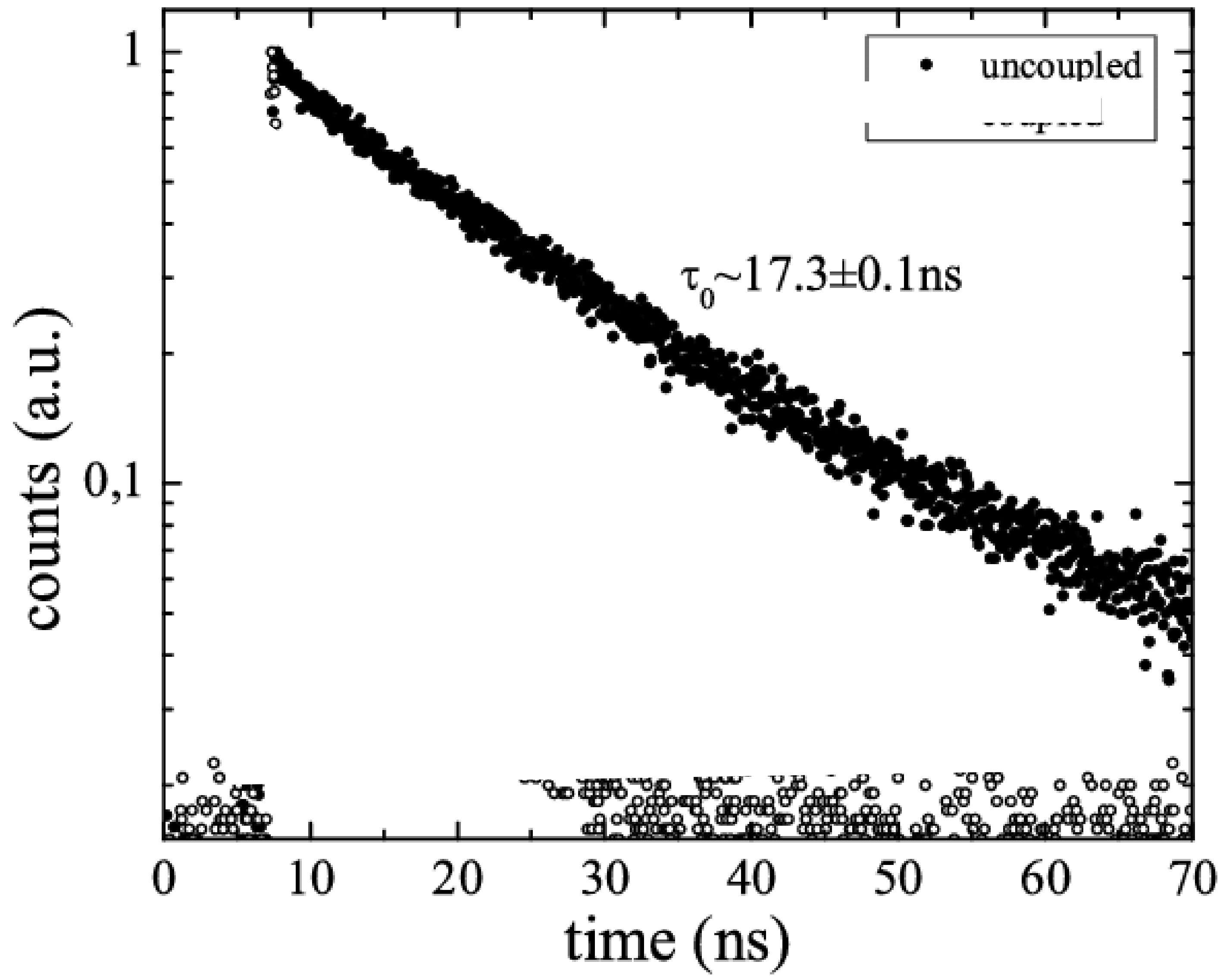


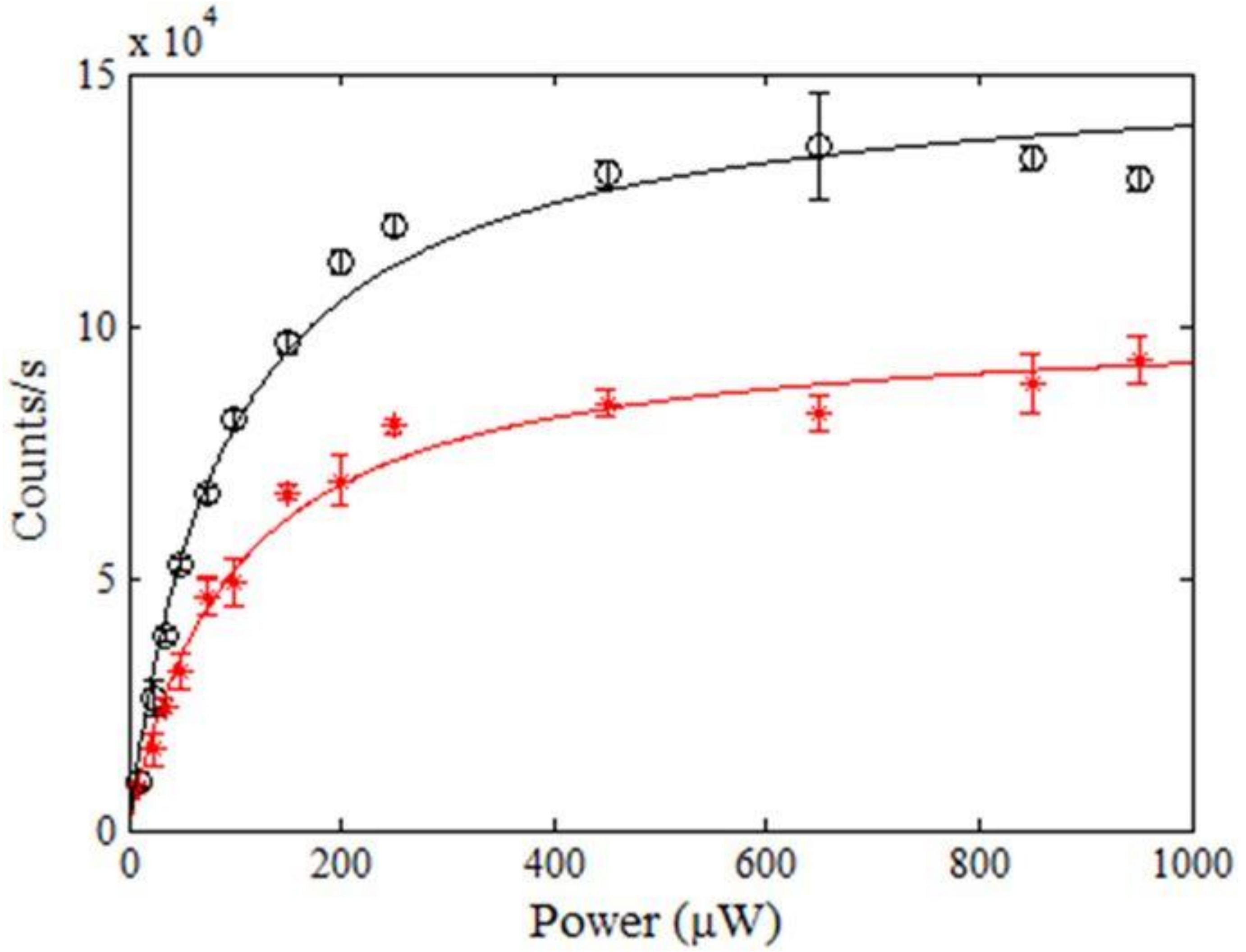


NV ЦЕНТРЫ









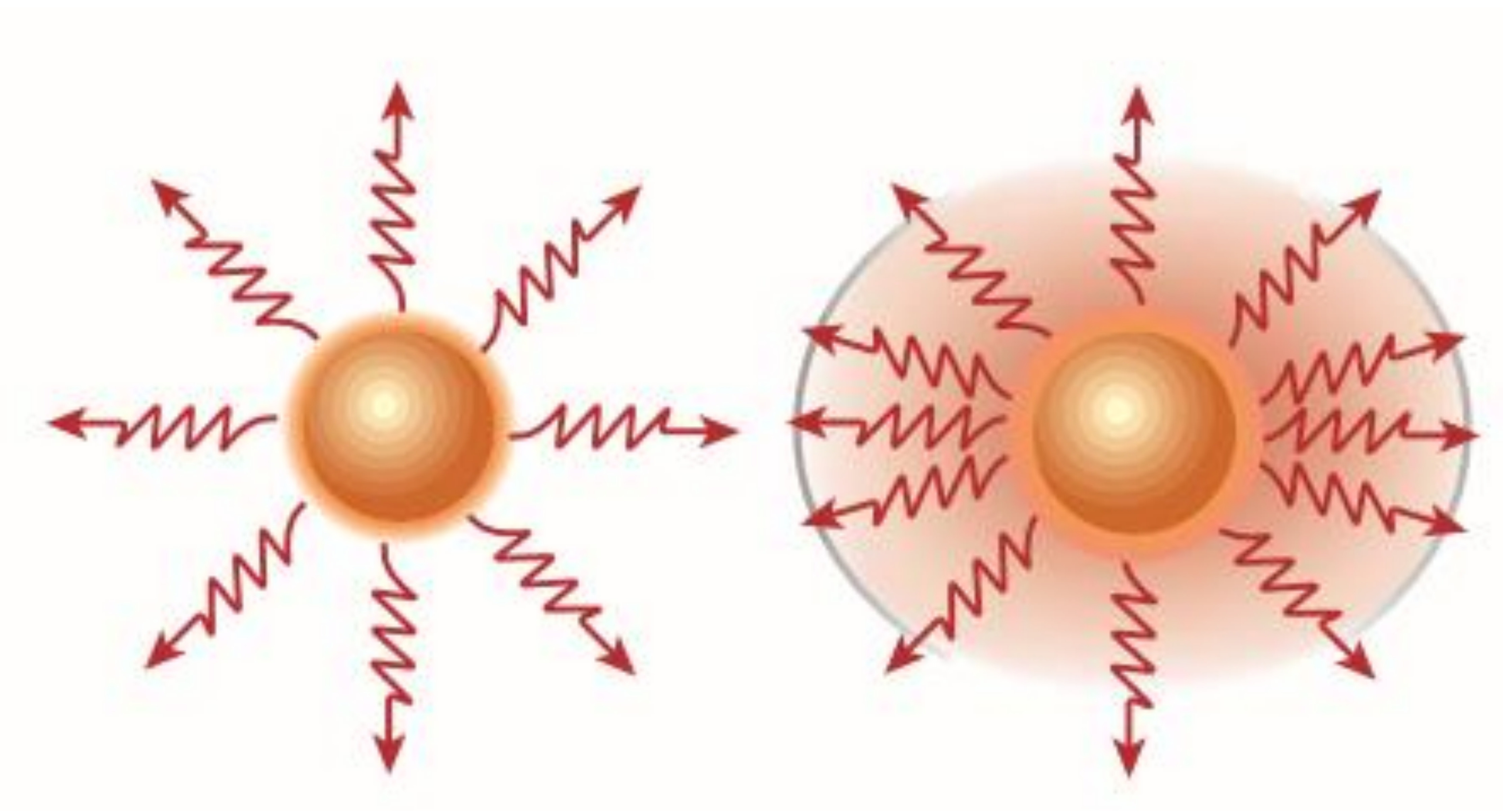
Без усиления

τ=17 ns

$I_{max} \approx 10^7$ photons/sec

- мало фотонов

ИЗЛУЧАТЕЛИ В РЕЗОНАТОРАХ



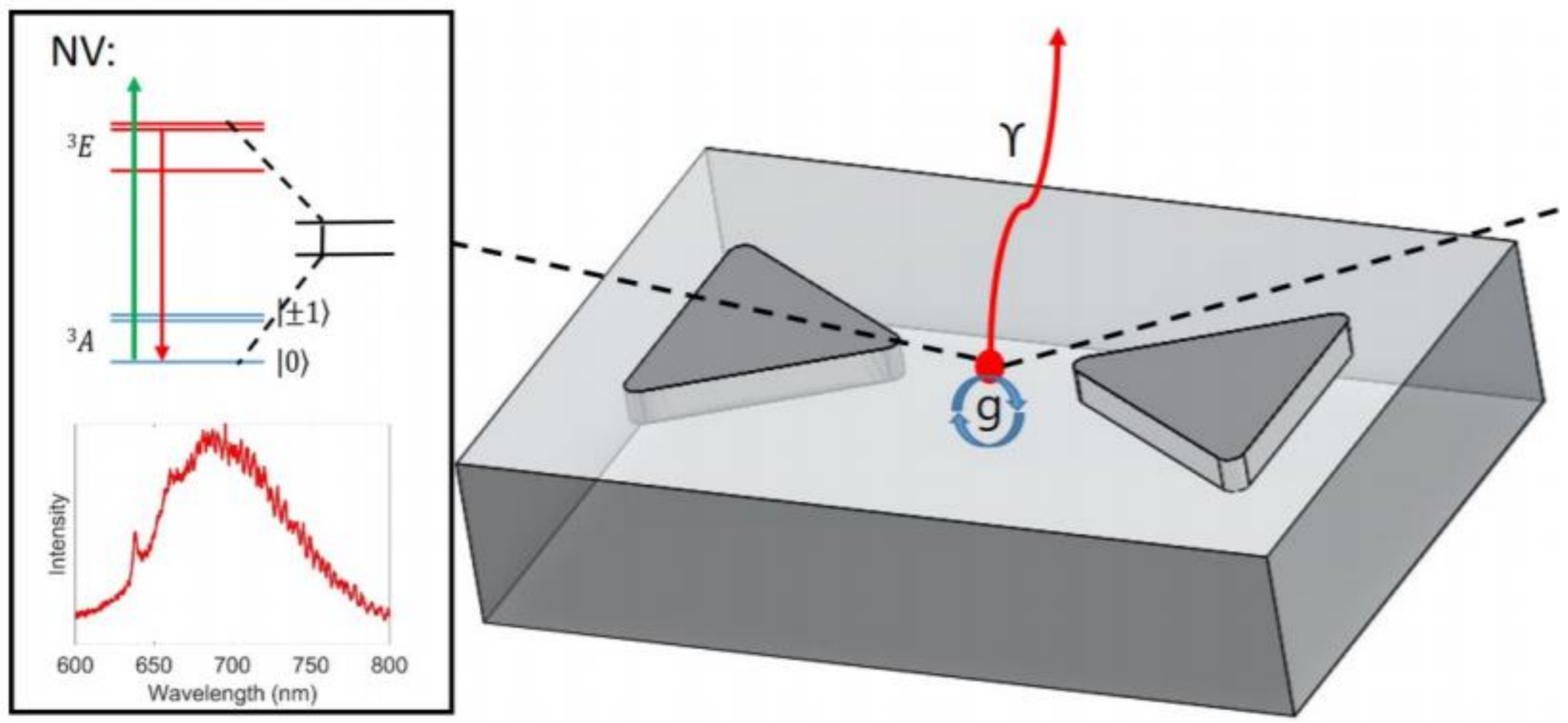
Золотое правило Ферми

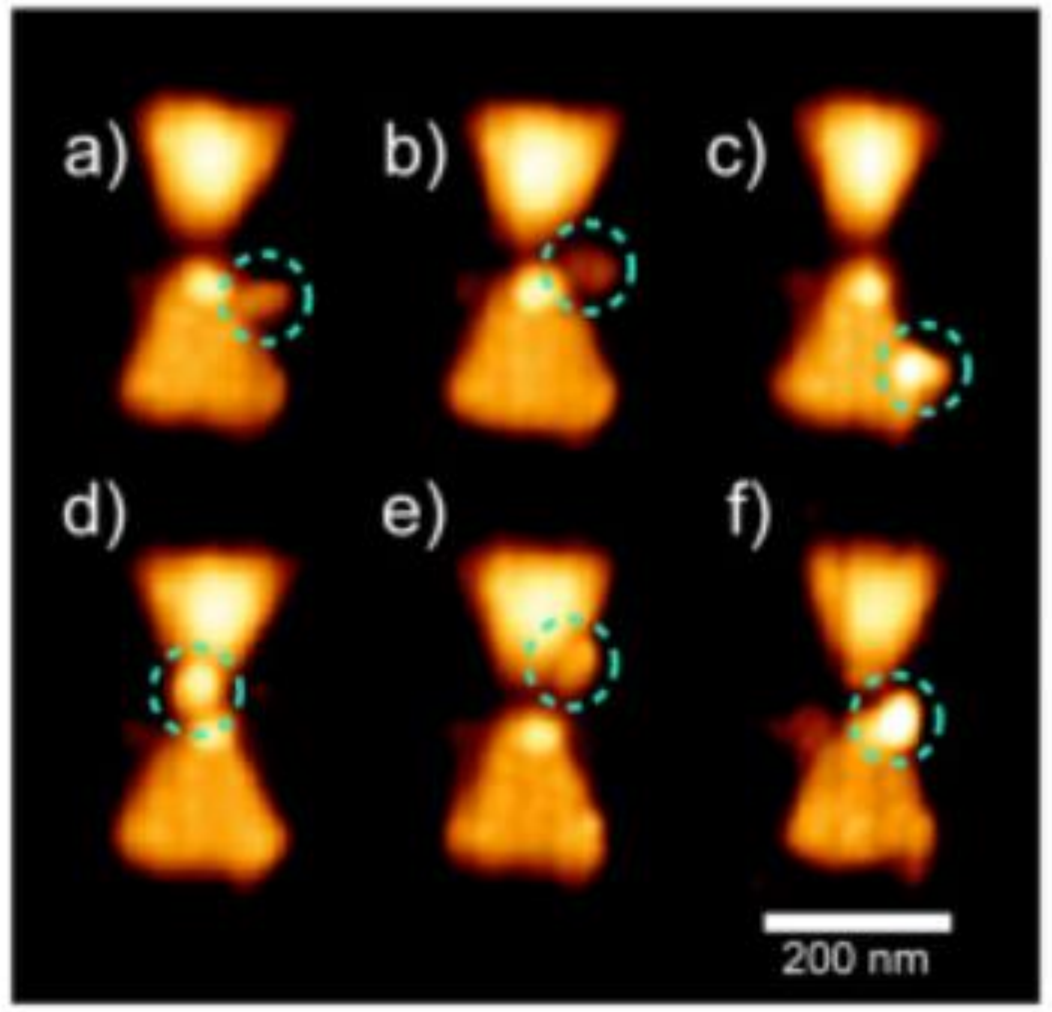
$$W_{i\to f} = \frac{2\pi}{\hbar}\left|\langle f|H'|i\rangle\right|^2 \rho$$

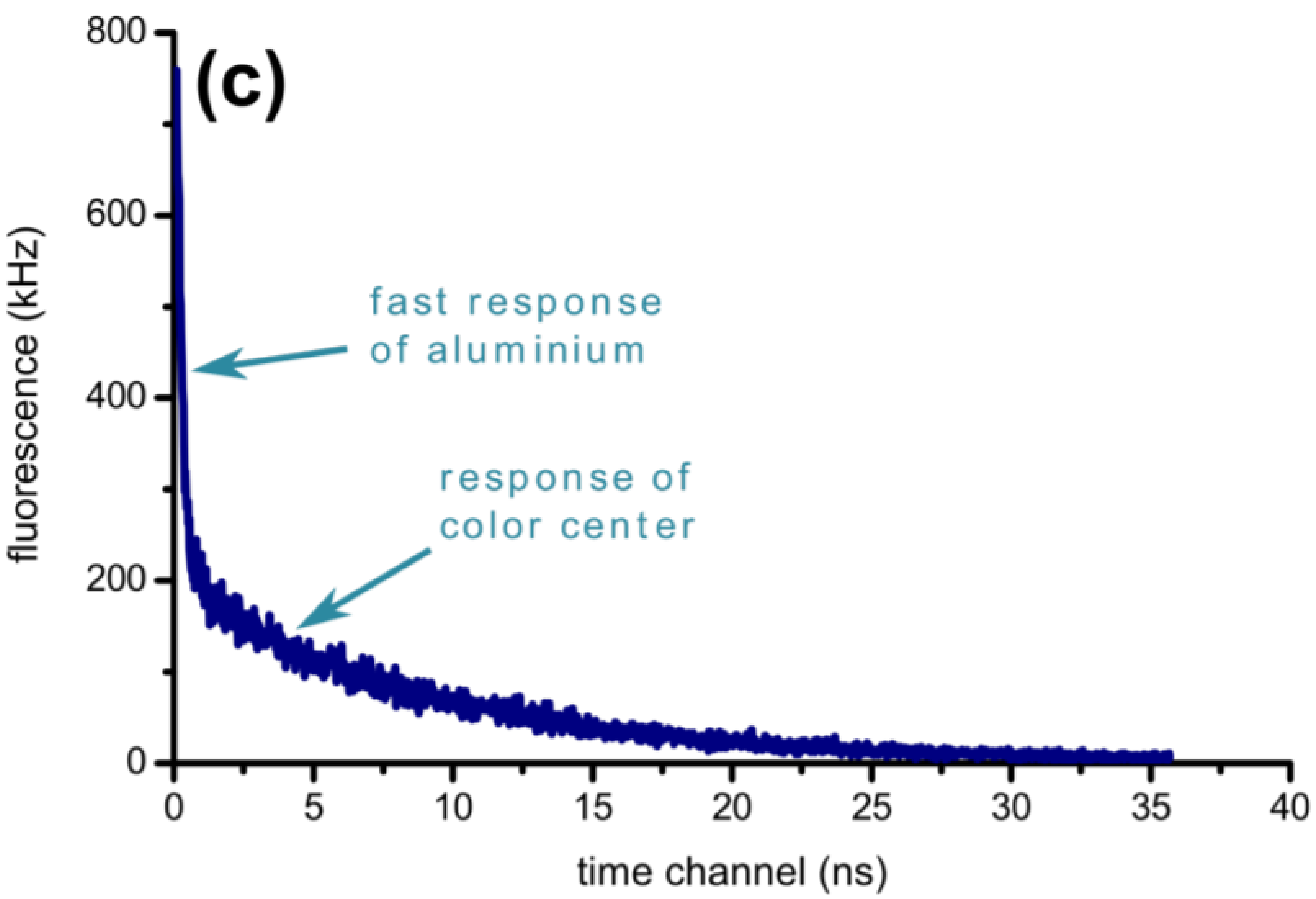
Эффект Парселла

$$F_p = \frac{3}{4\pi^2}\left(\frac{\lambda_c}{n}\right)^3 \frac{Q}{V}$$

ИЗЛУЧАТЕЛИ В РЕЗОНАТОРАХ

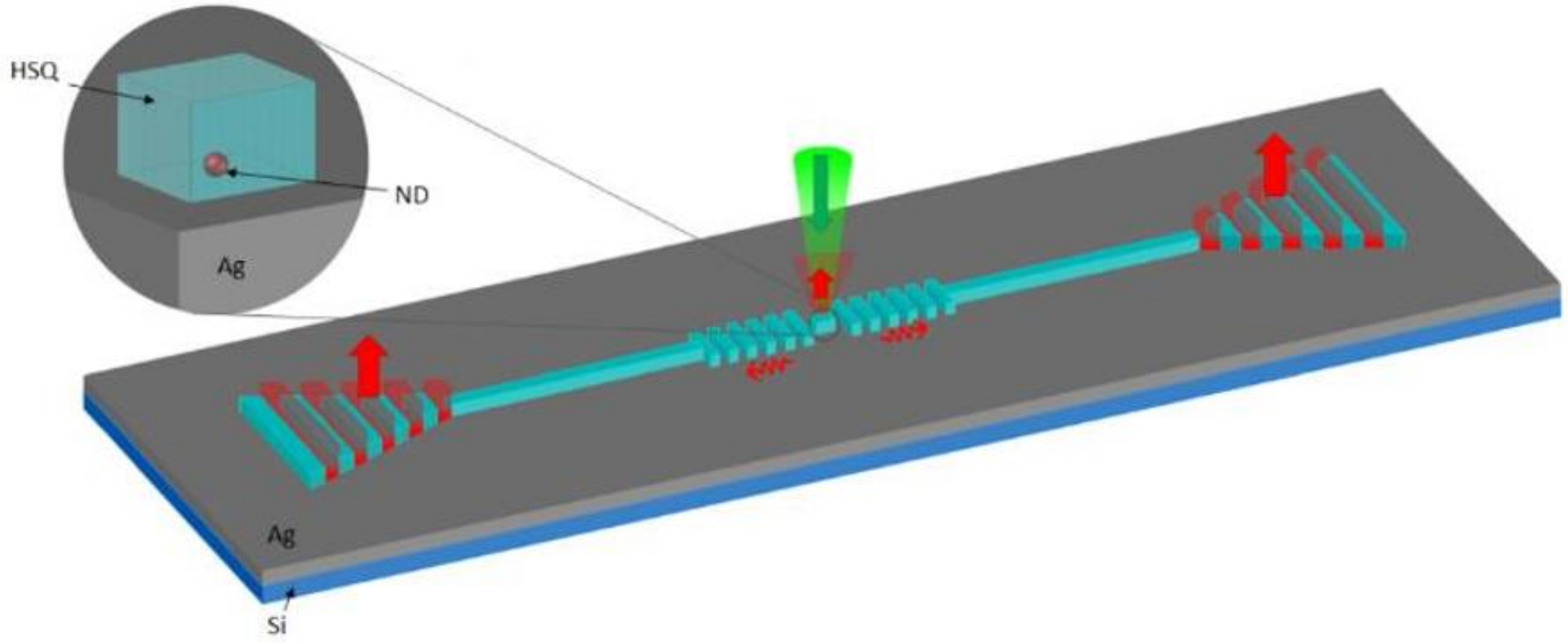


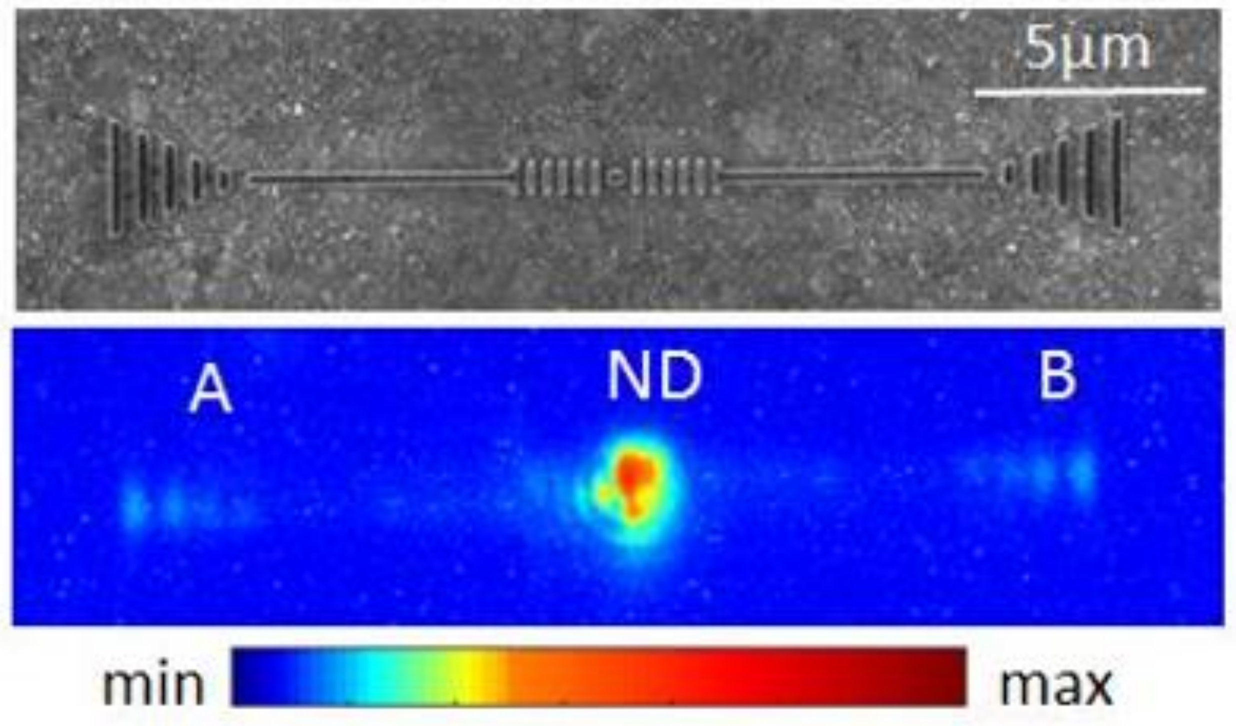




$$\frac{\Gamma}{\Gamma_0} \approx 4$$

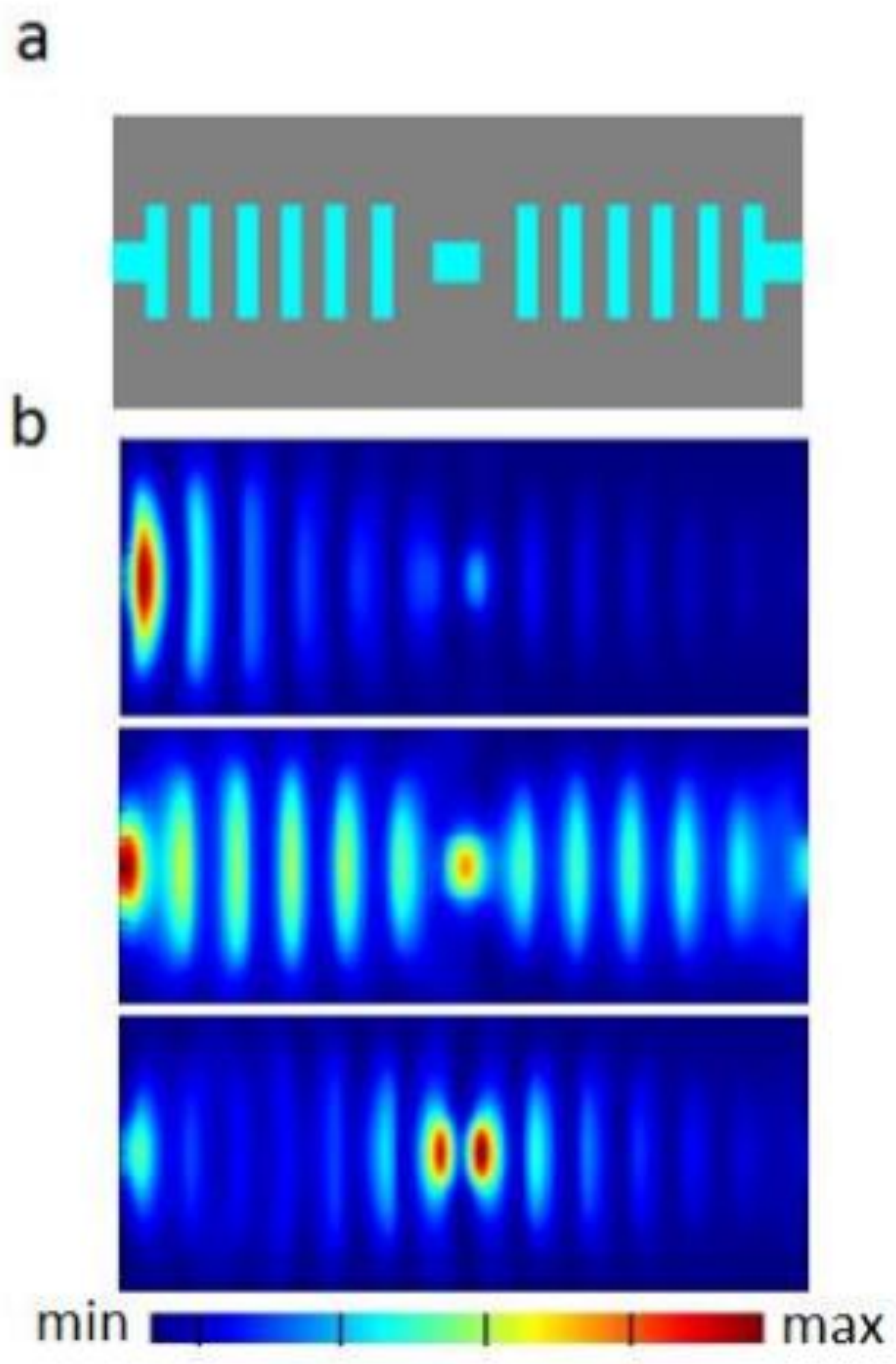
ИЗЛУЧАТЕЛИ В РЕЗОНАТОРАХ





$$Q \approx 70,$$

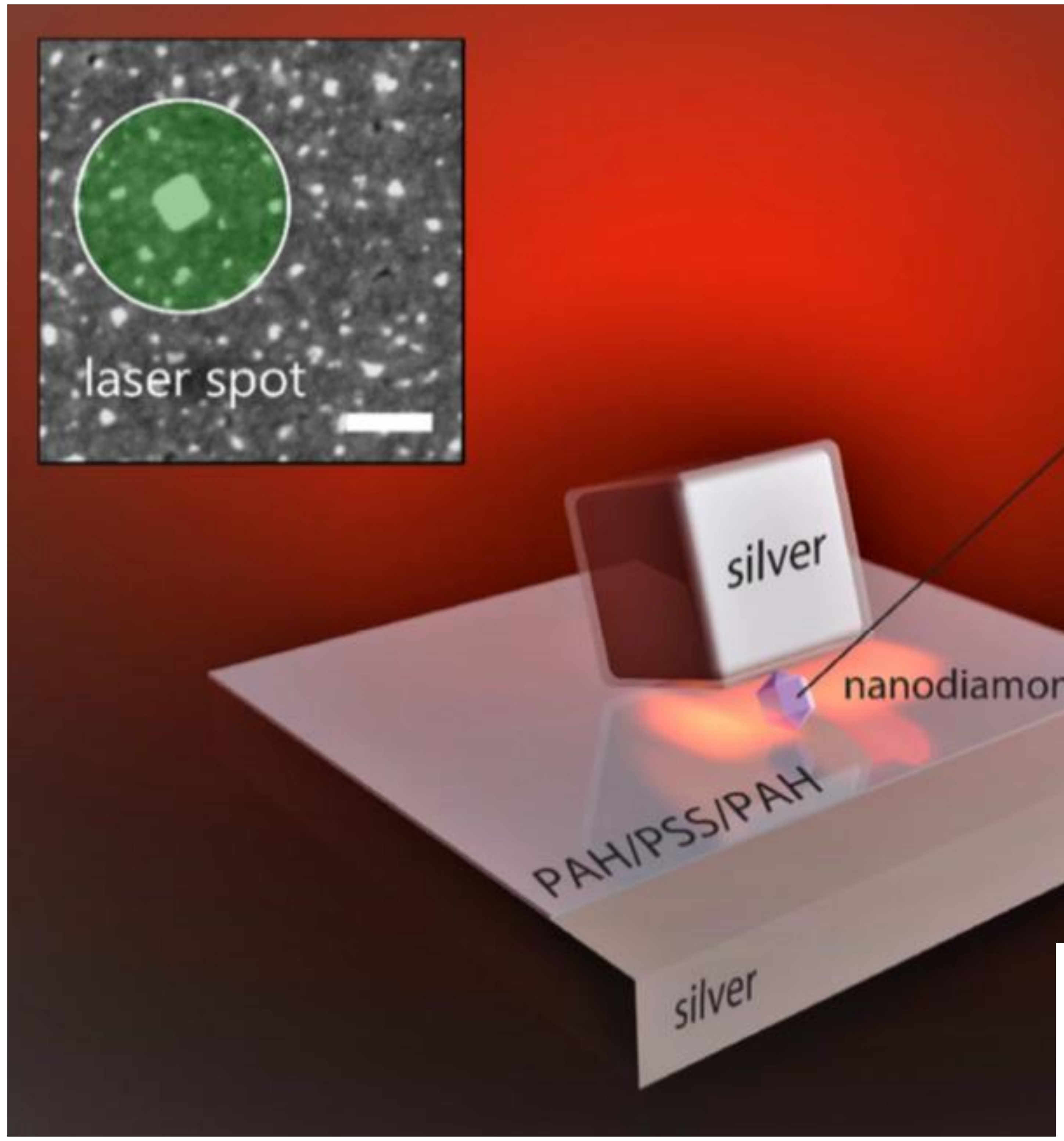
$$\frac{\Gamma}{\Gamma_0} \approx 50$$



Chip-integrated plasmonic cavity-enhanced single nitrogen-vacancy center emission

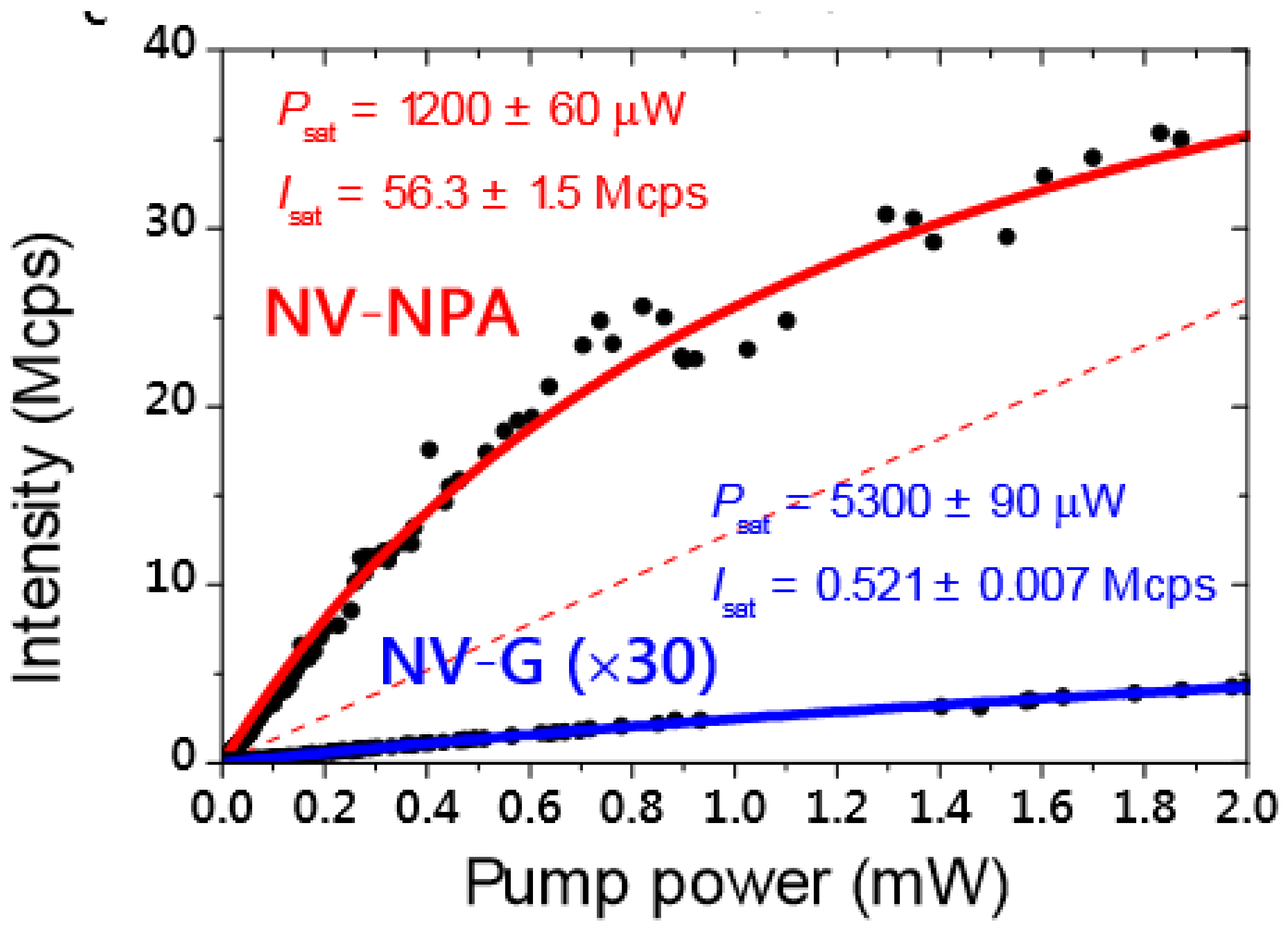
Hamidreza Siampour,* Shailesh Kumar and Sergey I. Bozhevolnyi

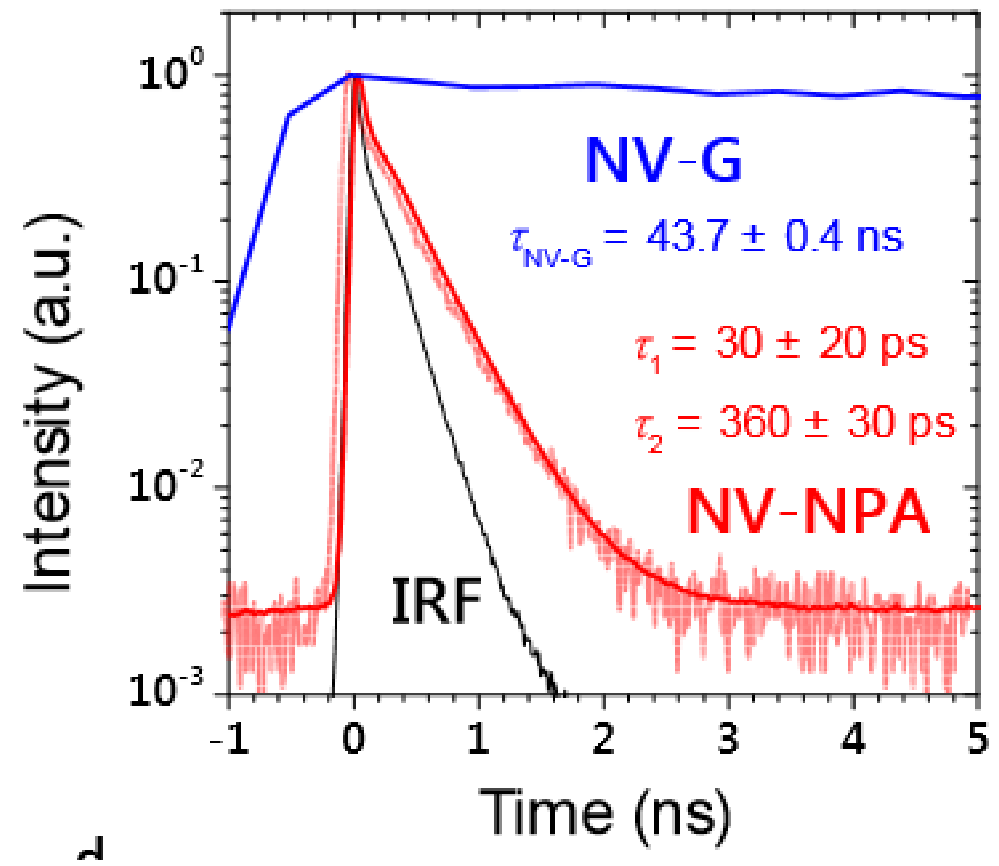
ИЗЛУЧАТЕЛИ В РЕЗОНАТОРАХ



$$F_p = \frac{3}{4\pi^2}\left(\frac{\lambda_c}{n}\right)^3 \frac{Q}{V}$$

$$\frac{\Gamma}{\Gamma_0} \approx 100$$



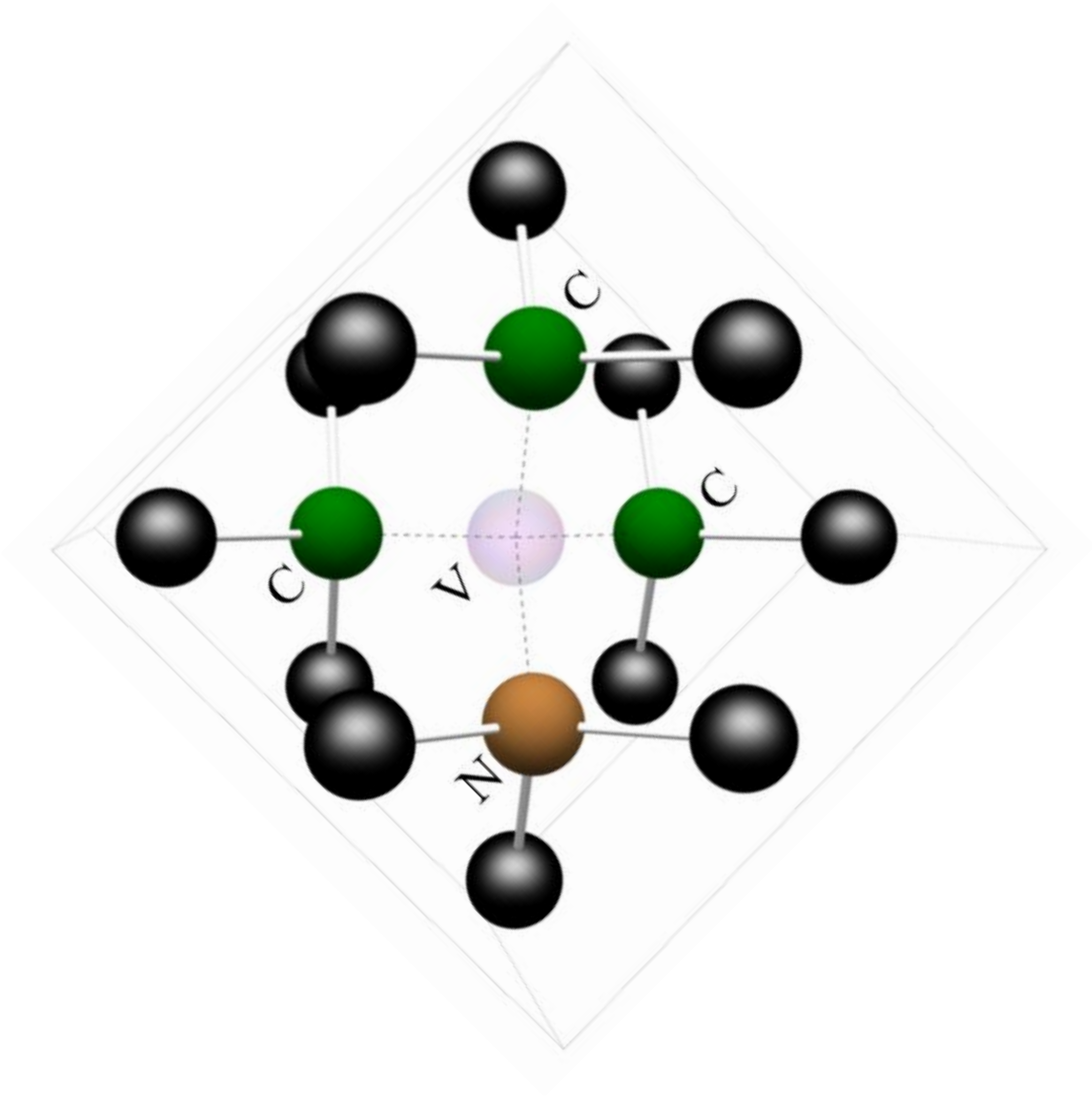


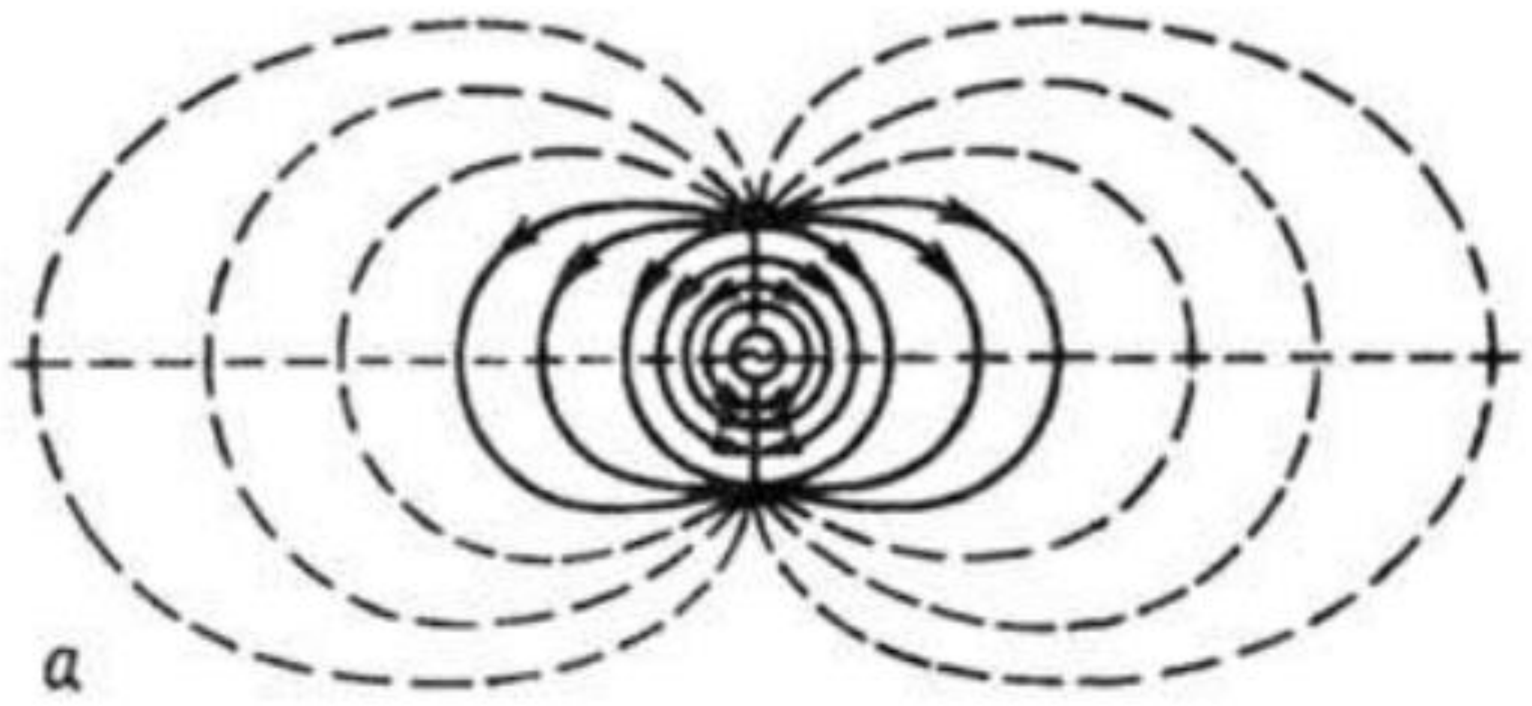
Увеличение числа фотоотсчетов
в 100 раз!

Ultrabright room-temperature sub-nanosecond emission from single nitrogen-vacancy centers coupled to nano-patch antennas

Simeon Bogdanov, Mikhail Y. Shalaginov, Alexei Lagutchev, Chin-Cheng Chiang, Deesha Shah, Aleksandr Baburin, Ilya Ryzhikov, Ilya Rodionov, Alexander V. Kildishev, Alexandra Boltasseva, and Vladimir M. Shalaev

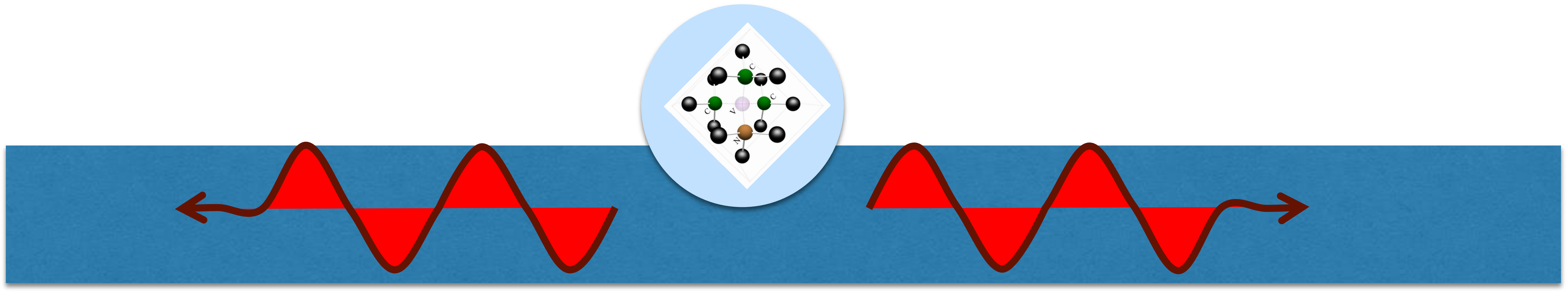
NV ЦЕНТРЫ





Направленность излучения

ЗАВЕДЕНИЕ ИЗЛУЧЕНИЯ NV ЦЕНТРА В ВОЛОКНО



Золотое правило Ферми

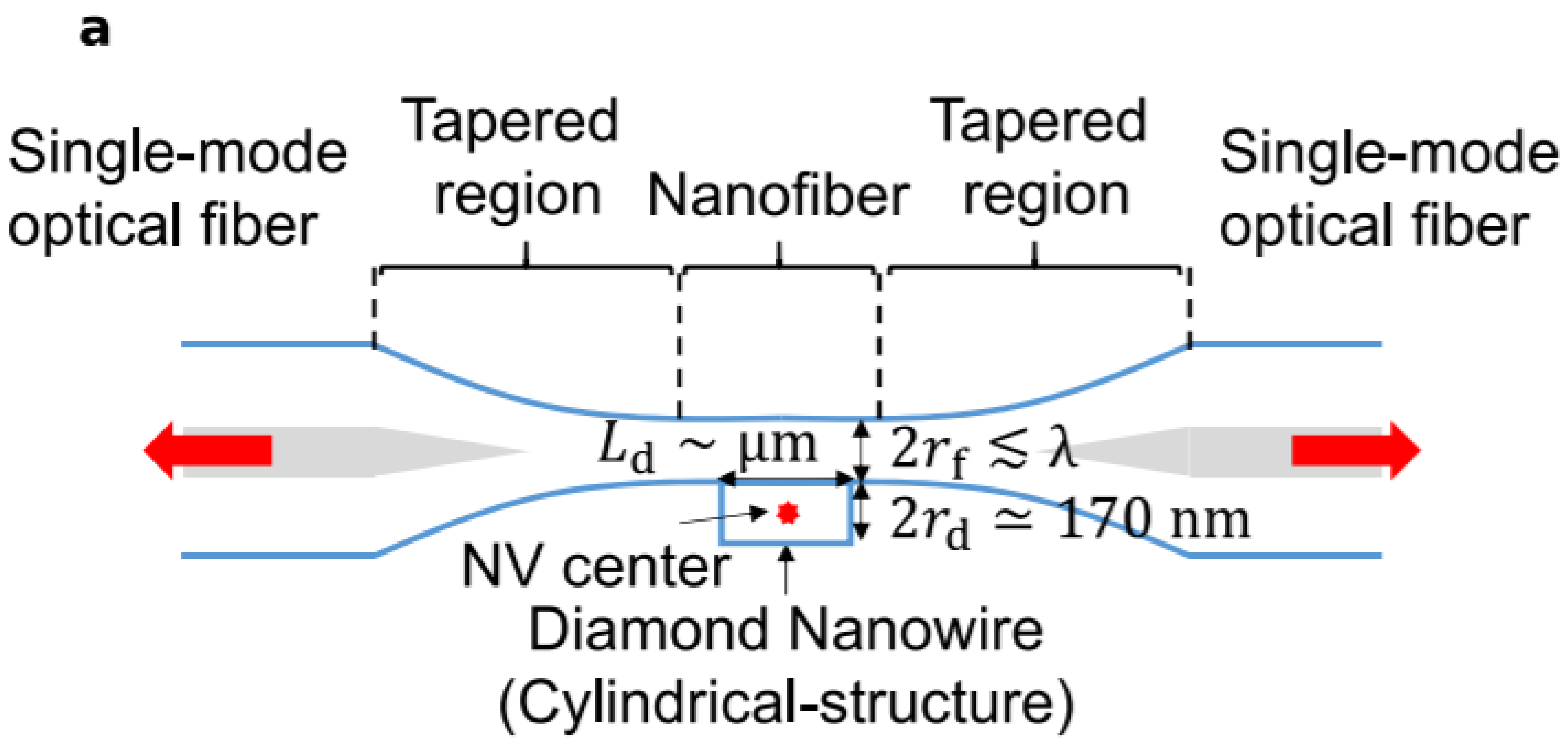
$$W_{i\to f} = \frac{2\pi}{\hbar}\left|\langle f|H'|i\rangle\right|^2 \rho$$

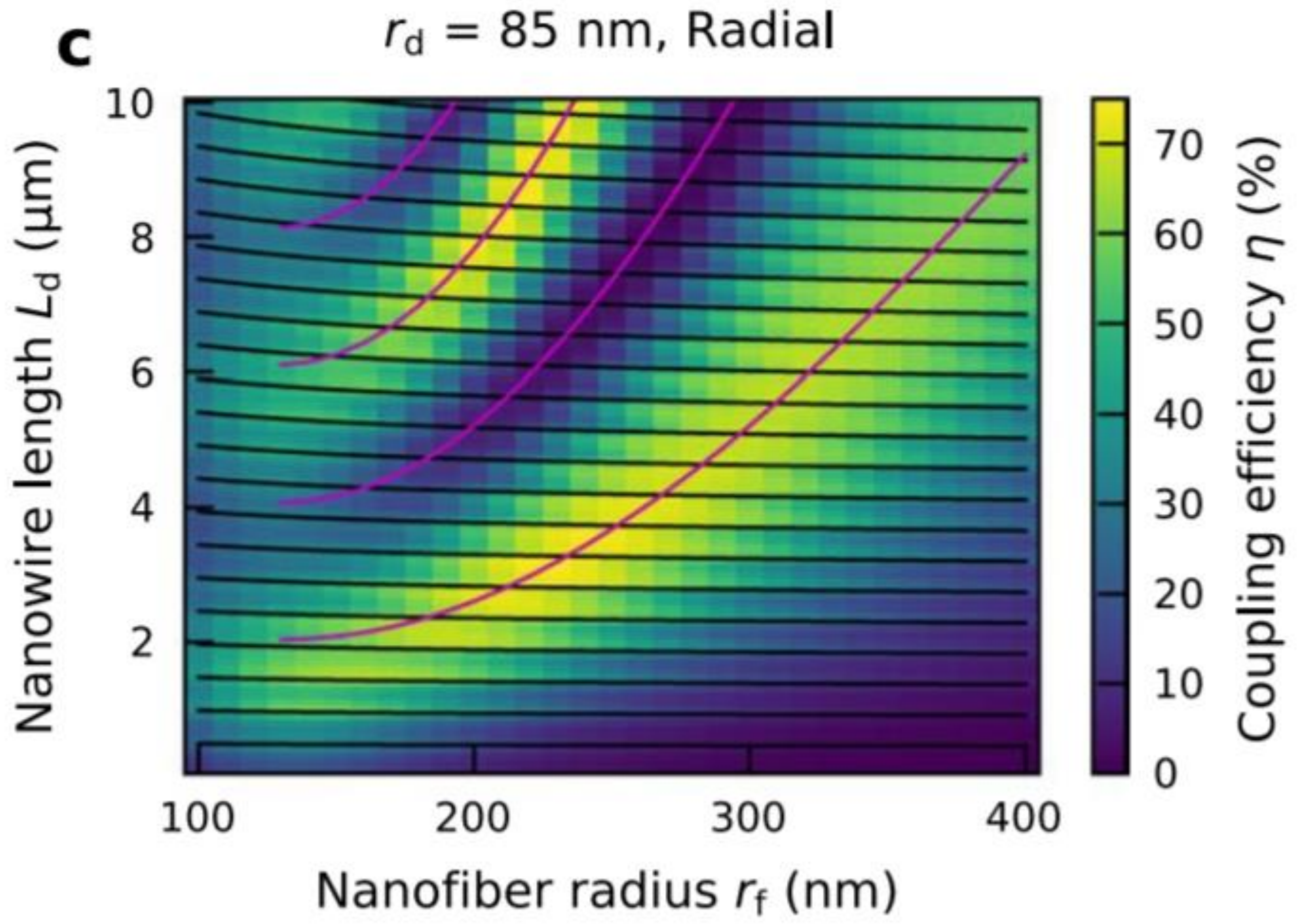
$$\hat{\mathcal{H}}^{\mathrm{JC}} = \sum_{i=0}^{n} \hbar\omega_i \hat{\sigma}_{i,i} + \hbar\omega_{\mathrm{ZPL}}\hat{\sigma}_{e,e} + \hbar\omega_c \hat{a}^\dagger \hat{a} + i\hbar \sum_{i=0}^{n} g_i (\hat{a}^\dagger \hat{\sigma}_{i,e} - \hat{\sigma}_{i,e}^\dagger \hat{a})$$

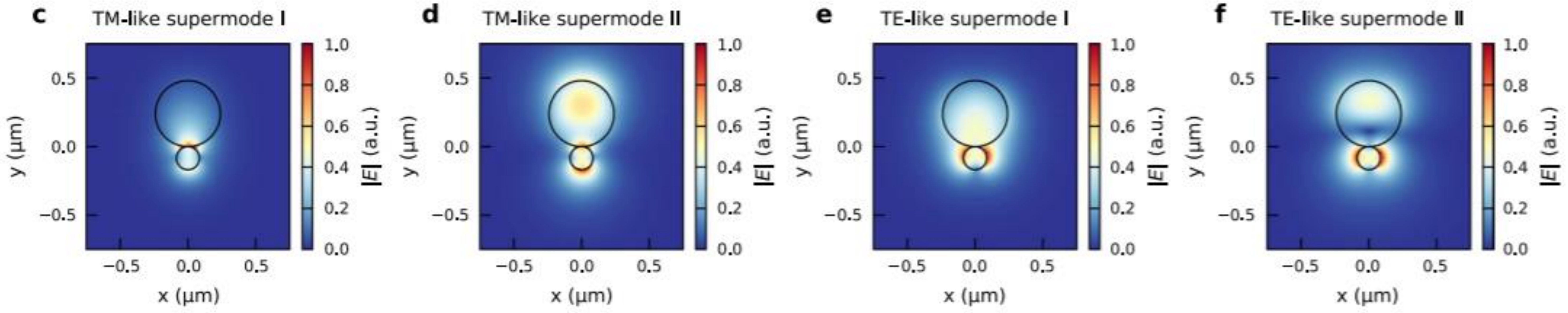
$$R_0 = \frac{4g_0^2}{\kappa + \gamma + \gamma^\star} \frac{1}{1 + \left(\frac{2\delta_0}{\kappa+\gamma+\gamma^\star}\right)^2}$$

$$R_i = \frac{4g_i^2}{\kappa + \gamma + \gamma_{i,i-1} + \gamma^\star} \frac{1}{1 + \left(\frac{2\delta_1}{\kappa+\gamma+\gamma_{i,i-1}+\gamma^\star}\right)^2}$$

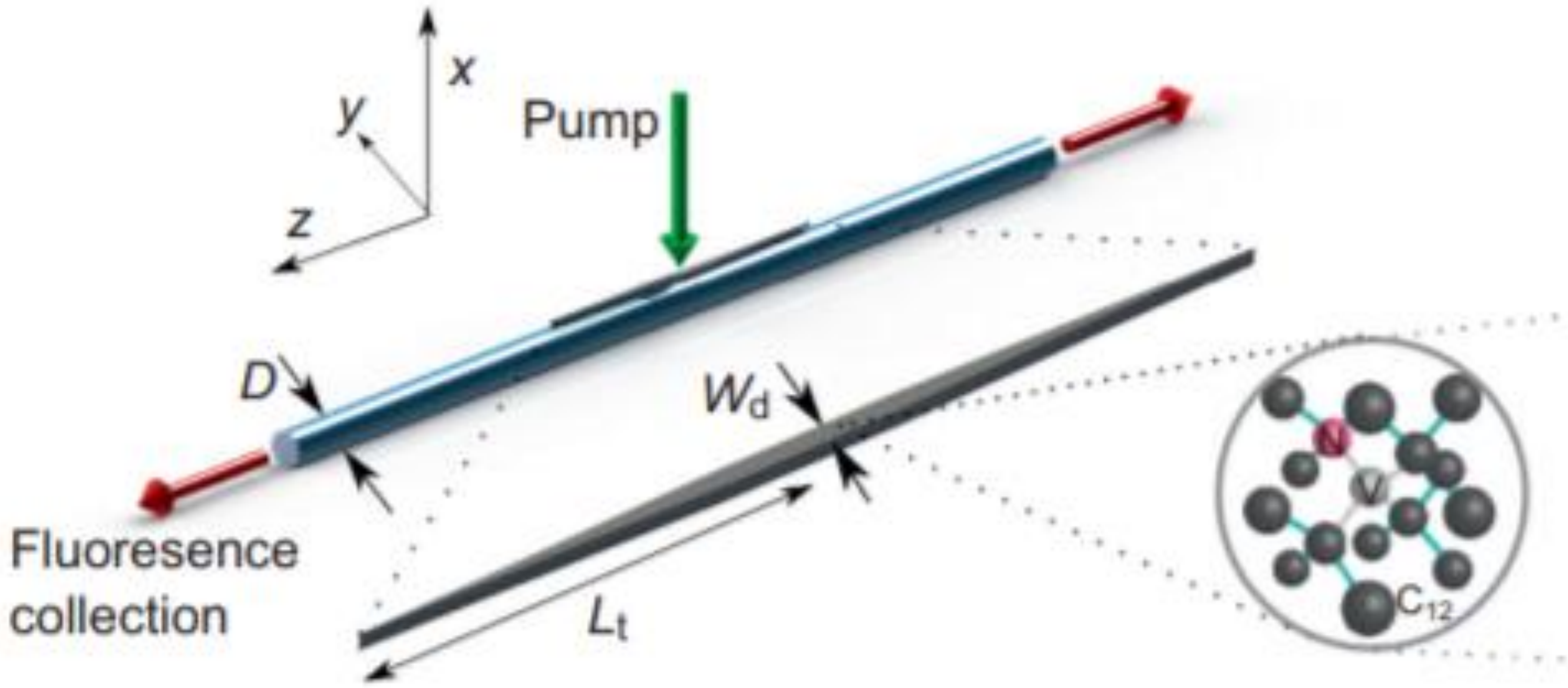
ВЗАИМОДЕЙСТВИЕ ИЗЛУЧАТЕЛЯ И ВОЛНОВОДА

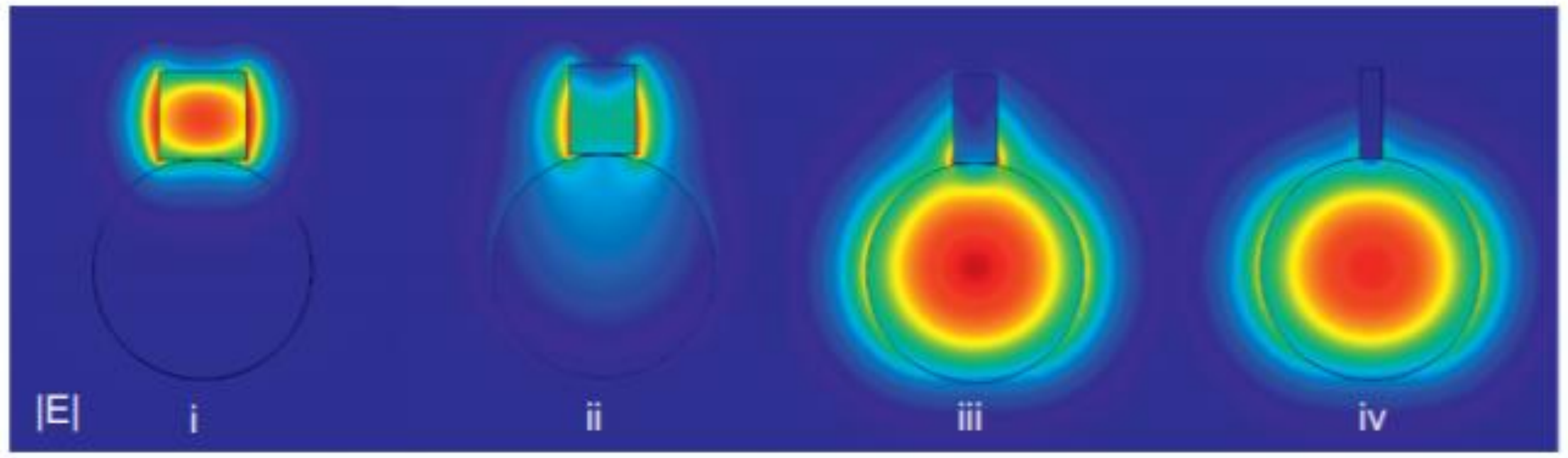






ВЗАИМОДЕЙСТВИЕ ИЗЛУЧАТЕЛЯ И ВОЛНОВОДА





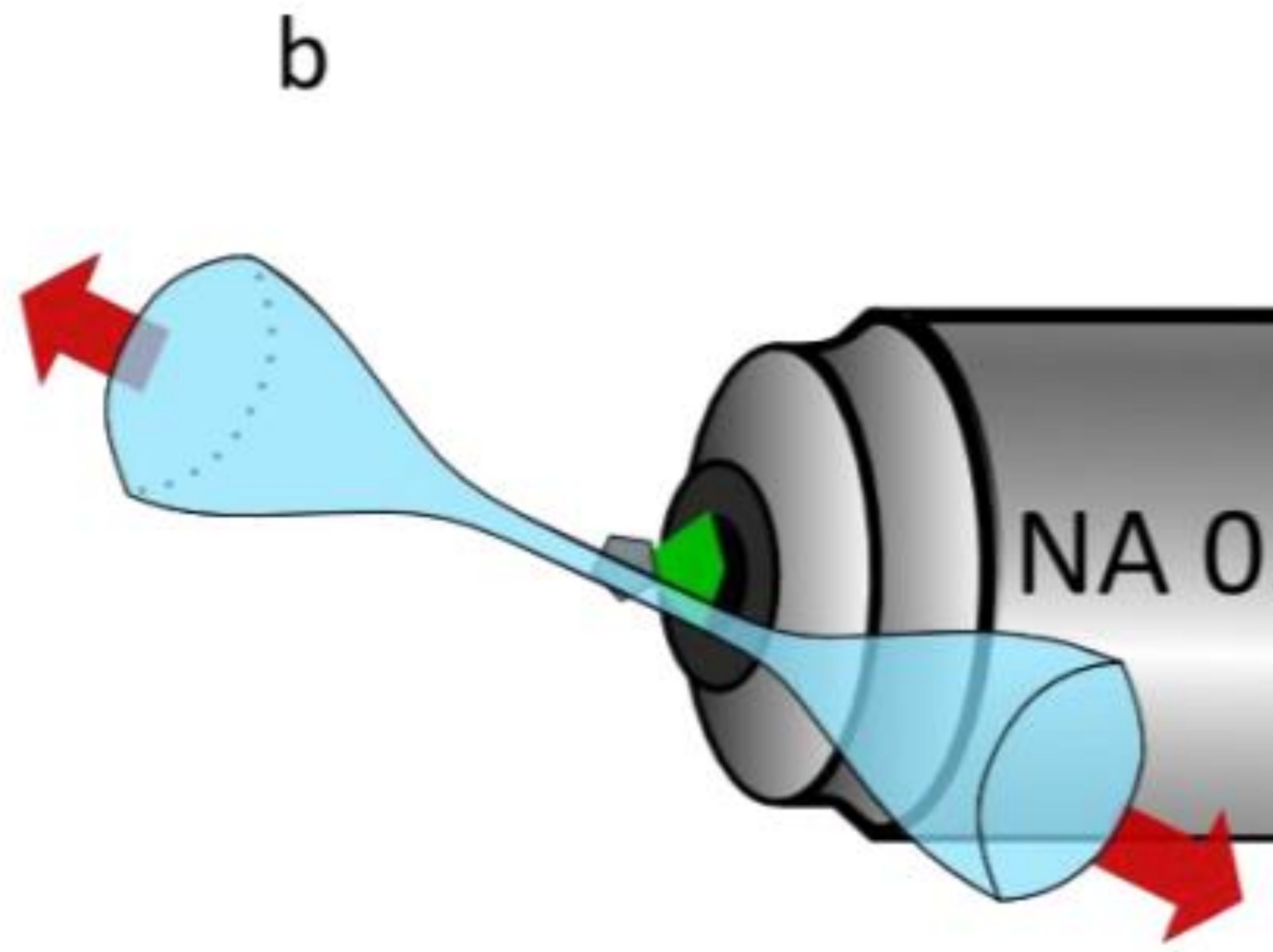
Efficient photon coupling from a diamond nitrogen vacancy center by integration with silica fiber

Rishi N Patel[1,2], Tim Schröder[1], Noel Wan[1], Luozhou Li[1], Sara L Mouradian[1], Edward H Chen[1] and Dirk R Englund[1]

$$\beta = \frac{\Gamma_{\text{guided}}}{\Gamma_{\text{decay}}} \qquad \Gamma^*_{\text{guided}} = \eta_{\text{apd}}\ \kappa_{\text{tg}}\ \kappa_{\text{taper}}\ \Gamma_{\text{guided}}$$

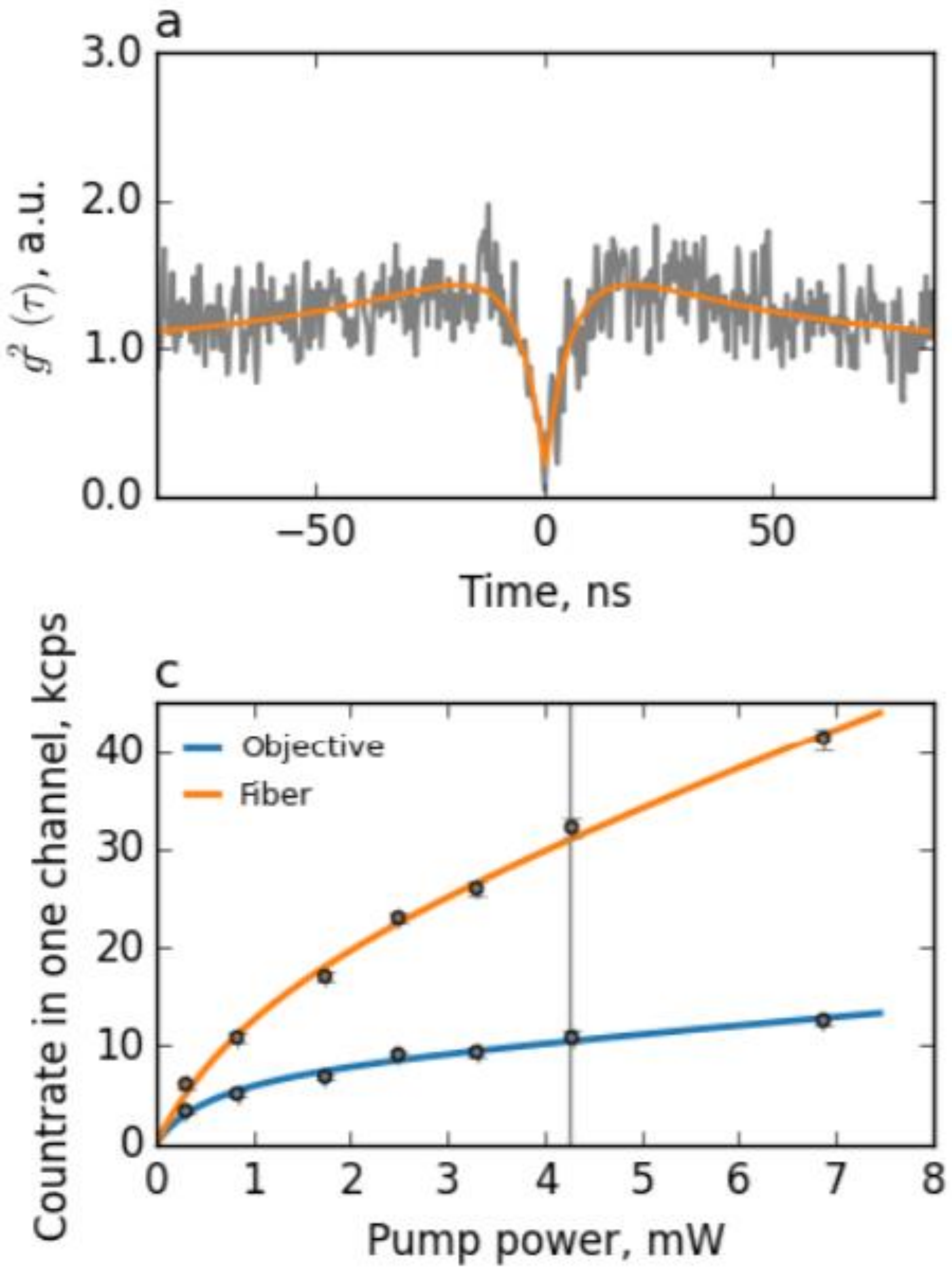
Эффективность заведения η≈15-30%

ВЗАИМОДЕЙСТВИЕ ИЗЛУЧАТЕЛЯ И ВОЛНОВОДА

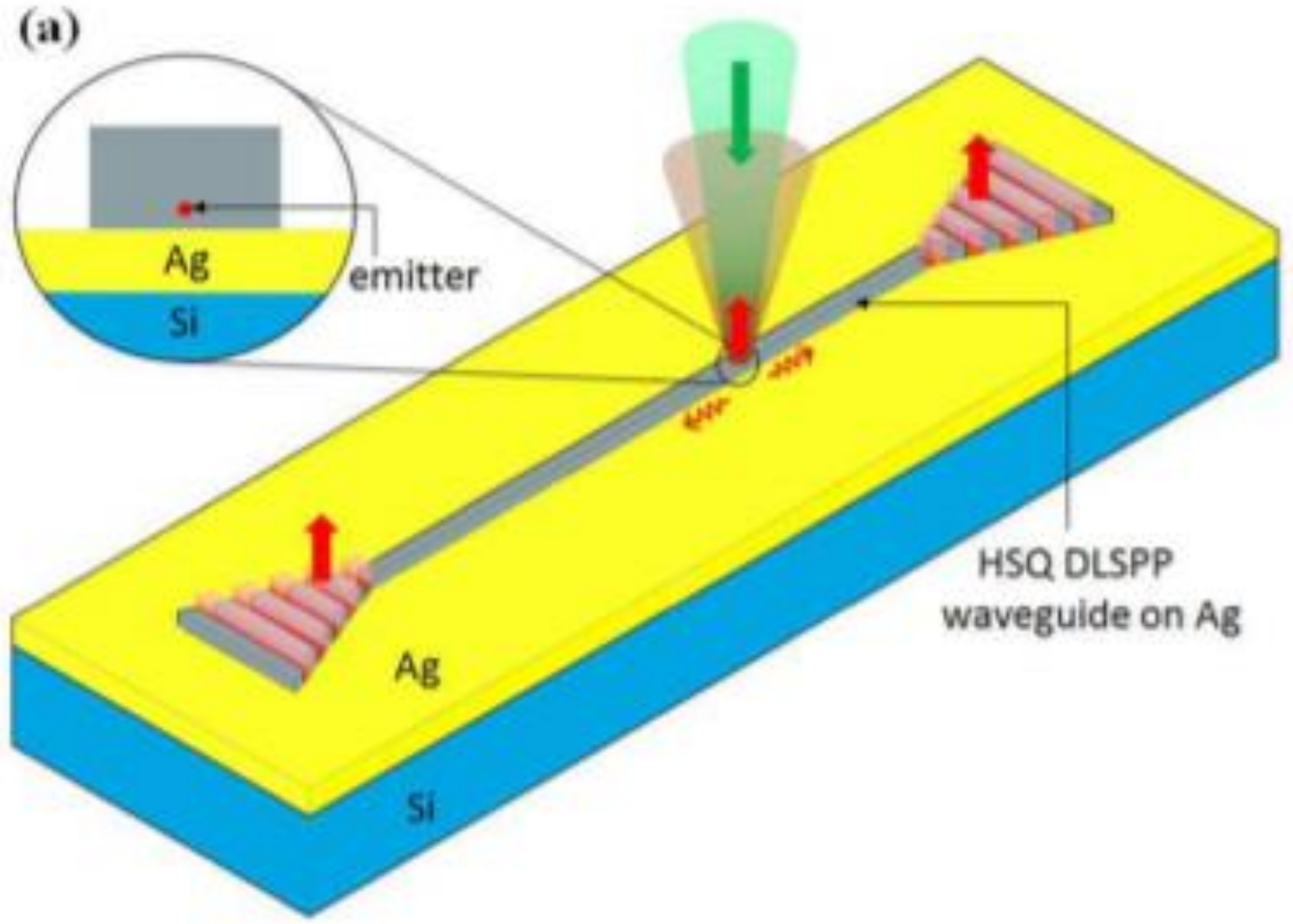


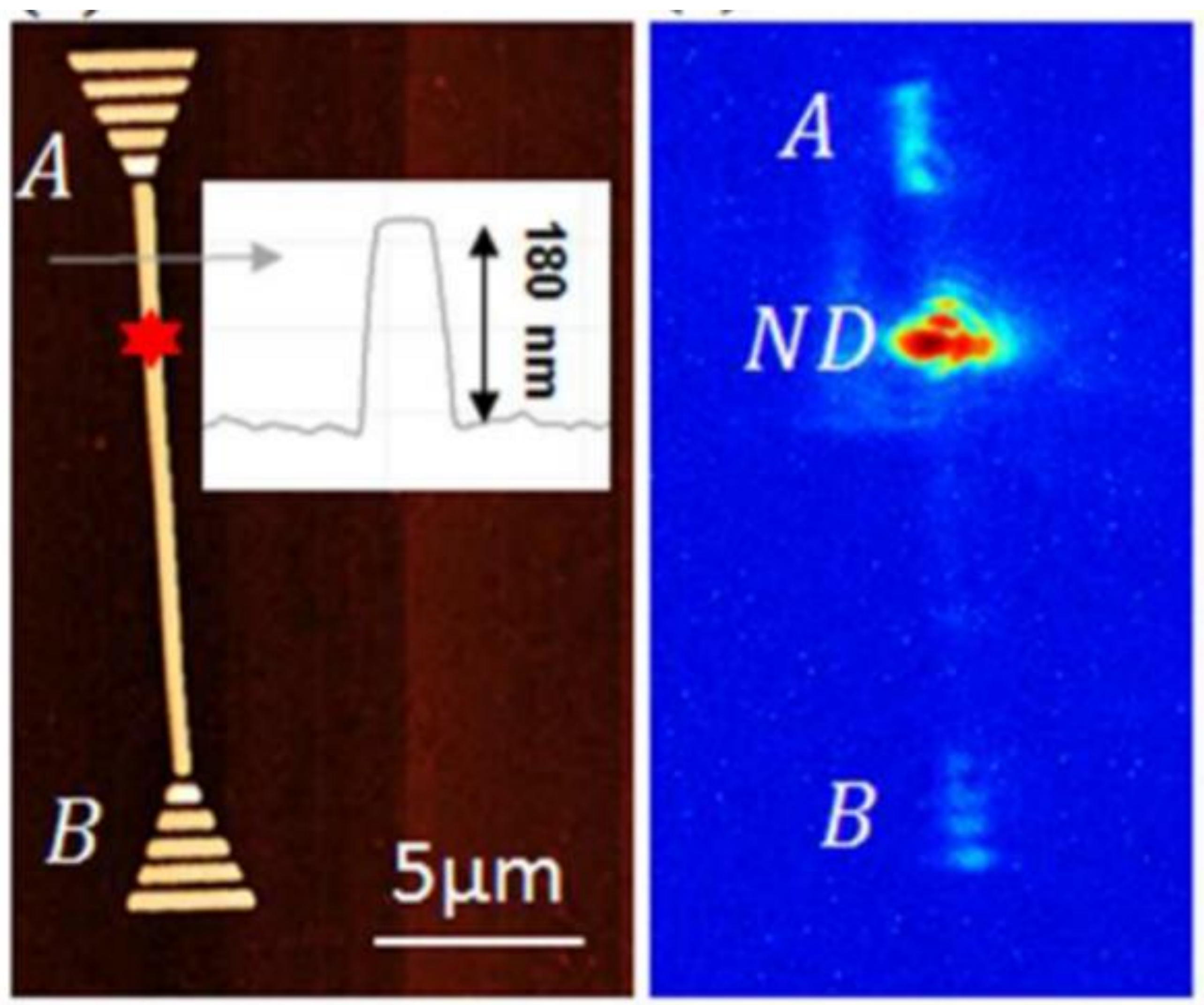
Coupling of single NV Center to adiabatically tapered optical single mode fiber

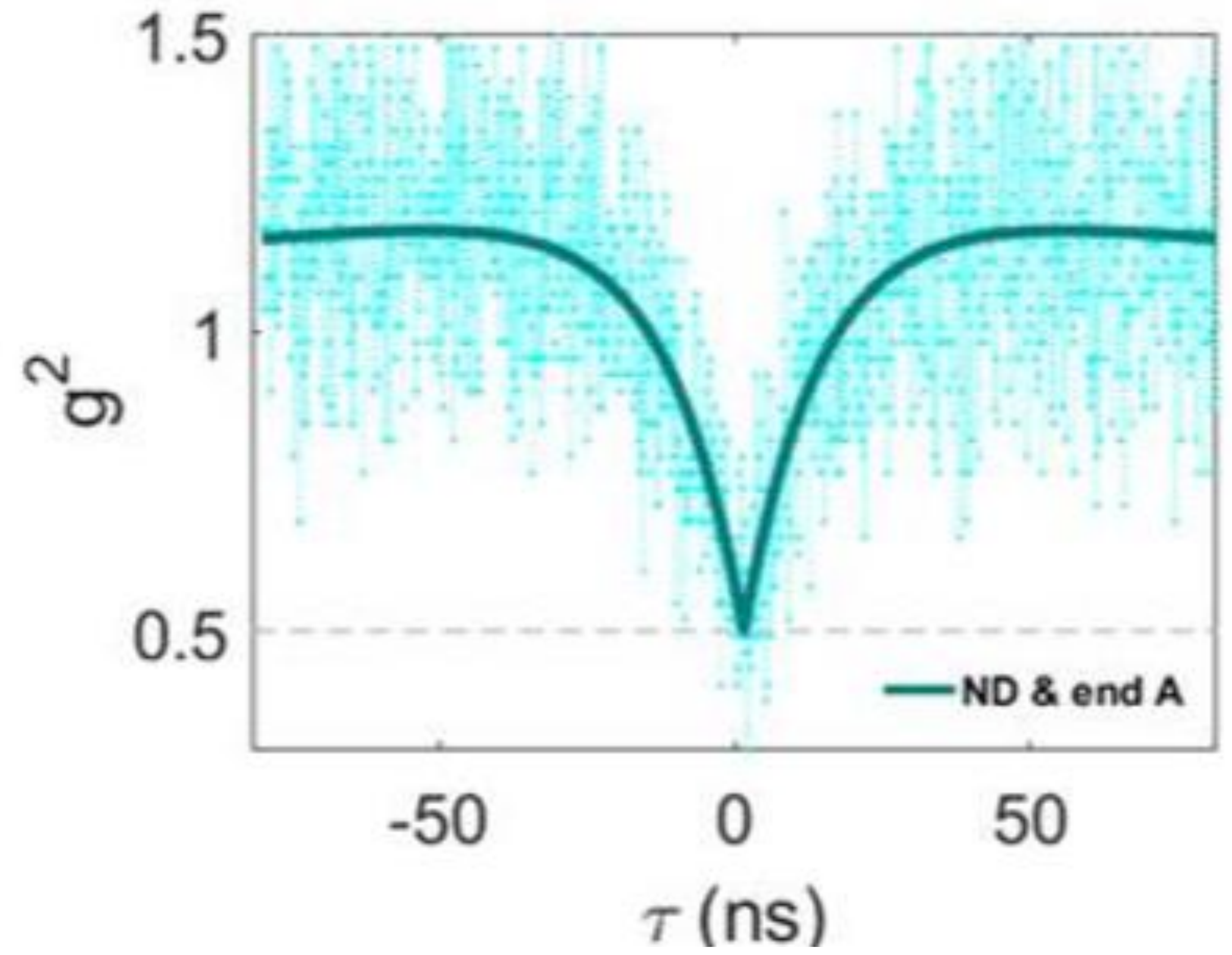
Vadim V. Vorobyov[1,2,3], Vladimir V. Soshenko[1,2,4], Stepan V. Bolshedvorskii[1,2,3], Javid Javadzade[3], Nikolay Lebedev[3], Andrey N. Smolyaninov[4], Vadim N. Sorokin[1,2], Alexey V. Akimov[5,2,1]



ВЗАИМОДЕЙСТВИЕ ИЗЛУЧАТЕЛЯ И ВОЛНОВОДА





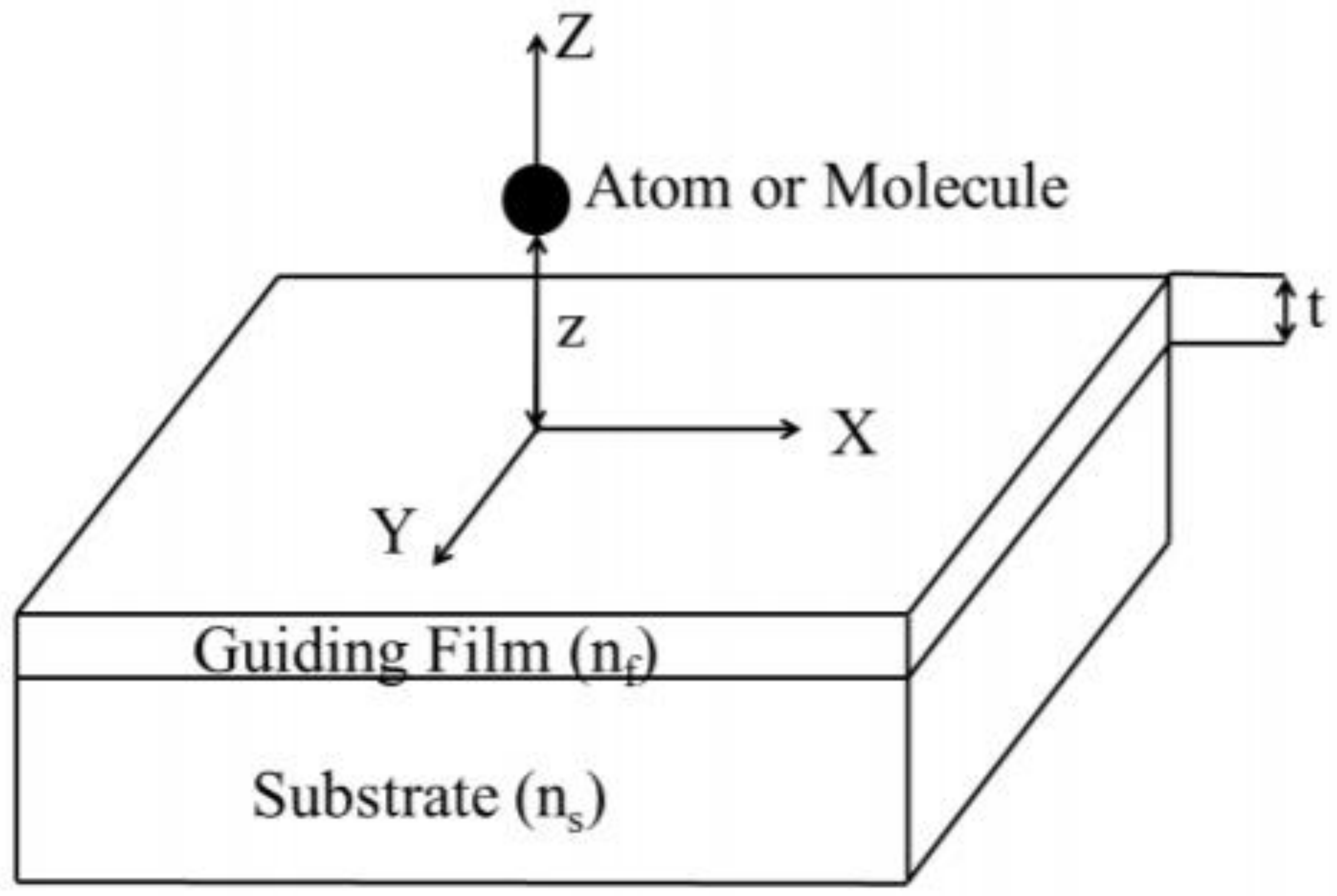


Эффективность заведения β≈50%

Chip-integrated plasmonic cavity-enhanced single nitrogen-vacancy center emission

Hamidreza Siampour,* Shailesh Kumar and Sergey I. Bozhevolnyi

2D ВОЛНОВОД



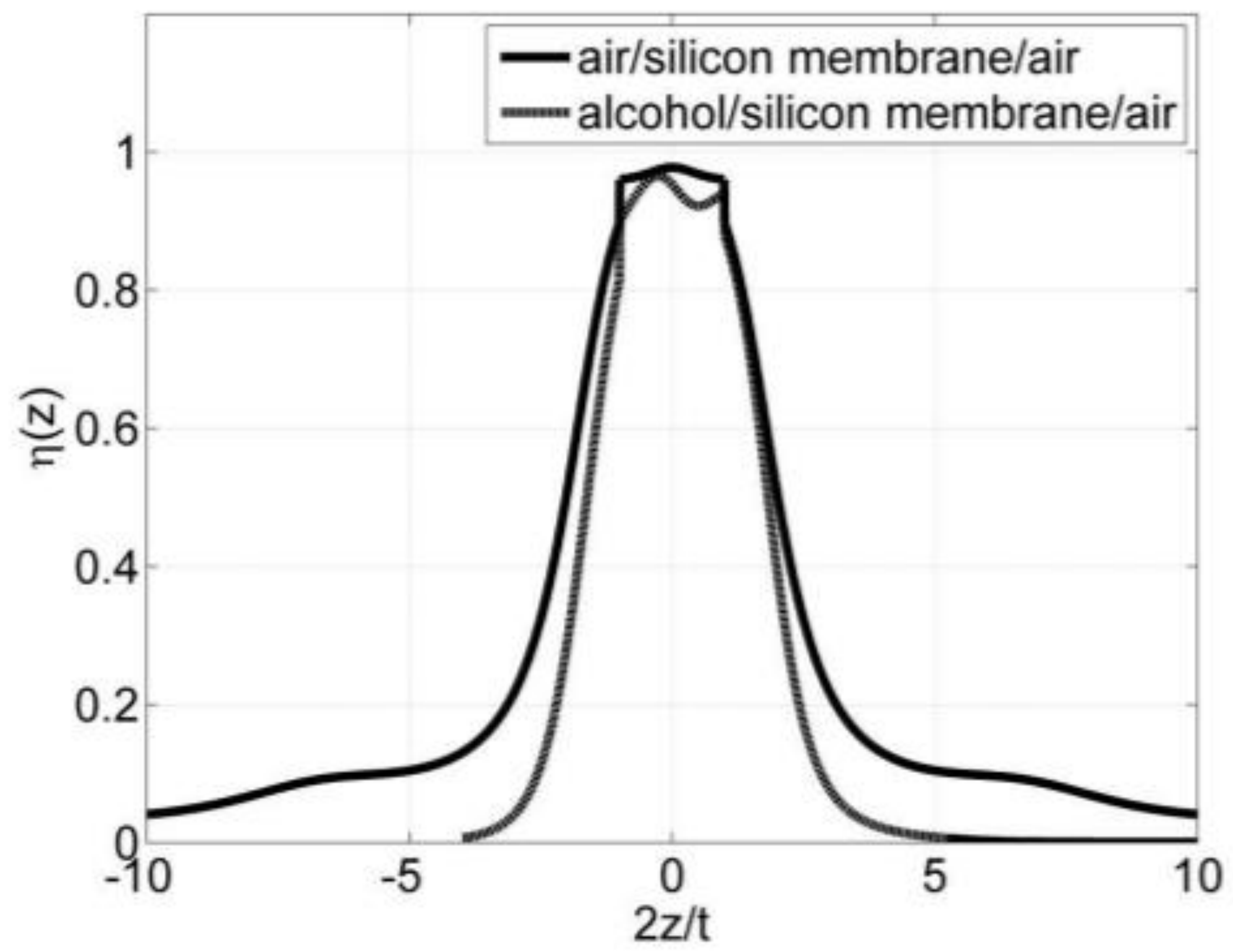
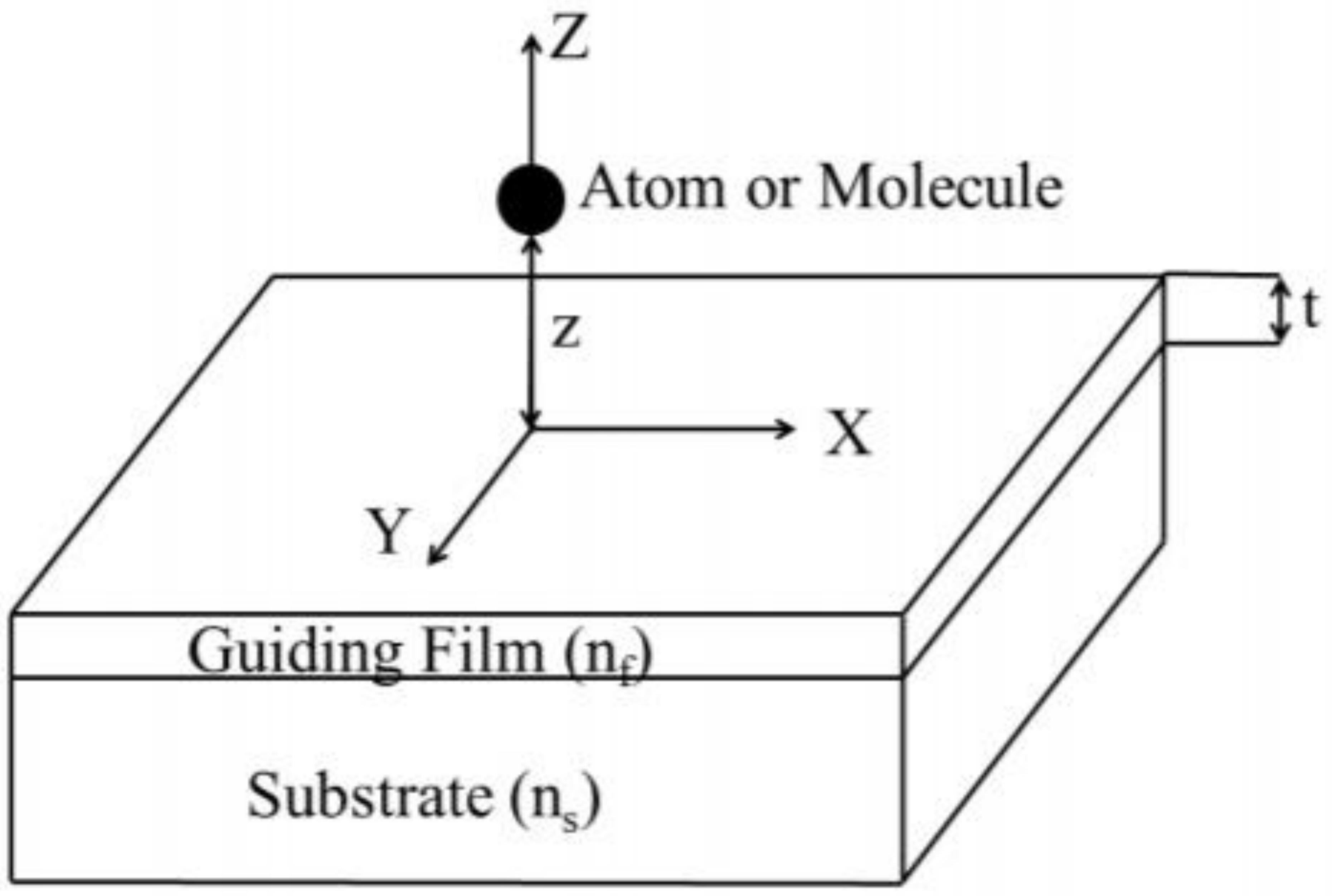


Figure 4.8: The coupling efficiency as a function of $2z/t$ of air/silicon membrane and alcohol/silicon membrane.

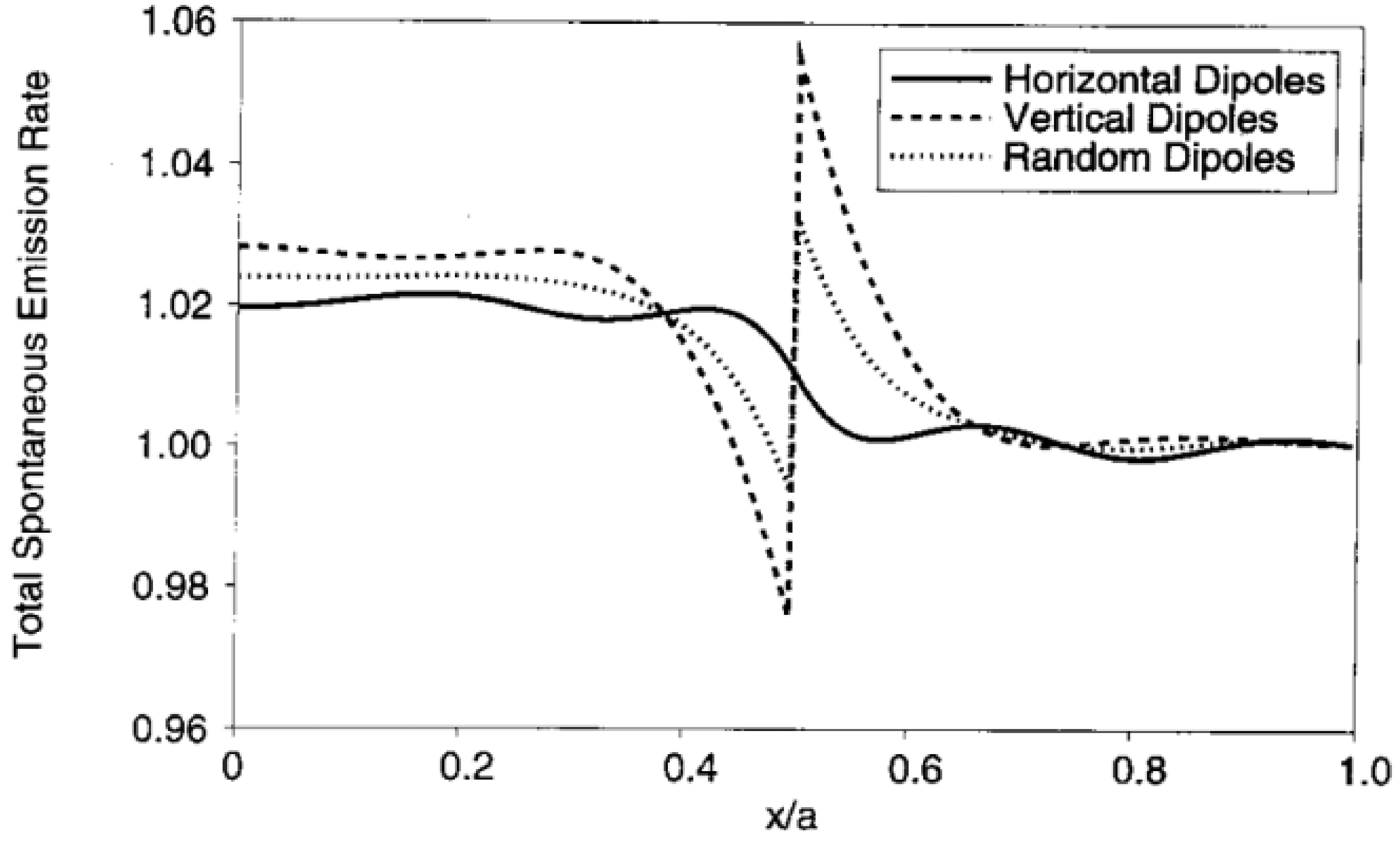
$$F_R{}^j(z) = \sum_{p=TE,TM} \sum_{\mu=Sub}^{Cover} \int_0^{2\pi} \int_0^{k_0 n_\mu} \frac{\hbar\omega_0}{2\epsilon_0} |E^j_{kp\mu}(\vec{r})|^2 \beta d\beta d\phi,$$

$$F_G{}^j(z) = \sum_{p=TE,TM} \sum_{\substack{\nu\geq 1 \\ k_\nu^{p,min}<k_0}} \int_0^{2\pi} \frac{\hbar\omega_0}{2\epsilon_0} |E^j_{kp\nu}(\vec{r})|^2 \beta^p_\nu(\vec{k_0}) \frac{d\beta^p_\nu}{dk}(k_0) d\phi,$$

2D ВОЛНОВОД



$$W_{\text{bound}} = \frac{e^2 r_{12}^2}{2\pi\hbar^2}\left(\frac{\beta}{v_g^K}\right)\sum_{\bar{P}}\sum_{K} N_{\bar{P}}^2(\omega_o, K)\int_{\varphi=0}^{2\pi} \times \left|\vec{F}_{\bar{P}}\,(\omega_o, K, x_a)\bullet\hat{r}\right|^2 d\varphi$$



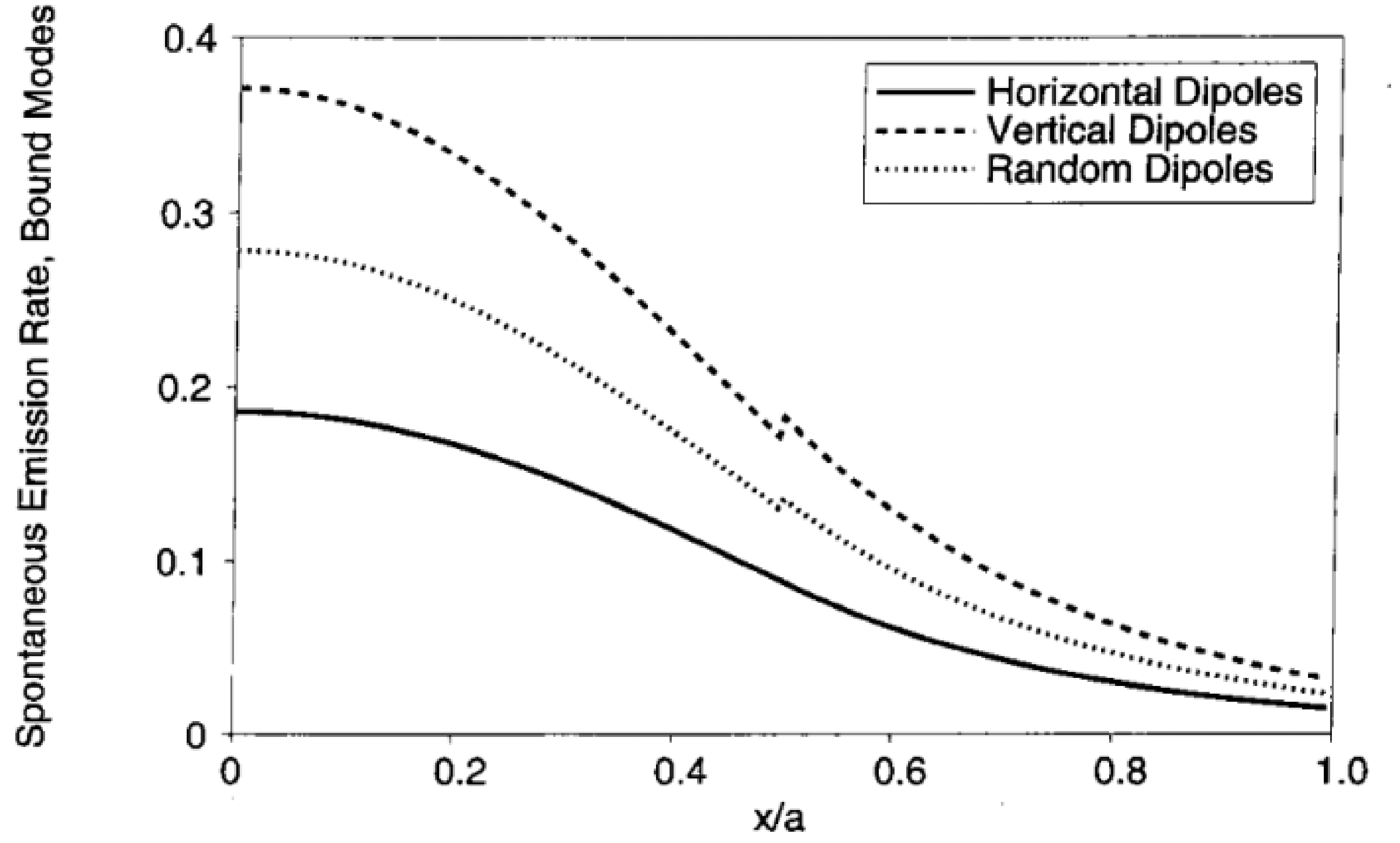
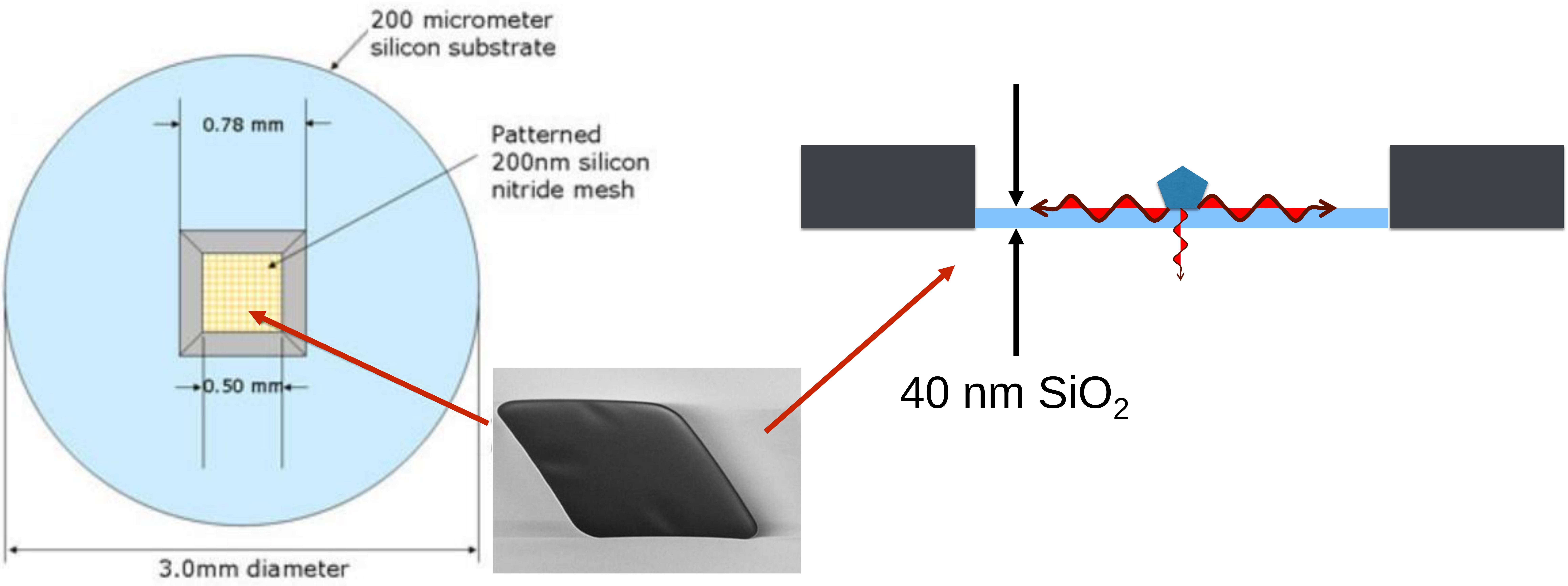
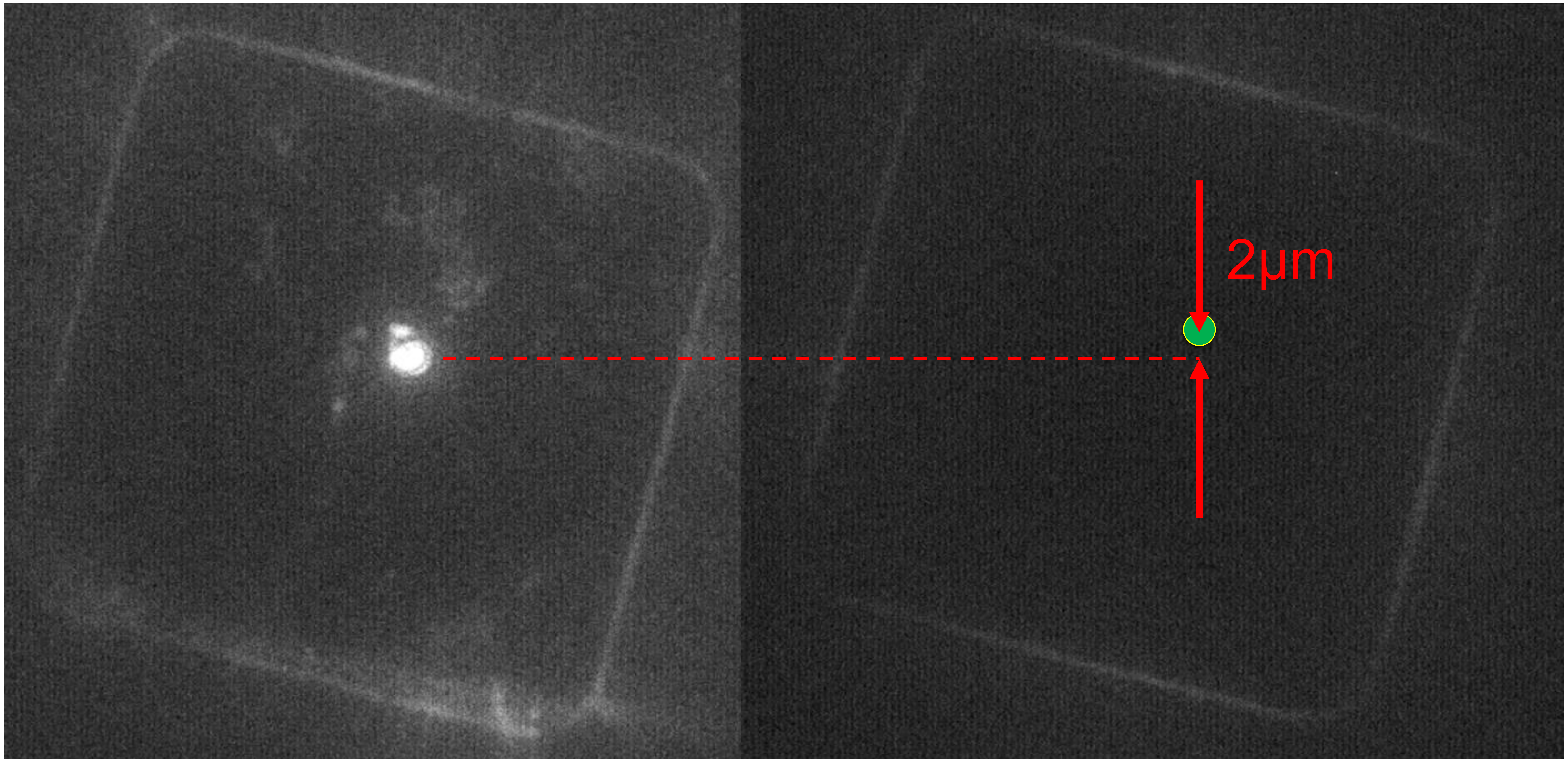


Fig. 5. Rates of spontaneous emission into bound modes for $n_1 = 1.50$ and $n_2 = 1.47$; $a = 2\ \mu$m; horizontal dipoles (solid line); vertical dipoles (dashed line); randomly-oriented dipoles (dotted line).

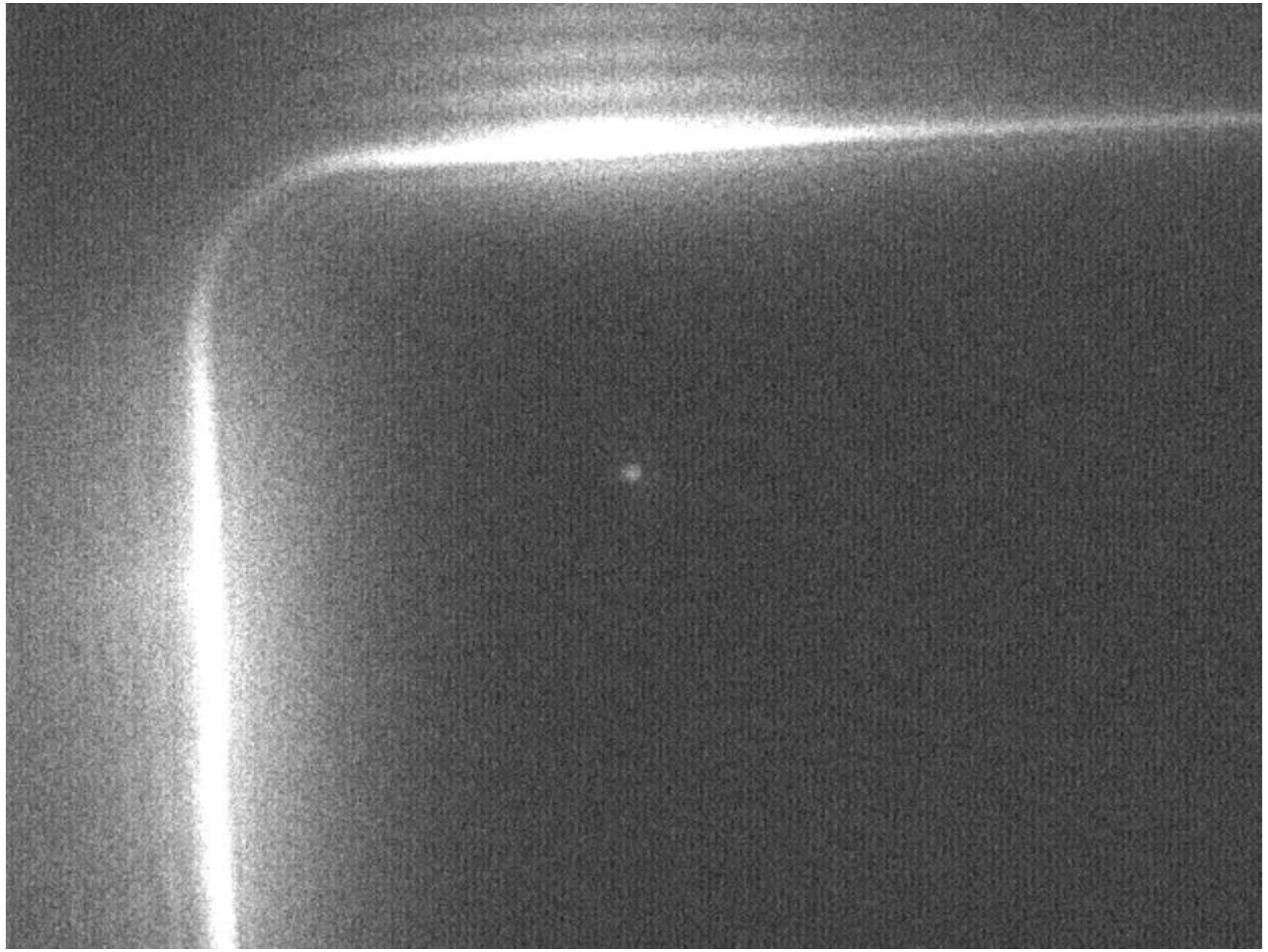
2D ВОЛНОВОД


200 micrometer
silicon substrate
0.78 mm
Patterned
200nm silicon
nitride mesh
0.50 mm
3.0mm diameter
40 nm SiO2

2D ВОЛНОВОД



2D ВОЛНОВОД

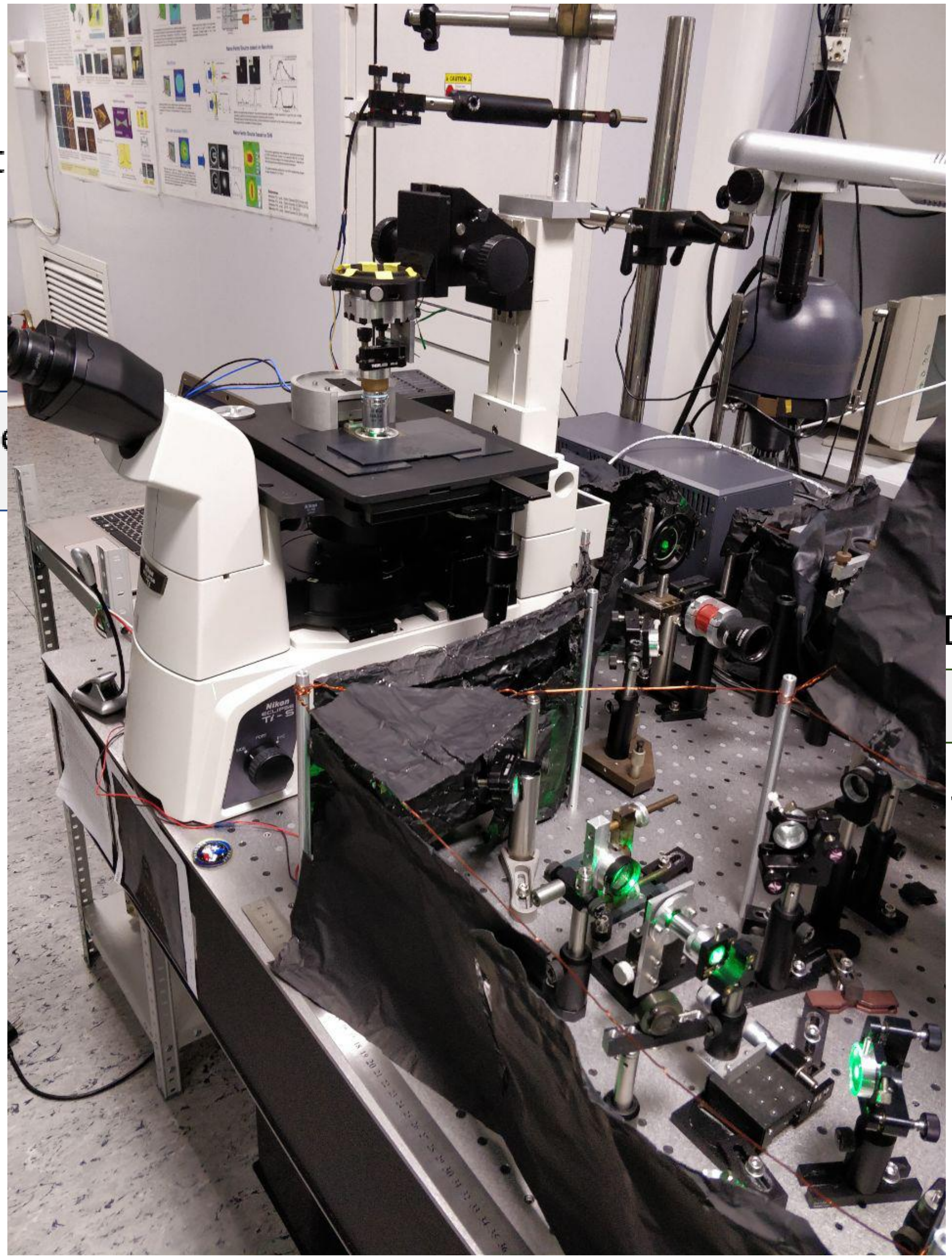


$$\frac{I_{total\ border}}{I_{NV}} = 60$$

ЭКСПЕРИМЕНТАЛЬНАЯ УСТАНОВКА

lifet

Las

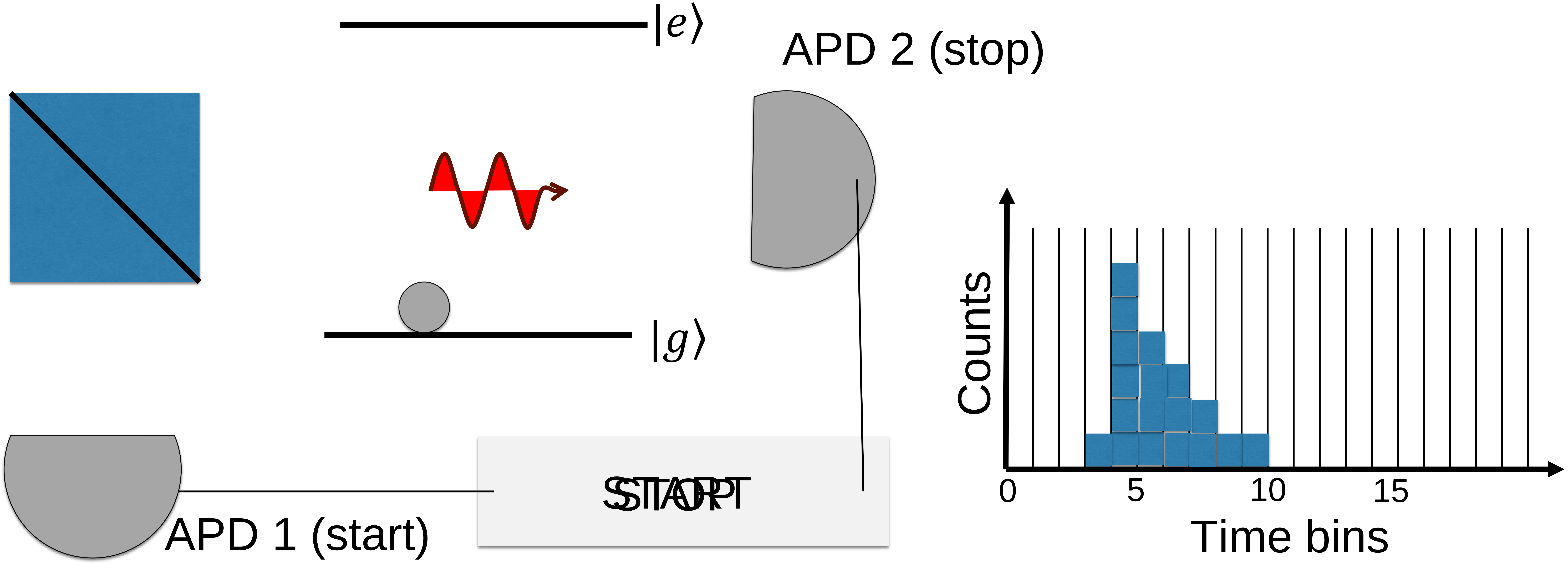


D 1

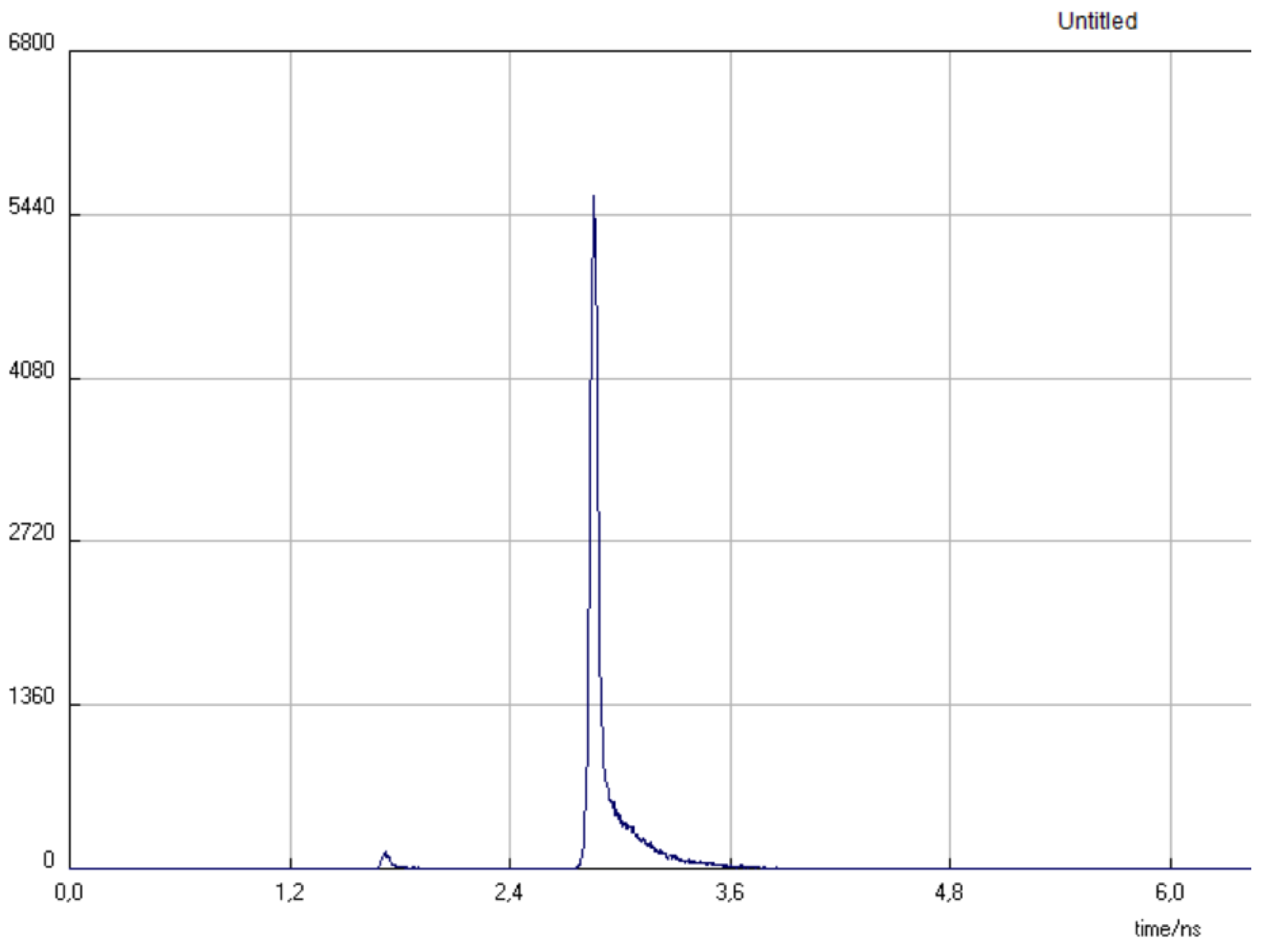
for $g^{(2)}(\tau)$

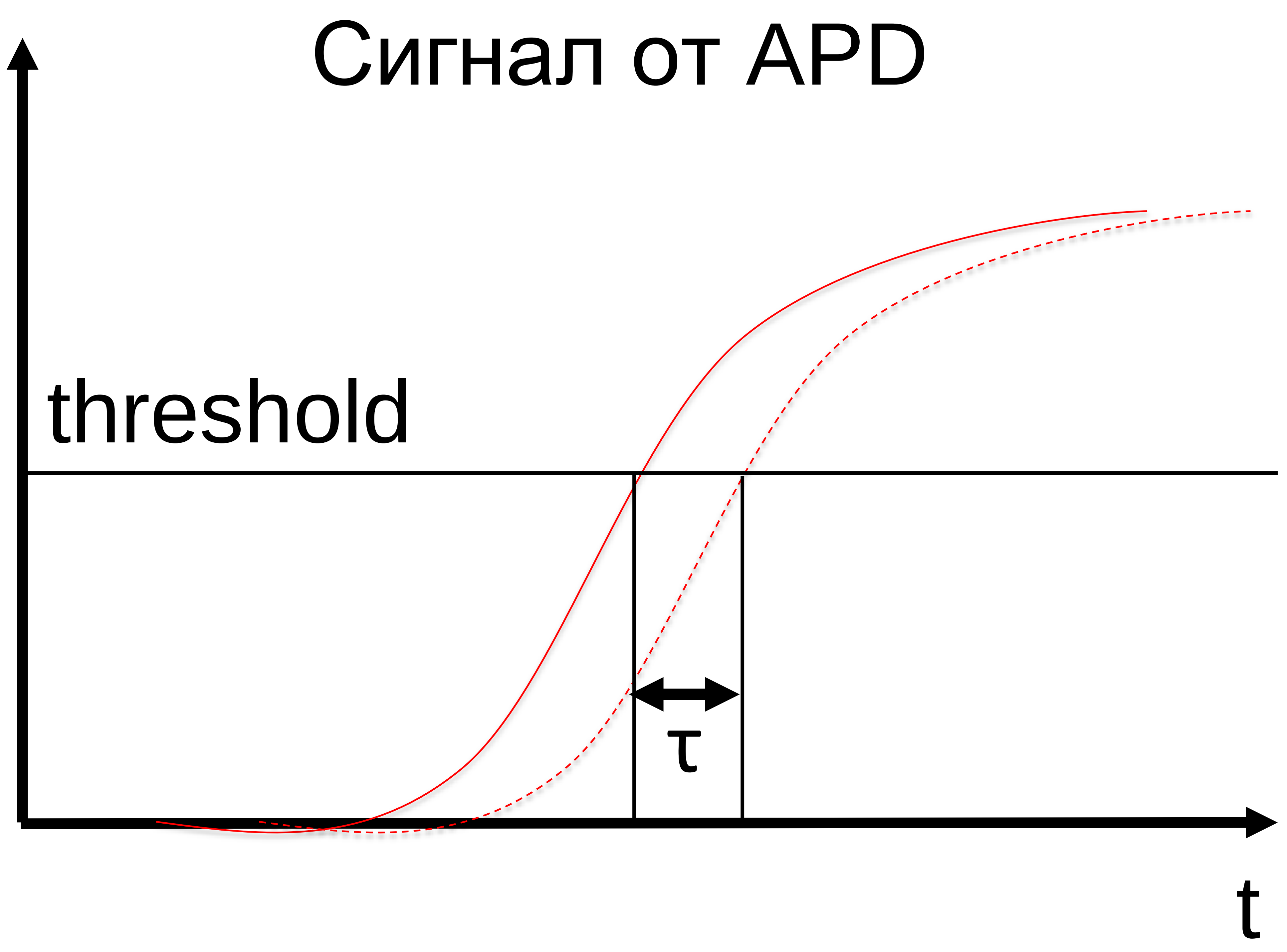
- 2D изображение
- Время жизни возбужденного состояния
- $g^{(2)}(\tau)$ – автокорреляционная функция
- Спектр
- Кривая насыщения

СХЕМА СТАРТ-СТОП ДЛЯ ИЗМЕРЕНИЯ ВРЕМЕНИ ЖИЗНИ ВОЗБУЖДЕННОГО СОСТОЯНИЯ

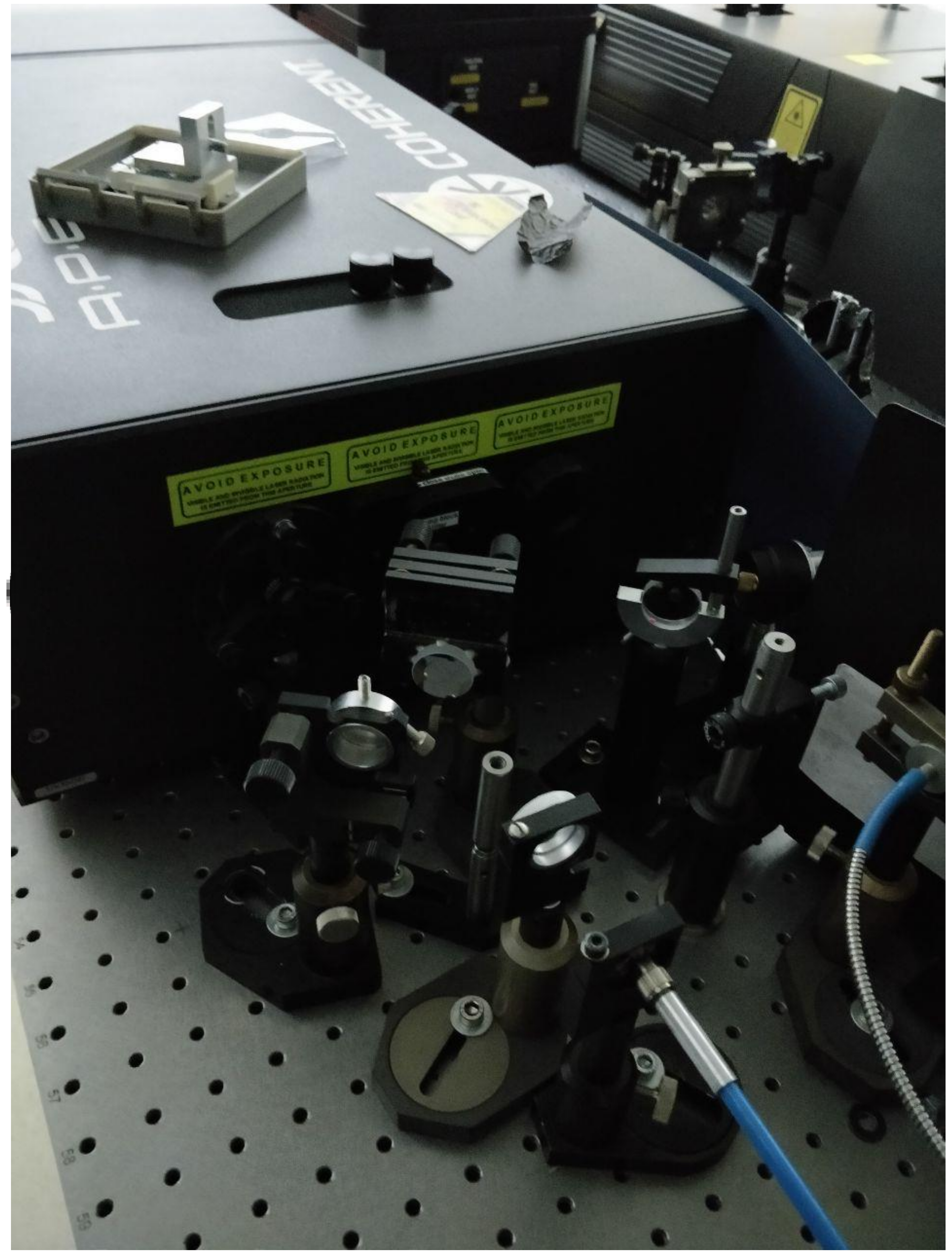


АППАРАТНАЯ ФУНКЦИЯ СИСТЕМЫ ИЗМЕРЕНИЯ КОРРЕЛЯЦИИ



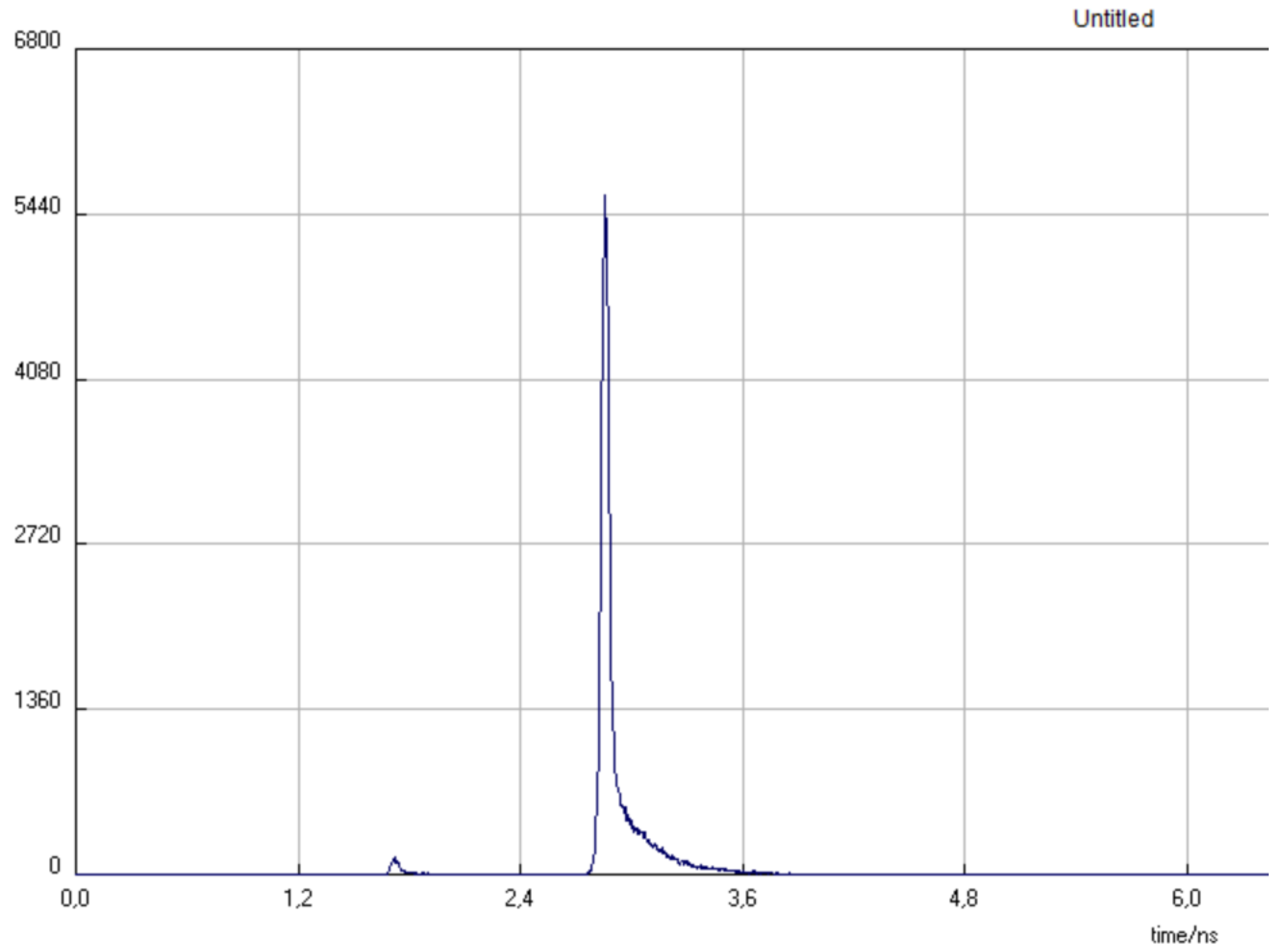


РАСПРОСТРАНЕНИЕ СВЕТА В МНОГОМОДОВОМ ВОЛОКНЕ



Без волокна

τ_{IRF}=0,052 ns



С волокном

τ_{IRF}=1,5 ns

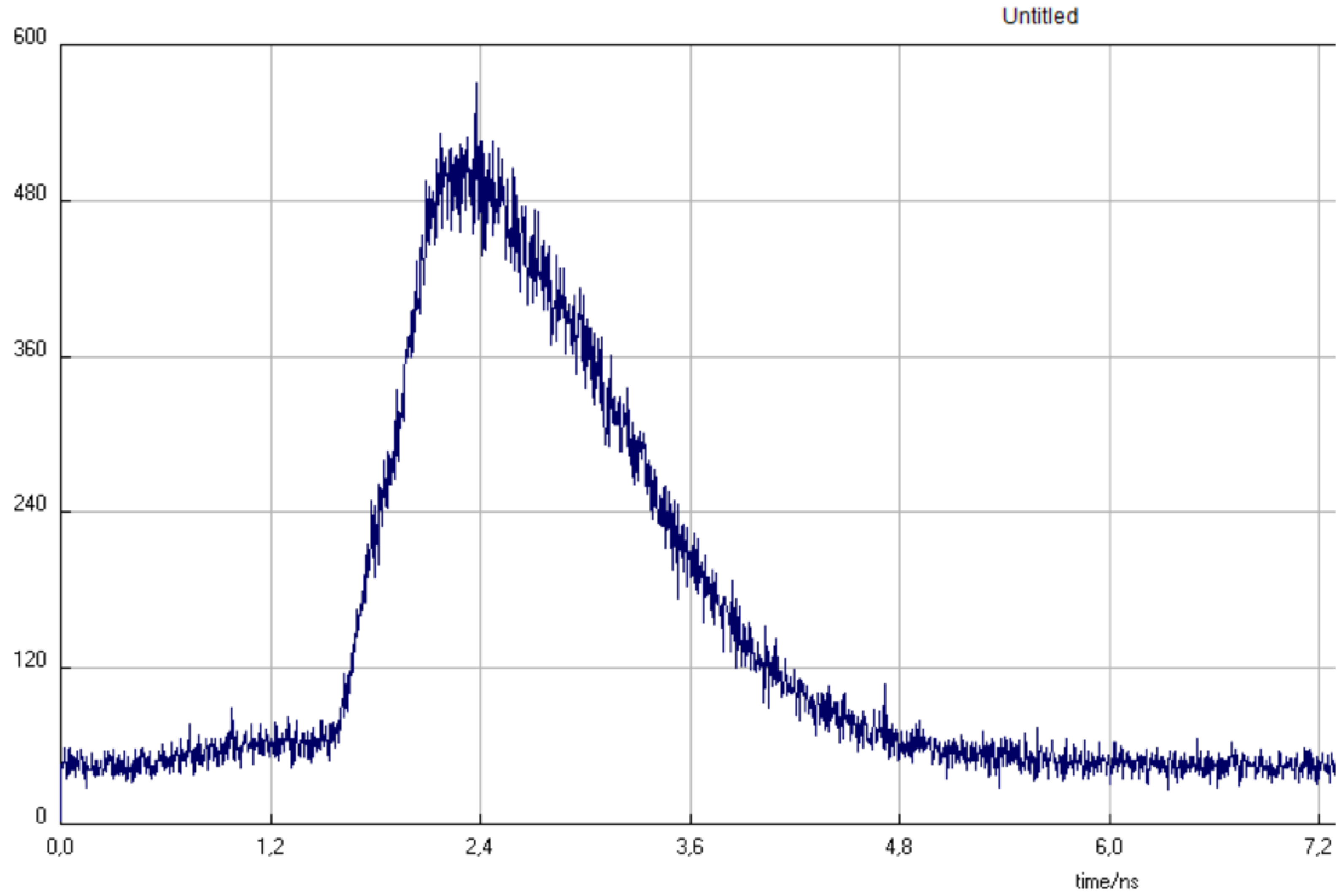
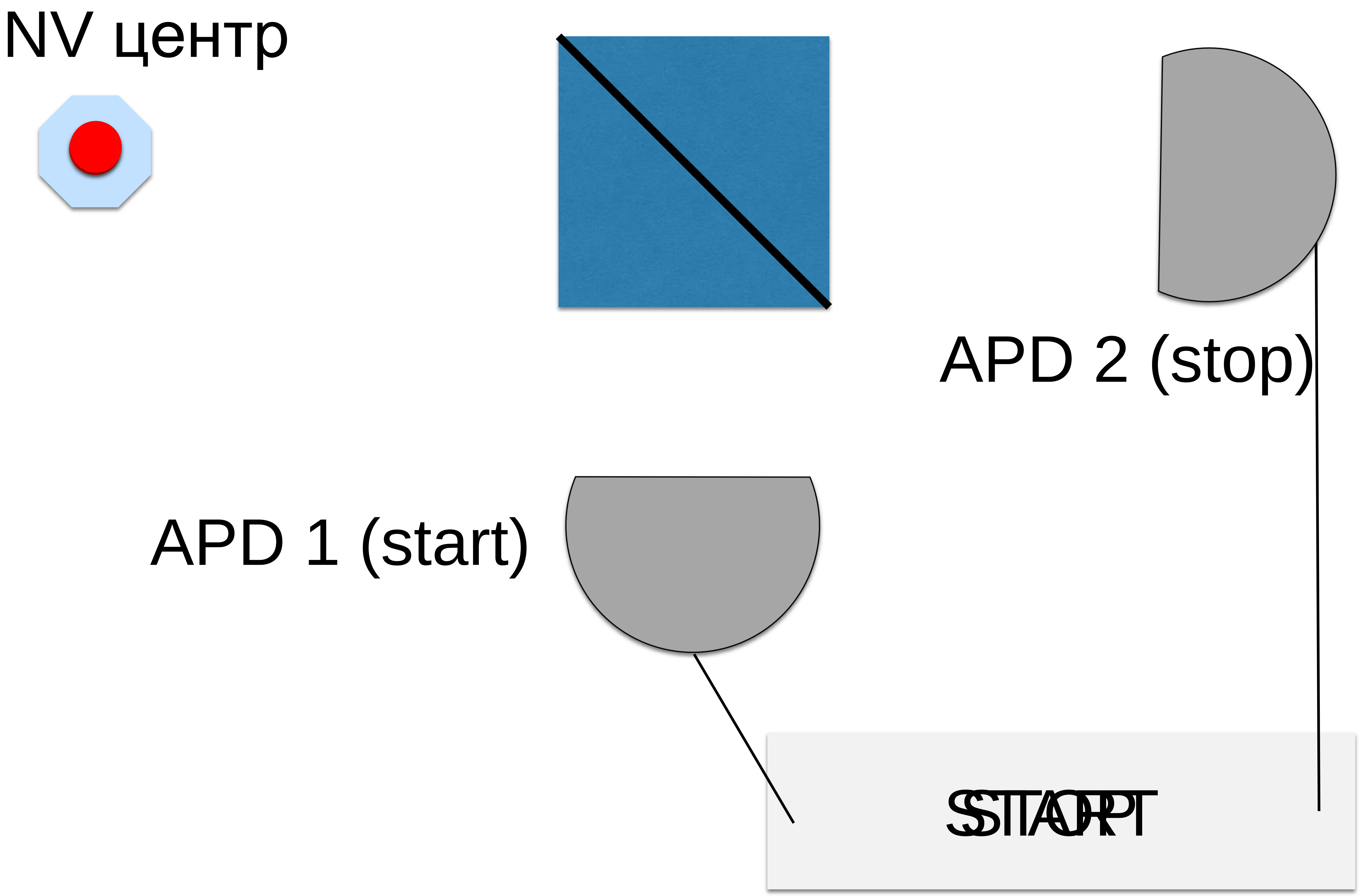
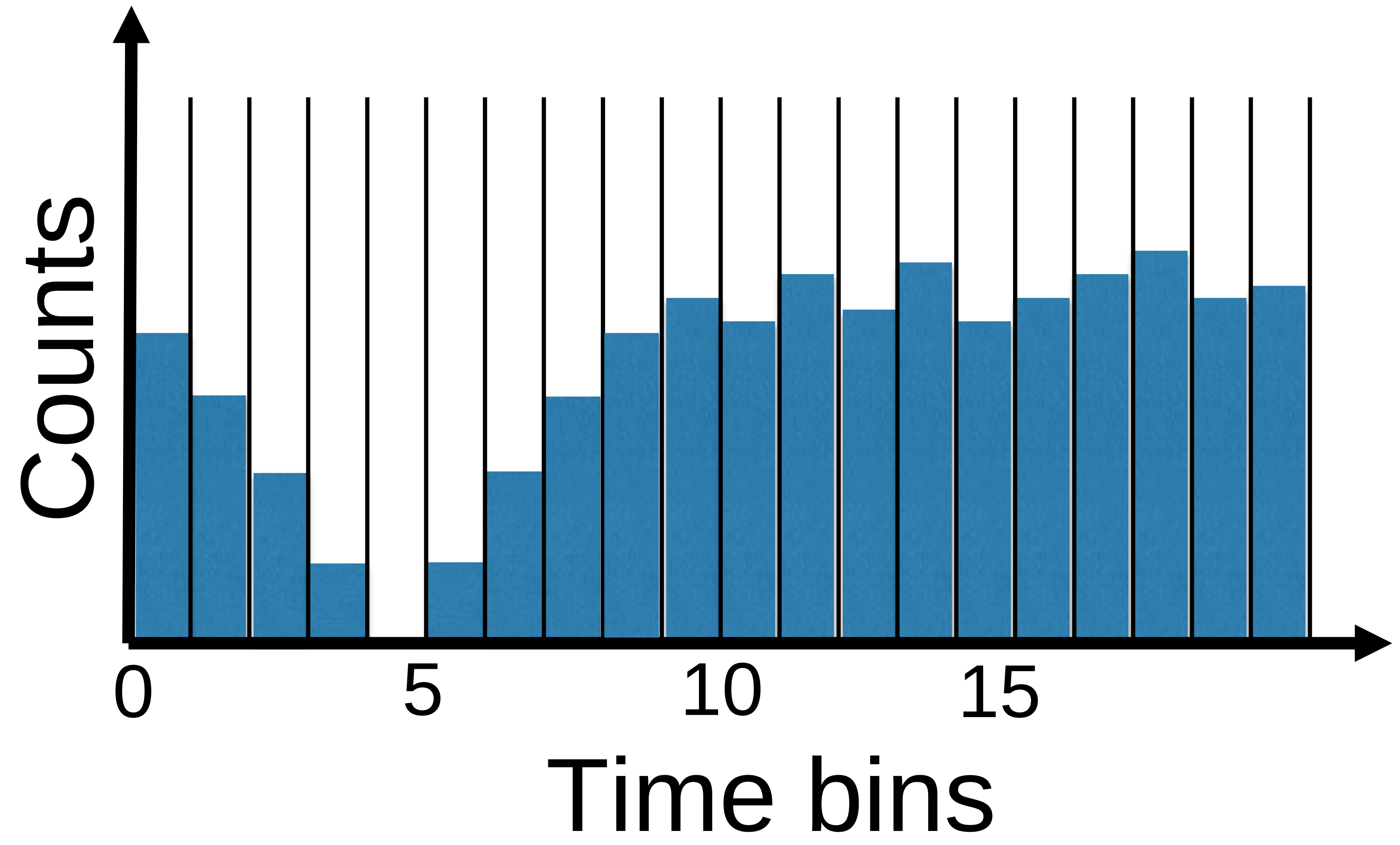


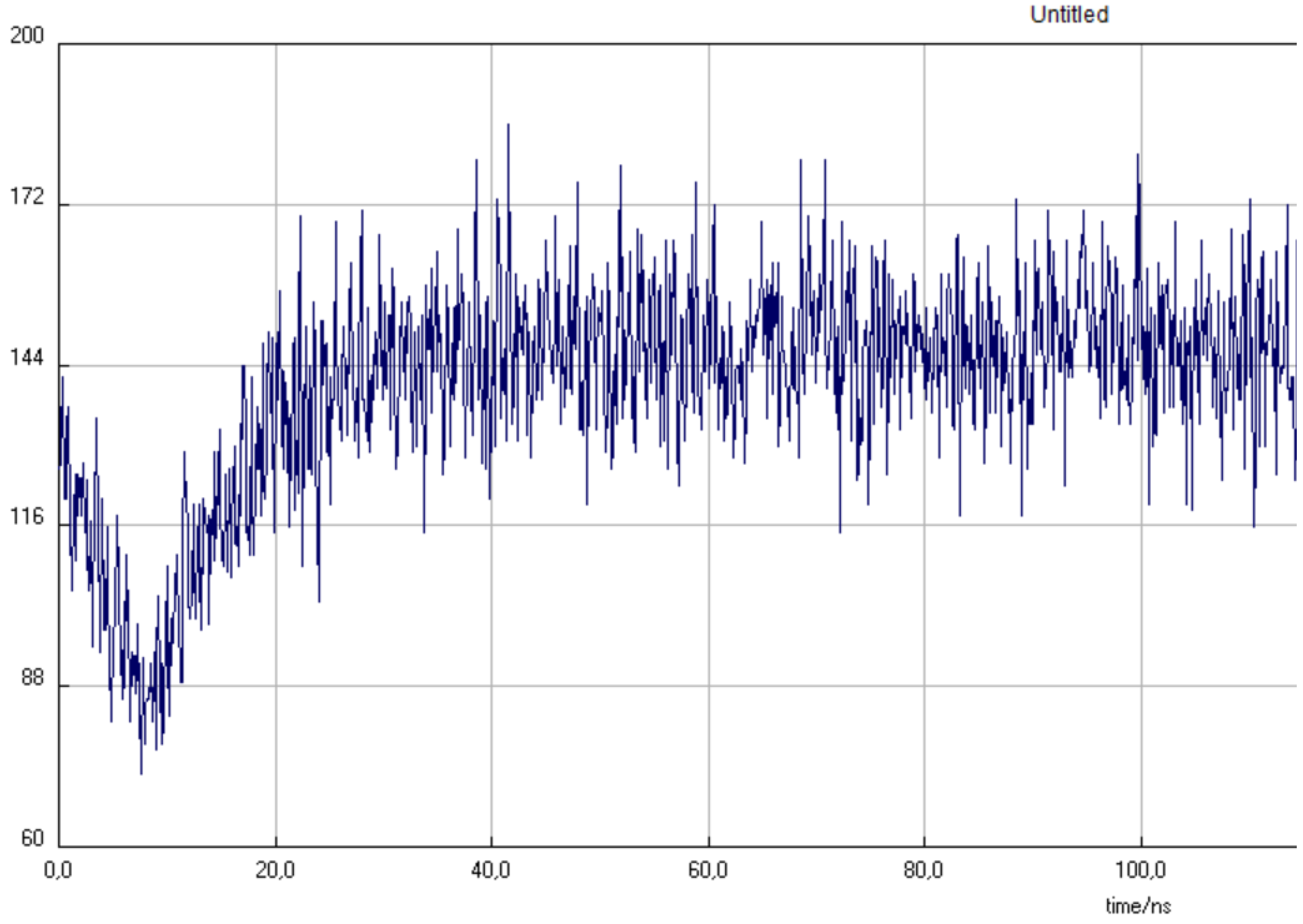
СХЕМА СТАРТ-СТОП ДЛЯ ИЗМЕРЕНИЯ ВРЕМЕНИ ЖИЗНИ ВОЗБУЖДЕННОГО СОСТОЯНИЯ

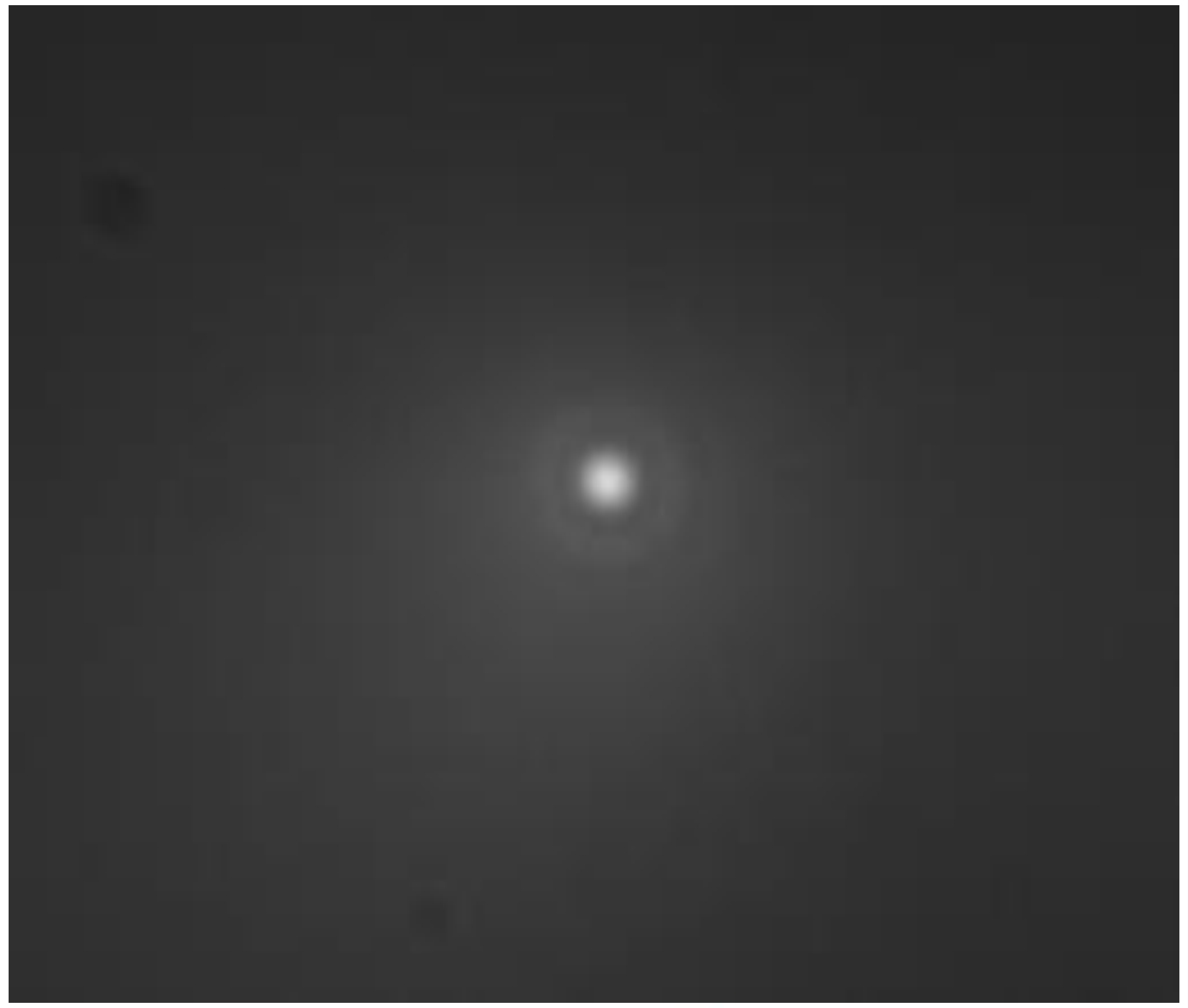


$$g^{(2)}(\tau) = \frac{\langle I(t) I(t+\tau) \rangle}{\langle I(t) \rangle^2}$$



ФУНКЦИЯ АВТОКОРРЕЛЯЦИИ





$$g_2(0)=\frac{\langle n(n-1)\rangle}{\langle n\rangle^2}=2^N\frac{\sum_{k=1}^{N}k(k-1)C_N^k}{\left(\sum_{k=1}^{N}kC_N^k\right)^2}=\frac{N-1}{N}$$

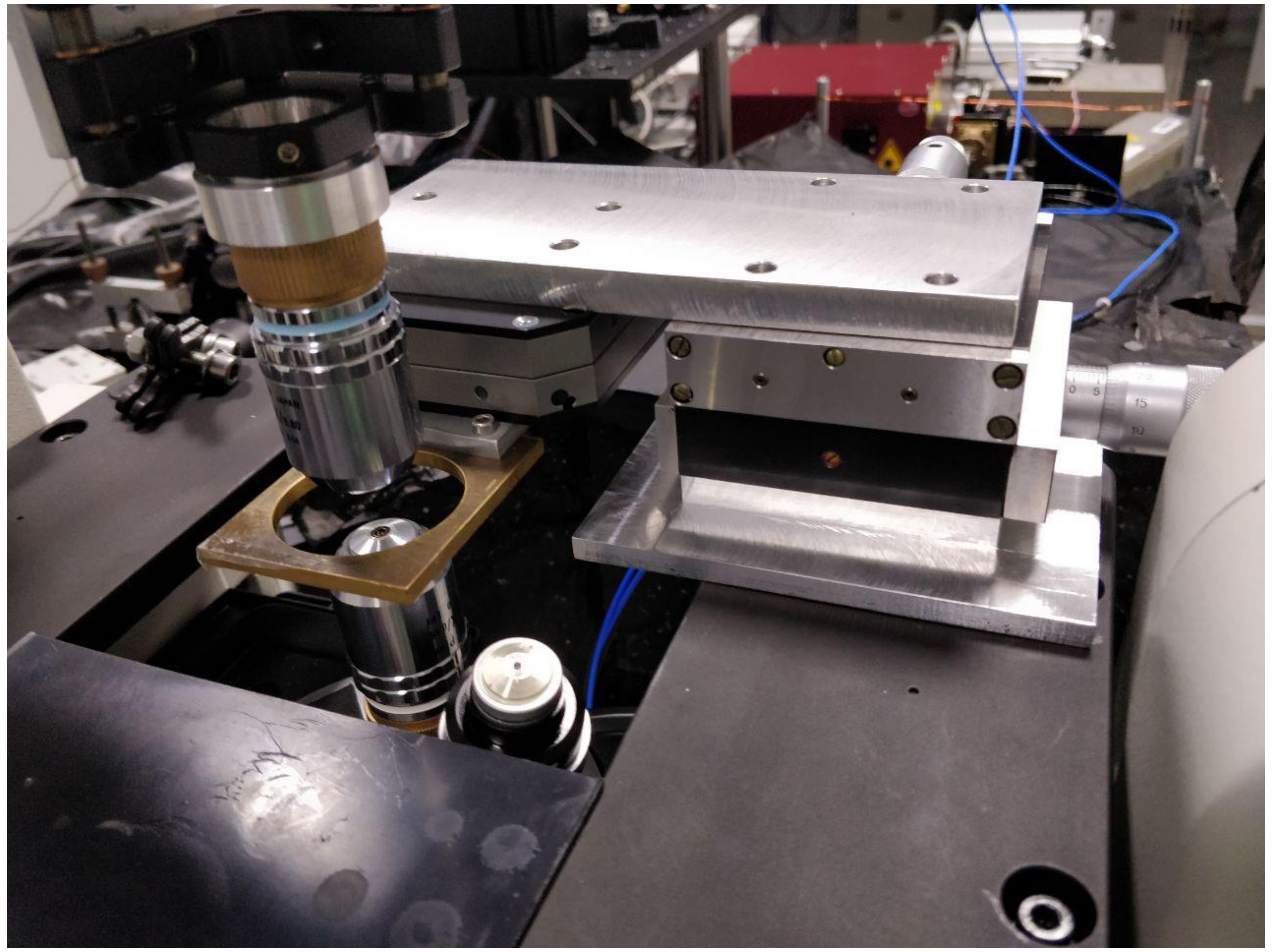
$N=1,\quad g_2(0)=0$

$N=2,\quad g_2(0)=1/2$

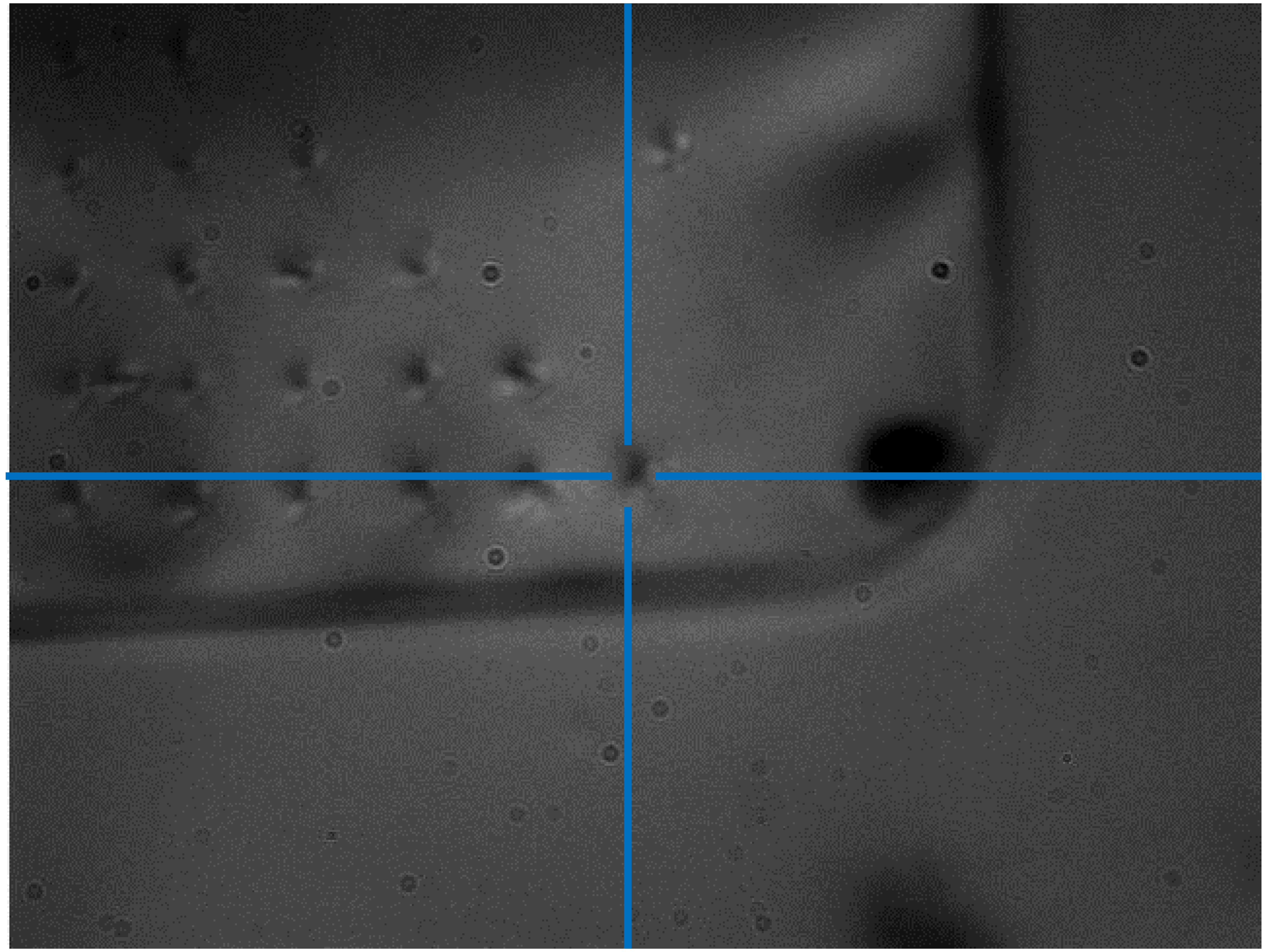
$N=3,\quad g_2(0)=2/3$

...

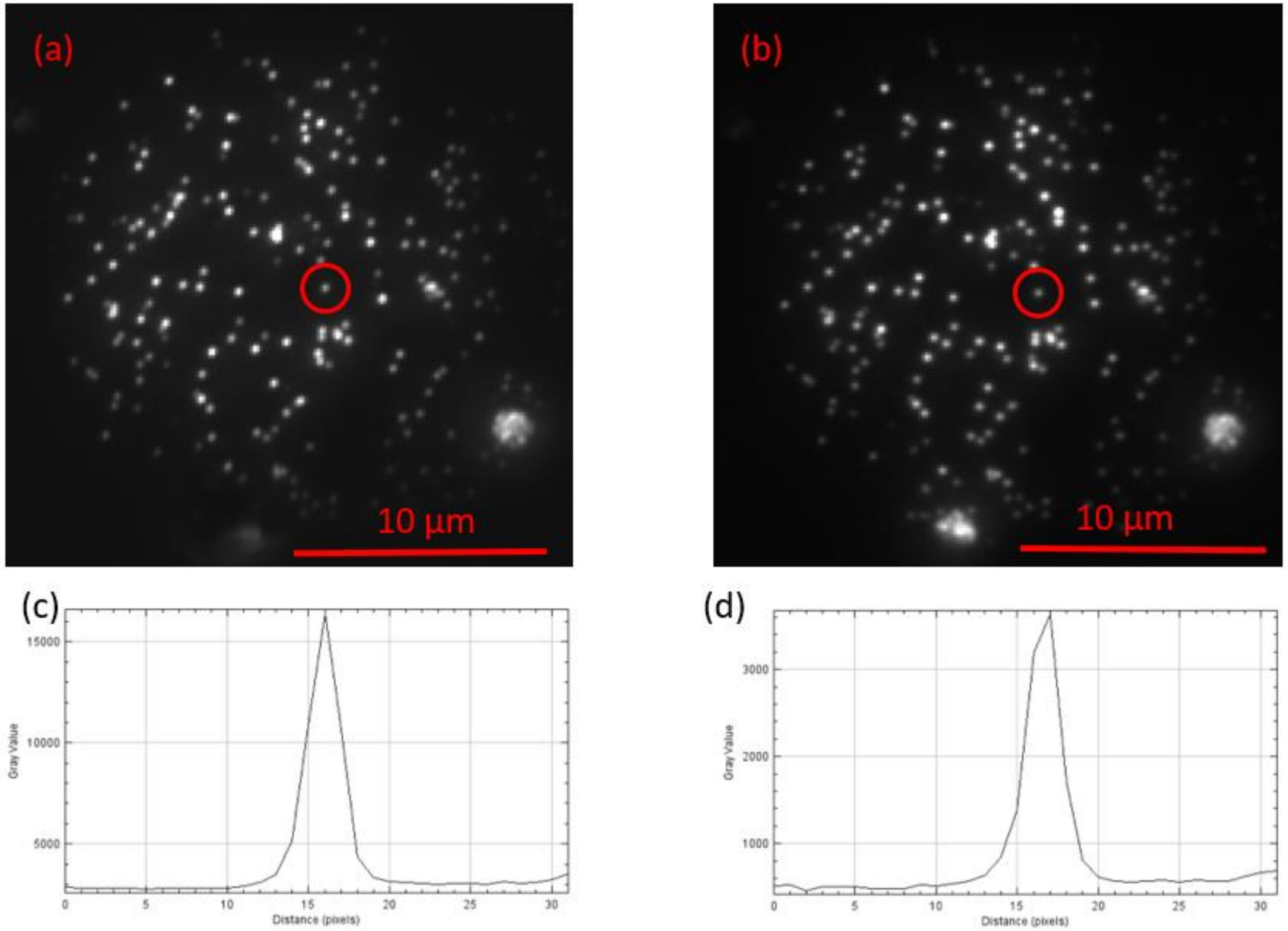
УВЕЛИЧЕНИЕ СТАБИЛЬНОСТИ МИКРОСКОПА

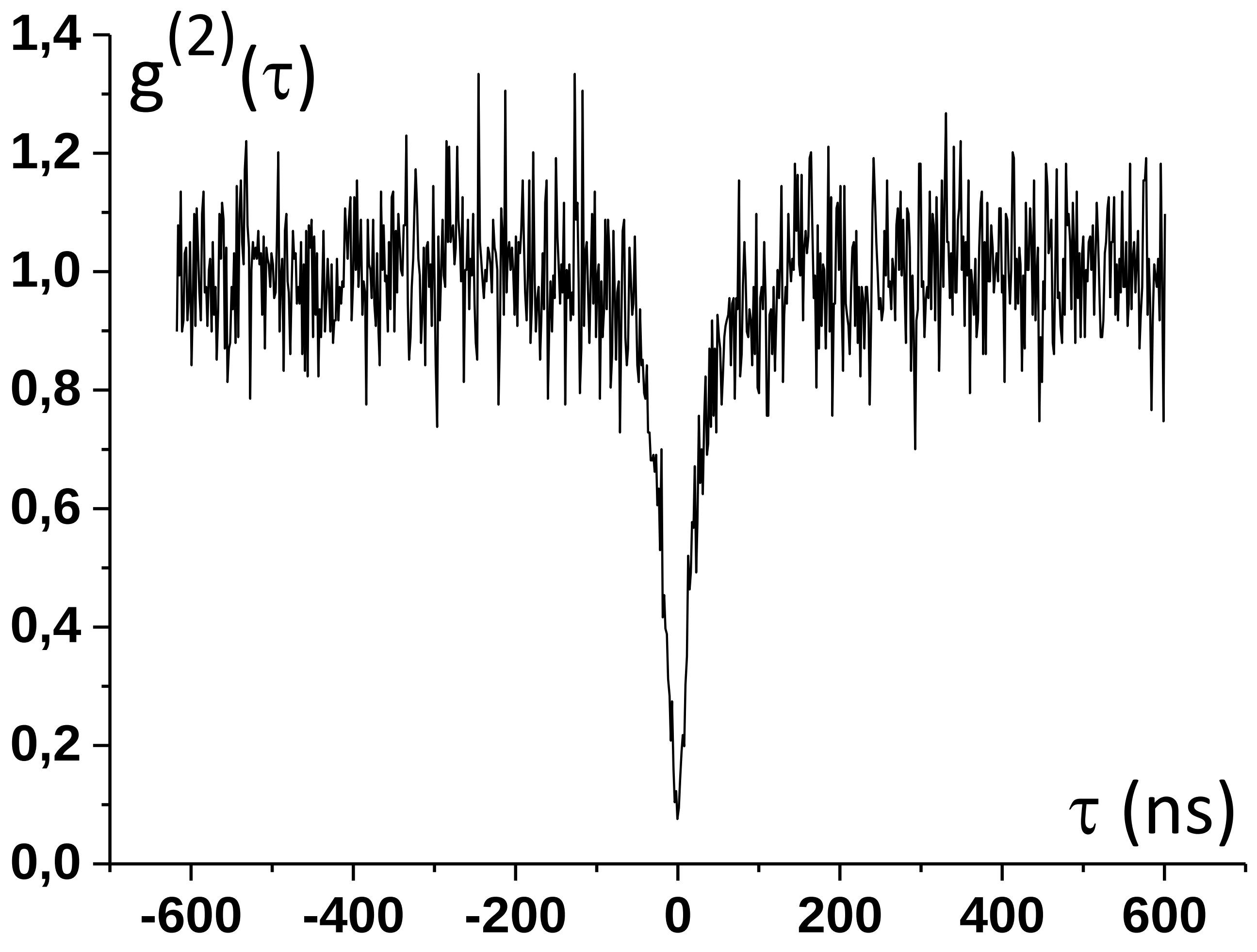


УВЕЛИЧЕНИЕ СТАБИЛЬНОСТИ МИКРОСКОПА



2D CCD КАМЕРА





SXCCD (3,000$)

Andor IXON (80,000$)