Field-Intensity Correlations of Light.

Institute of Physics ,
CAS, Beijing, China
OSA Student Chapter
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Luis A. Orozco
www.jqi.umd.edu

PHYSICS FRONTIER CENTER
JOINT QUANTUM INSTITUTE

The Optical Society

UNIVERSITY OF MARYLAND 1856

NIST

Review Article:

H. J. Carmichael, G. T. Foster, L. A. Orozco, J. E. Reiner, and P. R. Rice, “Intensity-Field Correlations of Non-Classical Light”. Progress in Optics, Vol. 46, 355-403, Edited by E. Wolf Elsevier, Amsterdam 2004.

- The main object of interest in quantum optics is the optical FIELD. That is what is quantized.

- Can we measure the FIELD of a state with an average of ONE PHOTON in it?

Correlation functions tell us something about the fluctuations.

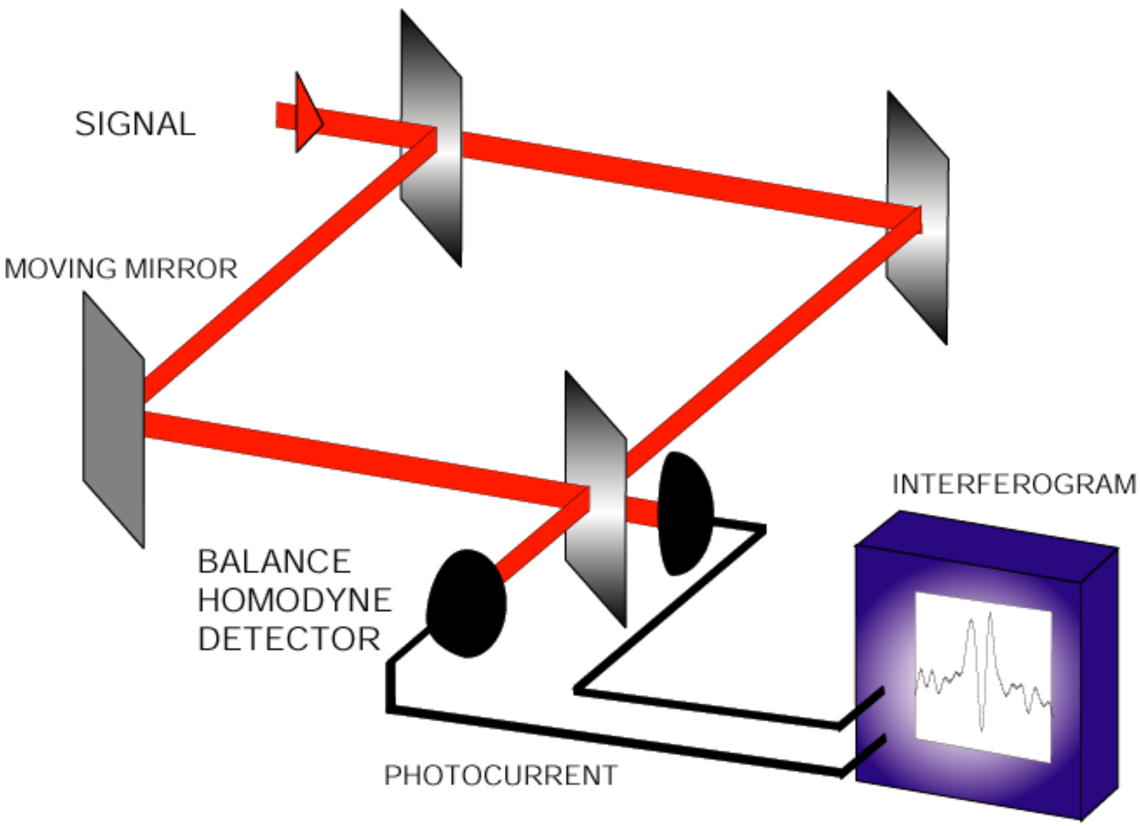
Correlations have classical bounds.

They are conditional measurements.

Can we use them to measure the field associated with a FLUCTUATION of one photon?

Mach Zehnder Interferometer Wave-Wave Correlation

$$g^{(1)}(\tau) = \frac{\langle E^*(t)E(t+\tau)\rangle}{\langle I(t)\rangle}$$

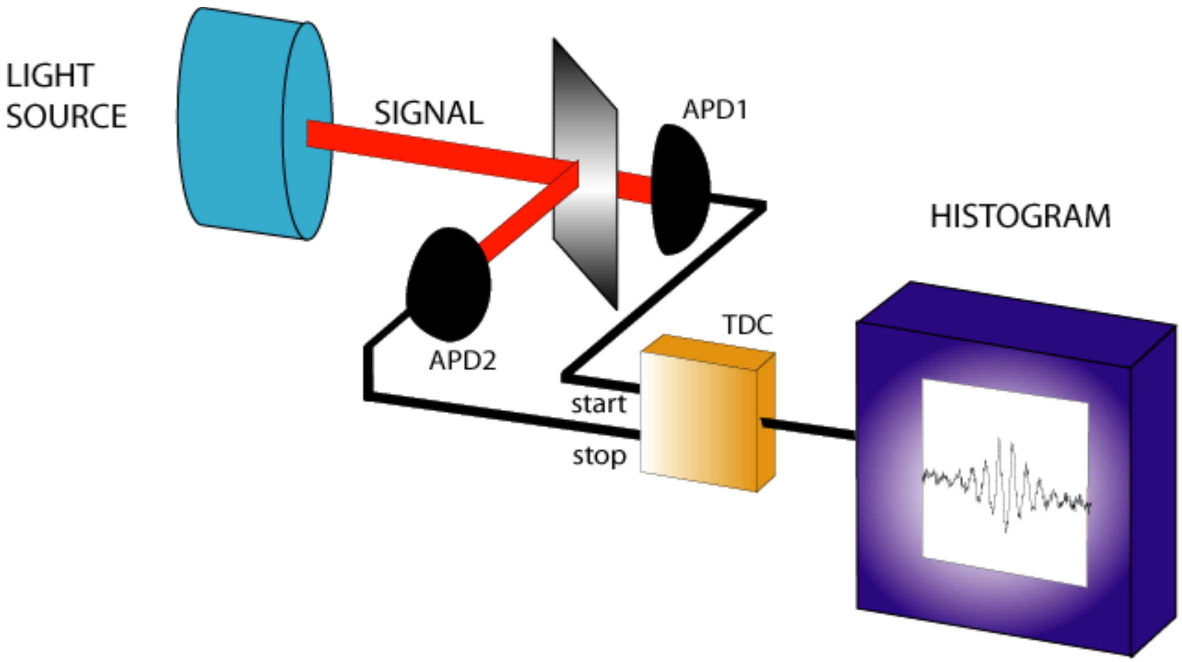


Spectrum of the signal:

$$F(\omega) = \frac{1}{2\pi}\int exp(i\omega\tau)g^{(1)}(\tau)d\tau$$

Basis of Fourier Transform Spectroscopy

Hanbury Brown and Twiss Intensity-Intensity Correlations



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

Cauchy-Schwarz

$$2I(t)I(t+\tau) \leq I^2(t) + I^2(t+\tau)$$

The correlation is largest at equal time

$$g^{(2)}(0) \geq 1$$

$$g^{(2)}(0) \geq g^{(2)}(\tau)$$

Intensity correlation function measurements:

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

Gives the probability of detecting a photon at time $t + \tau$ given that one was detected at time t. This is a conditional measurement:

$$g^{(2)}(\tau) = \frac{\left\langle \hat{I}(\tau) \right\rangle_c}{\left\langle \hat{I} \right\rangle}$$

A strategy starts to appear:

Correlation function; Conditional measurement.

Detect a photon: Prepare a conditional quantum mechanical state in our system.

The system has to have at least two photons.

Do we have enough signal?

$|LO|^2 \qquad + \qquad 2\ LO\ S \cos(\phi)$

SHOT NOISE SIGNAL

Optical Cavity QED

Quantum Electrodynamics for pedestrians. No renormalization needed. A single mode of the Electromagnetic field of a cavity.

ATOM + CAVITY

Perturbative: Coupling << Dissipation rates:Damping enhanced or suppressed (Cavity smaller than λ), Energy level shifts.

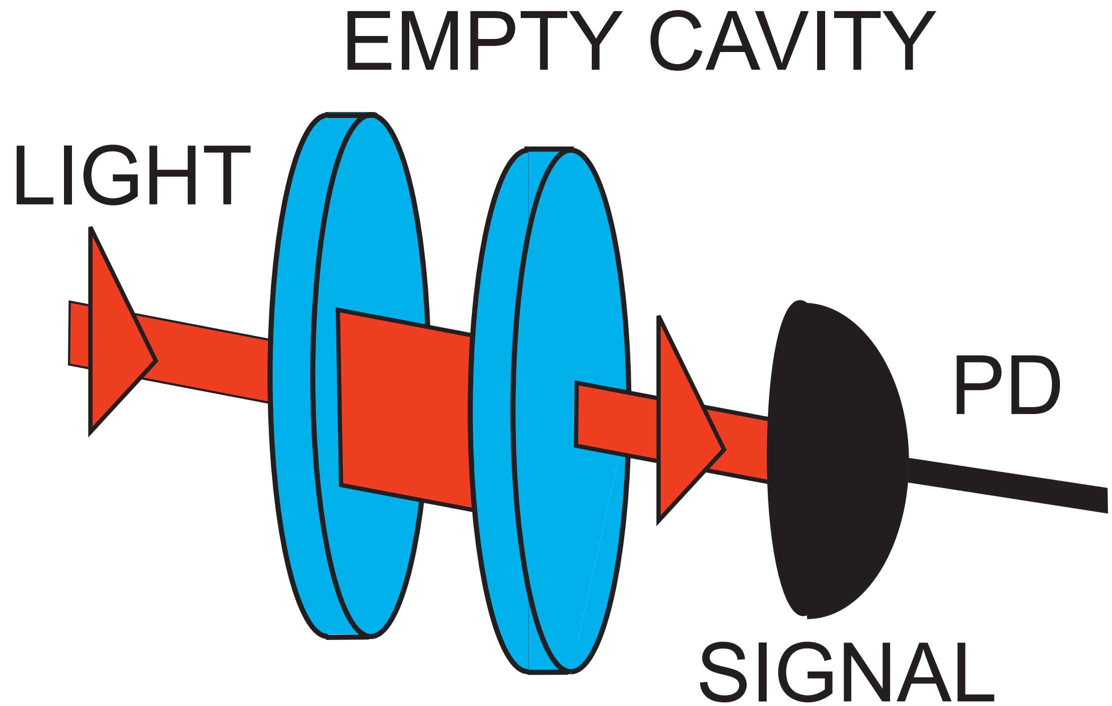
Non Perturbative: Coupling>>dissipation
Vacuum Rabi Splittings. Conditional dynamics.

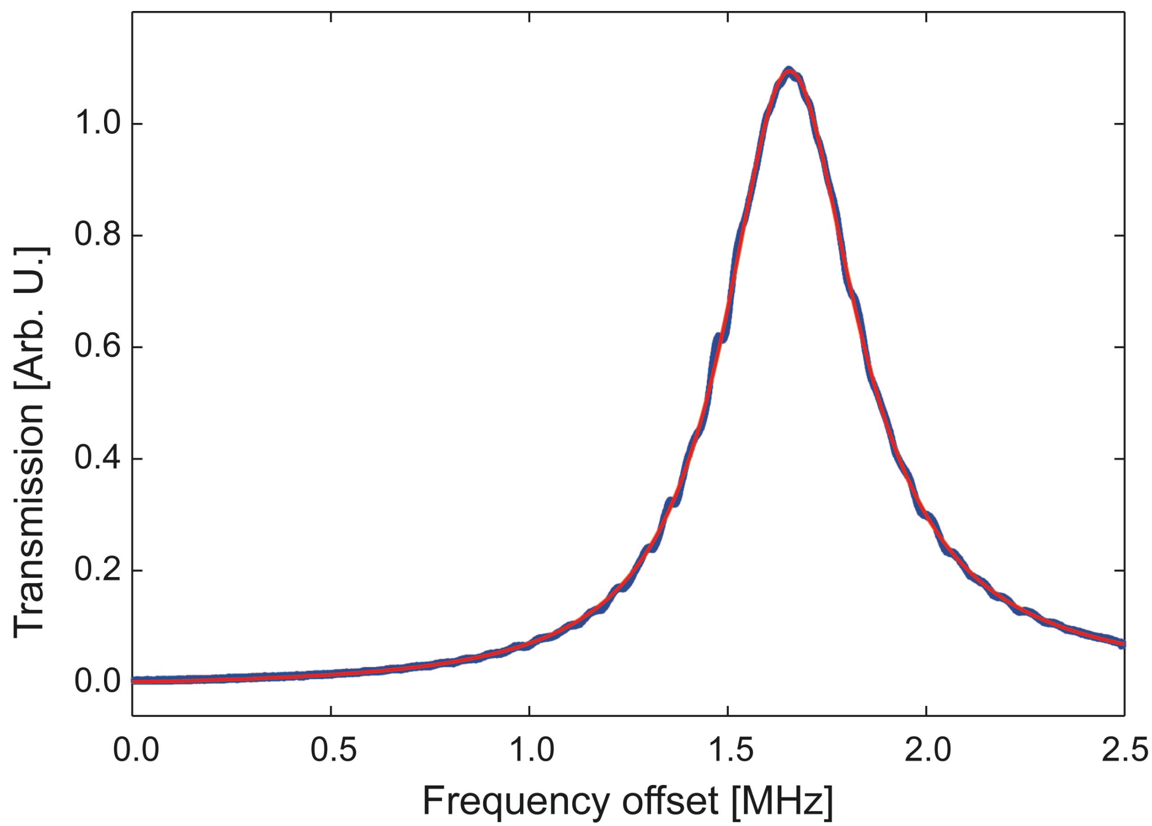
Dipole coupling between the atom and the cavity.

$$g = \frac{d \cdot E_v}{\hbar}$$

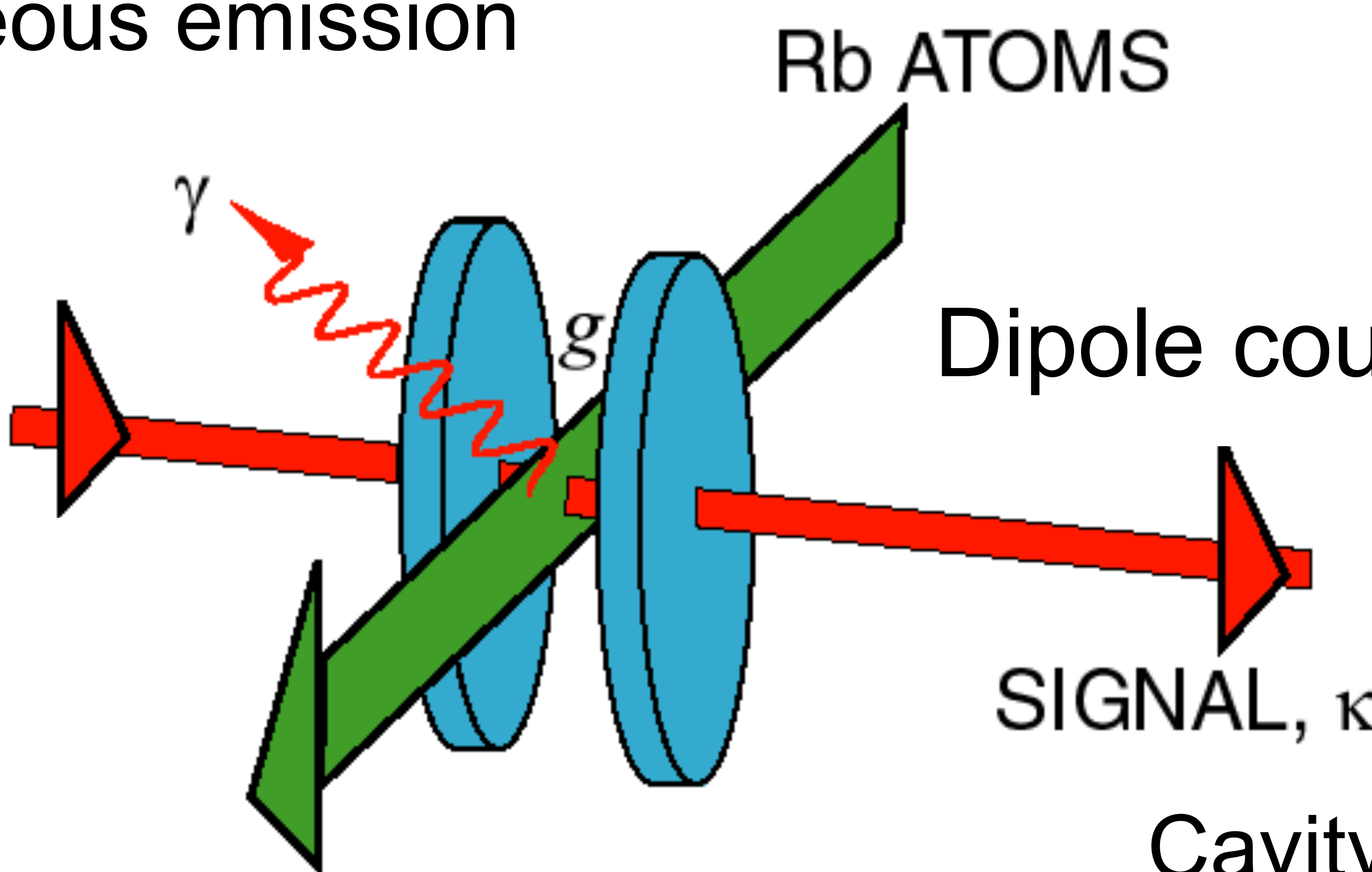
The field of one photon in a cavity with Volume V_{eff} is:

$$E_v = \sqrt{\frac{\hbar\omega}{2\varepsilon_0 V_{eff}}}$$


EMPTY CAVITY
LIGHT
PD
SIGNAL


Transmission [Arb. U.]
Frequency offset [MHz]
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0
2.5

Spontaneous emission



Dipole coupling

Cavity decay

Cooperativity for one atom: C_1

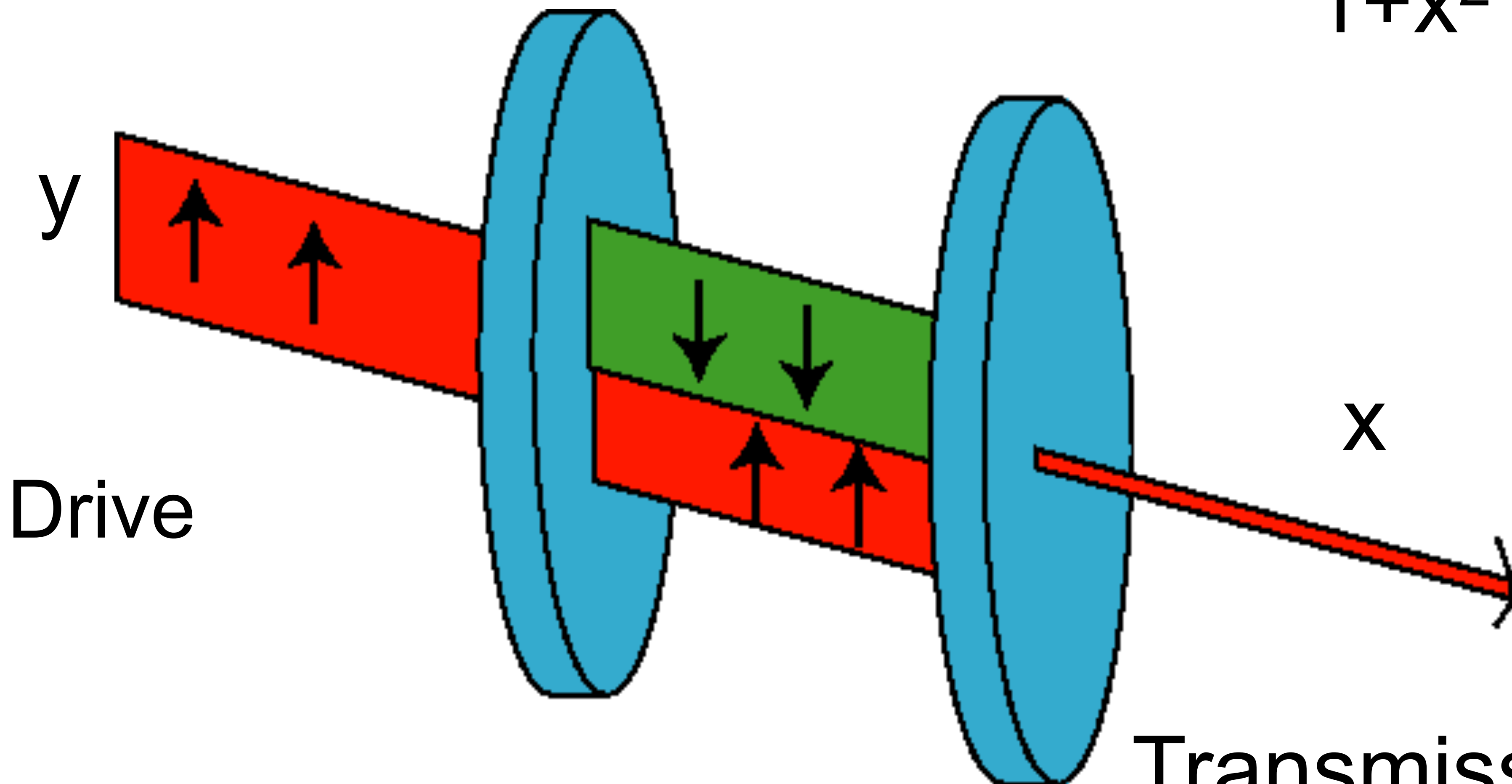
$$C_1 = \frac{g^2}{\kappa\gamma} \qquad C = C_1 N$$

Cooperativity for N atoms: C

$$g \approx \kappa \approx \gamma$$

Steady State

Atomic polarization: $\frac{-2Cx}{1+x^2}$

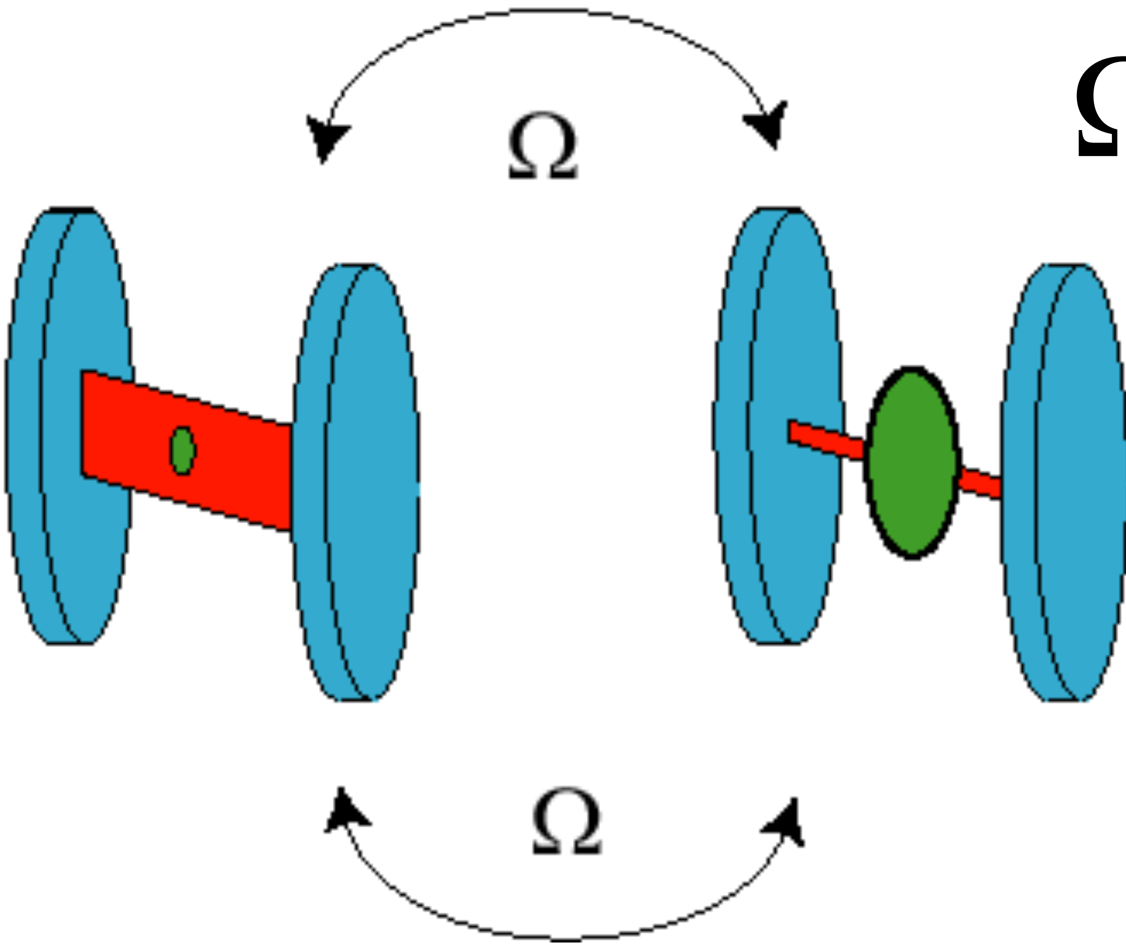


Transmission
$x/y = 1/(1+2C)$

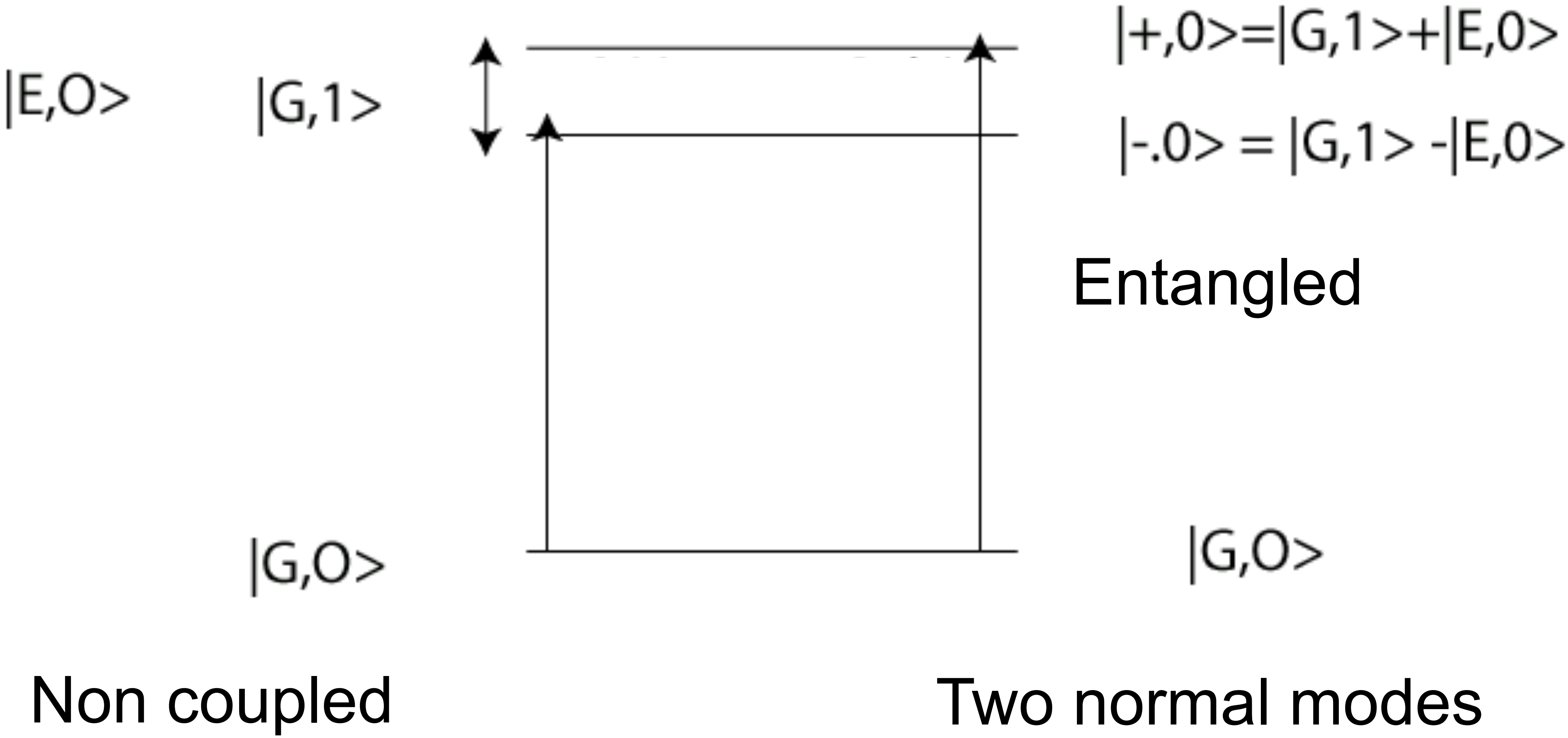
Dynamics of the Jaynes Cummings
Rabi oscillations:

Excitation exchange for *N* atoms:

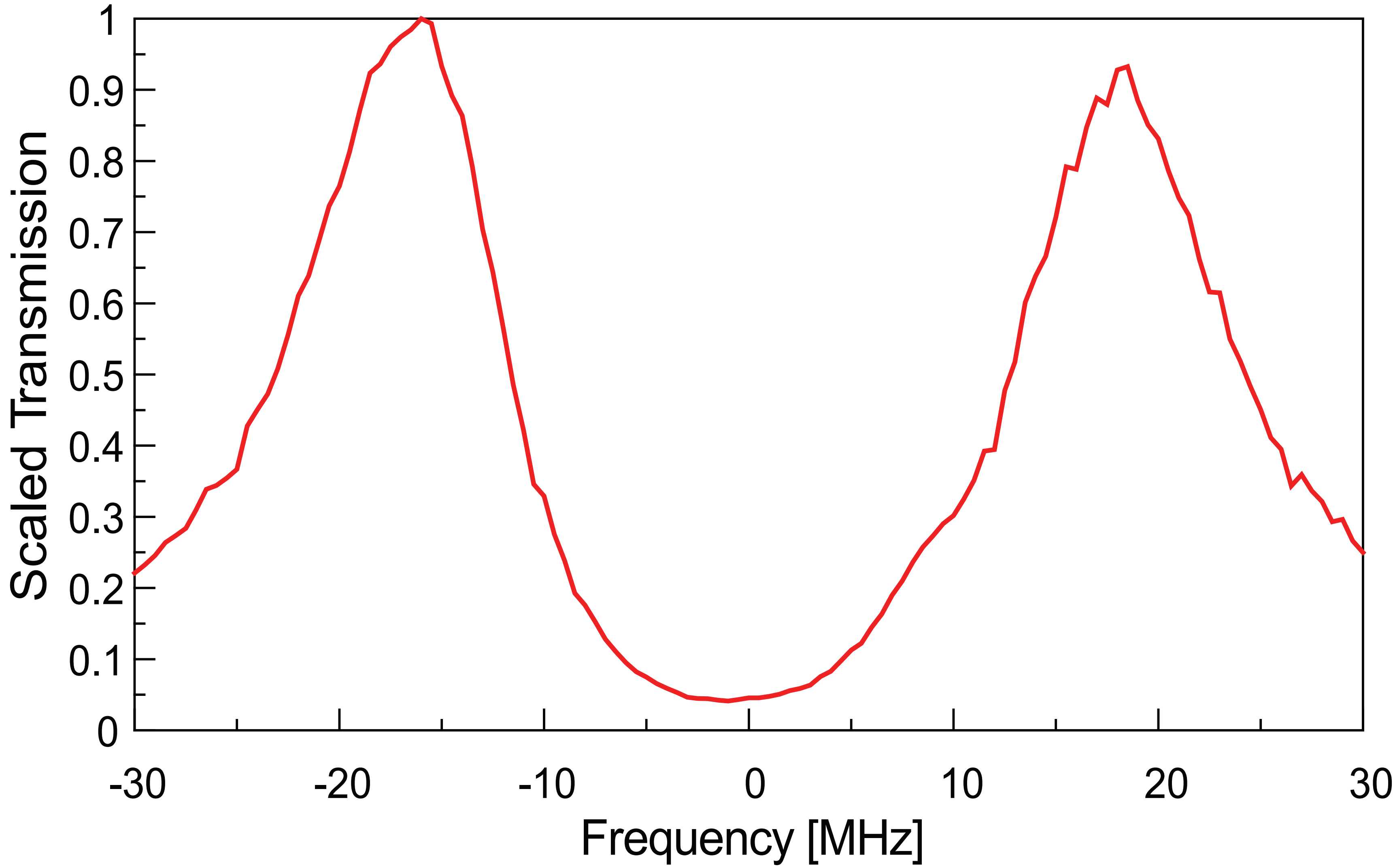
$$\Omega \approx g\sqrt{N}$$

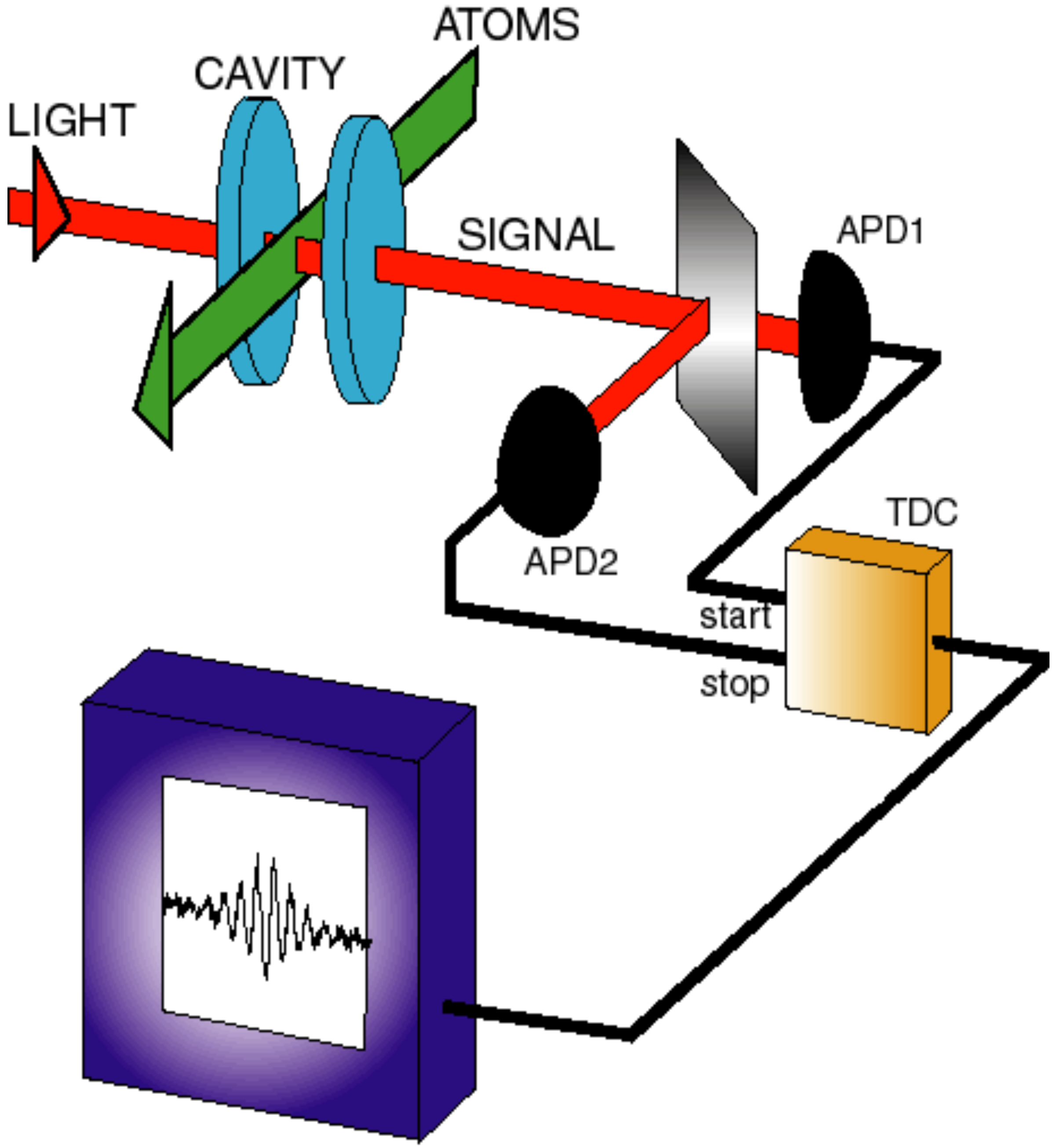


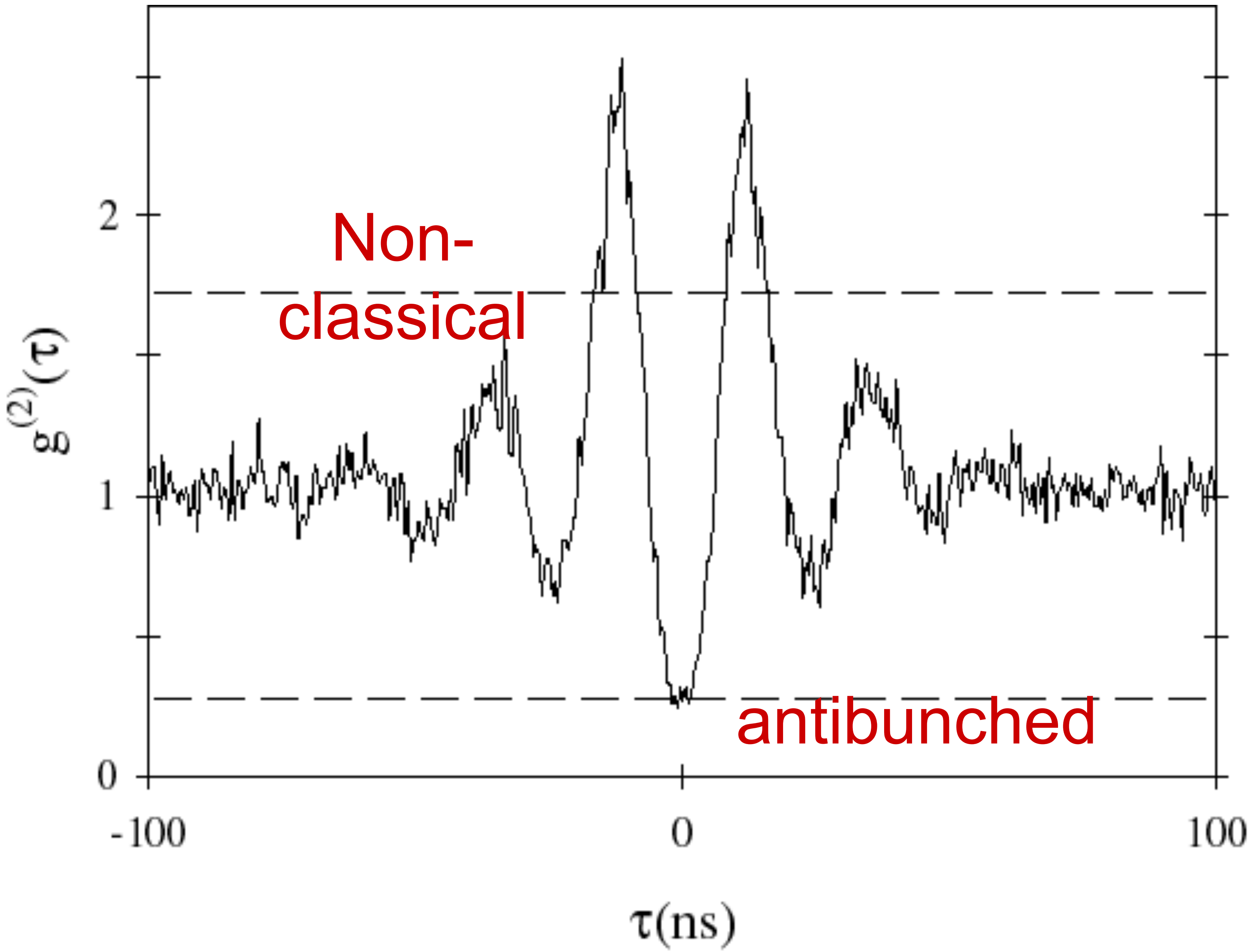
2g Vacuum Rabi Splitting



Transmission doublet instead of the single Fabry Perot resonance




ATOMS
CAVITY
LIGHT
SIGNAL
APD1
APD2
TDC
start
stop



Classically $g^{(2)}(0) > g^{(2)}(\tau)$
and also $|g^{(2)}(0)-1| > |g^{(2)}(\tau)-1|$

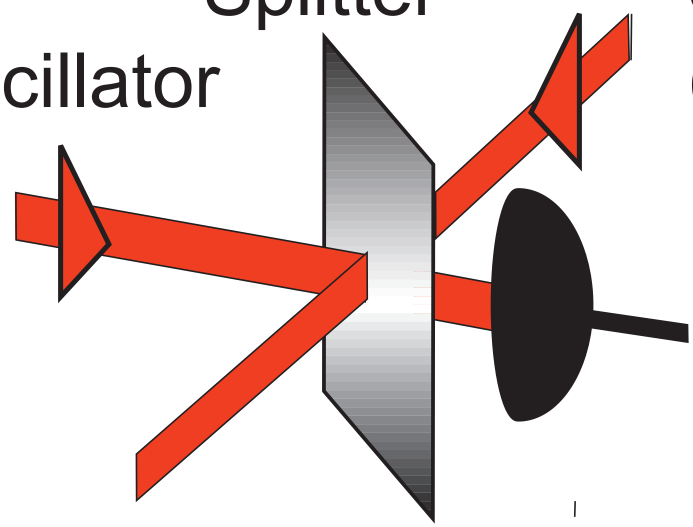
How to correlate fields and intensities?

Detection of the field: Homodyne.

Conditional Measurement: Only measure when we know there is a photon.

Source: Cavity QED

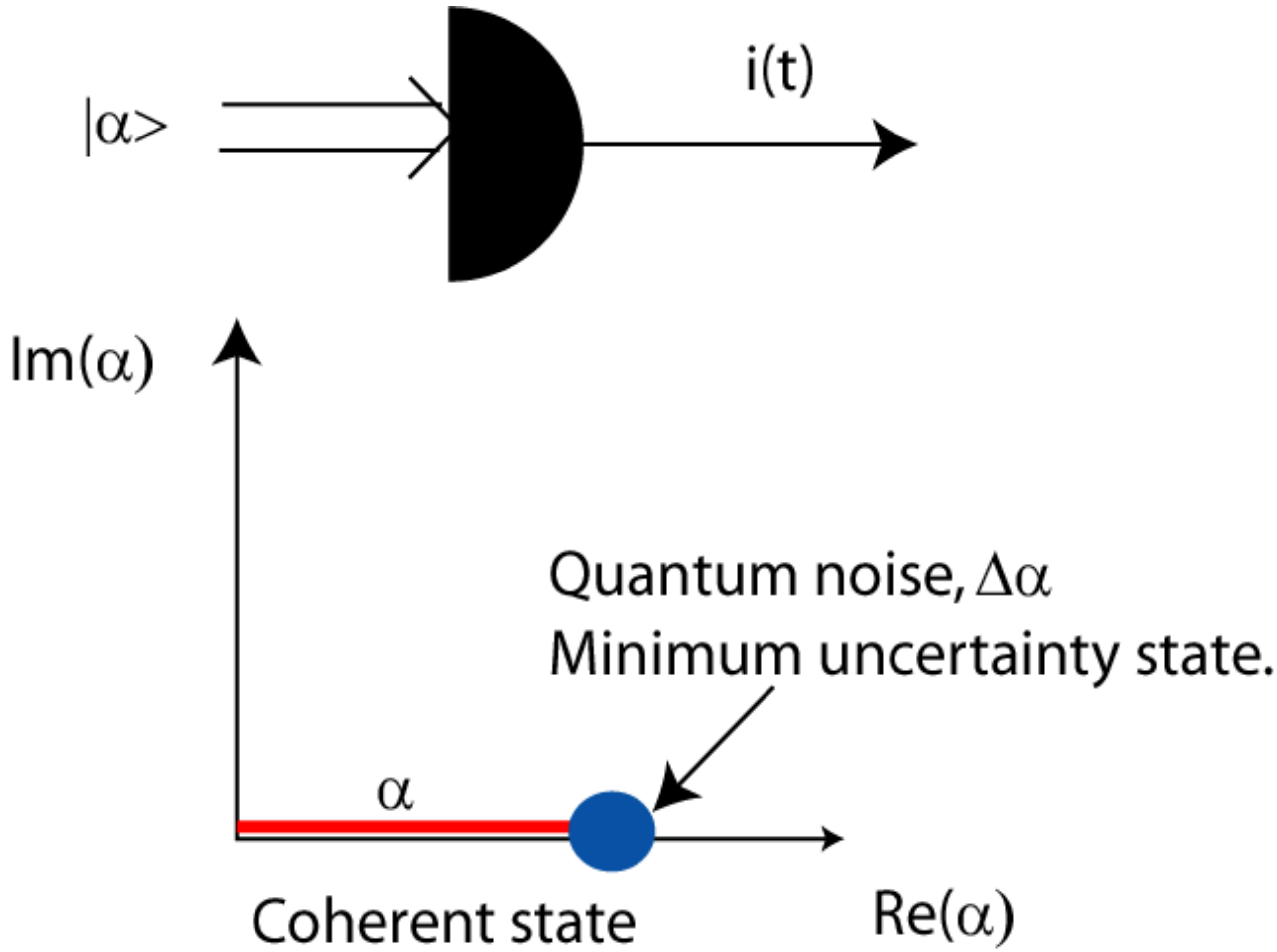
Homodyne Measurement



There is an interference between the Local Oscillator and the signal that is proportional to the amplitude of the signal

Photocurrent ~ $|L.O.\ \cos(\o)+S|^2$

$$|LO \cos(\phi) + S|^2 = |LO|^2 + 2\ LO\ S \cos(\phi) + |S|^2$$

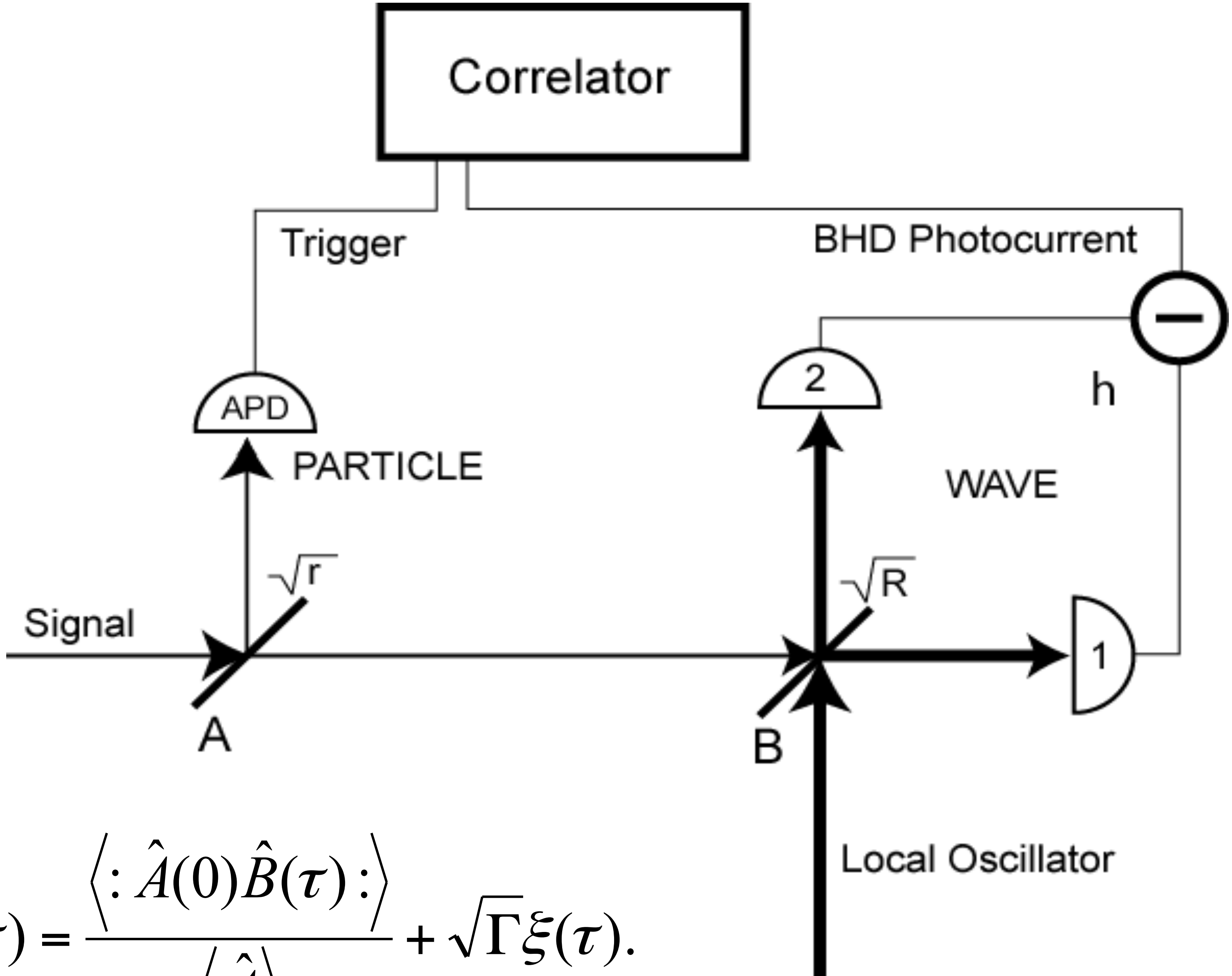


Perfect detector $I(t) = |\alpha + \Delta\alpha|^2$

$$I(t) = |\alpha|^2 + 2\,\alpha\,\Delta\alpha + |\Delta\alpha|^2 \quad ; \quad \langle \alpha^* \alpha \rangle = n$$

DC~n Shot noise ~$n^{1/2}$ neglect.

the Intensity-Field correlator.



$$H(\tau) = \frac{\left\langle :\hat{A}(0)\hat{B}(\tau): \right\rangle}{\left\langle \hat{A} \right\rangle} + \sqrt{\Gamma}\,\xi(\tau).$$

Condition on a Click

Measure the correlation function of the Intensity and the Field:

$$\langle I(t)\, E(t+\tau)\rangle$$

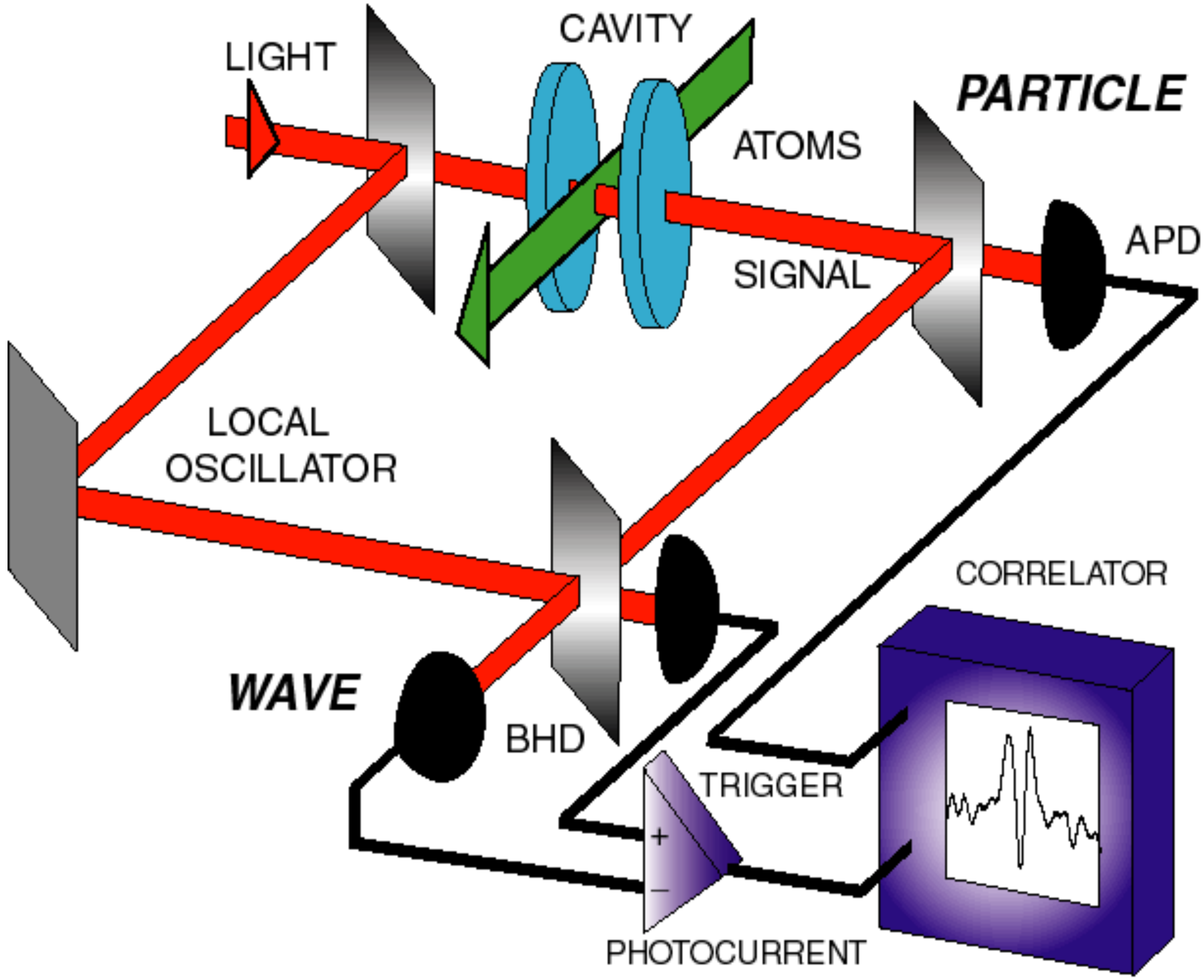
Normalized form:

$$h_\theta(\tau) = \langle E(\tau)\rangle_c / \langle E\rangle$$

From Cauchy Schwartz inequalities:

$$0 \le \bar{h}_0(0) - 1 \le 2$$

$$\left|\bar{h}_0(\tau) - 1\right| \le \left|\bar{h}_0(0) - 1\right|$$


CAVITY
LIGHT
PARTICLE
ATOMS
APD
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OSCILLATOR
CORRELATOR
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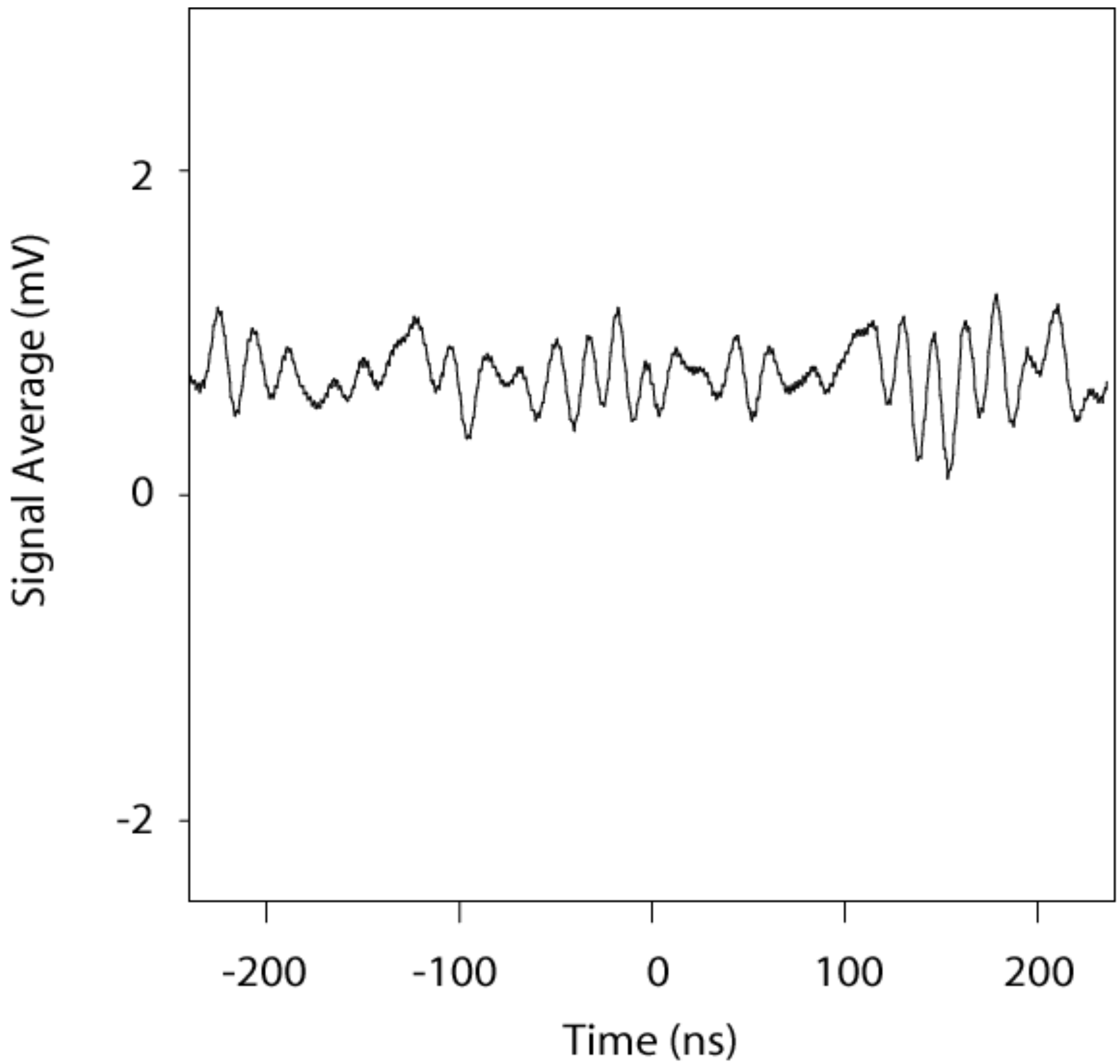
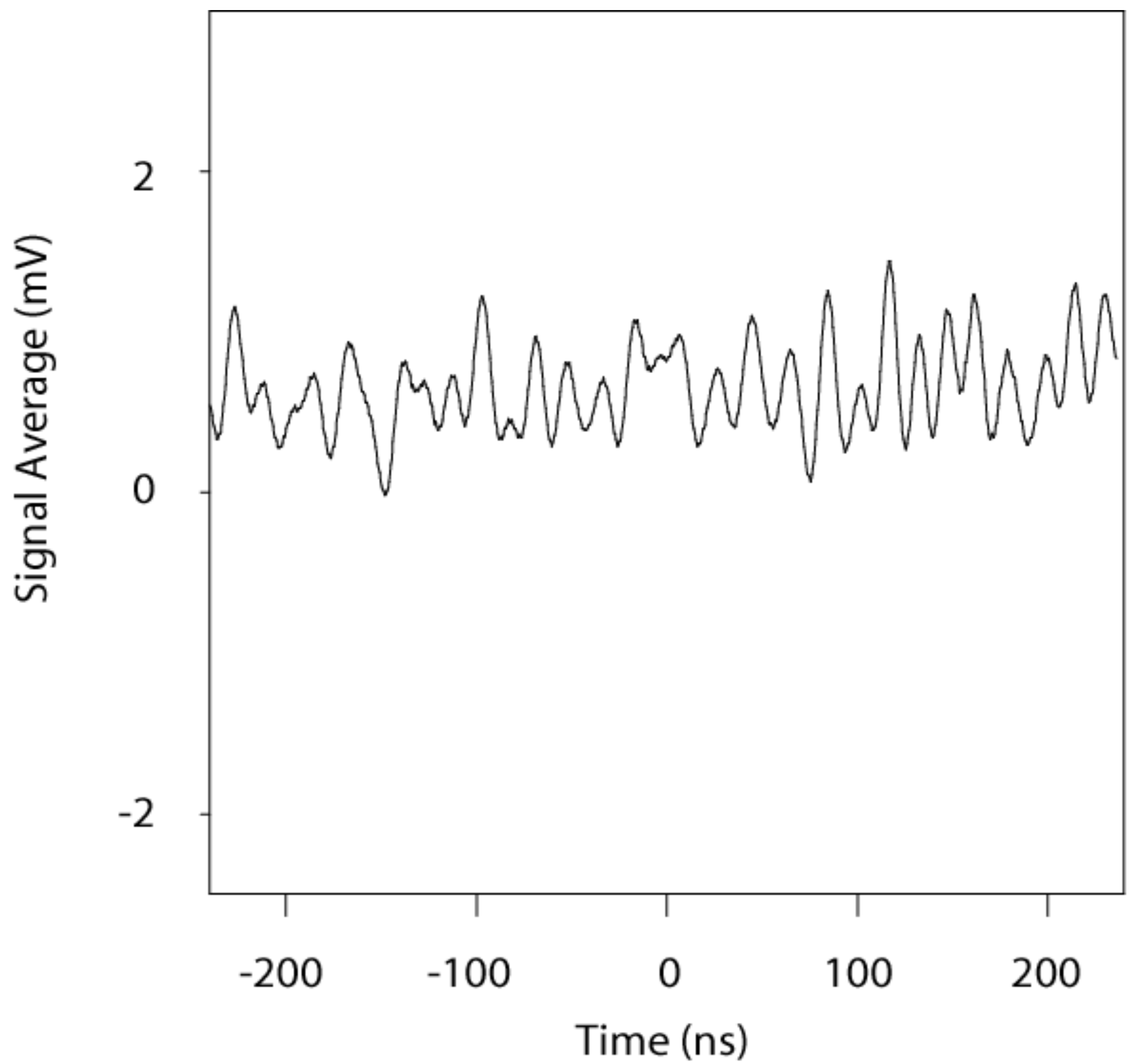
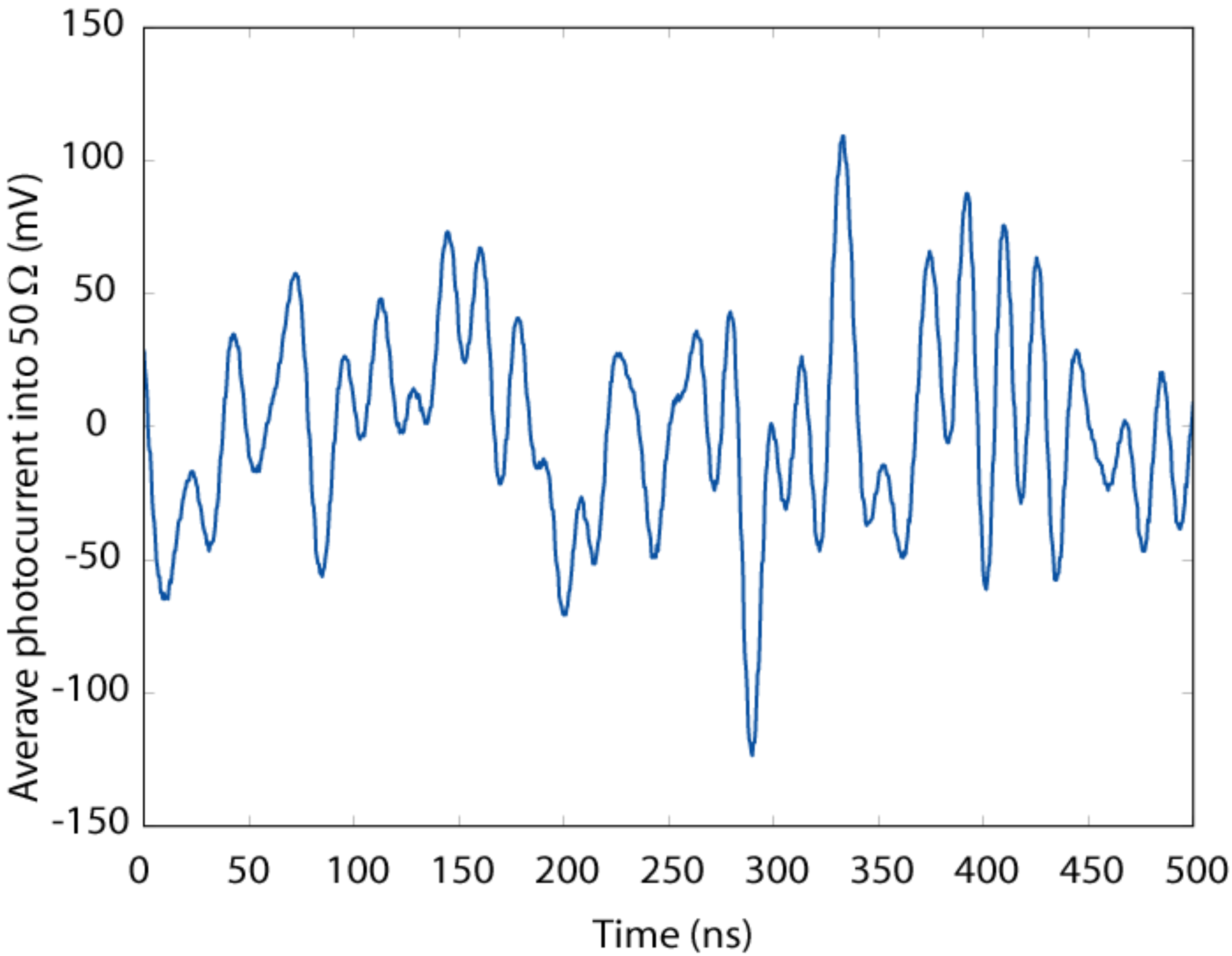
TRIGGER
+
–
PHOTOCURRENT

Photocurrent average with random conditioning

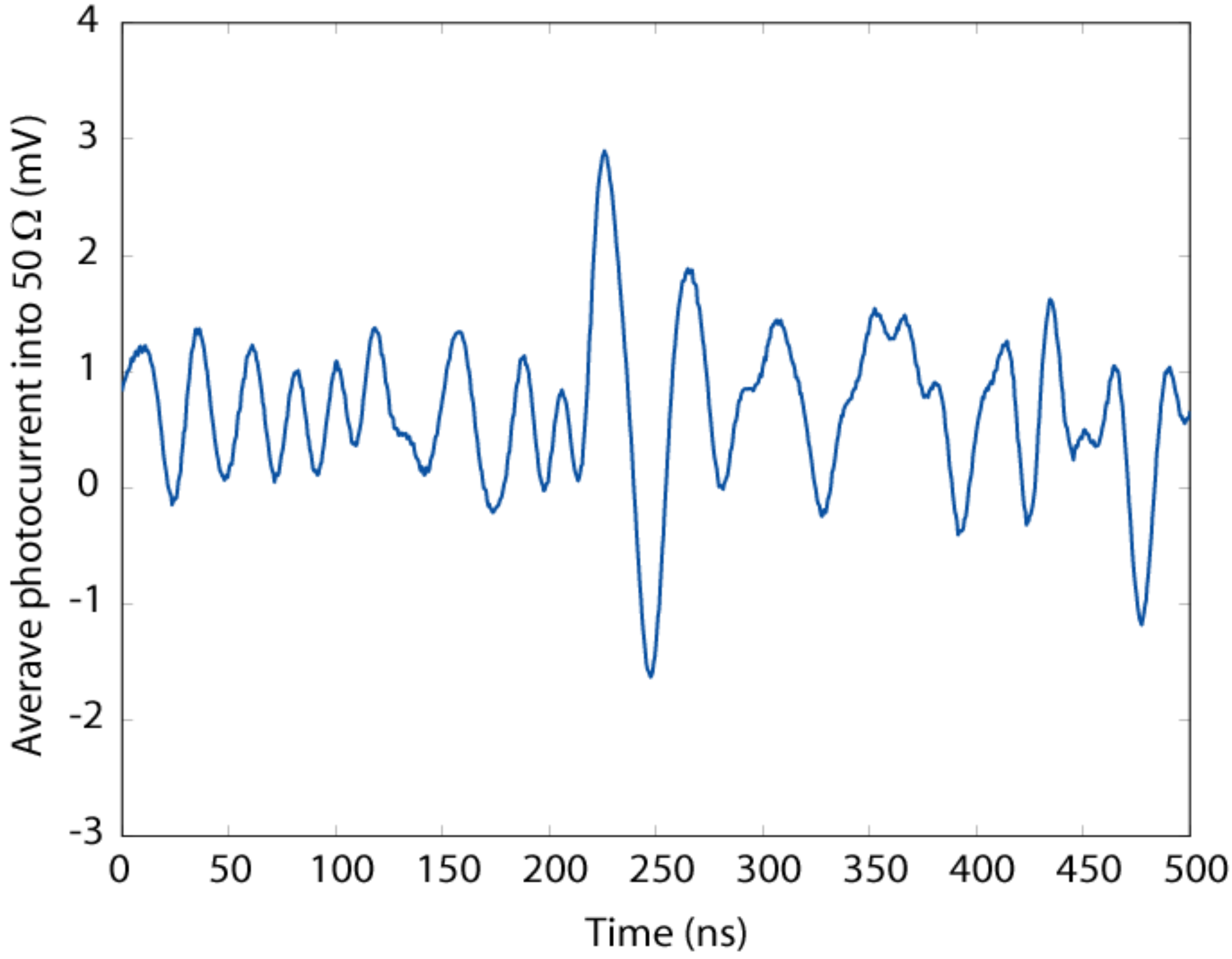


Conditional photocurrent with no atoms in the cavity.

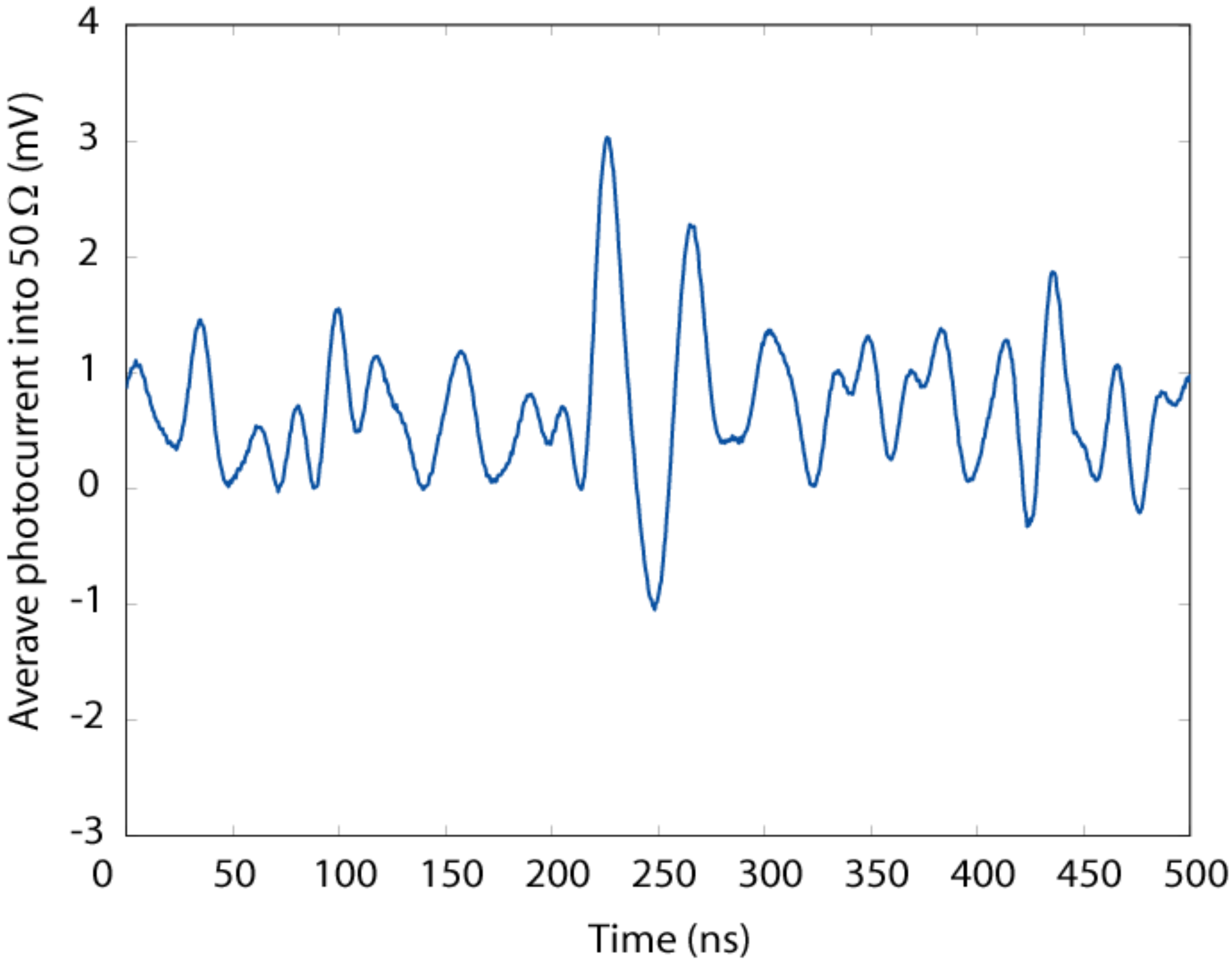




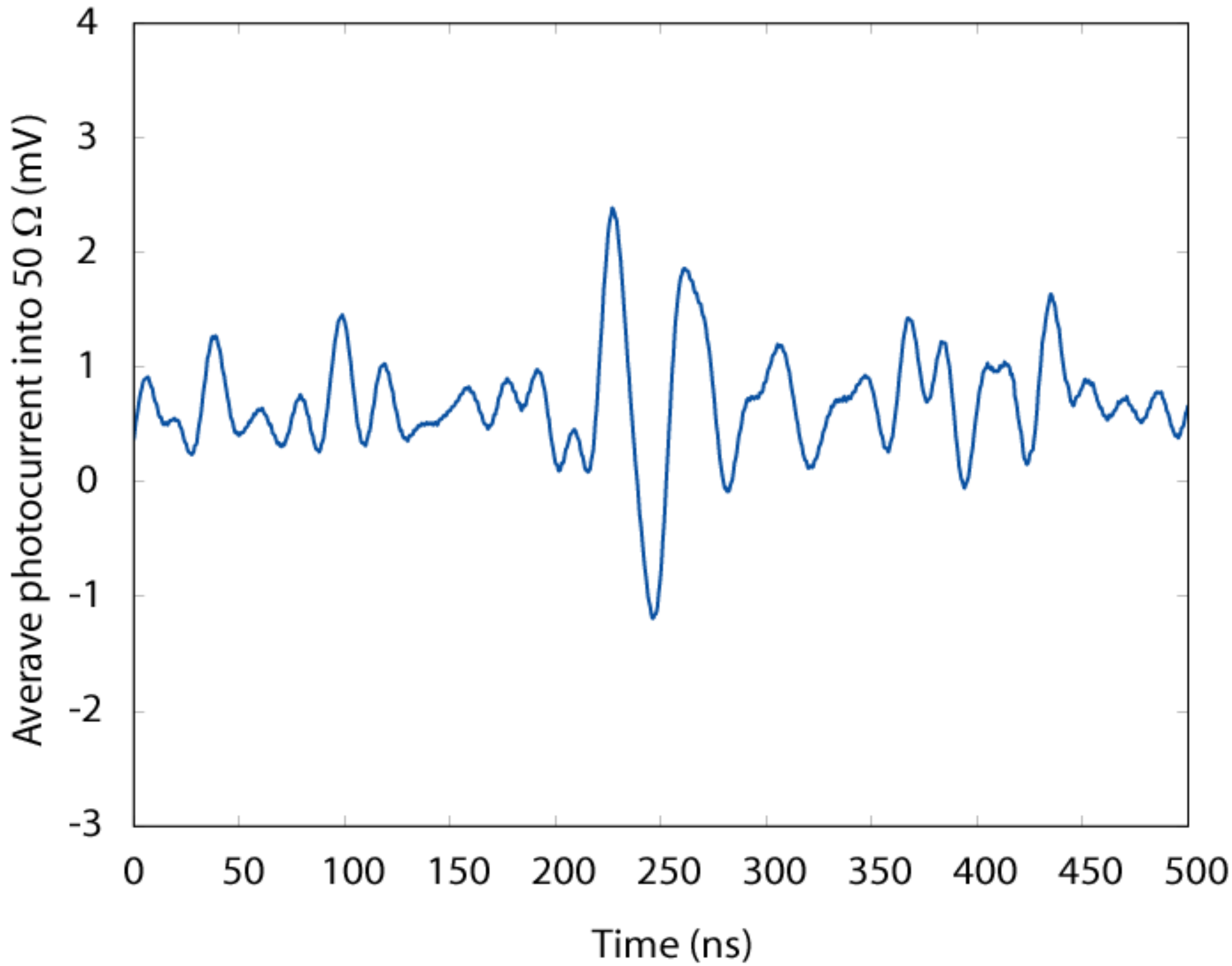
After 1 average



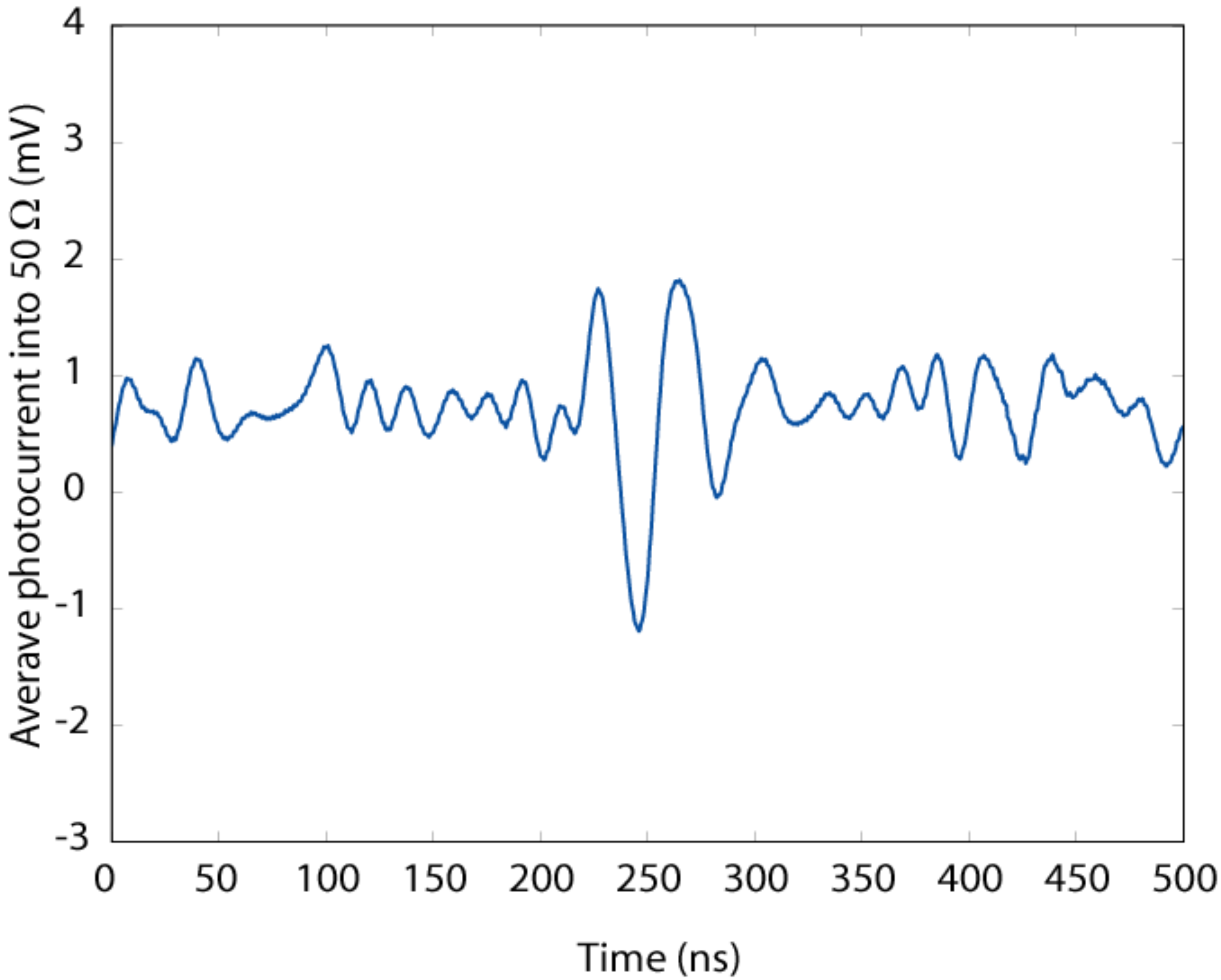
After 6,000 averages



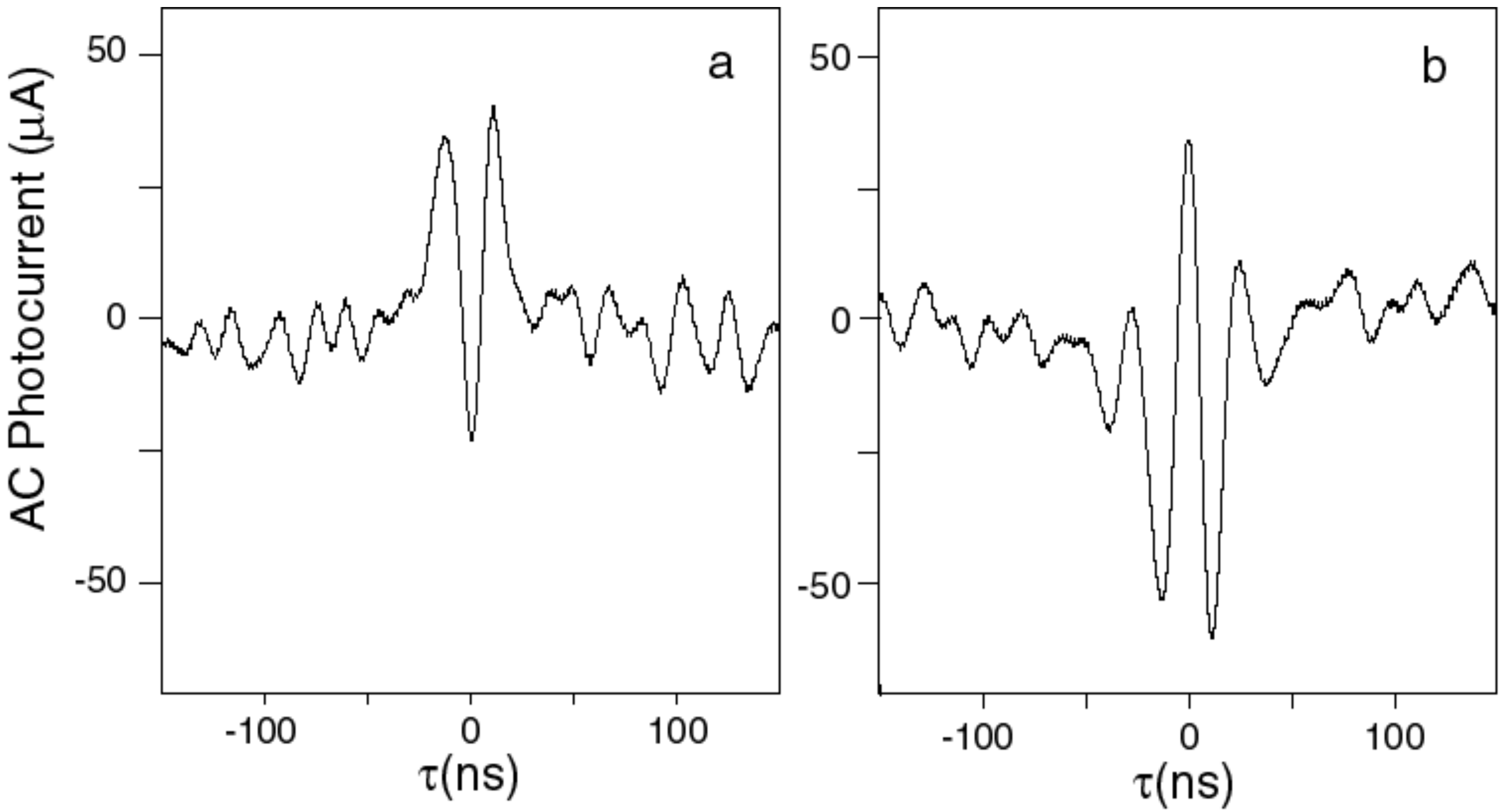
After 10,000 averages



After 30,000 averages

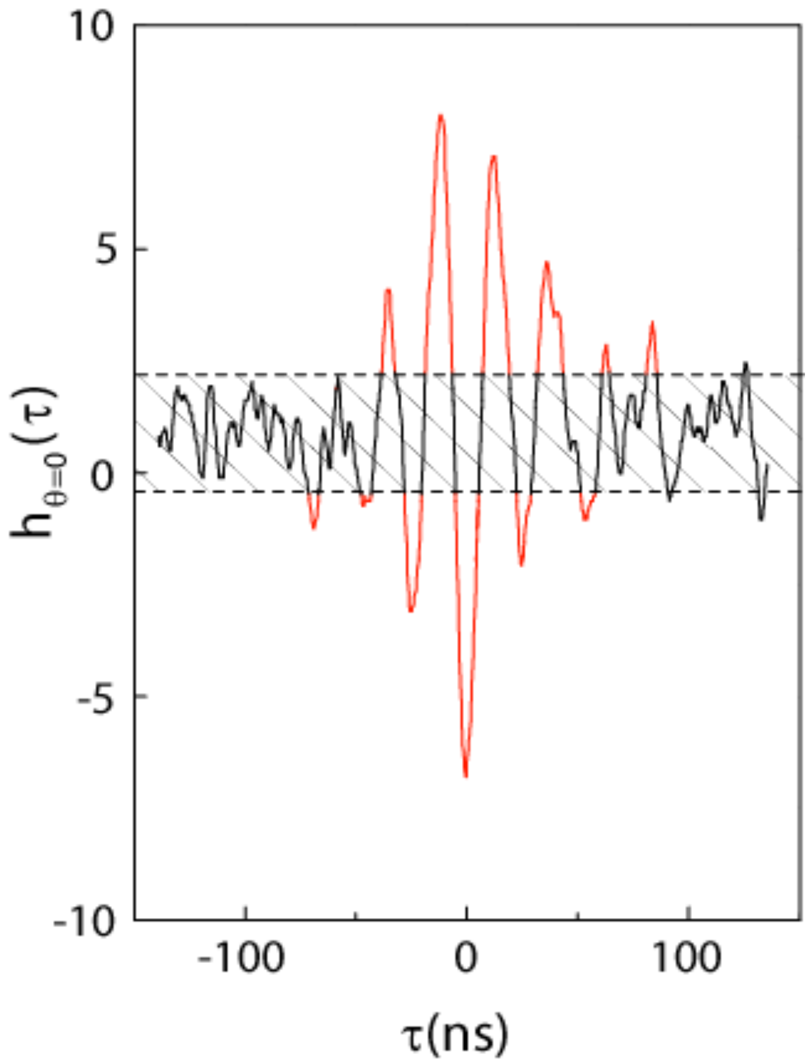


After 65,000 averages



Flip the phase of the Mach-Zehnder by 146^{o}

Monte Carlo simulations for weak excitation:



Atomic beam N=11

This is the conditional evolution of the field of a fraction of a photon [B(t)] from the correlation function.

$h_\theta(\tau) = \langle E(\tau)\rangle_c / \langle E\rangle$

The conditional field prepared by the click is:

$A(t)|0\rangle + B(t)|1\rangle$ with $A(t) \approx 1$ and $B(t) << 1$

We measure the field of a fraction of a photon!

Fluctuations are very important.

Conditional dynamics in cavity QED at low intensity:

$$|\Psi_{ss}\rangle = |0,g\rangle + \lambda|1,g\rangle - \frac{2g}{\gamma}\lambda|0,e\rangle + \frac{\lambda^2 pq}{\sqrt{2}}|2,g\rangle - \frac{2g\lambda^2 q}{\gamma}|1,e\rangle$$

$$\lambda = \langle \hat{a} \rangle, \quad p = p(g,\kappa,\gamma) \text{ and } q = q(g,\kappa,\gamma)$$

A photodetection conditions the state into the following non-steady state from which the system evolves.

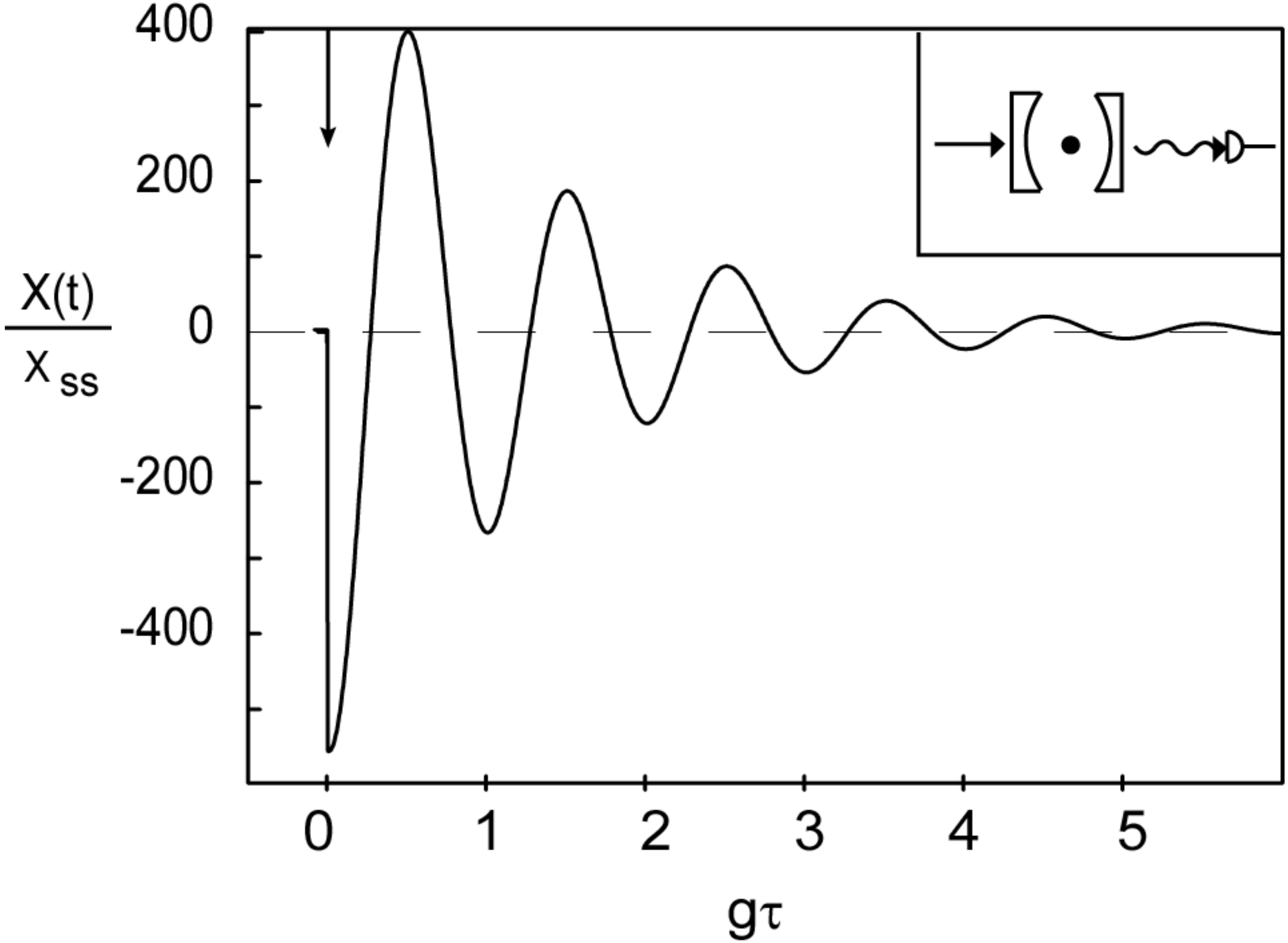
$$\hat{a}|\Psi_{ss}\rangle \Rightarrow |\Psi_c(\tau)\rangle = |0,g\rangle + \lambda pq|1,g\rangle - \frac{2g\lambda q}{\gamma}|0,e\rangle$$

$$|\Psi_c(\tau)\rangle = |0,g\rangle + \lambda\left[f_1(\tau)|1,g\rangle + f_2(\tau)|0,e\rangle\right] + O\left(\lambda^2\right)$$

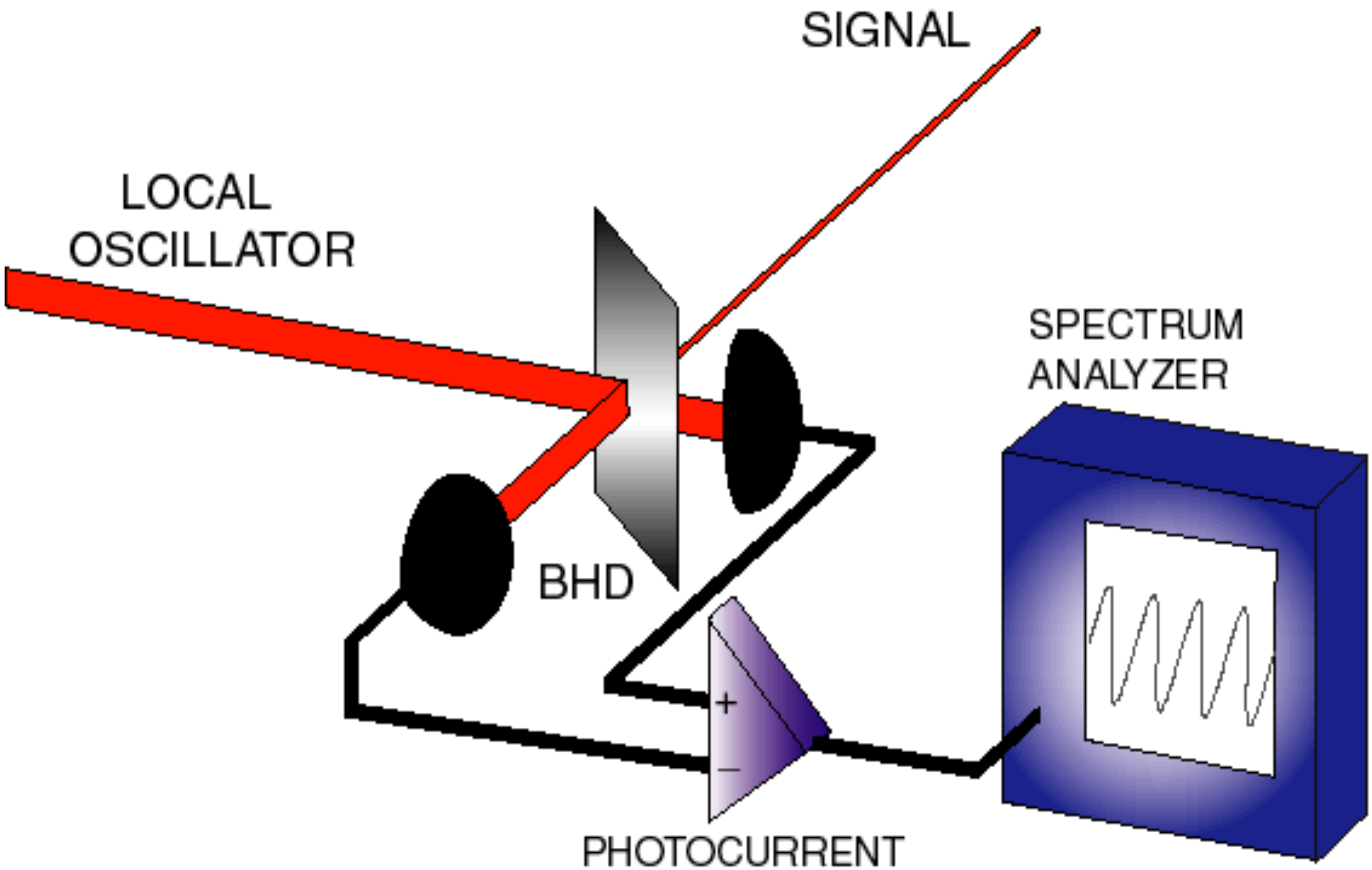
Field

Atomic Polarization

Regression of the field to steady state after the detection of a photon.



Detection of the Squeezing spectrum with a balanced homodyne detector (BHD).

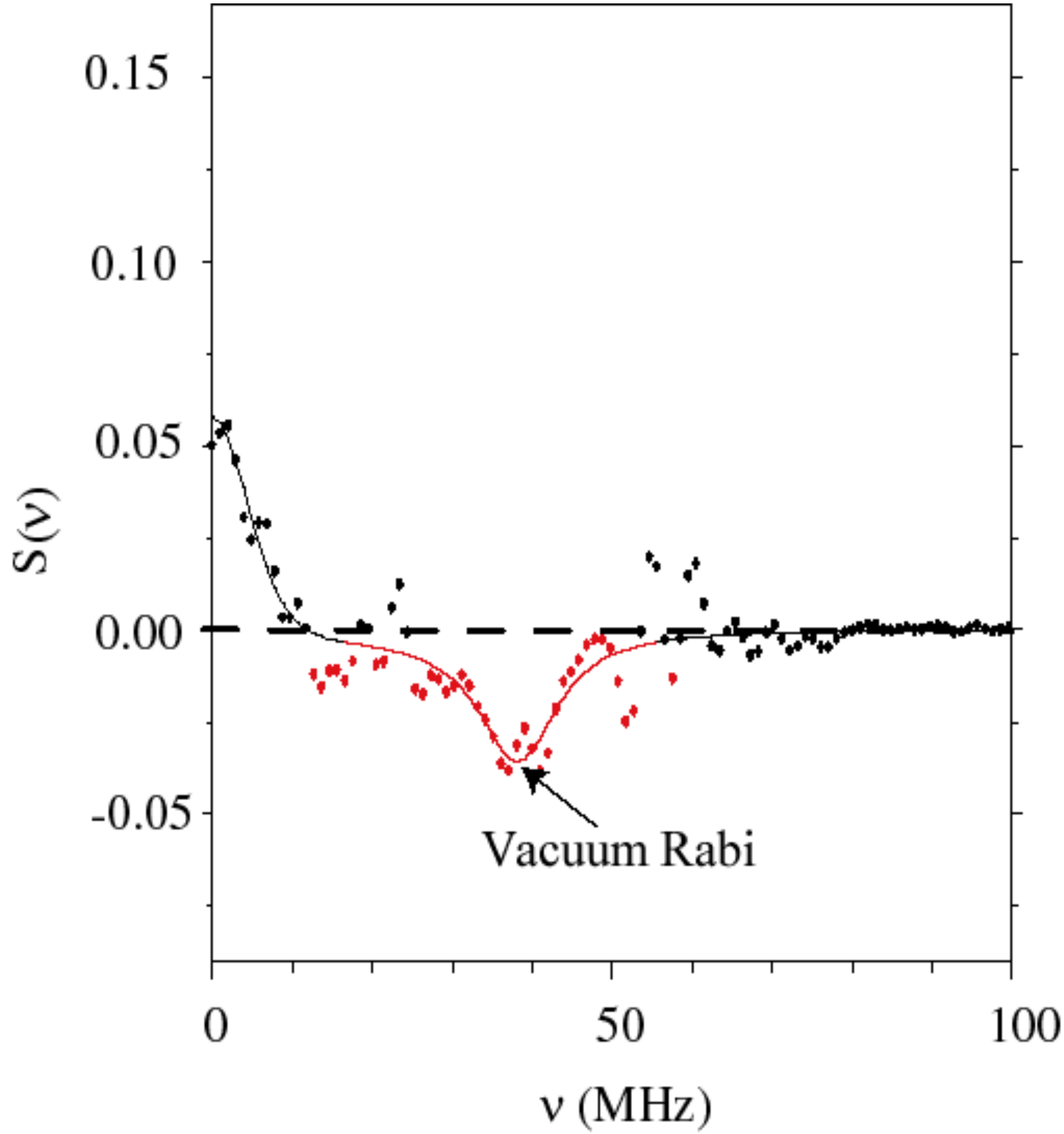


The fluctuations of the electromagnetic field are measured by the spectrum of squeezing. Look at the noise spectrum of the photocurrent.

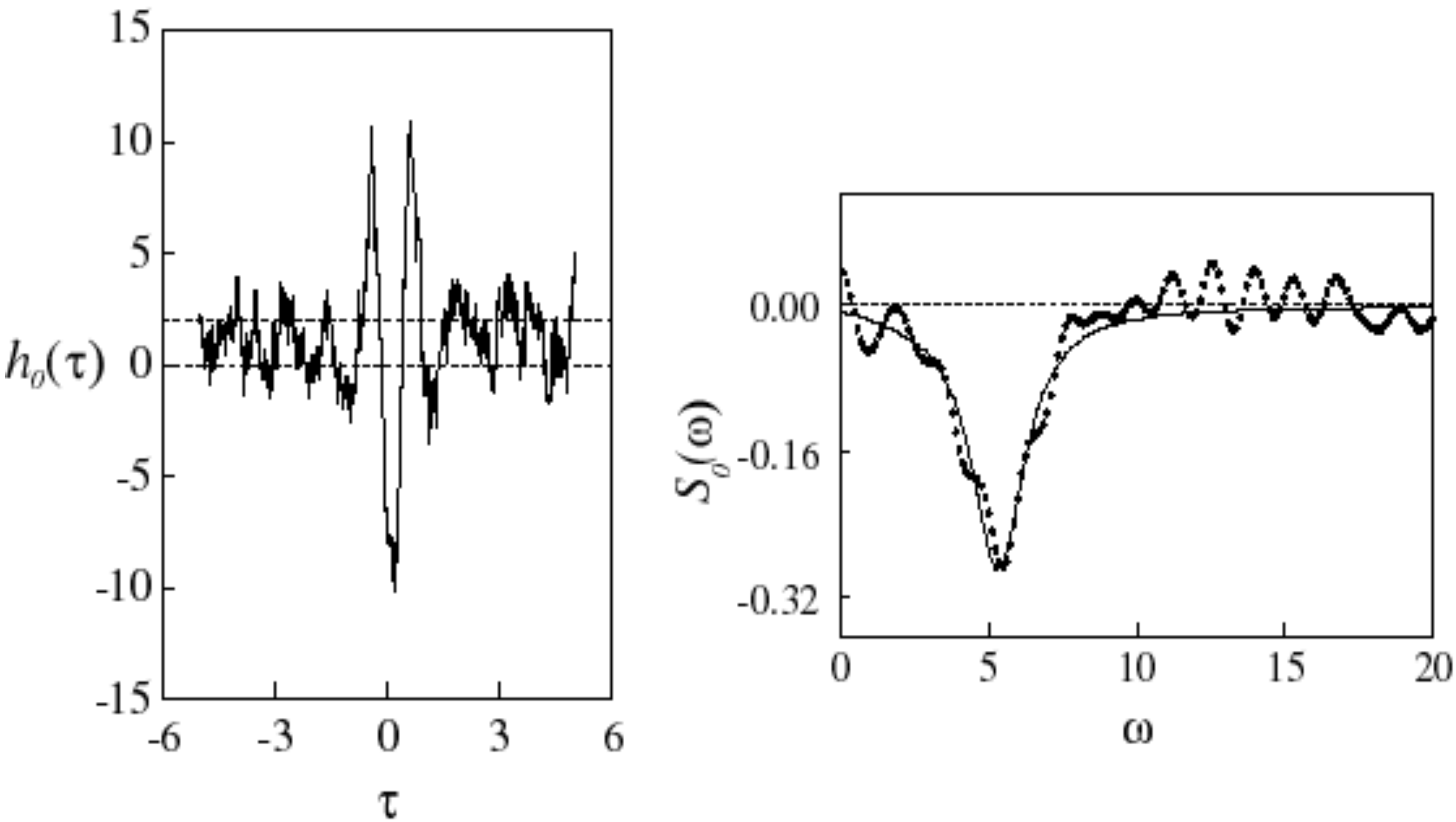
$$S(\nu, 0^\circ) = 4F\int_0^\infty \cos(2\pi\nu\tau)[\overline{h}_0(\tau) - 1]d\tau,$$

F is the photon flux into the correlator.

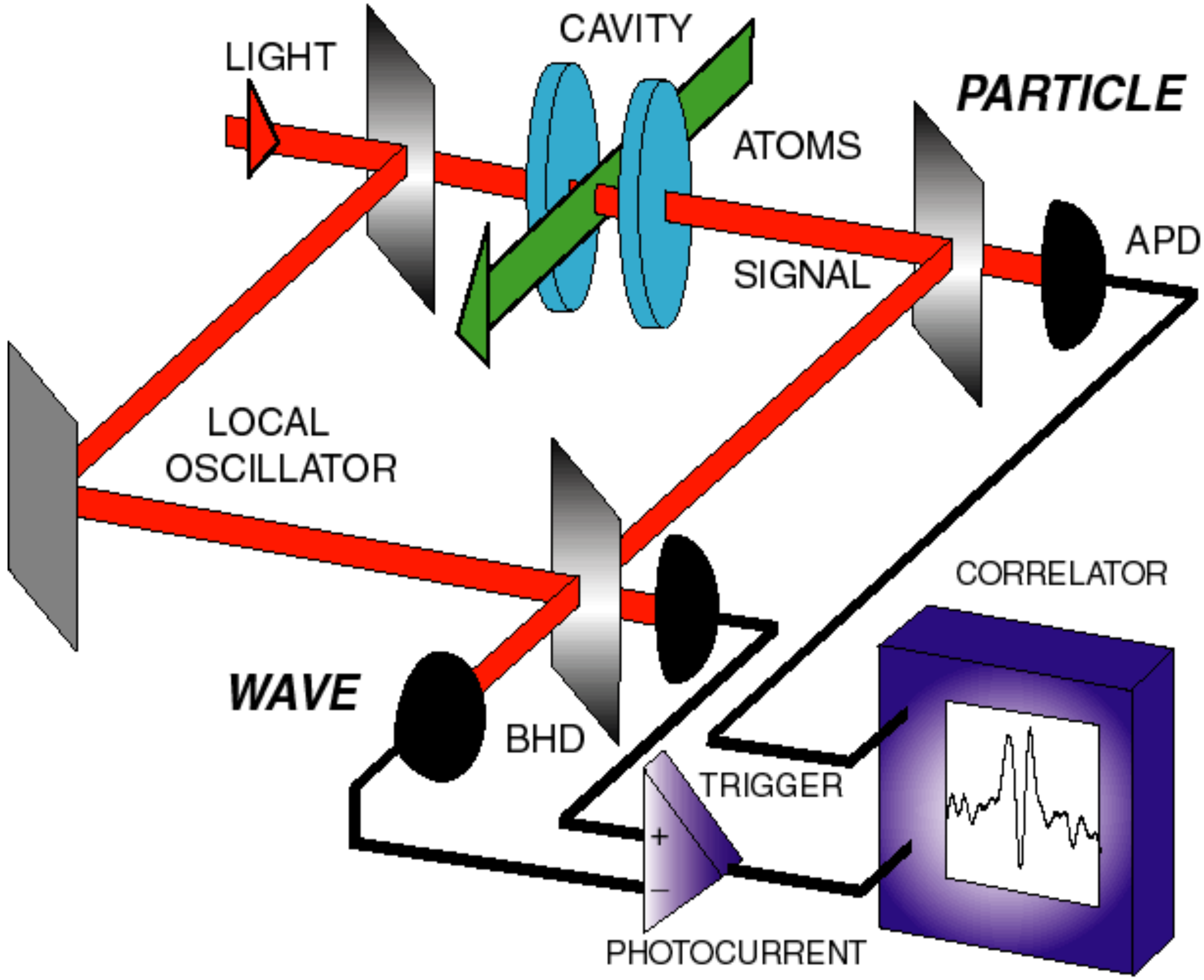
Spectrum of Squeezing from the Fourier Transform of $h_0(t)$



Monte Carlo simulations of the wave-particle correlation and the spectrum of squeezing in the low intensity limit for an atomic beam.



It has upper and a lower classical bounds



CAVITY
LIGHT
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WAVE
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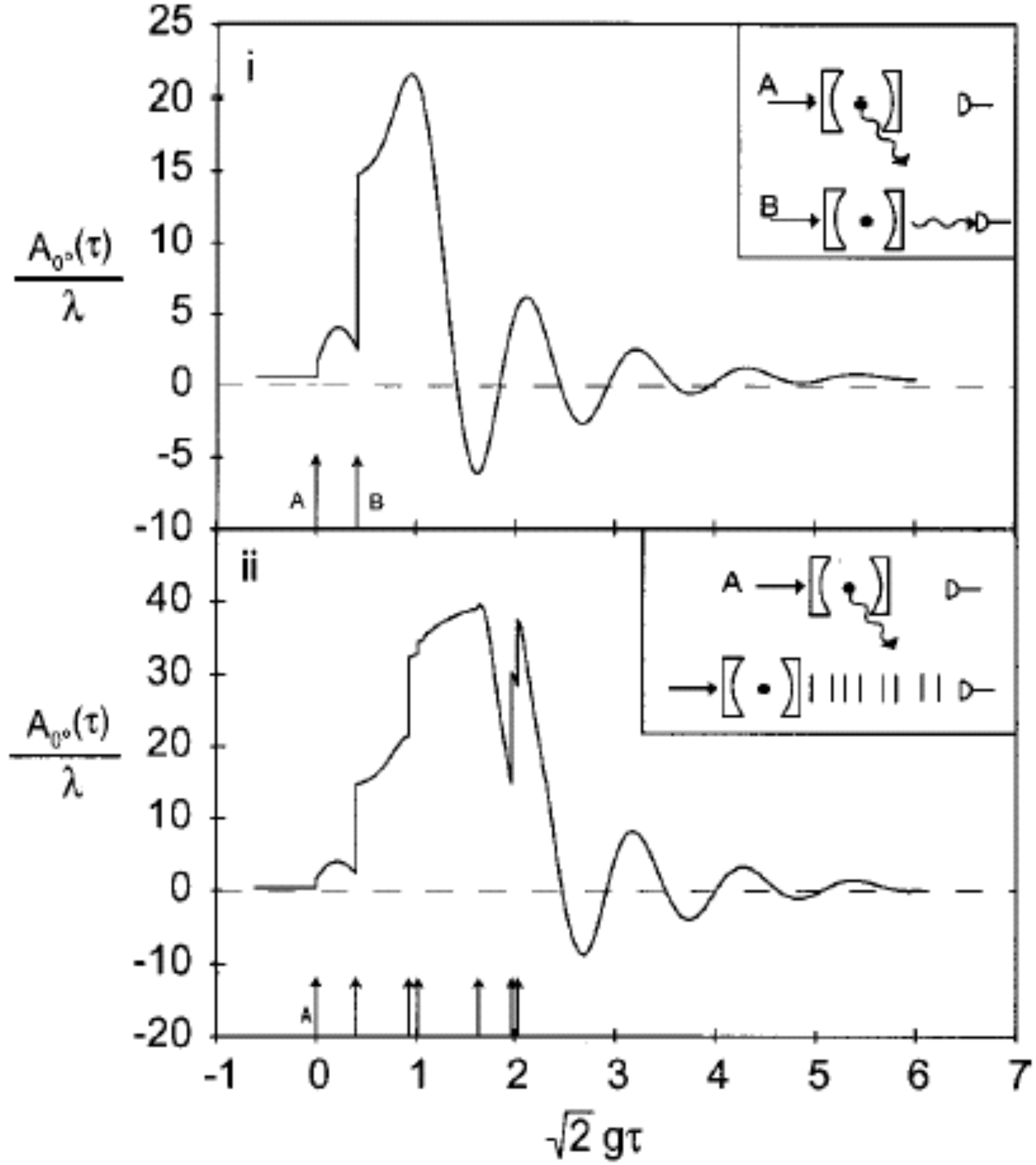
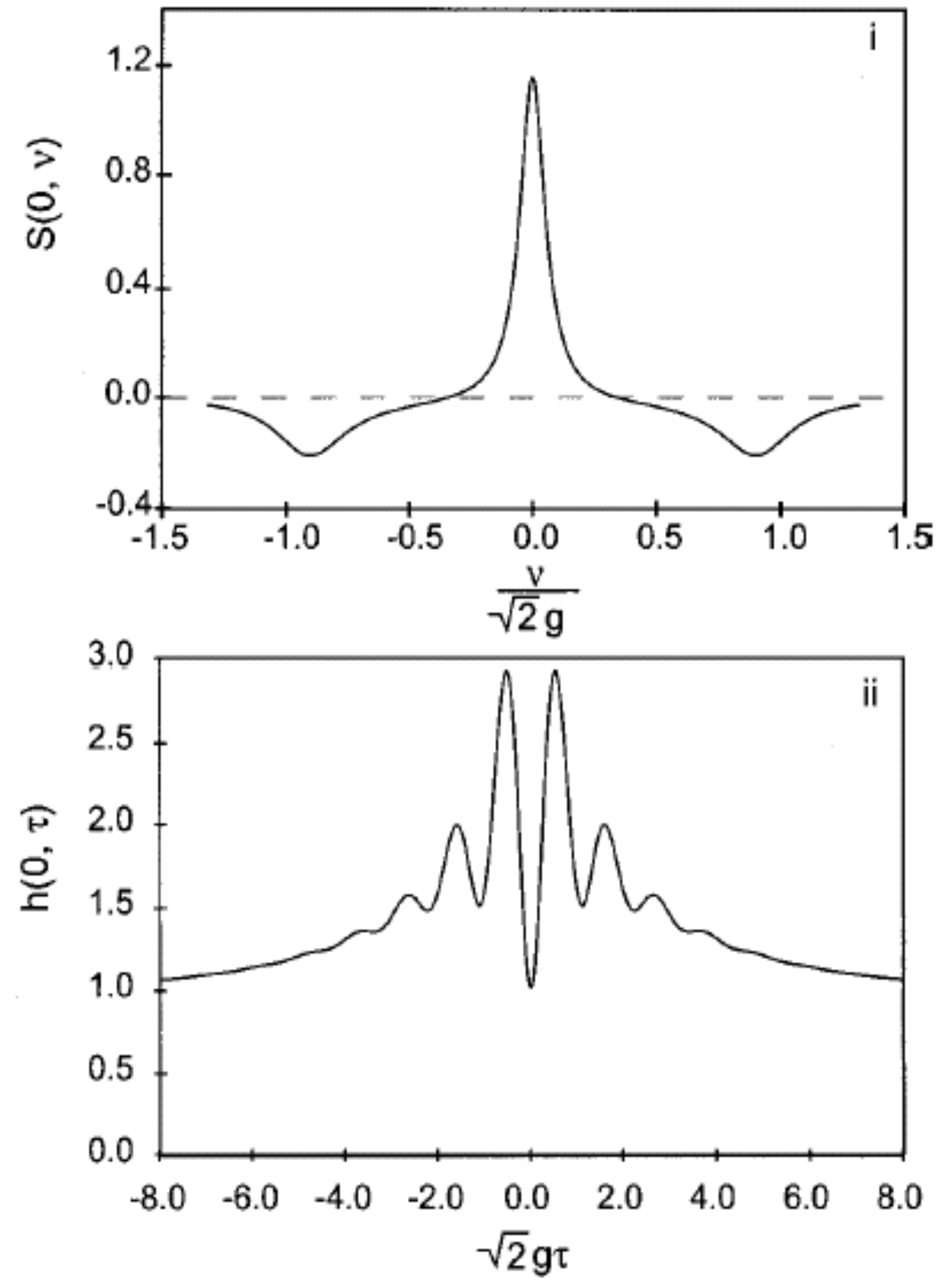
TRIGGER
+
–
PHOTOCURRENT

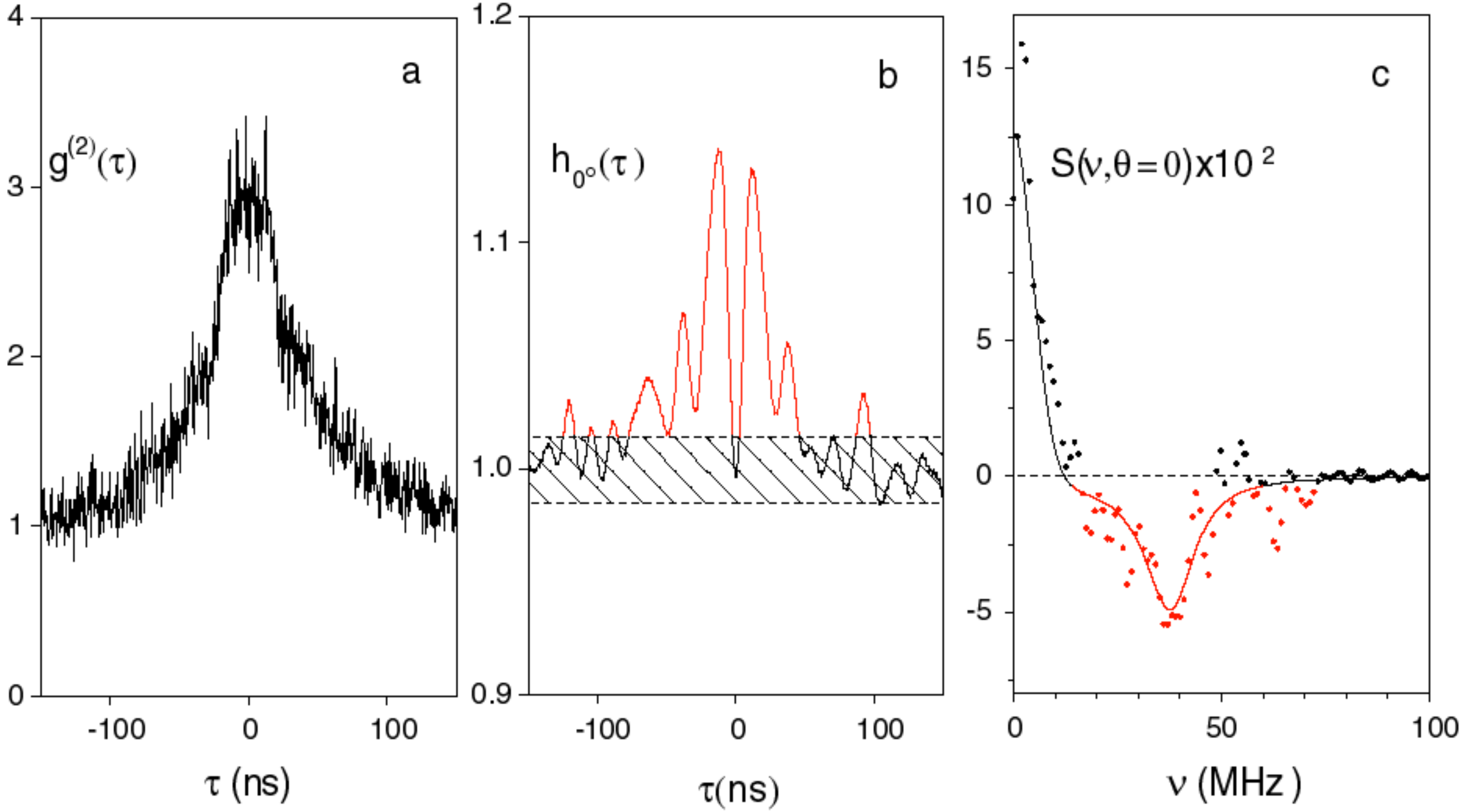


Single quantum trajectories simulation of cavity QED system with spontaneous emission.



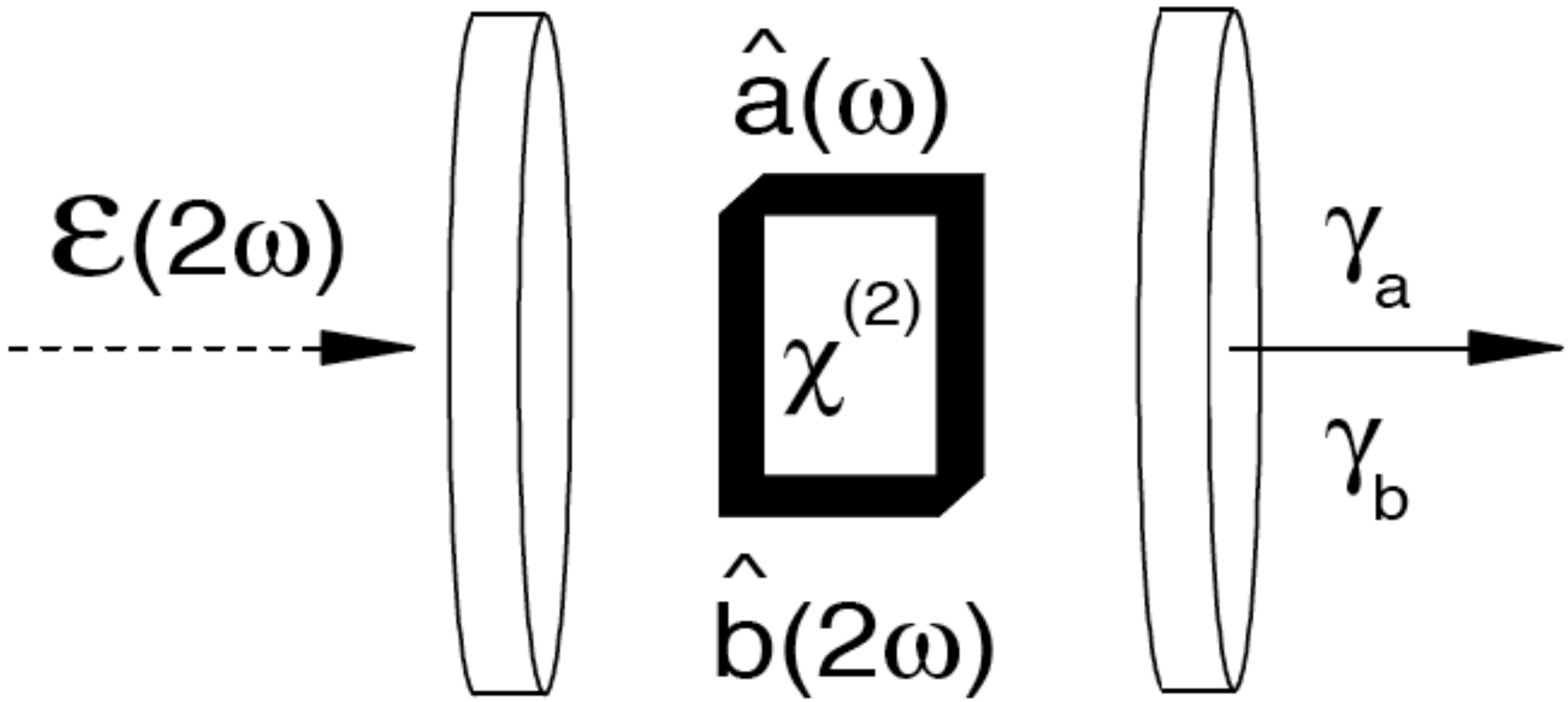
(i) Spectrum of squeezing obtained from the averaged (ii) h(0,t) correlation function that shows the effects of spontaneous emission.

Classical $g^{(2)}$ Non-classical h Squeezing



N=13; $1.2n_0$

Optical Parametric Oscillator



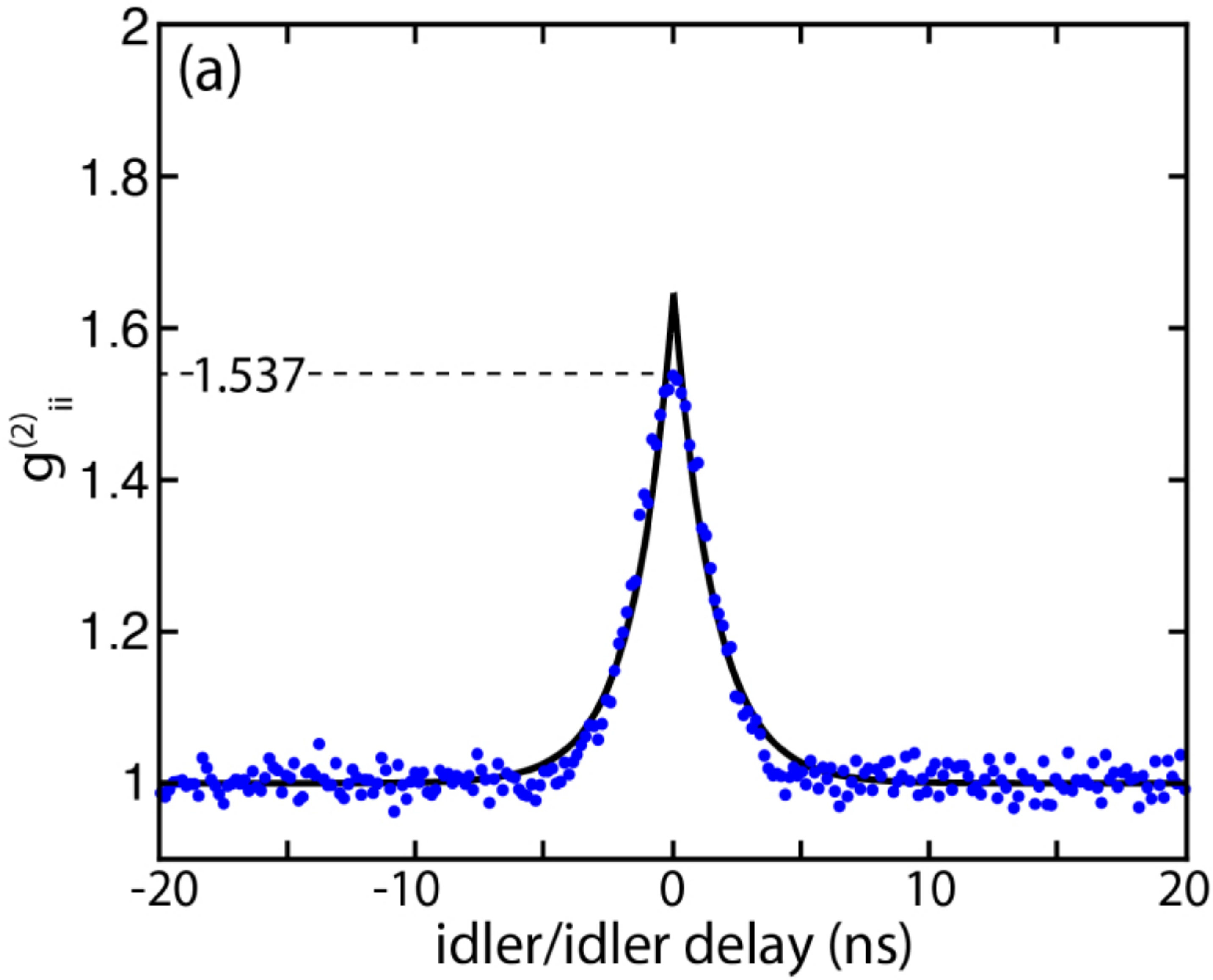
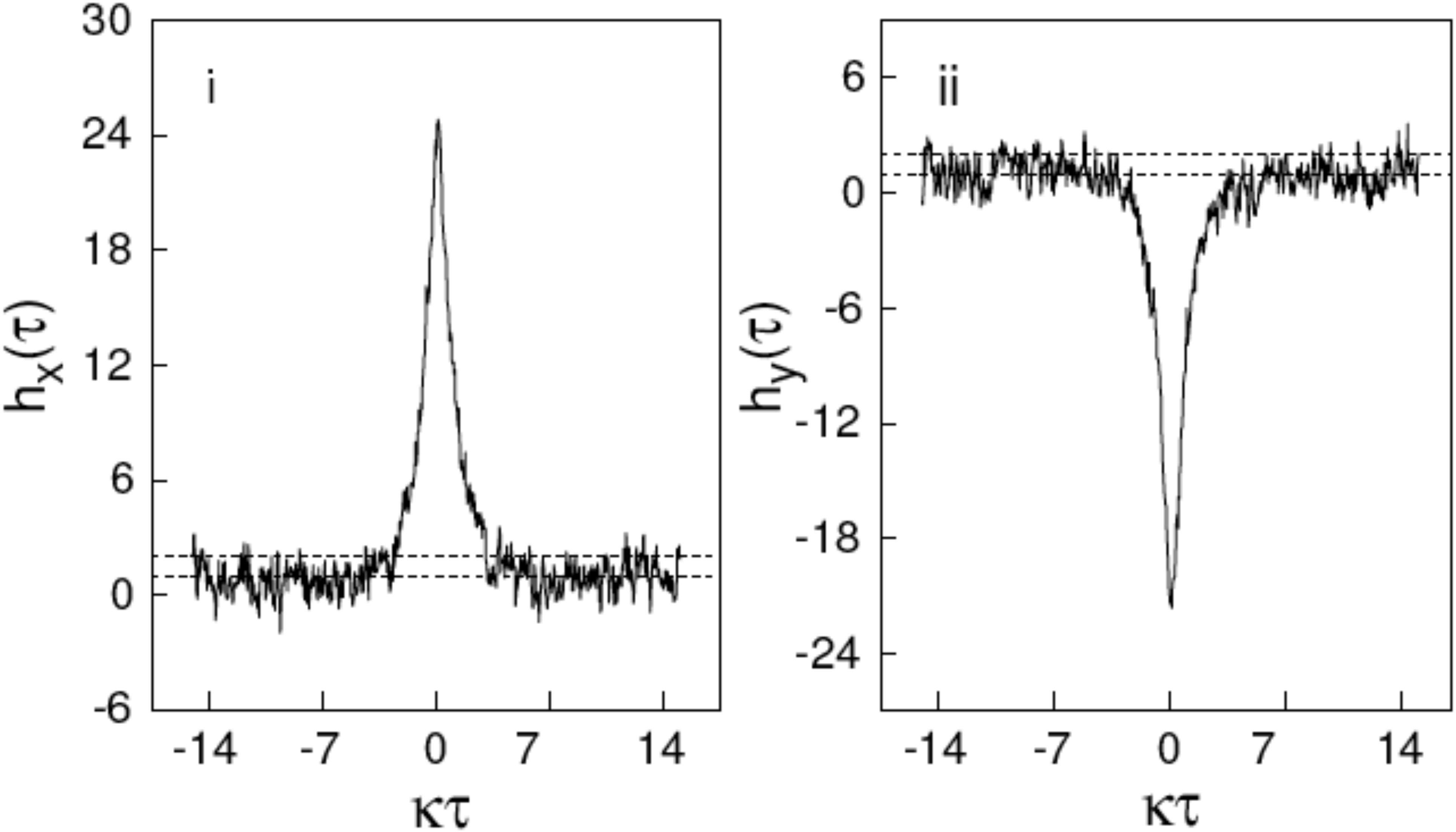


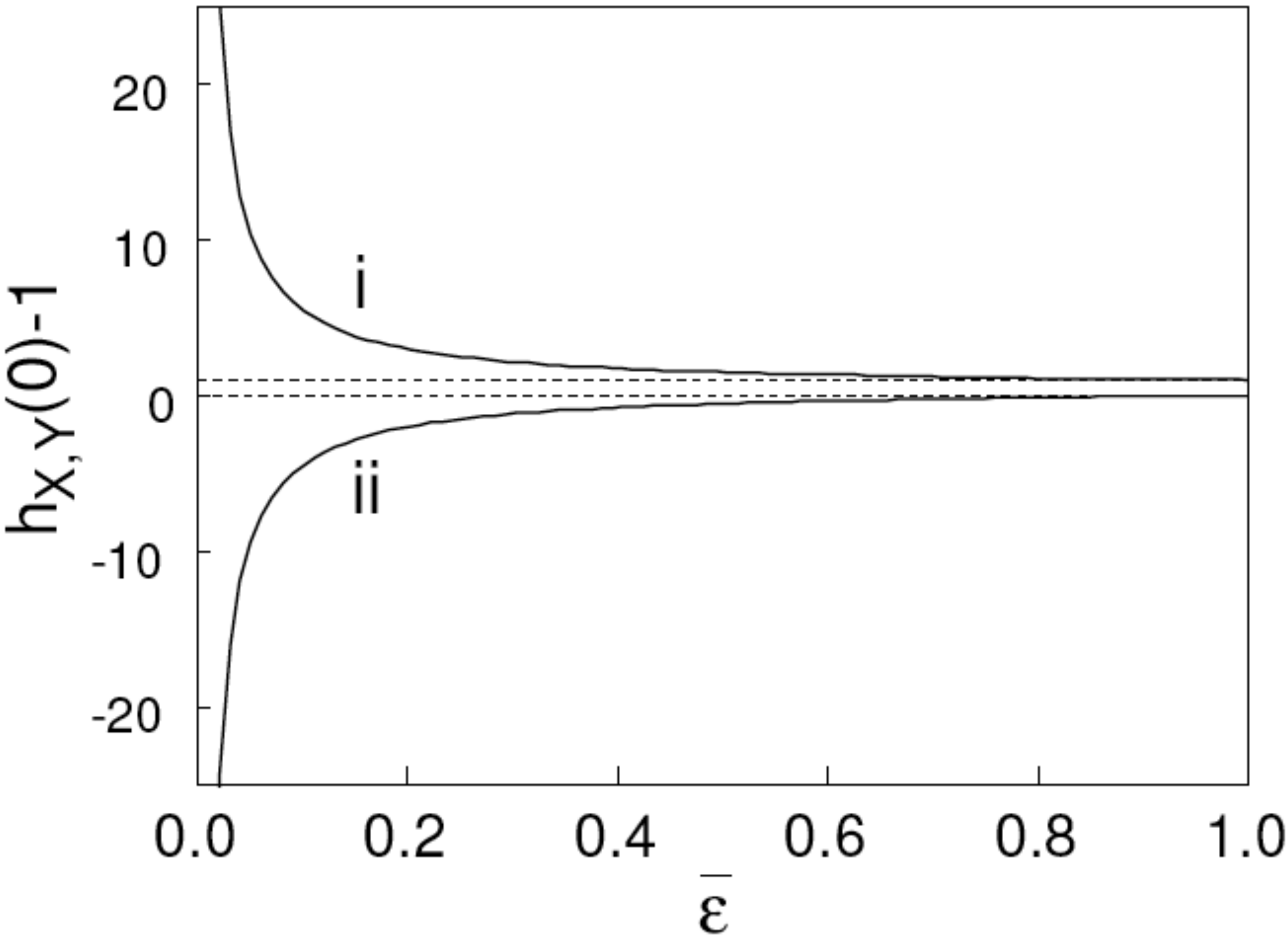
Fig. 4

Citation
Christian Reimer, Lucia Caspani, Matteo Clerici, Marcello Ferrera, Michael Kues, Marco Peccianti, Alessia Pasquazi, Luca Razzari, Brent E. Little, Sai T. Chu, David J. Moss, Roberto Morandotti, "Integrated frequency comb source of heralded single photons," Opt. Express **22,** 6535-6546 (2014);
https://www.osapublishing.org/oe/abstract.cfm?uri=oe-22-6-6535

Calculation of $h_\theta(\tau)$ in an OPO with the classical bounds



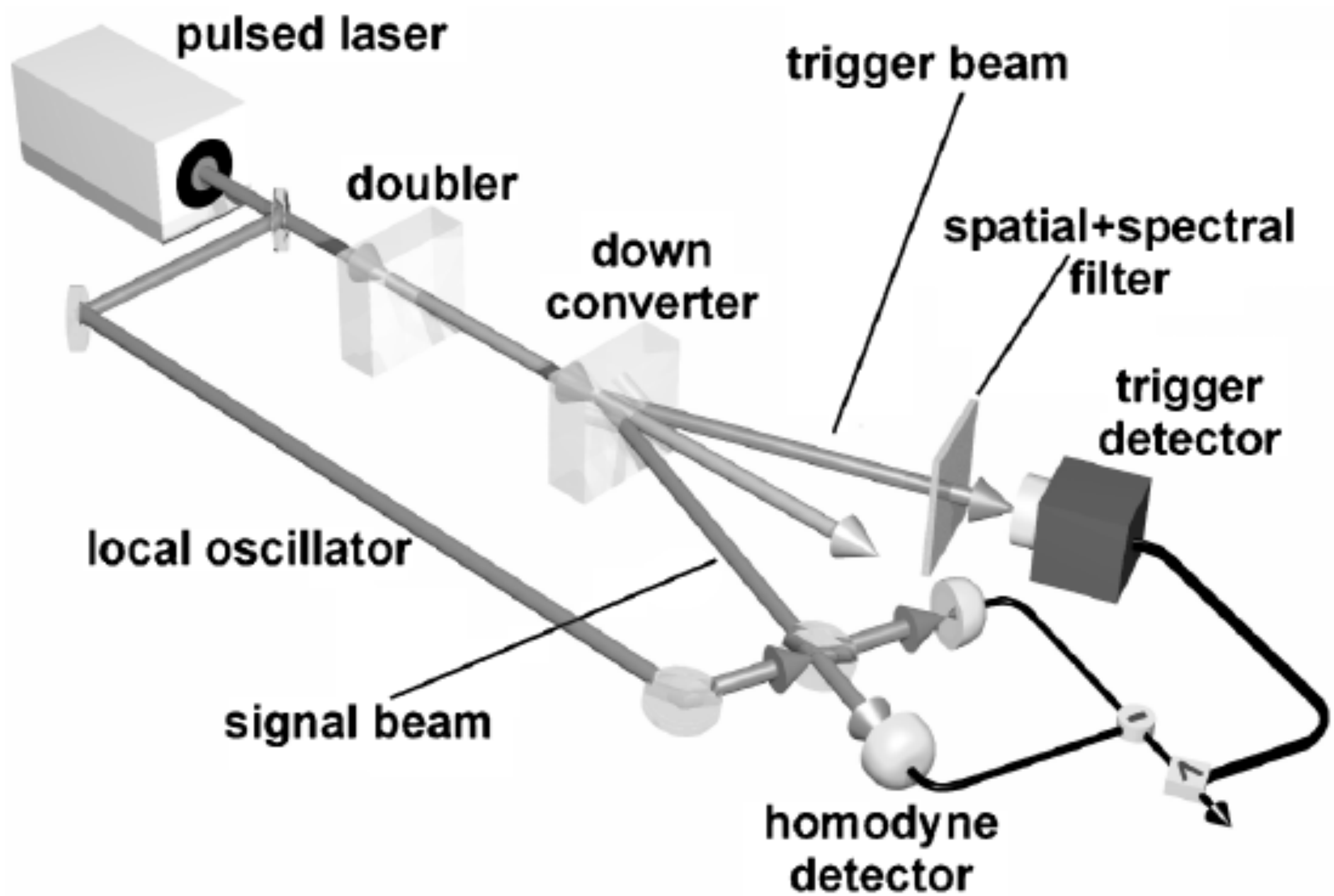
Maximum of $h_\theta(\tau)$ in an OPO below threshold



Quantum State Reconstruction of the Single-Photon Fock State

A. I. Lvovsky,* H. Hansen, T. Aichele, O. Benson, J. Mlynek,† and S. Schiller‡

Phys. Rev. Lett. 87, 050402 (2001)



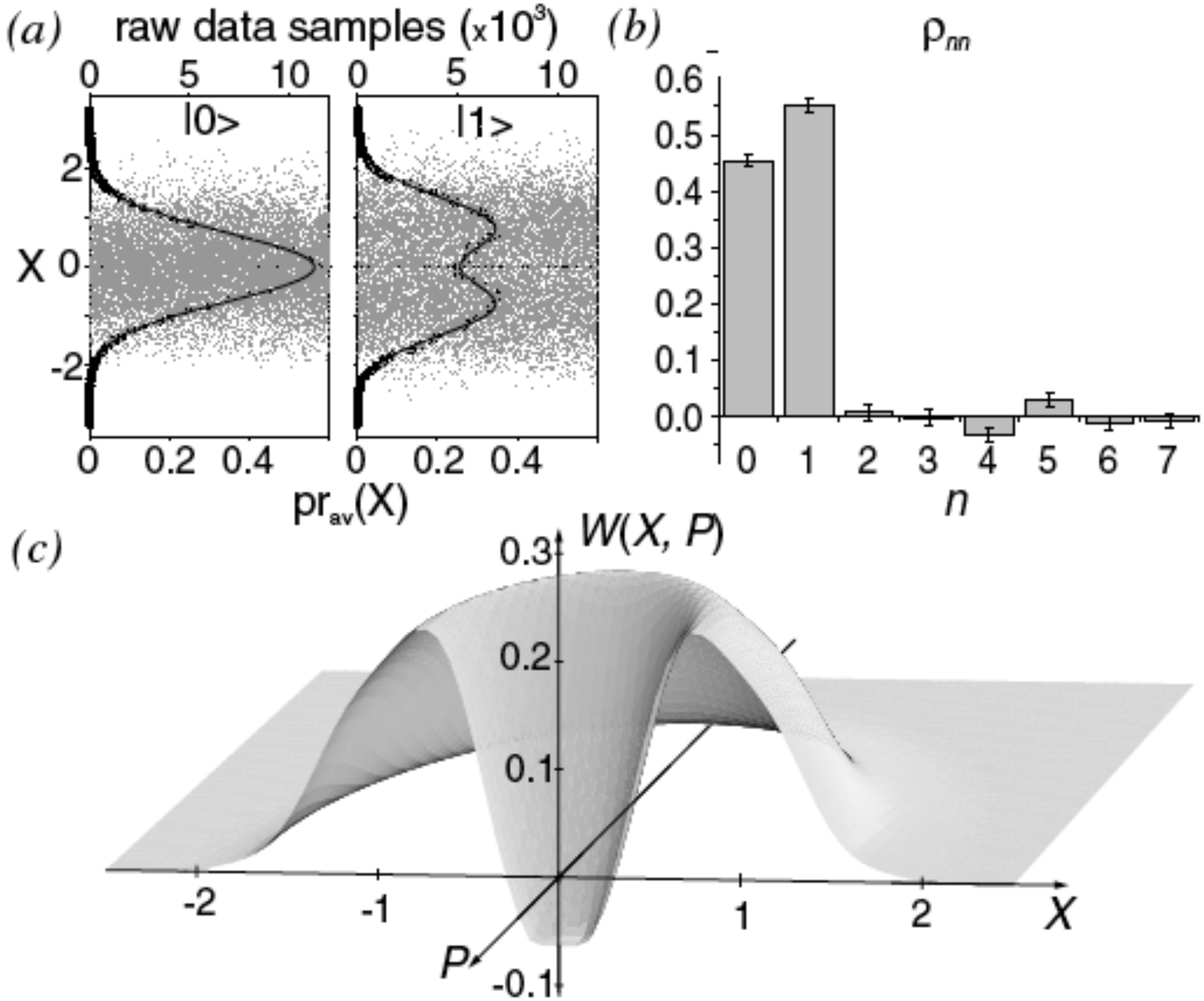


FIG. 4. Experimental results: (a) raw quantum noise data for the vacuum (left) and Fock (right) states along with their histograms corresponding to the phase-randomized marginal distributions; (b) diagonal elements of the density matrix of the state measured; (c) reconstructed WF which is negative near the origin point. The measurement efficiency is 55%.

Conclusions:

- The wave-particle correlation $h_\theta(\tau)$ measures the conditional dynamics of the electromagnetic field. The Spectrum of Squeezing $S(\Omega)$ and $h_\theta(\tau)$ are Fourier Transforms of each other.
- Many applications in many other problems of quantum optics and of optics in general: microscopy, degaussification, weak measurements, quantum feedback.
- Possibility of a tomographic reconstruction of the dynamical evolution of the electromagnetic field state.

Thanks