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bottom

Laser applications to the study of atomic quantum structure.

2017 OSA Siegman International School on Lasers, Lecture 3

CIO, León, México, August 2017

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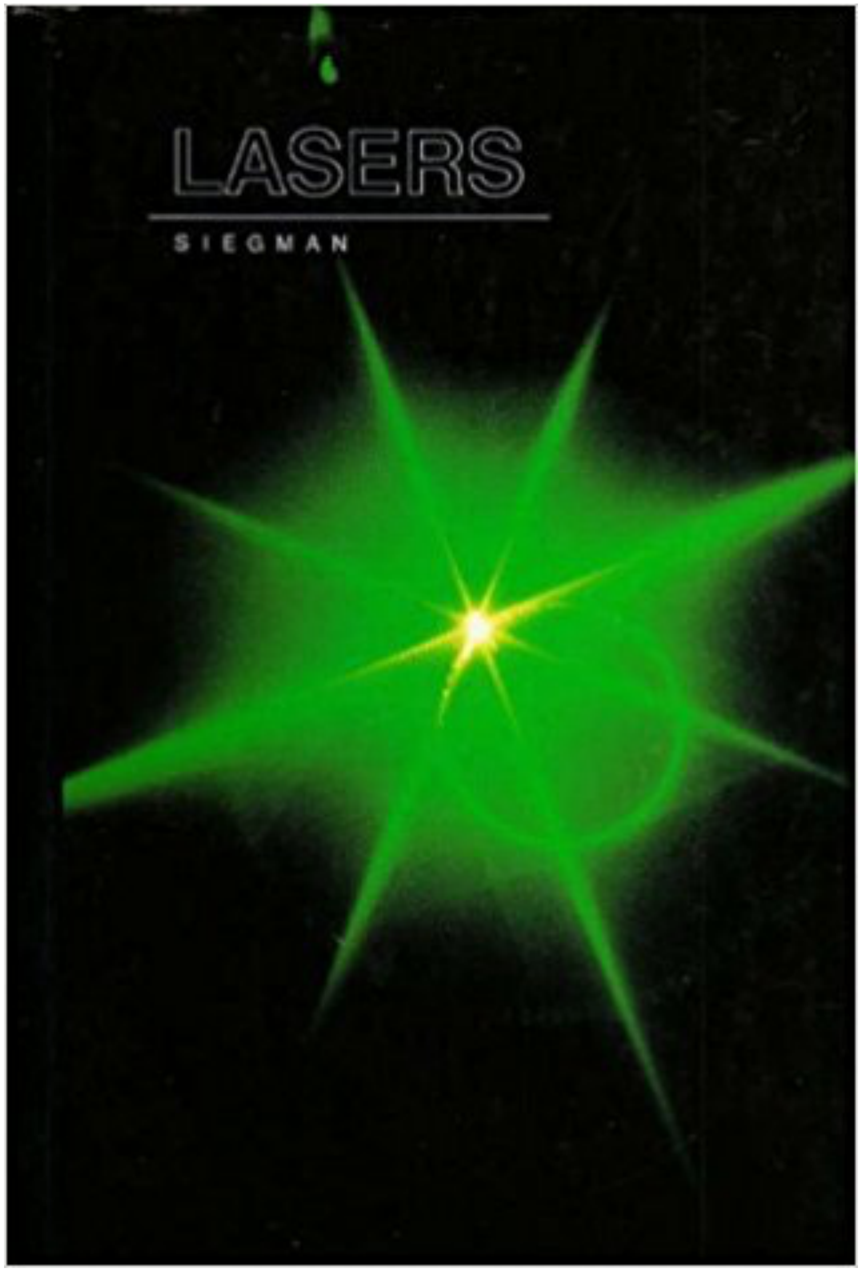
NIST



Anthony E Siegman
(1931-2011)

Plan of the course:

1st lecture: Introduction to the interaction of light with atoms, (nanofibers).

2nd lecture: Atom-light interaction of a two level atom (nanofibers at low intensity).

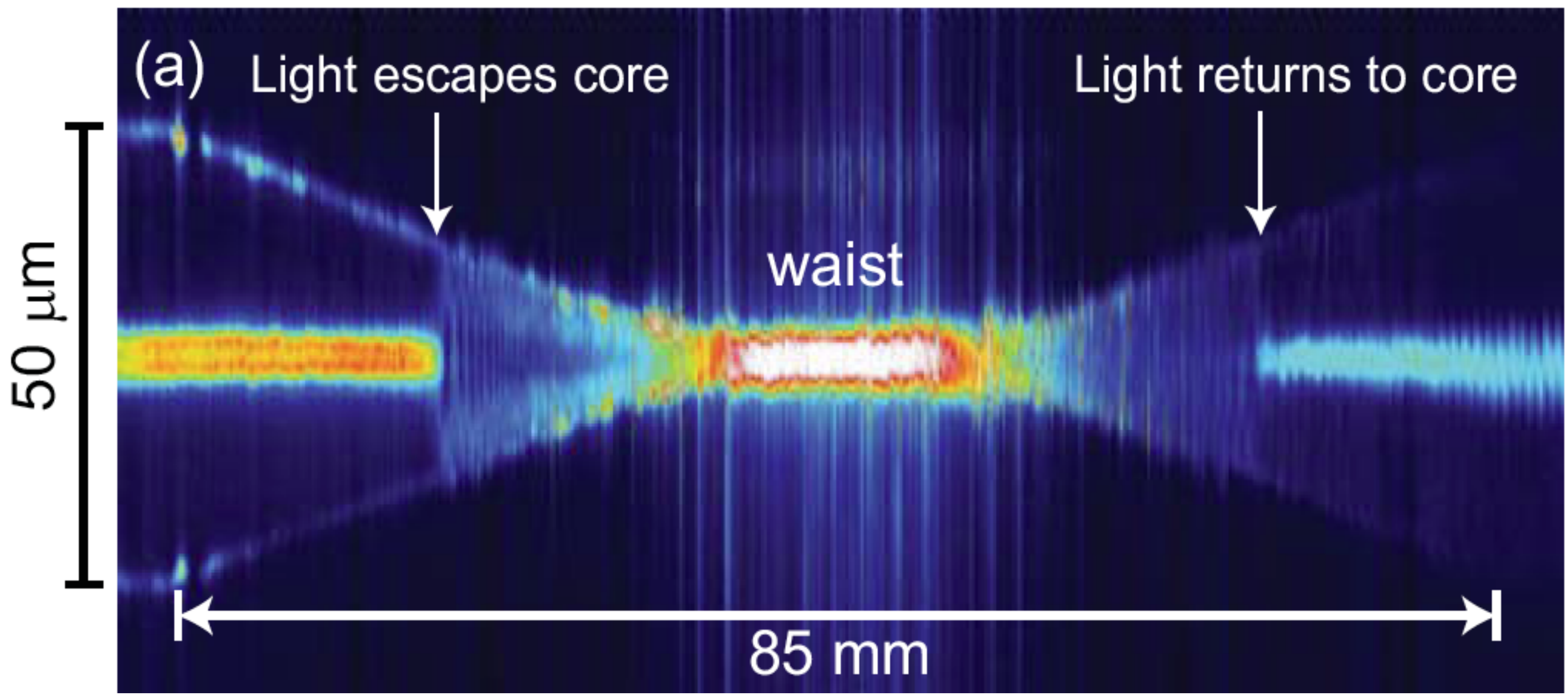
3rd lecture: Atom-light interaction of a two level atom (QO, cavity QED).

4th lecture: Different types of laser traps for atoms, (nanofibers, cavity QED, and spectroscopy).

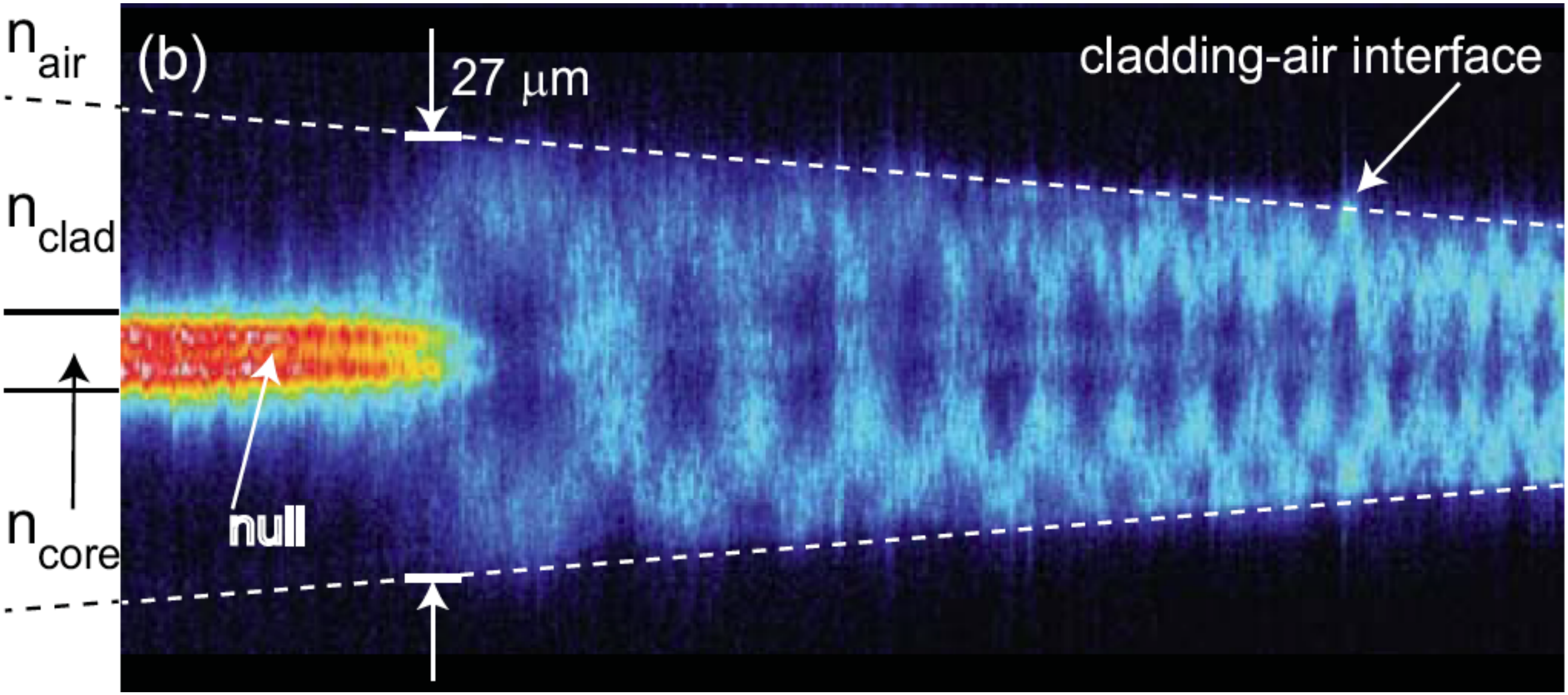
5th lecture: Weak interaction studies with Fr, a proposal.

The HE_{11} mode of the nanofiber core escapes into the cladding and then gets back into the core.

Raleigh scattering

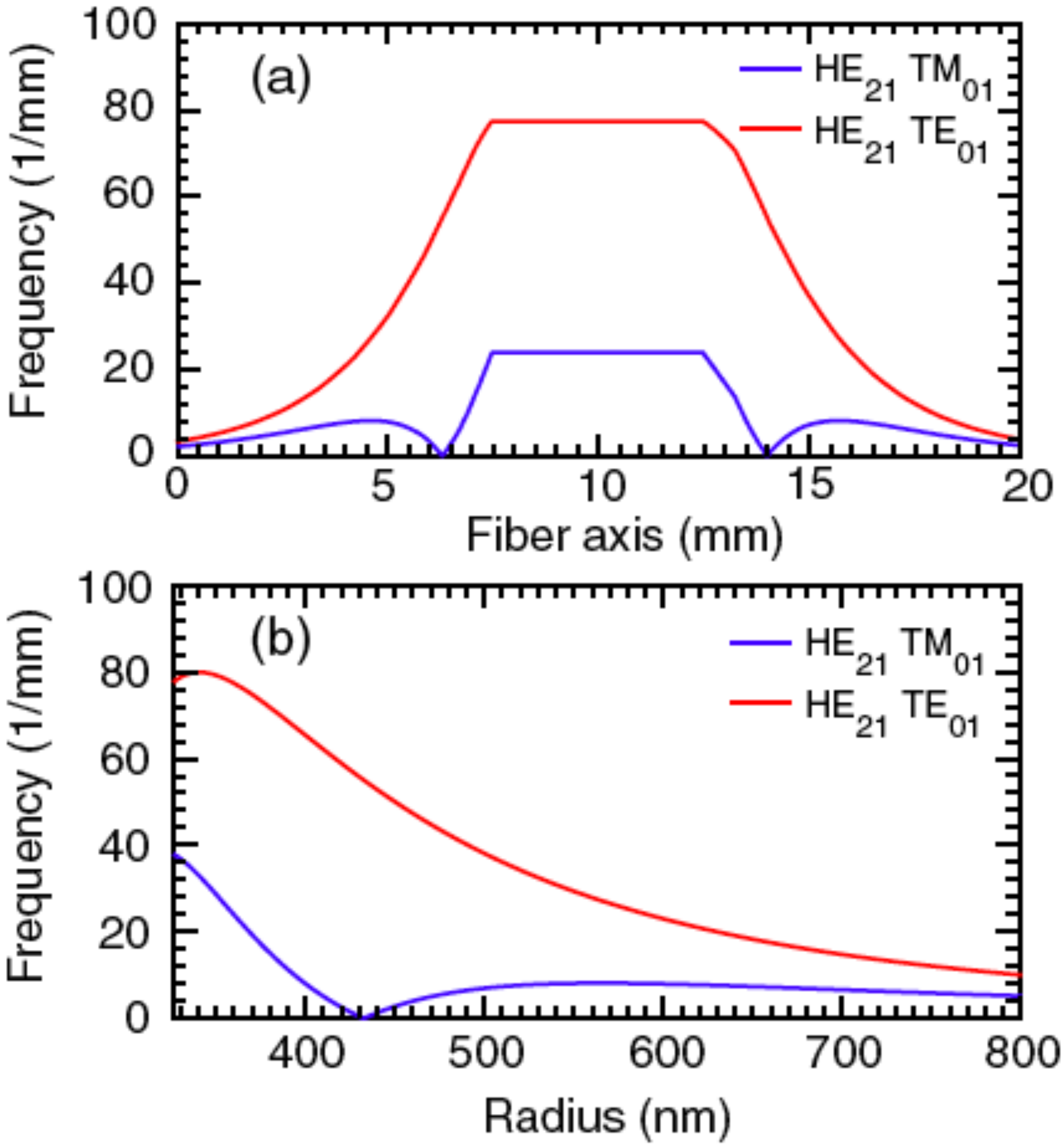


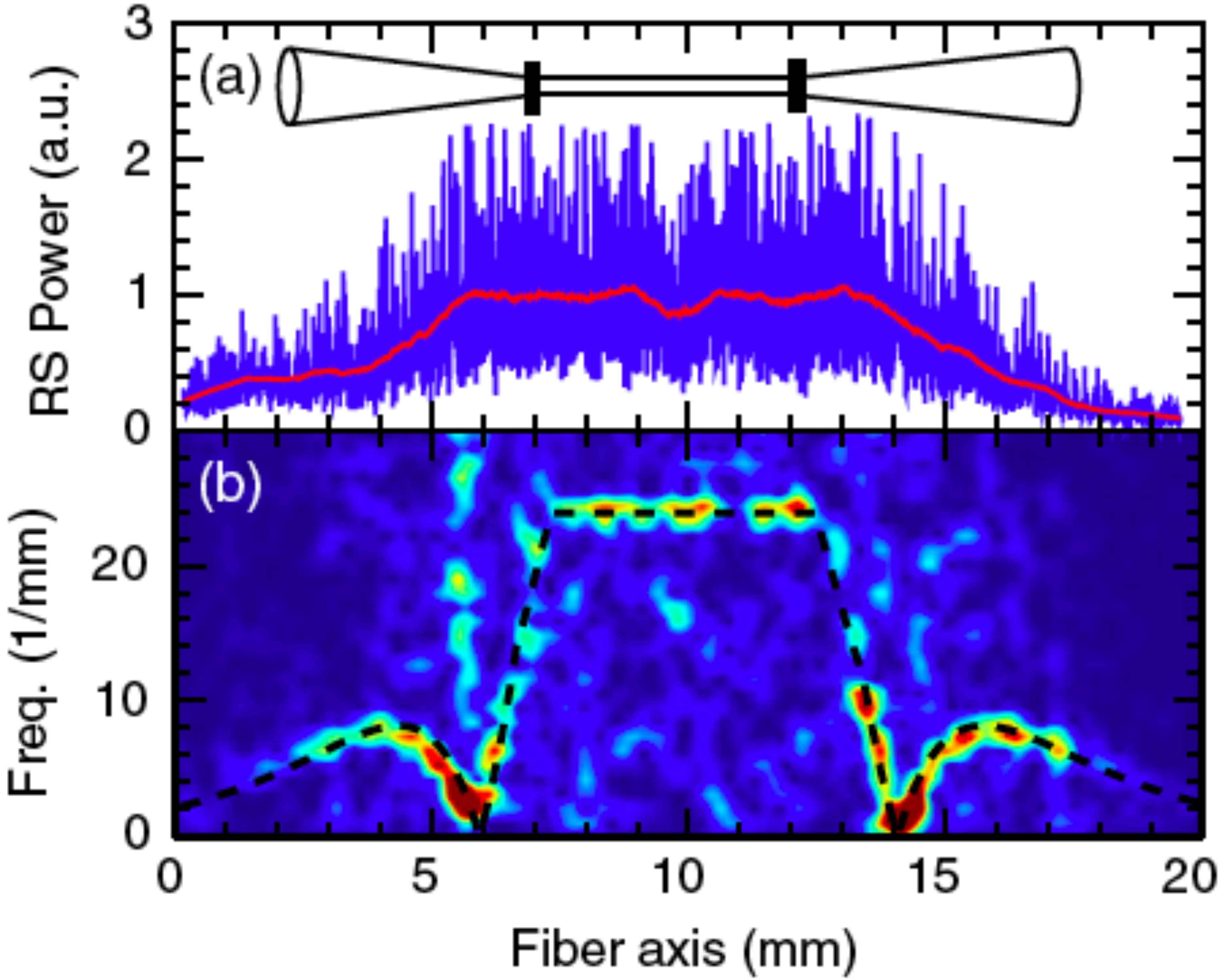
Raleigh scattering



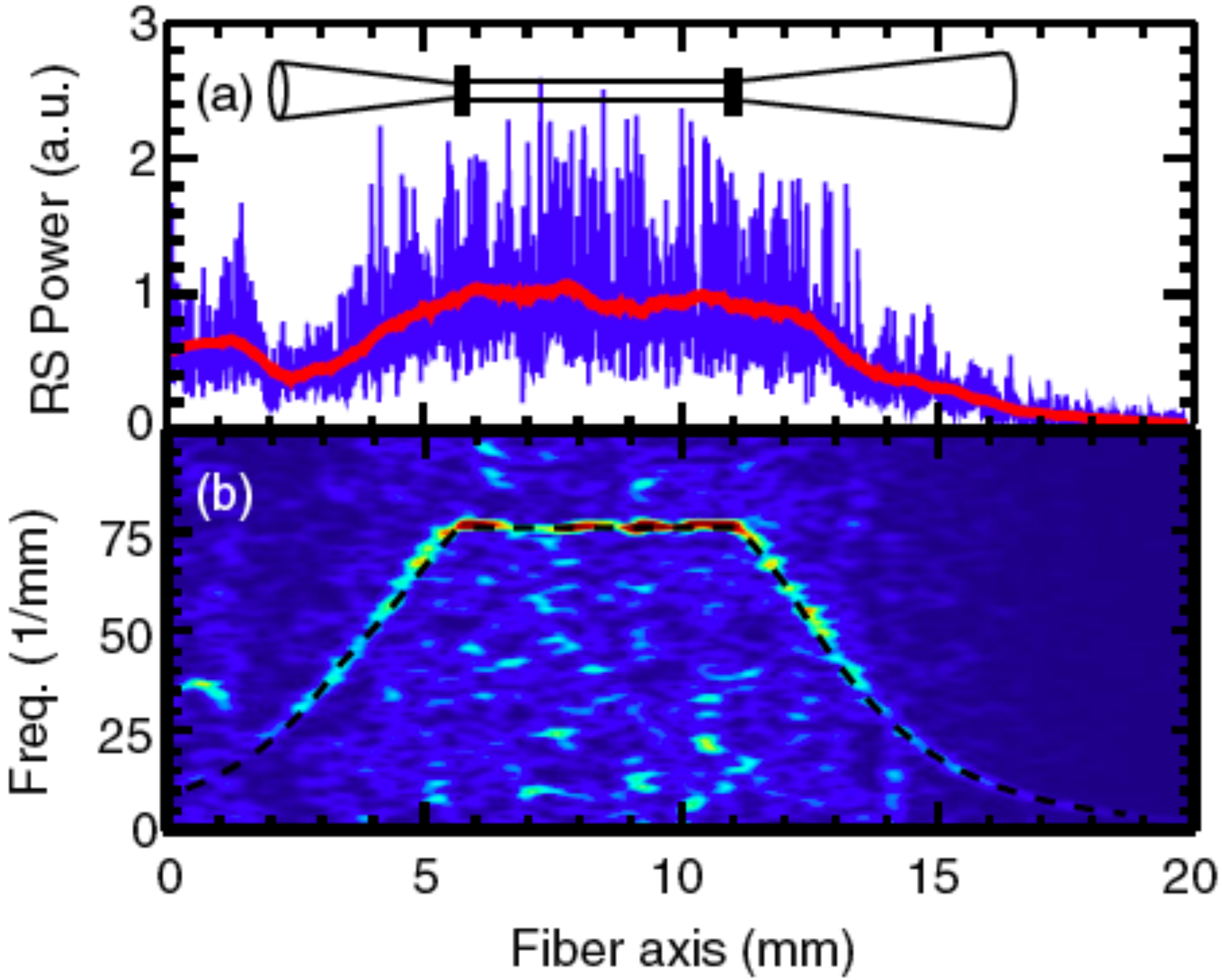
The spatial frequency increases

How to measure the radius with the beating frequency





(a)
(b)
RS Power (a.u.)
Freq. (1/mm)
Fiber axis (mm)
0
1
2
3
0
10
20
0
5
10
15
20



(a)
RS Power (a.u.)
0
1
2
3
(b)
Freq. (1/mm)
0
25
50
75
0
5
10
15
20
Fiber axis (mm)

Bibliography 3rd lesson:

Pablo interactions through a nanofiber”
arXiv:1704.07486v2

3rd lecture: Atom-light interaction of a two level atom (Quantum Optics, cavity QED)

1. A note on quantum optics correlations.

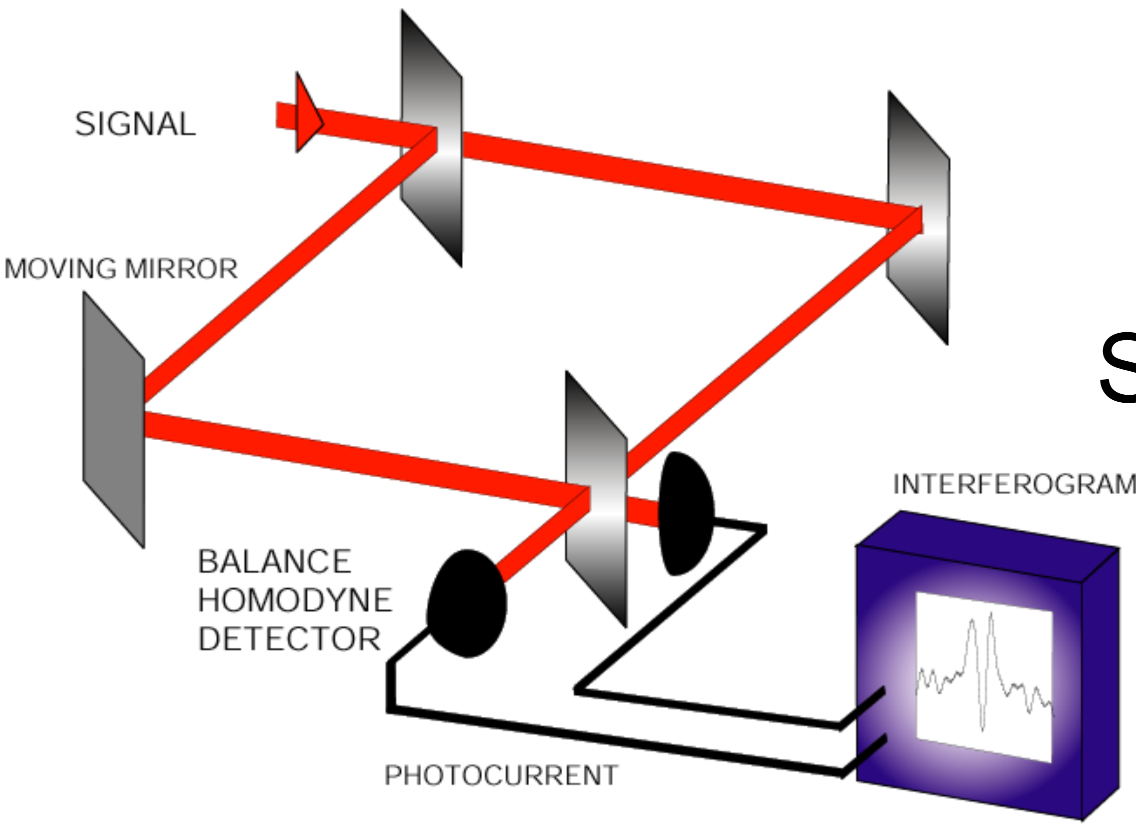
Correlation functions tell us something about the fluctuations.

Correlations have classical bounds.

They are conditional measurements.

Mach Zehnder Interferometer Wave-Wave Correlation

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

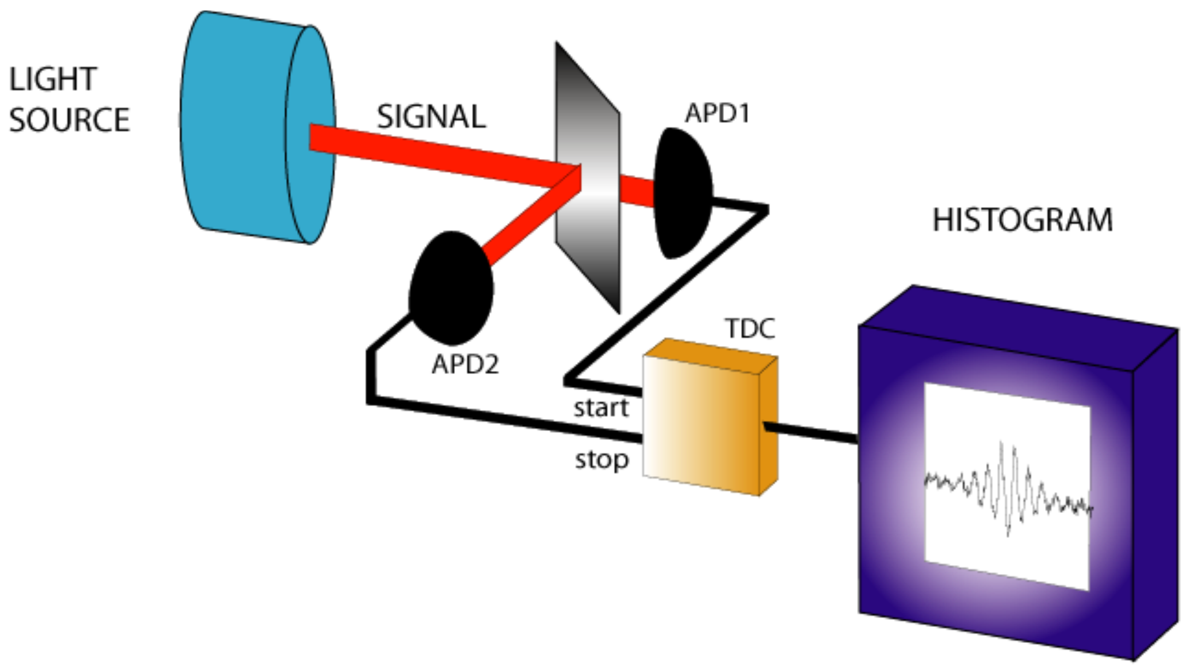


Spectrum of the signal:

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

Basis of Fourier Transform Spectroscopy

Hanbury-Brown and Twiss Intensity-Intensity Correlations



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

HBT question: Can we use the fluctuations in the intensity to measure size of a star? They were radio astronomers.

Intensity correlations

$$g^{(2)}(0) = \frac{\langle I(t)^2 \rangle}{\langle I(t) \rangle^2}$$

$$= \frac{\langle (I_0 + \delta(t))^2 \rangle}{\langle I_0 + \delta(t) \rangle^2}$$

$$= 1 + \frac{\langle \delta(t)^2 \rangle}{I_0^2}$$

Intensity correlations

$$g^{(2)}(0) = 1 + \frac{\langle \delta(t)^2 \rangle}{I_0^2}$$

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

Cauchy-Schwarz

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

$$|g^{(2)}(\tau) - 1| \leq |g^{(2)}(0) - 1|$$

The correlation is largest at equal time (τ=0), it can not increase.

Photon Correlations:

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

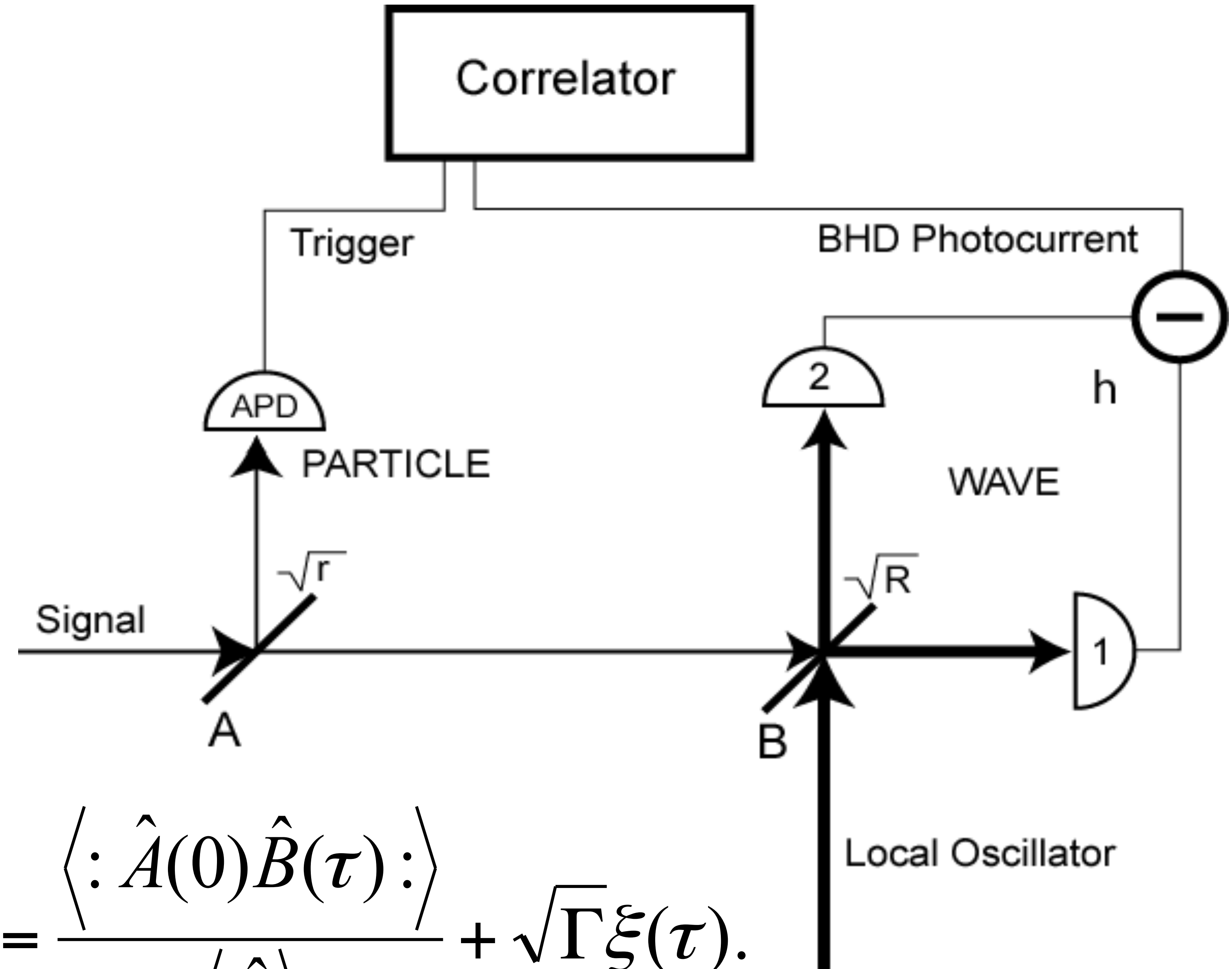
Conditional probability: If you detect a photon at time *t* it gives is the probability that you detect a second photon after a time τ . Measures the fluctuations, the variance, the uncertainty!

$g^{(2)}(0)=1$ Poissonian

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

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

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:

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

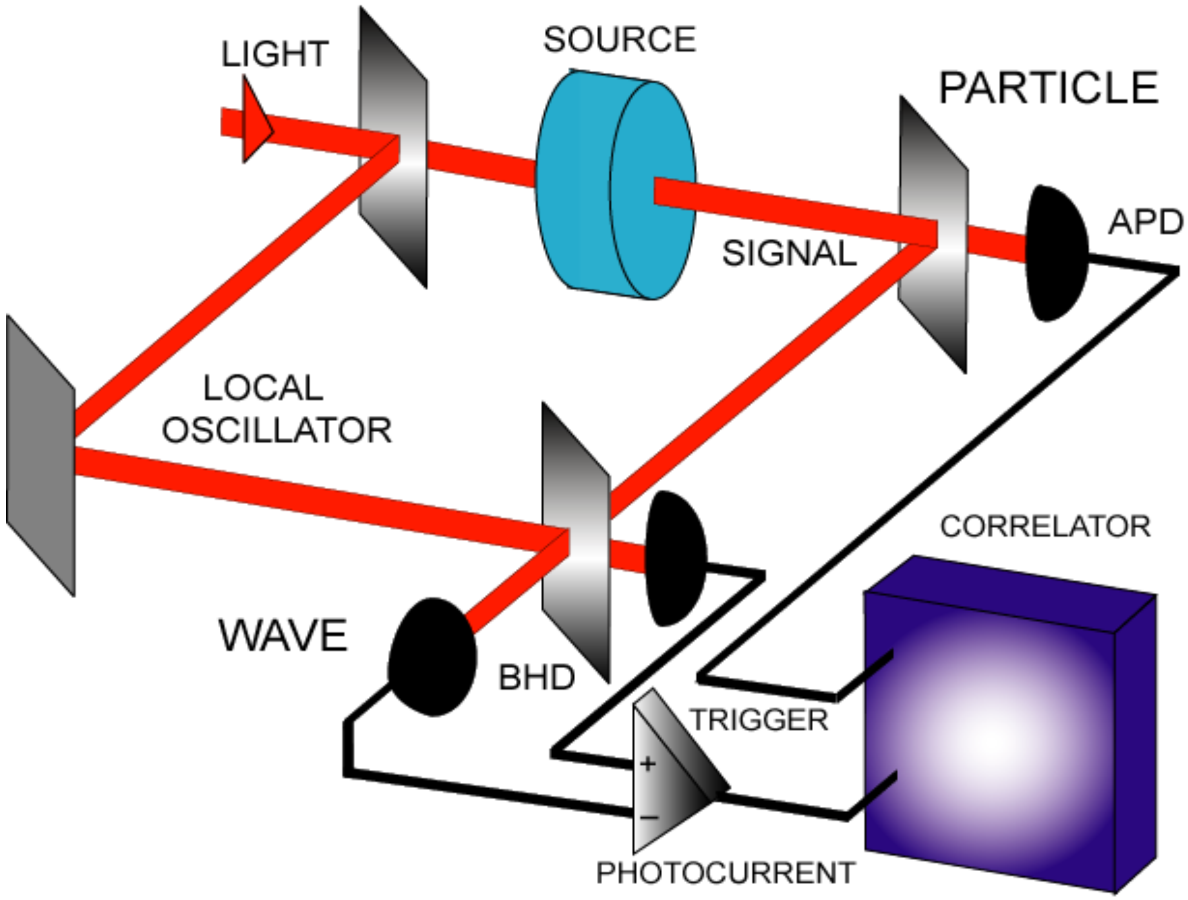
Normalized form:

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

From Cauchy Schwartz inequalities:

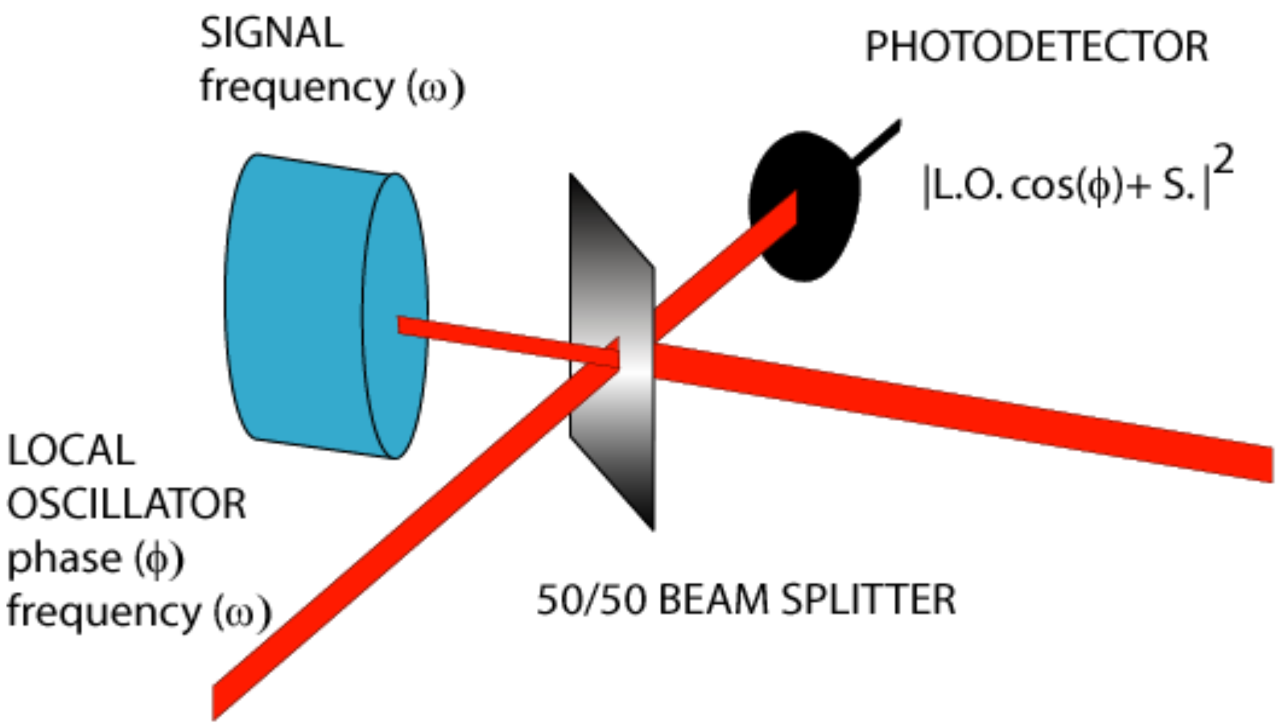
$$0 \le \bar{h}_0(0) - 1 \le 2 \qquad \left|\bar{h}_0(\tau) - 1\right| \le \left|\bar{h}_0(0) - 1\right|$$

Intensity-Field Correlator



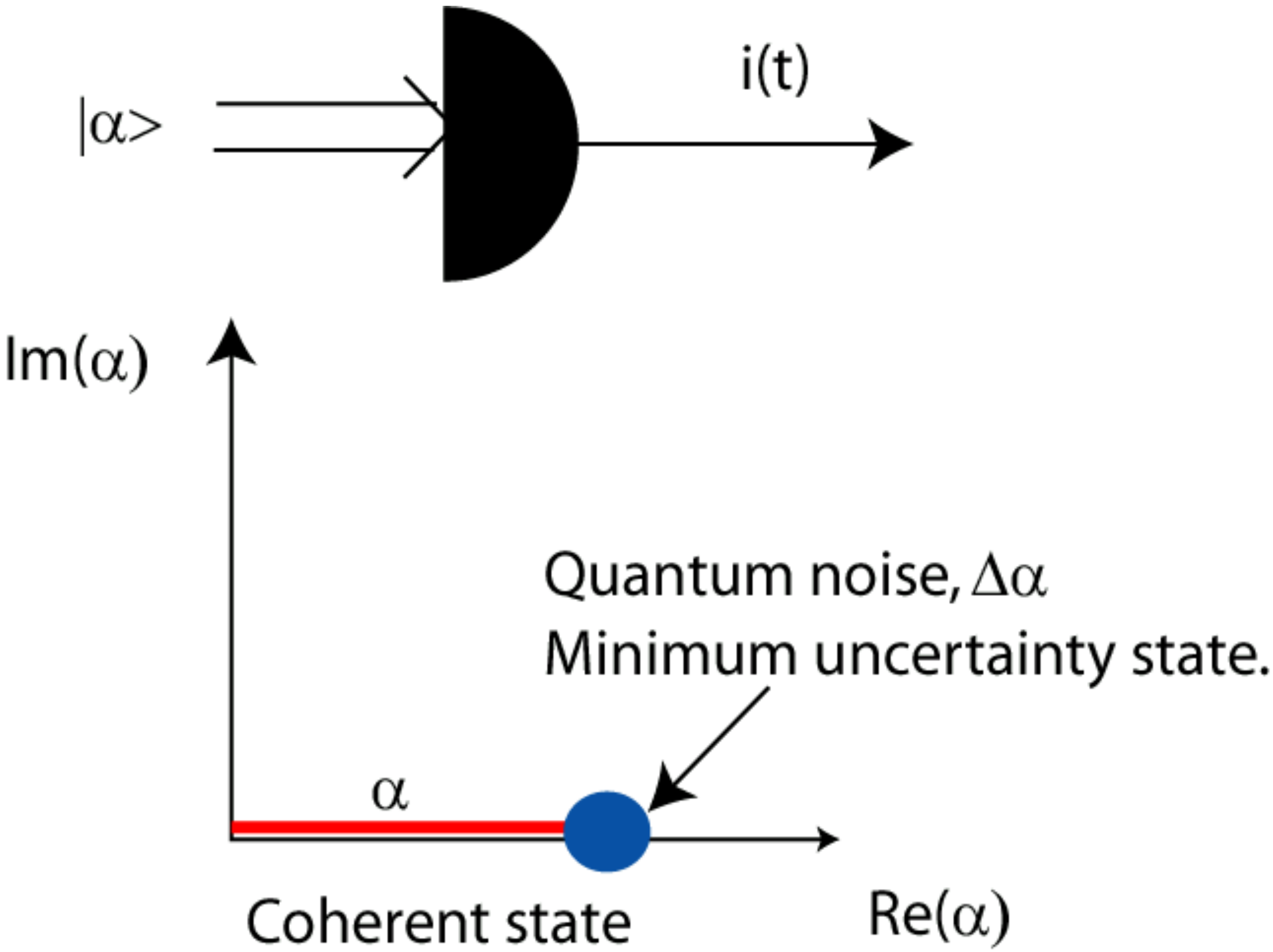
$$H(t) = \langle I(t)E(t)\rangle = \langle E(t)\rangle_{\text{conditioned}}$$

Homodyne Measurement



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

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

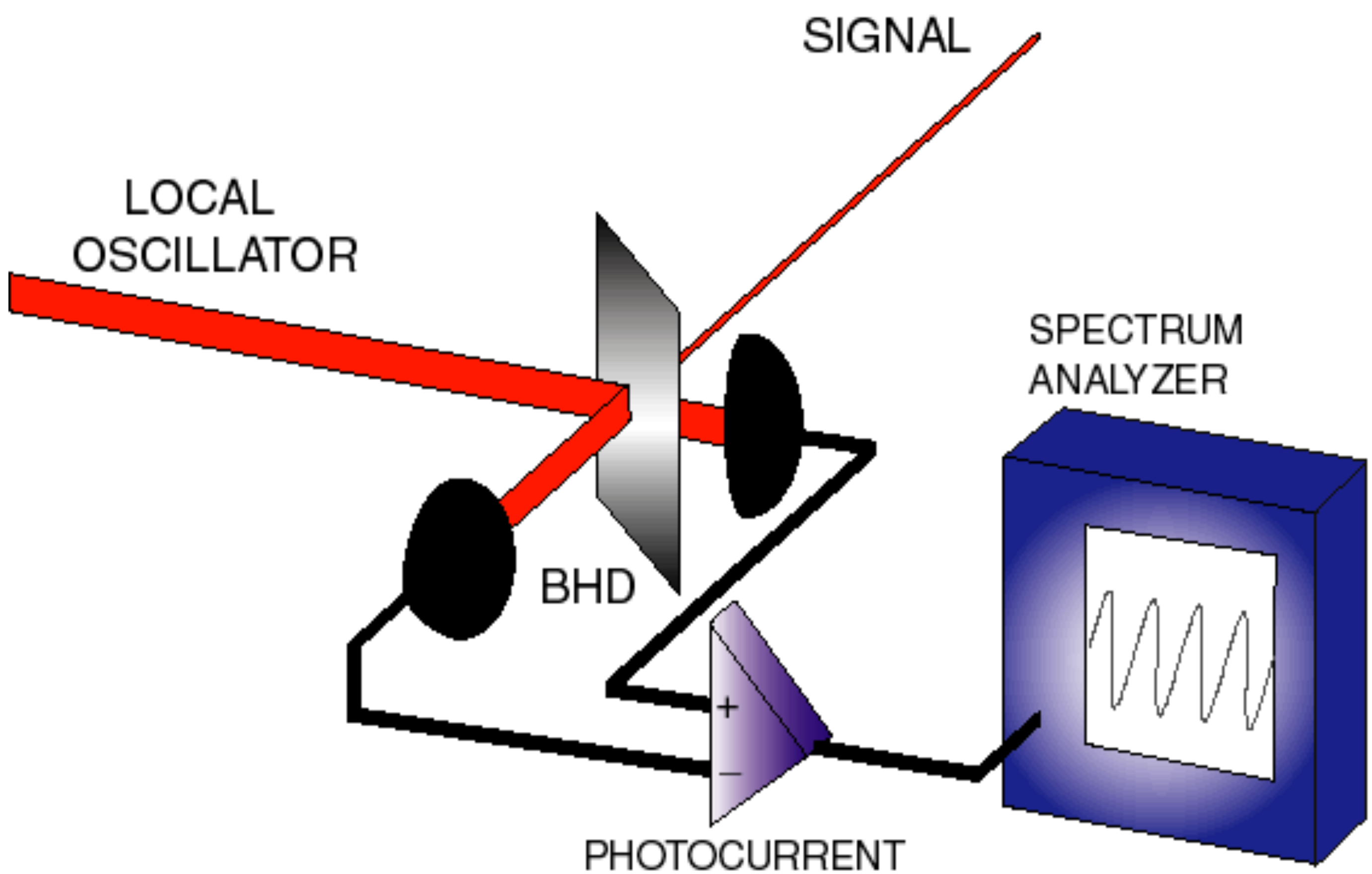


Perfect detector $i(t) = |\alpha + \Delta\alpha|^2$

$I(t) = |\alpha|^2 + 2\ \alpha\ \Delta\alpha + |\Delta\alpha|^2$; $<\alpha^* \alpha> = n$

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

Detection of the Squeezing spectrum with a balanced homodyne detector (BHD). Always measures the spectral density, look at the power in the noisy photocurrent. The result depends on the phase of the local oscillator, on the efficiency of the detectors. It is necessary to establish the shot noise level.



What do we expect to see?
For one shot…..

AC Output → 2 L.O.* (ΔL.O. + S(t))

shot noise signal

Averaging over many shots N_s ….

Output →2 L.O. $(\Sigma_i (\Delta L.O.) + N_s S(t))/N_s$

2 L.O. $(\zeta(t, \Gamma) (N_s)^{1/2} + N_s S(t))/N_s$

Output → $H(\tau) \sim 2$ L.O. $(S(t) + \zeta(t, \Gamma)/(N_s)^{1/2})$

With $<\zeta^*(t, \Gamma)\, \zeta(t, \Gamma)>$ delta correlated, shot noise.

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

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

F is the photon flux into the correlator.

2. Cavity QED

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. (Vacuum Rabi Frequency)

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

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

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

Hamiltonian

$$\hat{H} = \hat{H}_1 + \hat{H}_1 + \hat{H}_2 + \hat{H}_3 + \hat{H}_4 + \hat{H}_5 \ ,$$

$$\hat{H}_1 = \hbar\omega_c \hat{a}^\dagger \hat{a} + \frac{1}{2}\hbar\omega_a \sum_{j=1}^{N} \hat{\sigma}_j^z \ ,$$ Free atoms free field

J.C $$\hat{H}_2 = i\hbar \sum_{j=1}^{N} g_j \left(\hat{a}^\dagger \hat{\sigma}_j^- e^{-i\vec{k}\cdot\vec{r}_j} - \hat{a}\hat{\sigma}_j^+ e^{i\vec{k}\cdot\vec{r}_j} \right)$$ Interaction

$$\hat{H}_3 = \sum_{j=1}^{N} \left(\hat{\Gamma}_A \hat{\sigma}_j^+ + \hat{\Gamma}_A^\dagger \hat{\sigma}_j^- \right) \ ,$$ Atomic decay

$$\hat{H}_4 = \hat{\Gamma}_F \hat{a}^\dagger + \hat{\Gamma}_F^\dagger \hat{a} \ ,$$ Cavity decay

$$\hat{H}_5 = i\hbar \left(\hat{a}^\dagger \mathcal{E} e^{-i\omega_l t} - \hat{a}\mathcal{E}^* e^{i\omega_l t} \right) \ .$$ Drive

semiclassical decorrelation replacing $g_j\langle\hat{a}\hat{\sigma}_j^k\rangle$ by $g_j\langle\hat{a}\rangle\langle\hat{\sigma}_j^k\rangle$

Maxwell Bloch Equations are then:

Radiation field:

Driven H. O.

$$\frac{\partial}{\partial t}\langle\hat{a}\rangle = -\kappa(1+i\theta)\langle\hat{a}\rangle + \sum_{j=1}^{N} g_j\langle\hat{\sigma}_j^-\rangle + \mathcal{E},$$

Atomic polarization:

$$\frac{\partial}{\partial t}\langle\hat{\sigma}_j^-\rangle = -\gamma_\perp(1+i\Delta)\langle\hat{\sigma}_j^-\rangle + g_j\langle\hat{a}\rangle\langle\hat{\sigma}_j^z\rangle,$$

Atomic inversion:

$$\frac{\partial}{\partial t}\langle\hat{\sigma}_j^z\rangle = -\gamma_\parallel\left(\langle\hat{\sigma}_j^z\rangle + 1\right) - 2g_j\left(\langle\hat{a}\rangle\langle\hat{\sigma}_j^+\rangle + \langle\hat{a}^\dagger\rangle\langle\hat{\sigma}_j^-\rangle\right).$$

The cavity and atomic detunings θ and Δ are defined as

$$\theta = \frac{\omega_c - \omega_l}{\kappa} \quad \text{and} \quad \Delta = \frac{\omega_a - \omega_l}{\gamma_\perp}.$$

The stationary solution of the Maxwell-Bloch equations is

$$\mathcal{E} = \kappa\langle\hat{a}\rangle\left[1 + i\theta + (1 - i\Delta)\frac{g_0^2}{\kappa\gamma_\perp}\sum_{j=1}^{N}\frac{|\psi(\vec{r_j})|^2}{1 + \Delta^2 + 4g_0^2\langle\hat{a}\rangle\langle\hat{a}^\dagger\rangle|\psi(\vec{r_j})|^2/\gamma_\parallel\gamma_\perp}\right]$$

$$C = C_1\bar{N} = \frac{g_0^2\bar{N}}{2\gamma_\perp\kappa} \qquad y = x[(1 + 2C\chi) + i(\theta - 2C\Delta\chi)]\ ,$$

where χ has the form

$$\chi = \frac{1}{V}\int\frac{|\psi(\vec{r})|^2}{1 + \Delta^2 + |x\psi(\vec{r})|^2 V/\int|\psi(\vec{r})|^4\, d^3r}\, d^3r\ .$$

In the case of a plane wave ring cavity ($\psi(\vec{r}) = 1$) this immediately simplifies to $\chi = 1/(1 + \Delta^2 + |x|^2)$ and the state equation becomes

$$y = x\left(1 + \frac{2C}{1 + \Delta^2 + |x|^2}\right) + ix\left(\theta - \frac{2C\Delta}{1 + \Delta^2 + |x|^2}\right)$$

Some Implementations:

Rydbergs on Superconducting cavities (Microwaves)

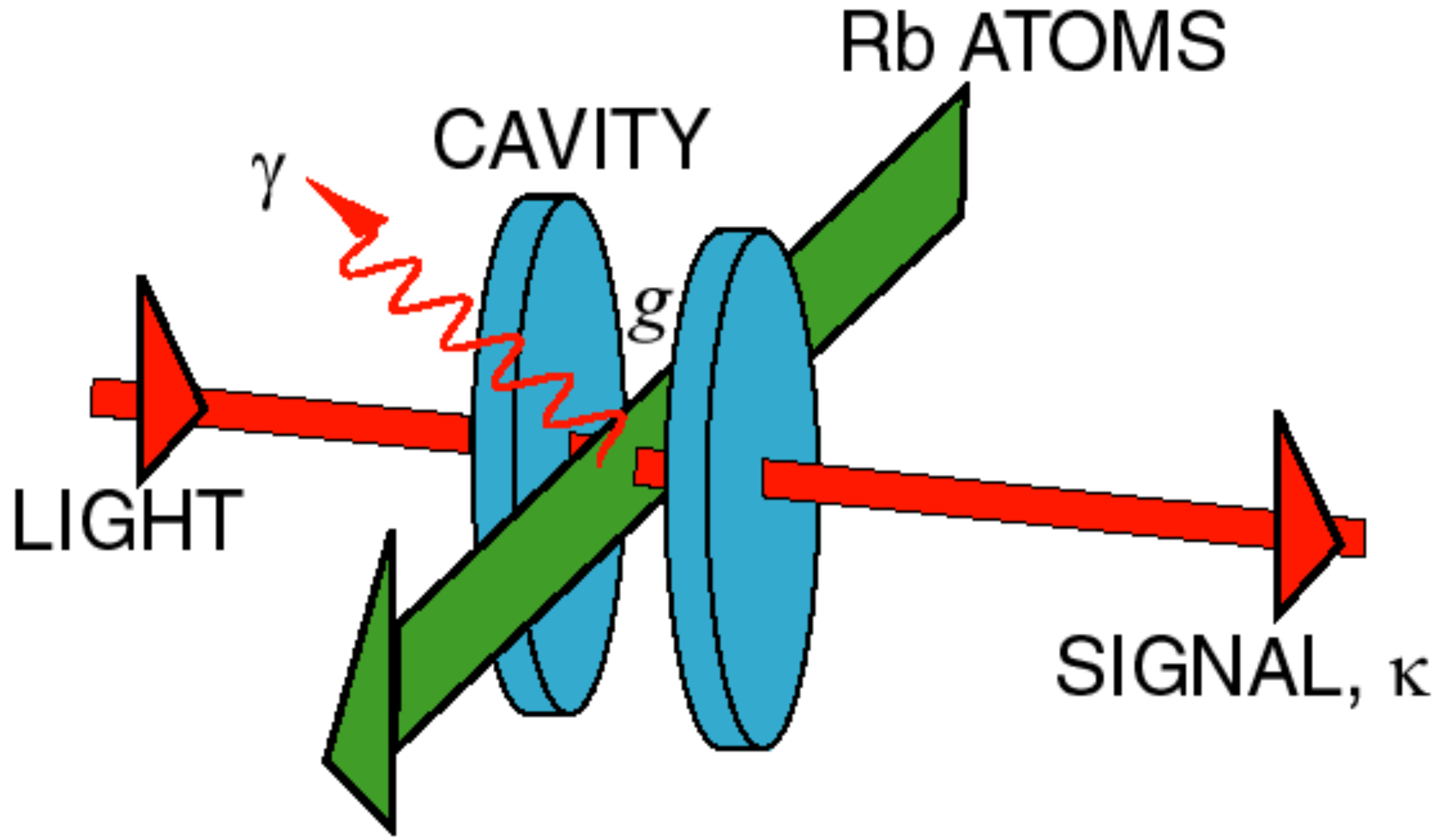
Alkali atoms on Optical Cavities (Optical)

Quantum dots on microcavities (Microwaves)

Trapped ions and vibrational mode (phonons)

Circuit QED Superconducting qbits on microwave resonators (Microwaves)

Waveguide QED (Microwaves and Optical)



$$\frac{g}{2\pi} = 8.8\ \mathrm{MHz}$$

$$\frac{\kappa}{2\pi} = 6.0\ \mathrm{MHz}$$

$$\frac{\gamma}{2\pi} = 6.0\ \mathrm{MHz}$$

$$C_1 = \frac{g^2}{\kappa\gamma} = 2.0$$

$$n_0 = \frac{\gamma^2}{3g^2} = 0.04$$

What do we expect on resonance for the normalized fields (x,y) and the normalized intensities (X,Y)? Normalized by I_0

$$y=x[1+2C/(1+x^2)] \quad ; \quad Y=X[1+2C/(1+X)]^2$$

For low intensity, the input y and the output x are linearly related,

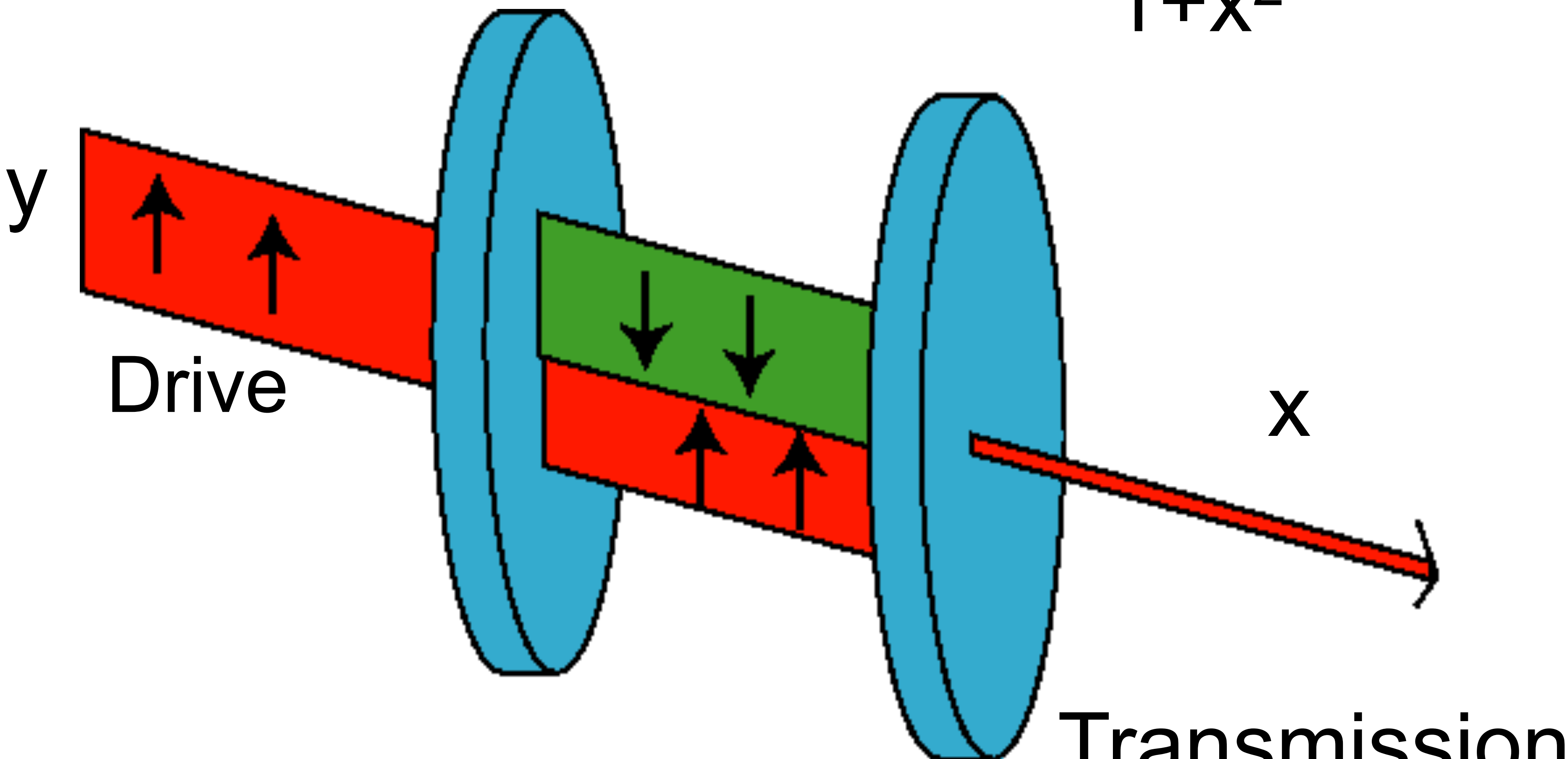
$$y = x\,(1+2C) \quad ; \quad Y=X(1+2C)^2$$

For very high intensity X>>1,

$$y = x \quad ; \quad Y=X+4C$$

Steady State

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

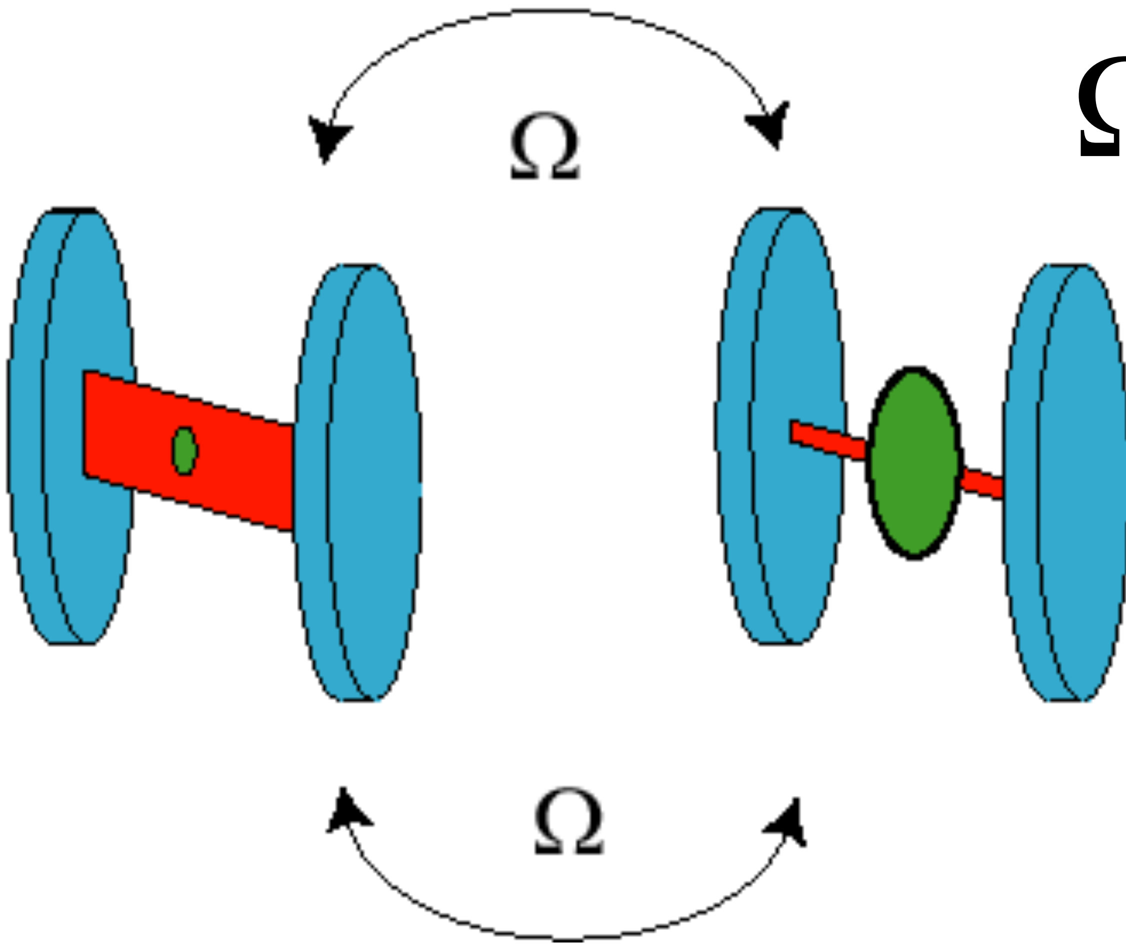


Dynamics J. C. Rabi Oscillations:

Exchange of Excitation:

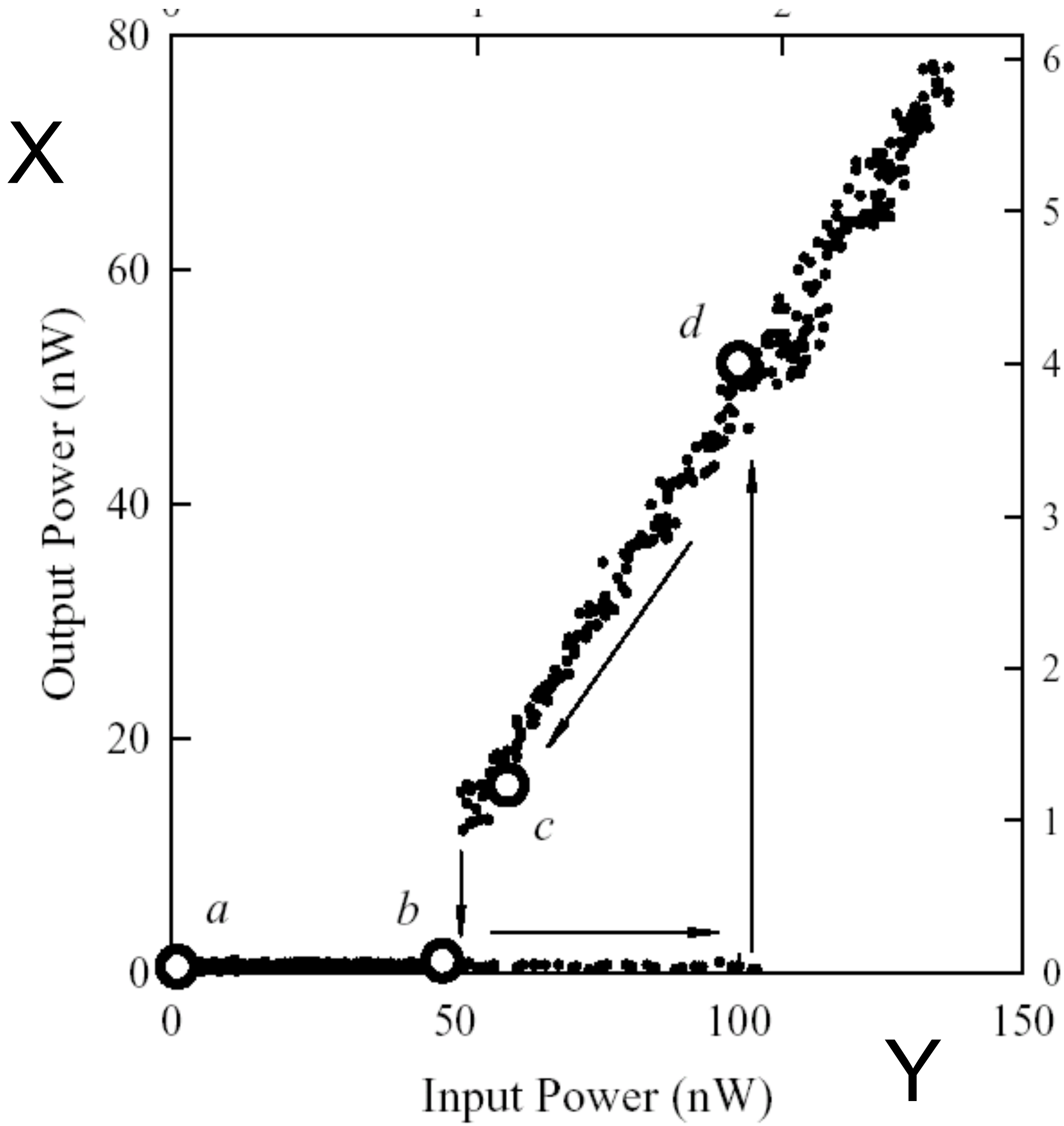
Cavity Mode and Atoms

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



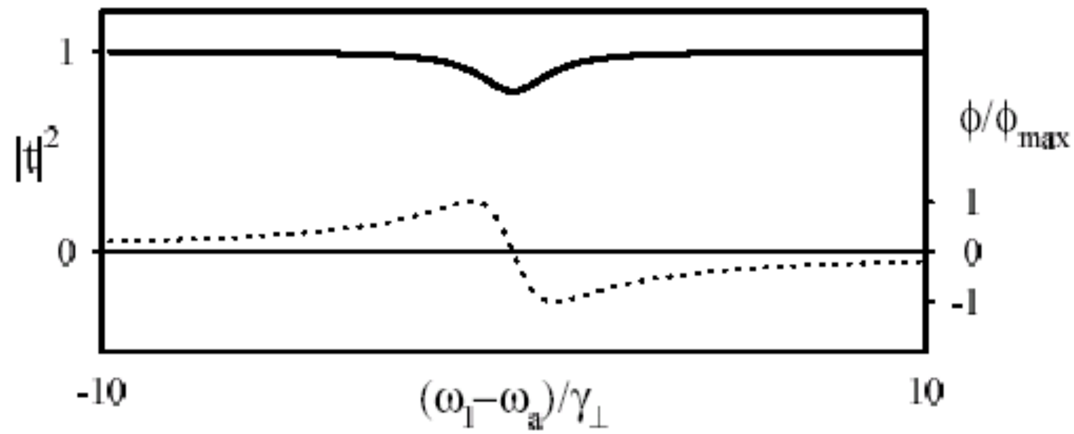
At intermediate intensity, there can be saturation, there is the possibility of a phase transition. It happens in this simple model for the case of $C>4$. C (Cooperativity) is the negative of the laser pump parameter. It is the ratio of the atomic losses to the cavity losses or also can be read as the ratio between the good coupling (g) and the bad couplings (κ,γ).

Input-Output hysteresis curve

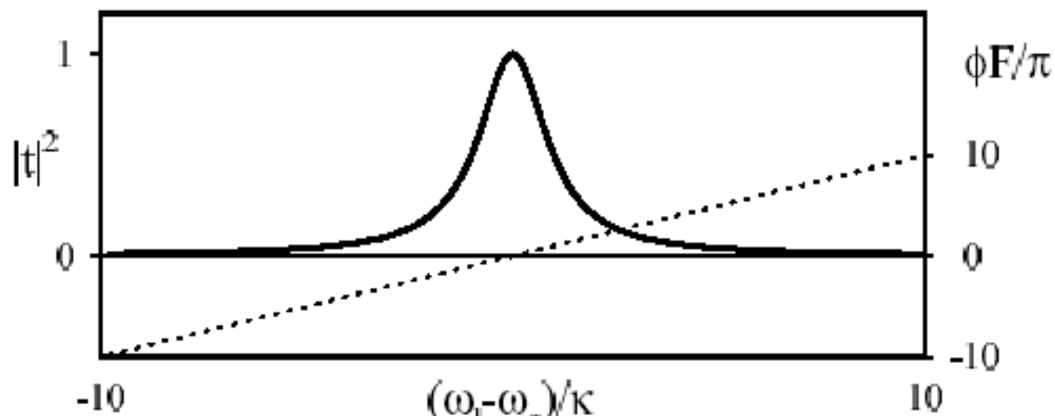


Vacuum Rabi splitting (optics explanation)

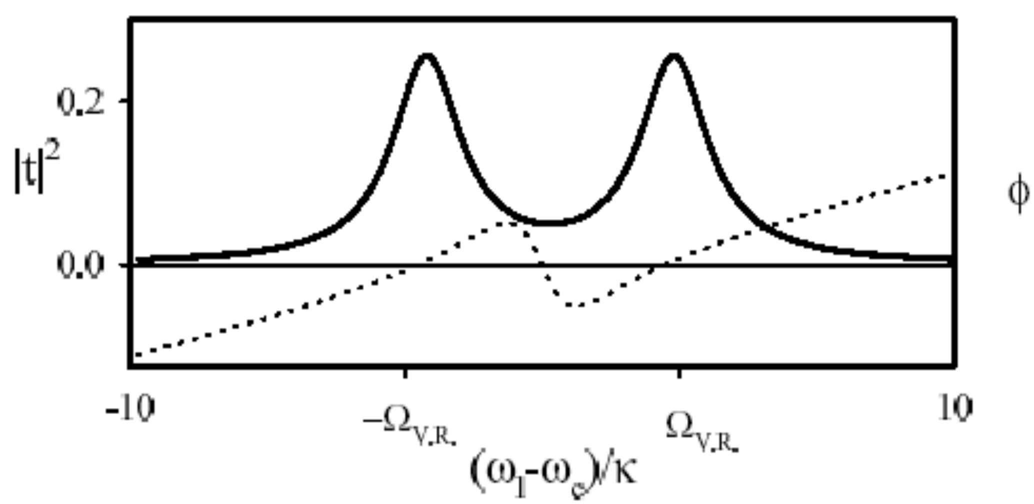
Transmission of light of different frequencies close to resonance and phase delay for atoms alone.



Transmission of light of different frequencies close to resonance and phase delay for cavity alone.



Transmission of light of different frequencies close to resonance and phase delay for atoms and cavity combined. Note that the peaks happen where the phase crosses zero.



Normal mode calculation with Ω excitation.

Transmission (field)

$$\frac{x}{y} = \frac{A}{i\Omega - \Omega_1} + \frac{B}{i\Omega - \Omega_2}\,, \qquad A = \kappa\frac{\gamma_\perp + \Omega_1}{\Omega_1 - \Omega_2}\,,$$

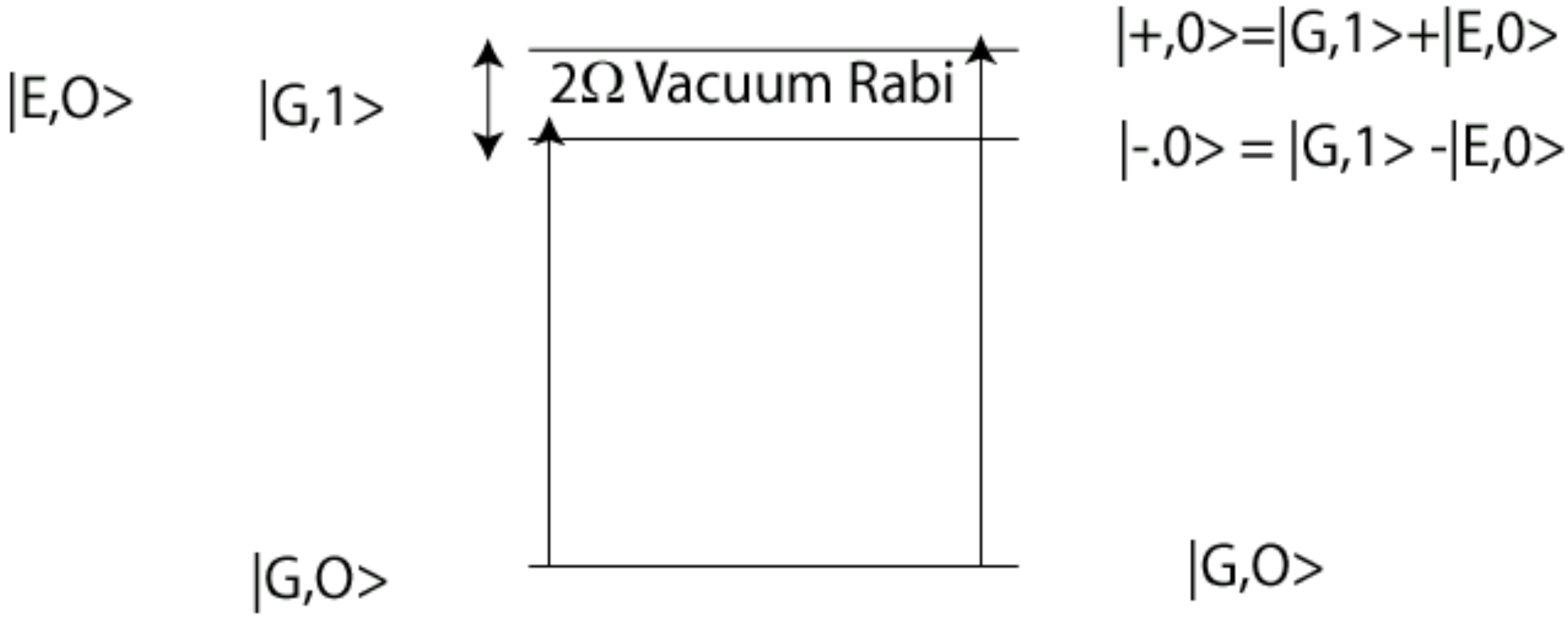
$$\Omega_{V.R.} = g_0\sqrt{\bar{N}} \qquad B = \kappa\frac{\gamma_\perp + \Omega_2}{\Omega_2 - \Omega_1}\,,$$

The width is the average width

$$\Omega_{1,2} = -\frac{\kappa + \gamma_\perp}{2} \pm i\sqrt{-\left(\frac{\kappa - \gamma_\perp}{2}\right)^2 + \frac{\Omega_{V.R.}^2}{1 + \gamma_\perp^2|x|^2/(\gamma_\perp^2 + \Omega^2)}}\,.$$

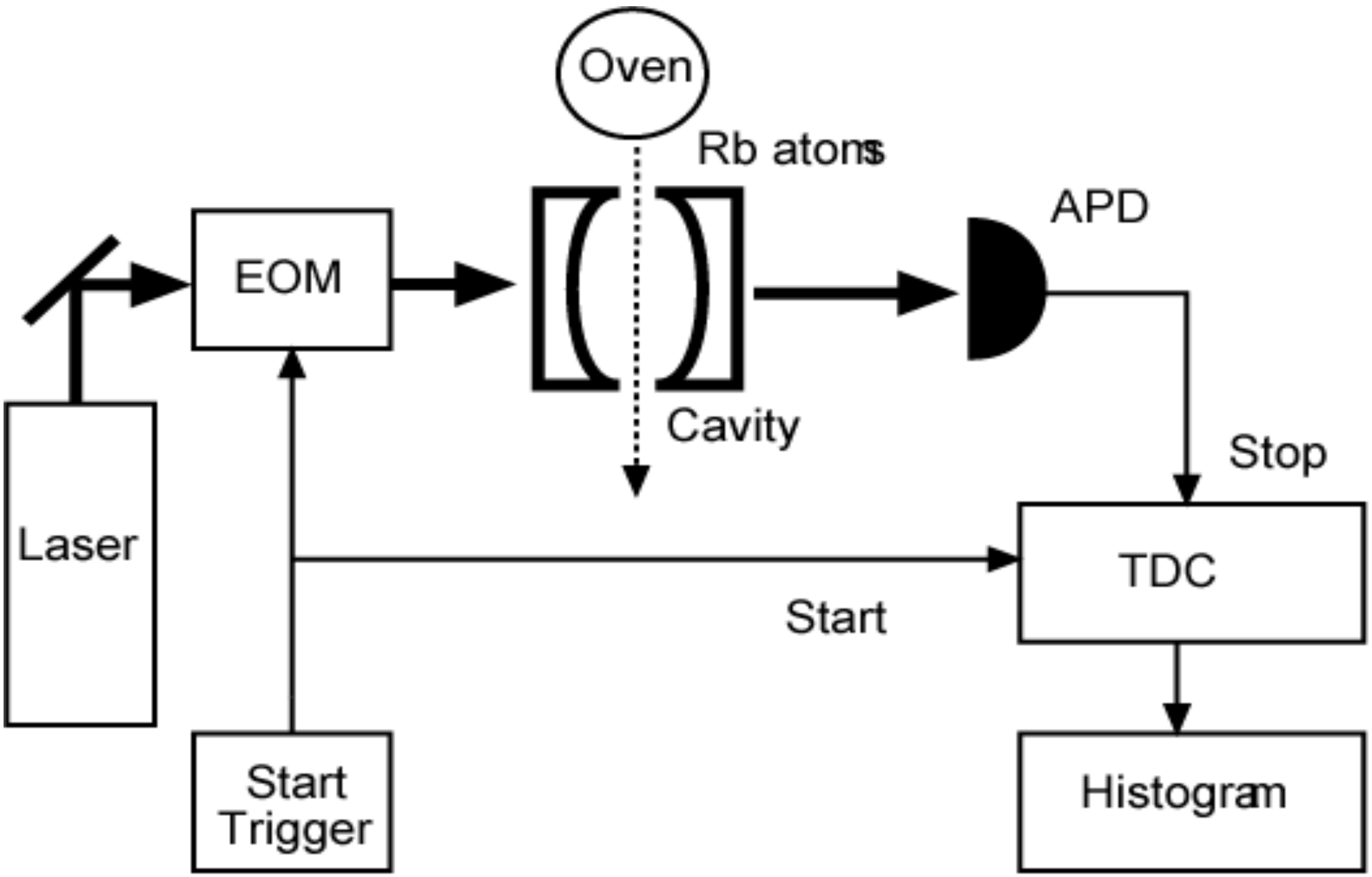
Here is the intenstiy that causes the anharmonicity

We are going to probe the eigenvalue structure of the system:
The first excited state is split from the coupling between atoms and cavity so the

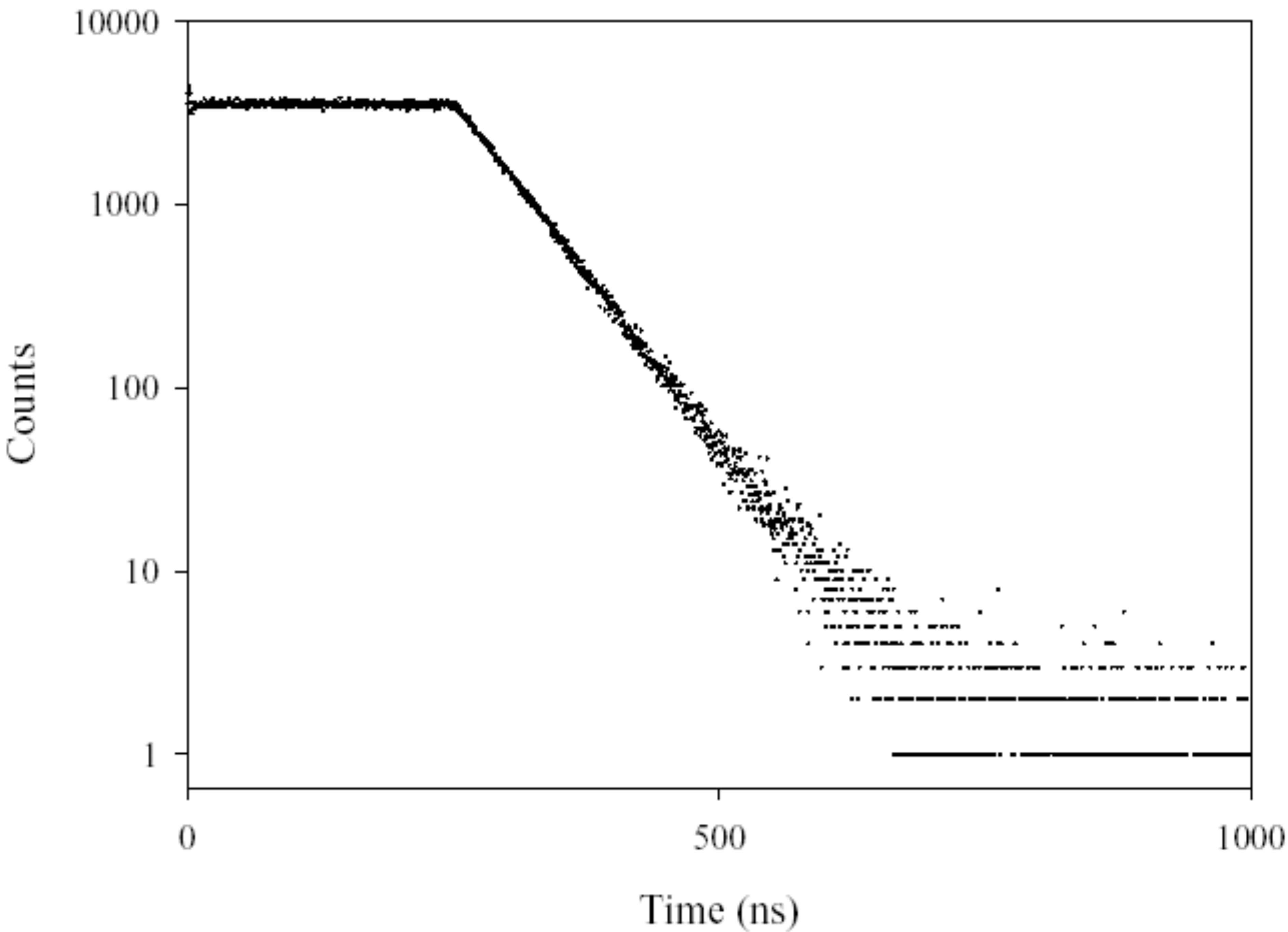


In the spectroscopy we should see two peaks from the transitions between the ground state and the excited states. (AM modulation)

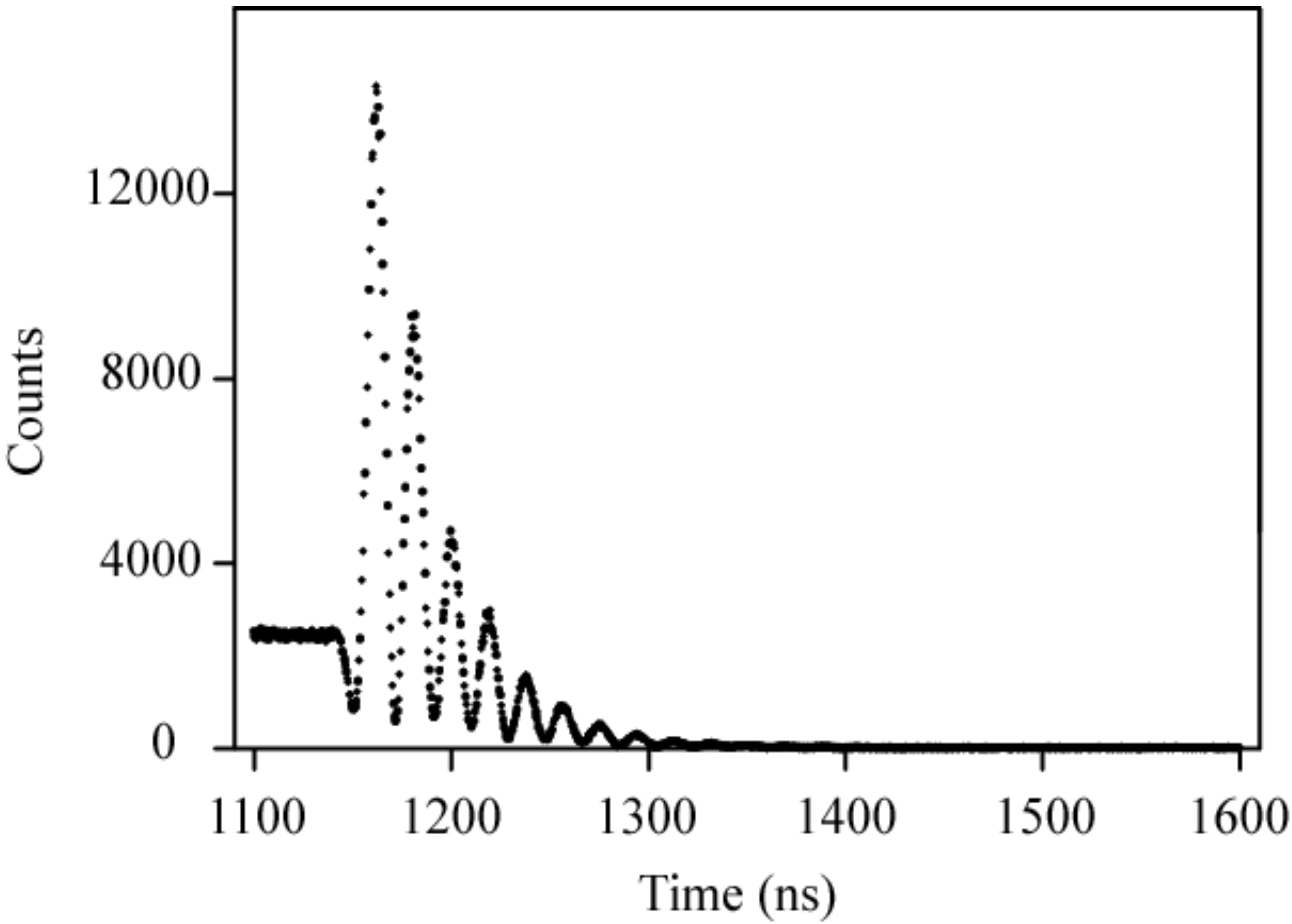
Study the system dynamics in the time domain. Step response.



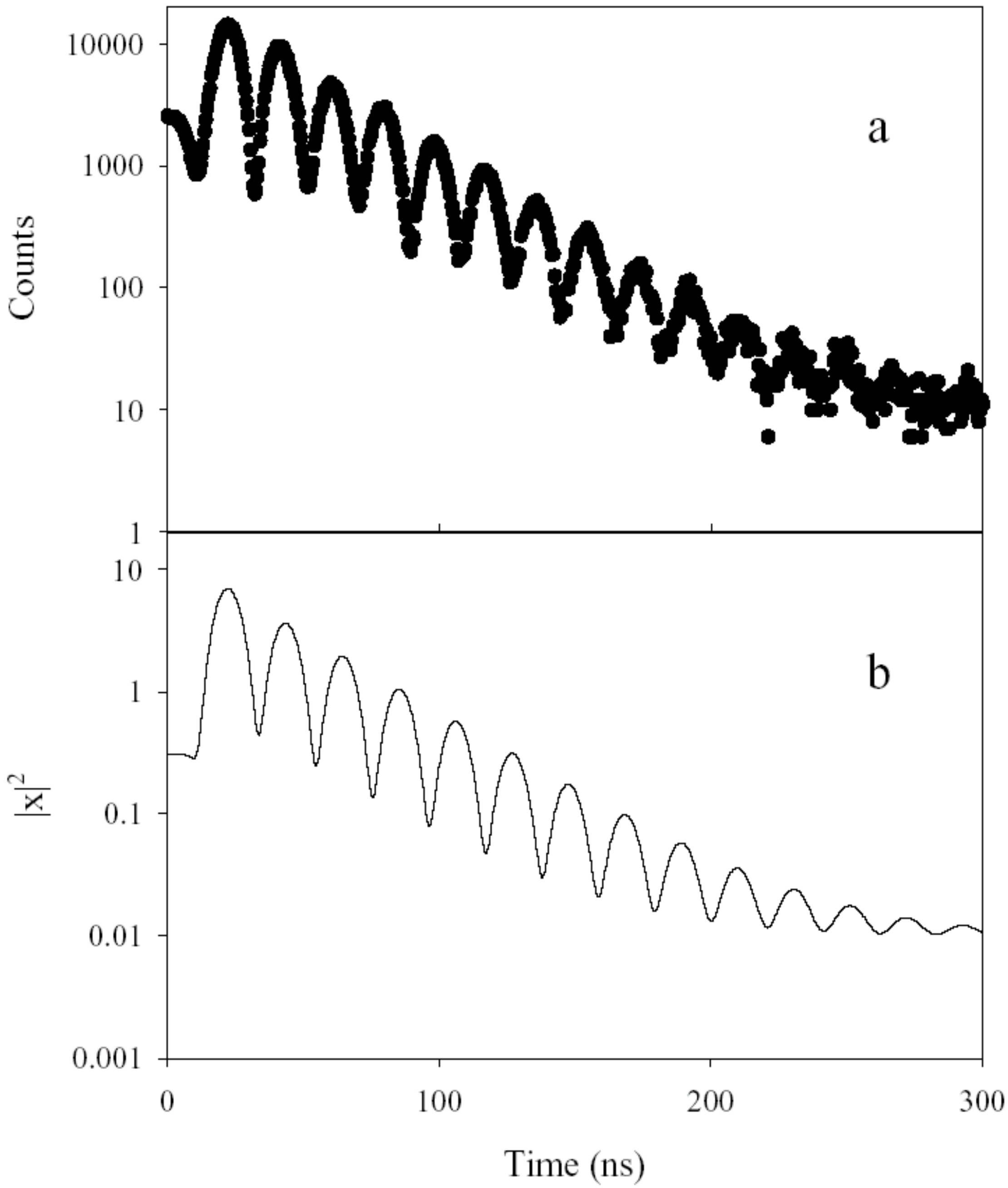
Empty cavity response

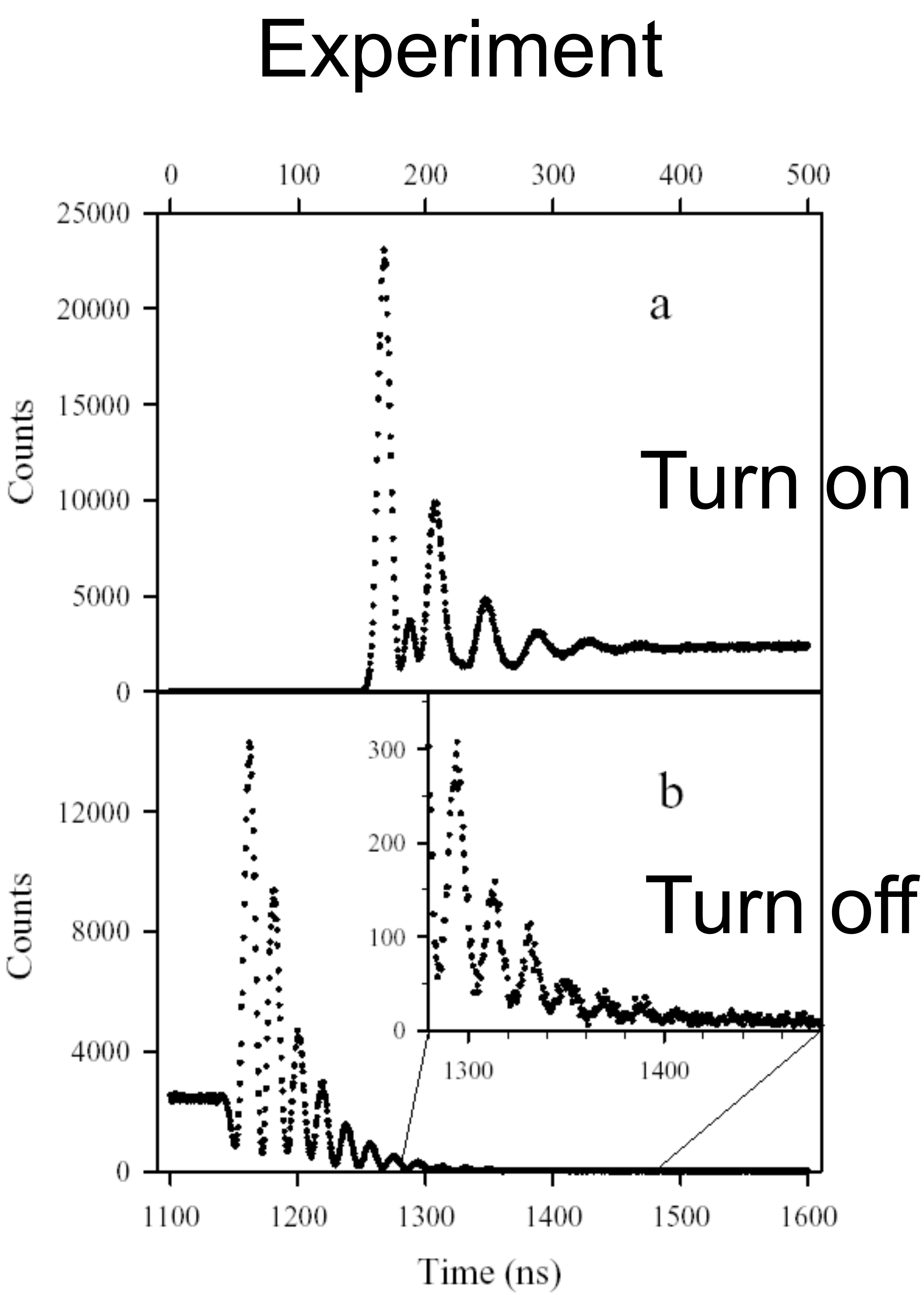


Intensity response to step down of the atoms-cavity system.

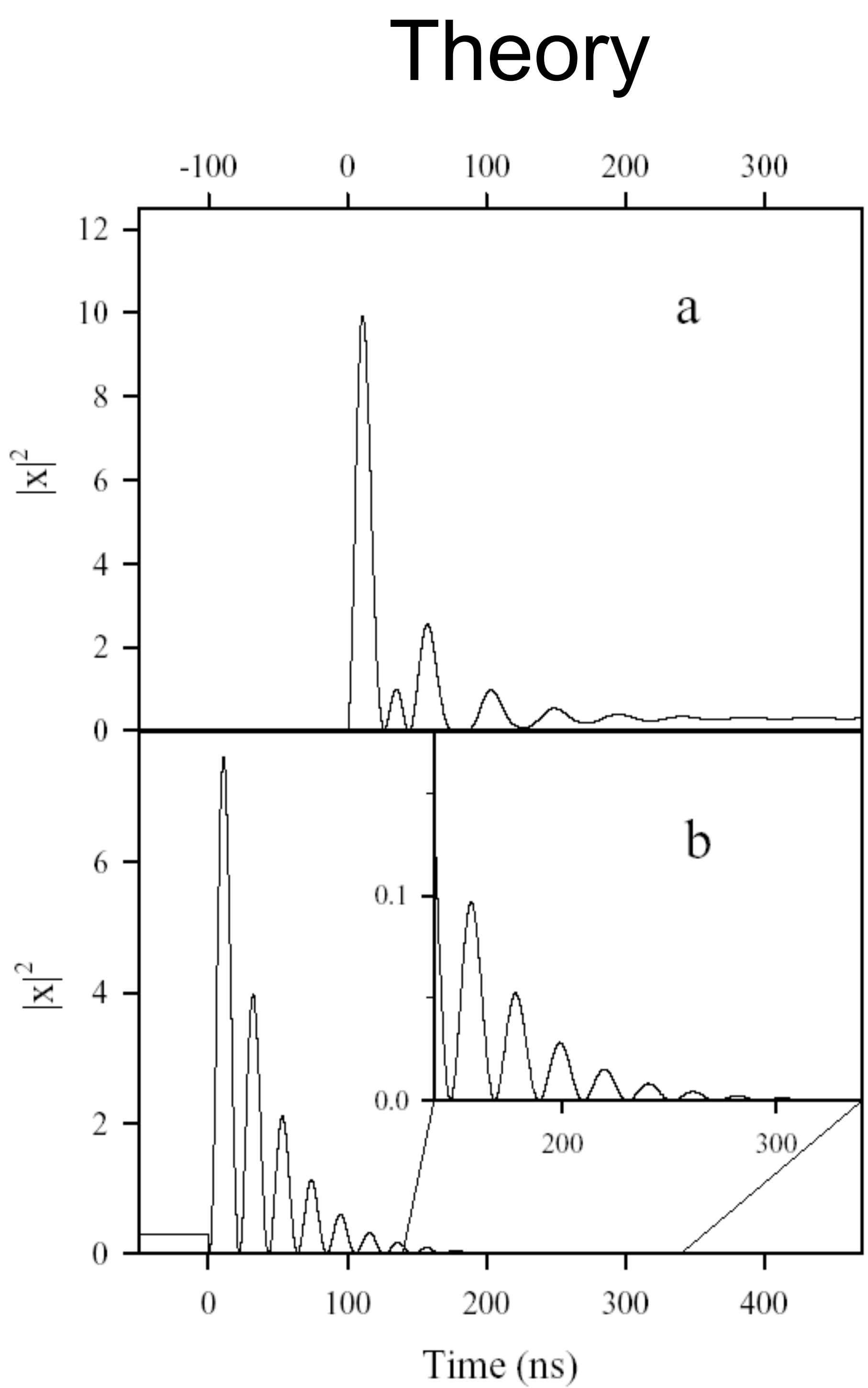


Response in logarithmic scale; a) experiment, b) theory.



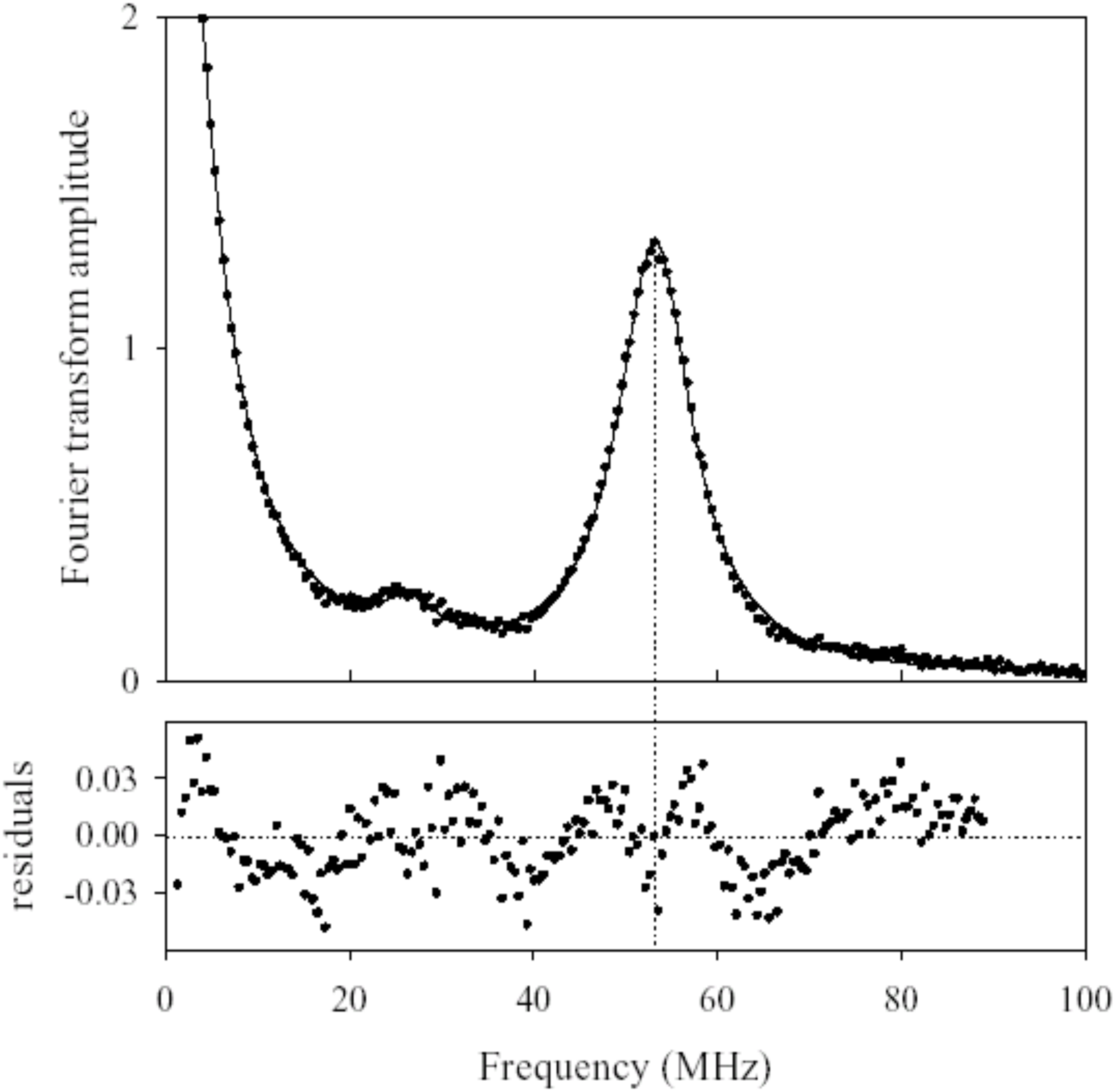


Experiment
Counts
Time (ns)
a
b
Turn on
Turn off

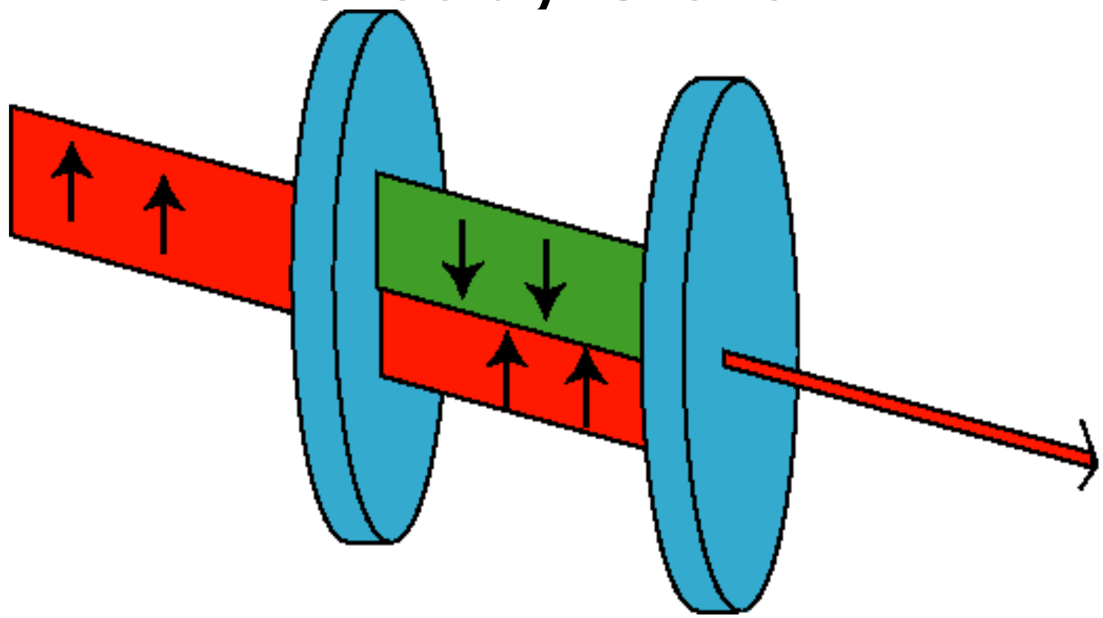


Theory
$|x|^2$
Time (ns)
a
b

Fourier Transform of the Step down response

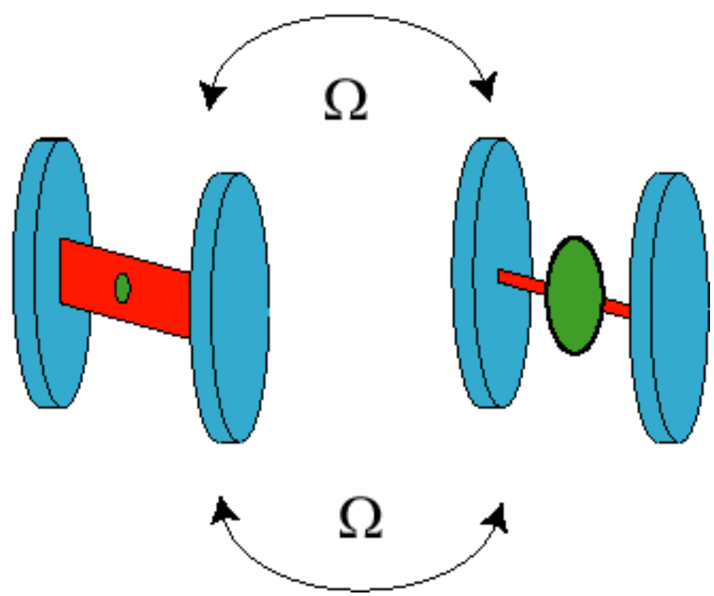


Steady State:



Exchange of Excitation:

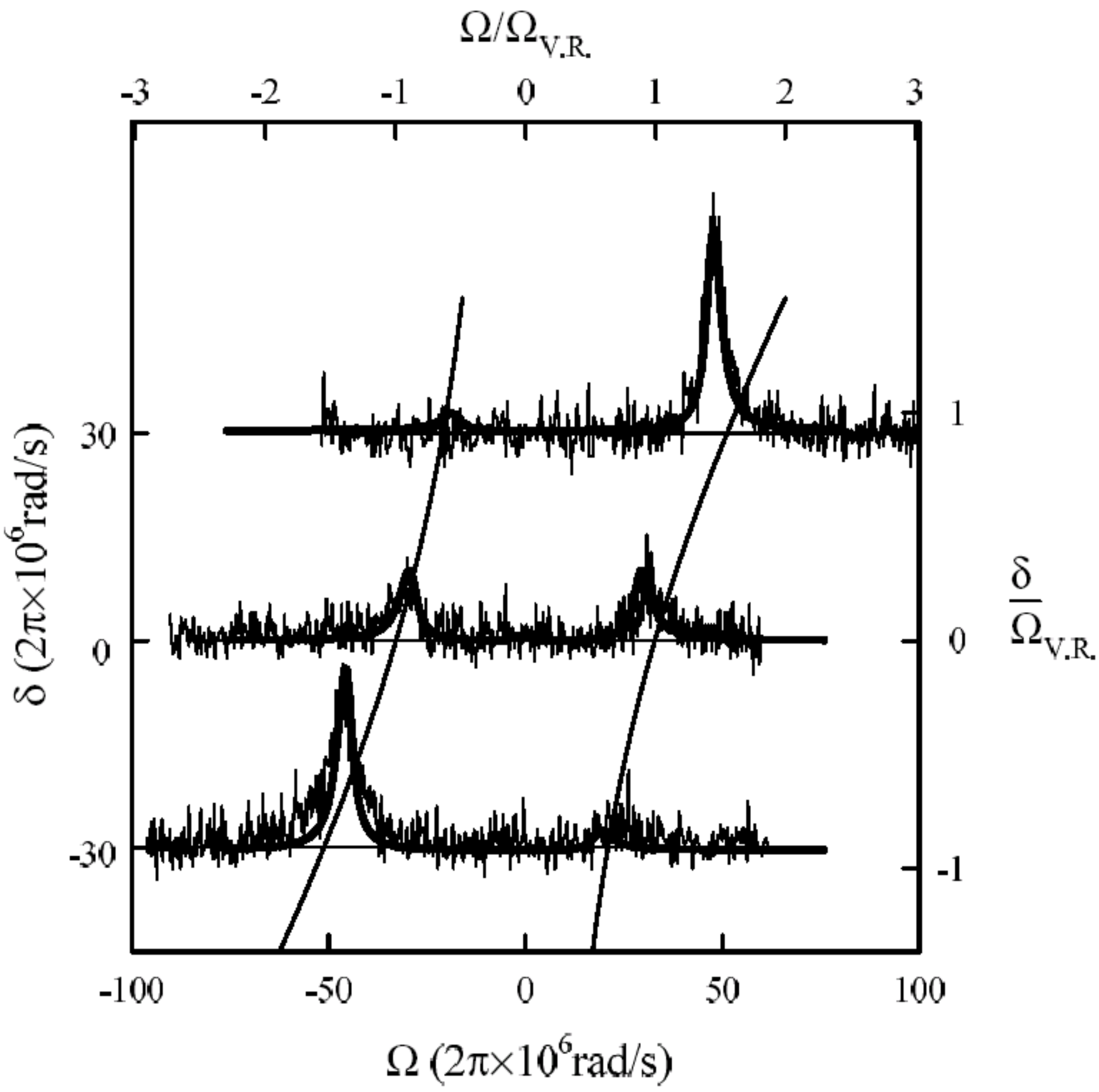
Cavity Mode and Atoms



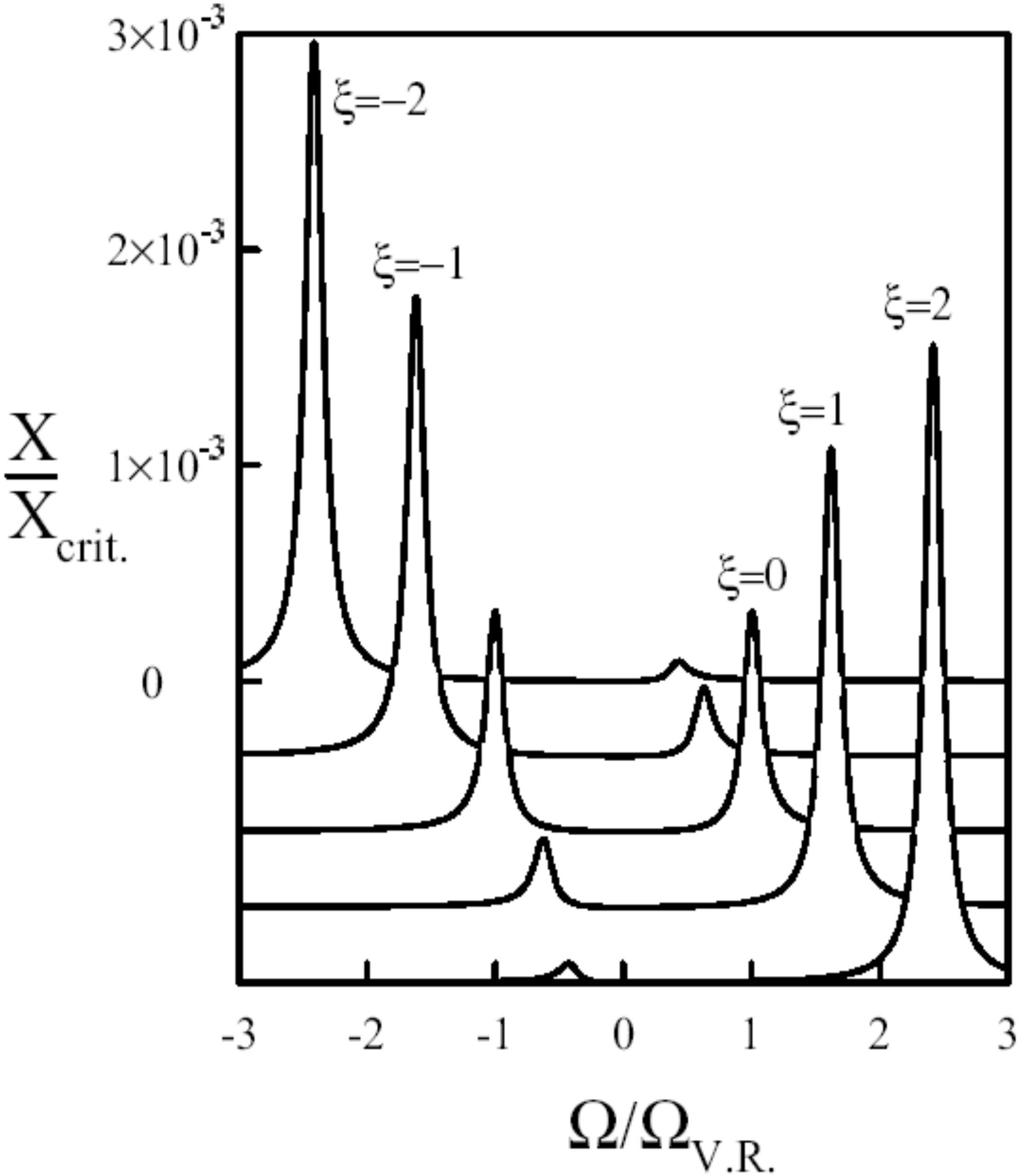
$$\Omega \approx g\sqrt{N}$$

Frequency domain study of Vacuum Rabi Splitting

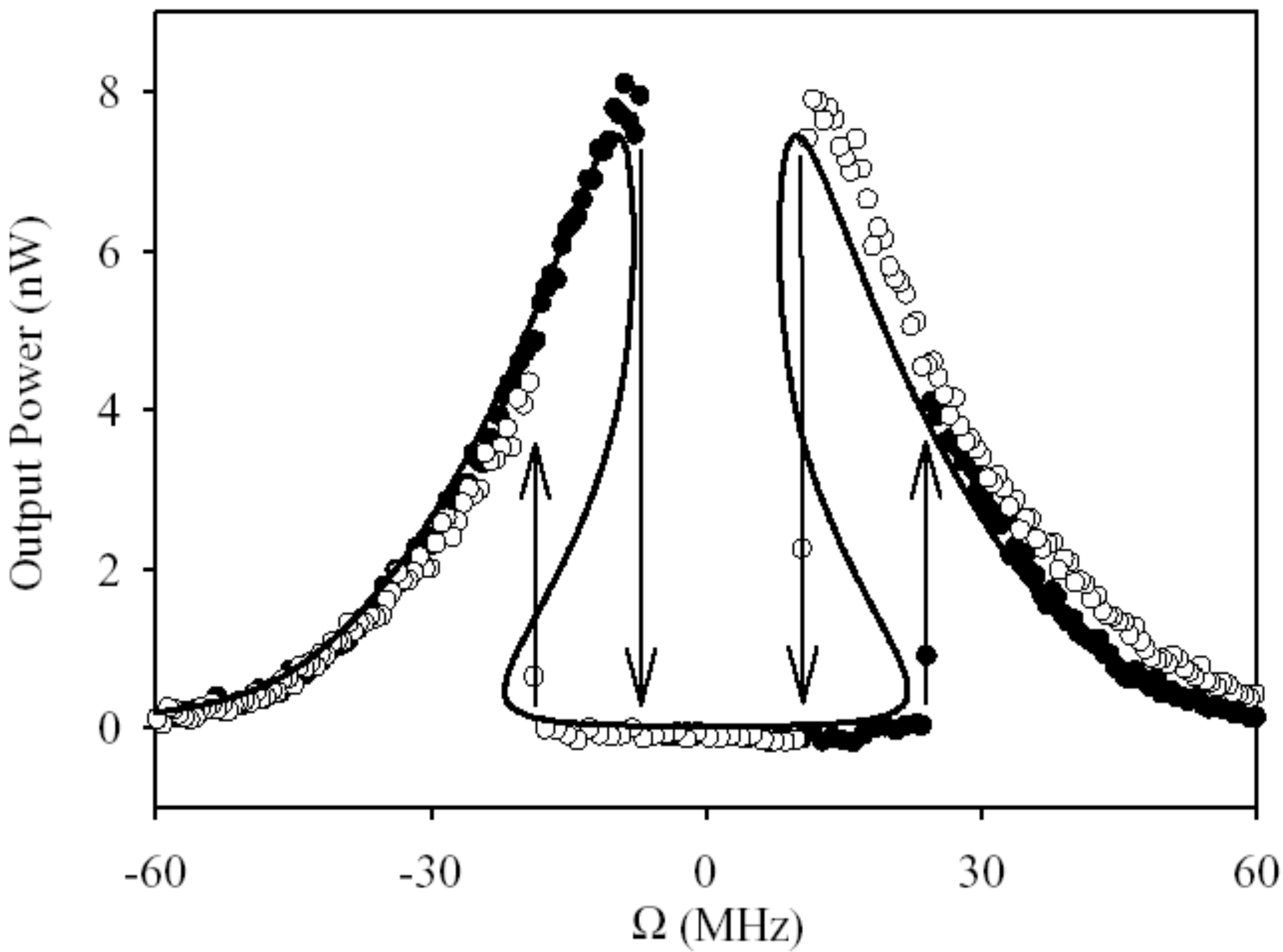
Transmission Spectra at low intensity for different atomic detunings. Note the Vacuum Rabi peaks and the "avoided crossing" of the two coupled modes.



Calculation of the low intensity transmission spectra for different atomic detunings

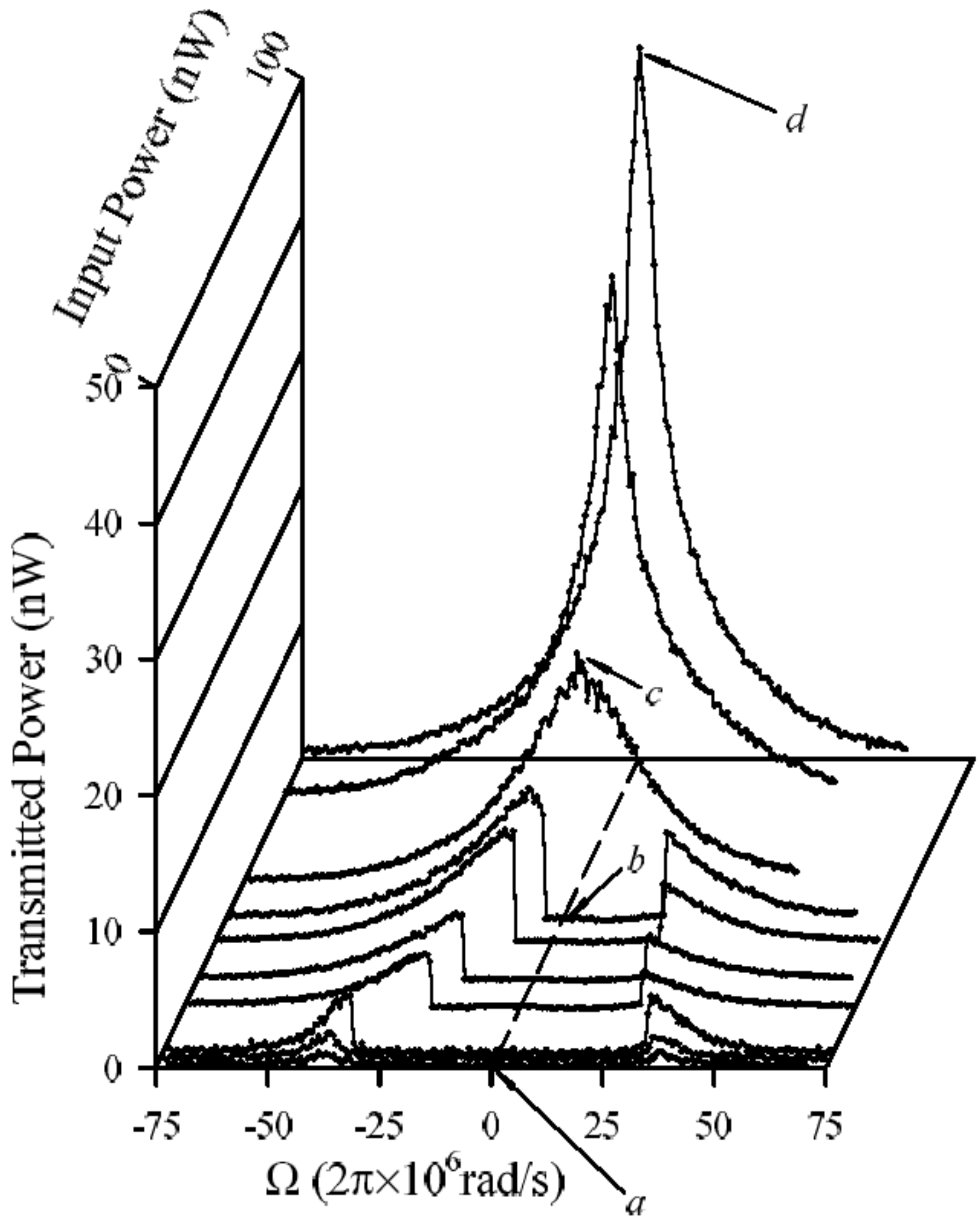


Anharmonic oscillator

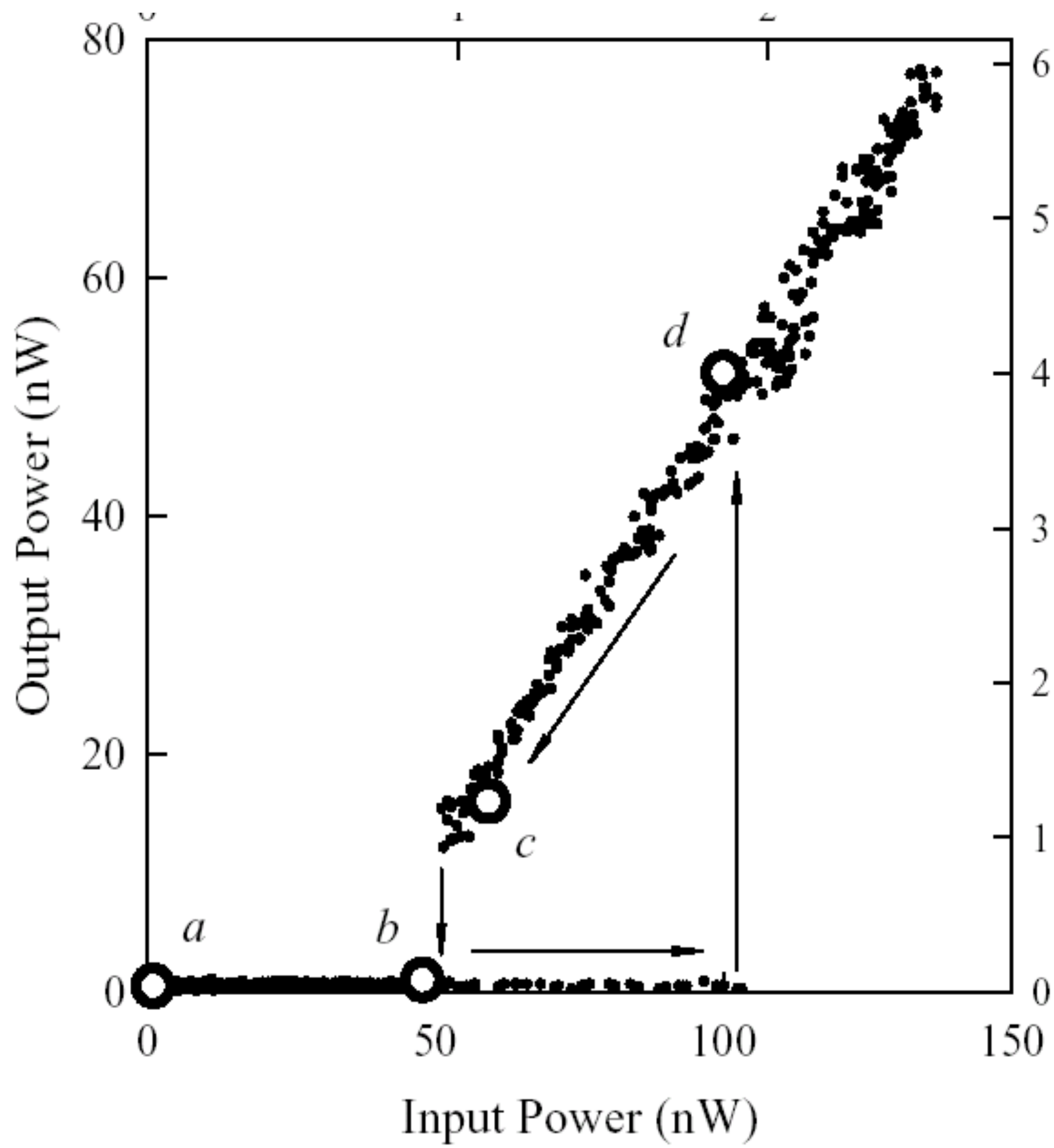


Hysteresis (changing frequency) from the coupled atoms-cavity system. Two different scans with equal input intensities are shown. Filled circles mark the scans with increasing laser frequency; open circles mark scans with decreasing laser frequency. The lines are theoretical calculations from a semiclassical theory.

Transmission spectra for different intensities and no detuning.



(a) Vacuum Rabi peaks, (b) anharmonic oscillator, (c) broanened single peak, and (d) Fabry Perot resonance with the atoms saturated.

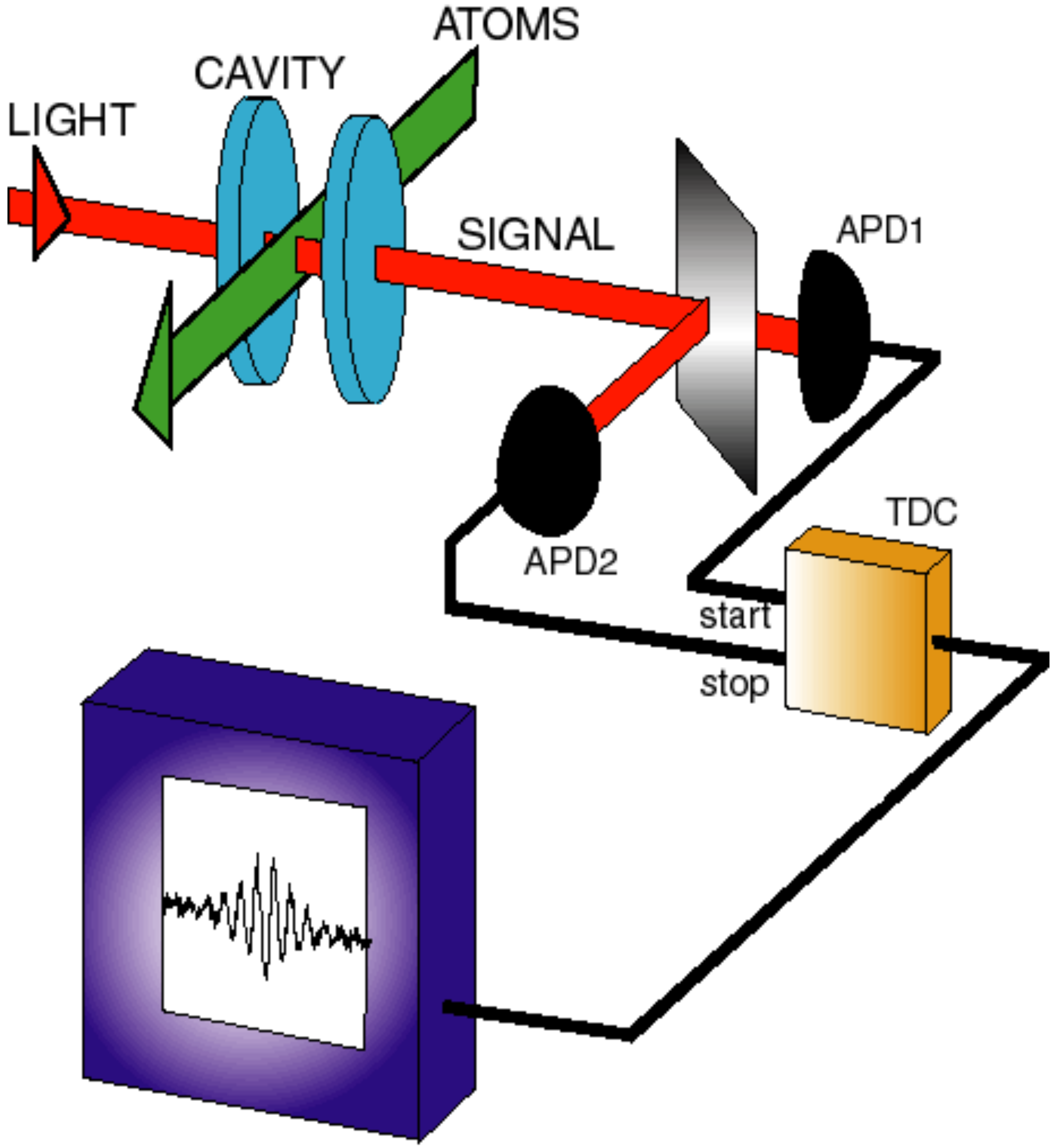


When we turn off the input (Y) the polarization has all the energy stored and gives it back to the cavity just as two coupled oscillators

3. Quantum Optics in Cavity QED

Are there some quantum effects in cavity QED?

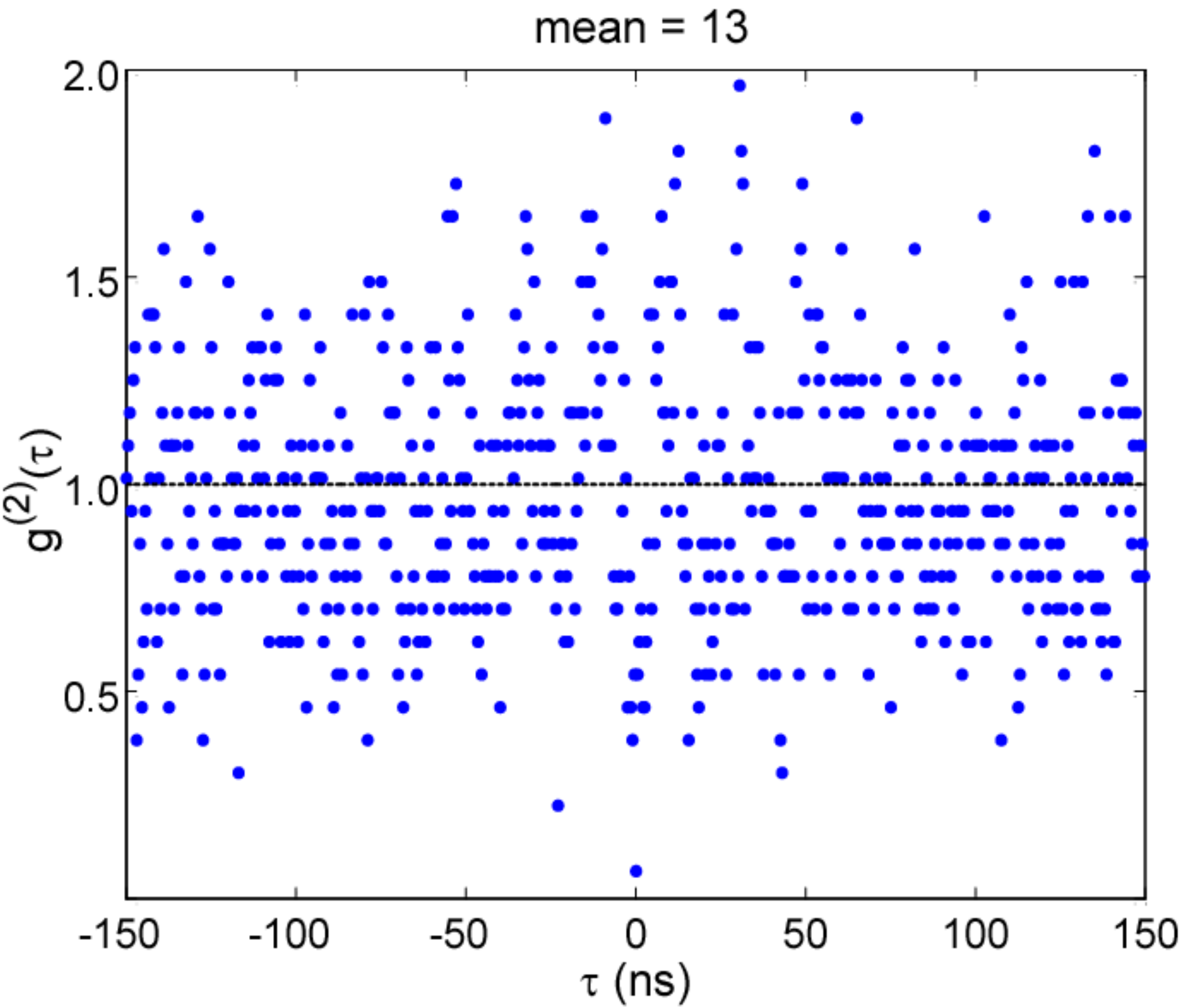
Look at the fluctuations

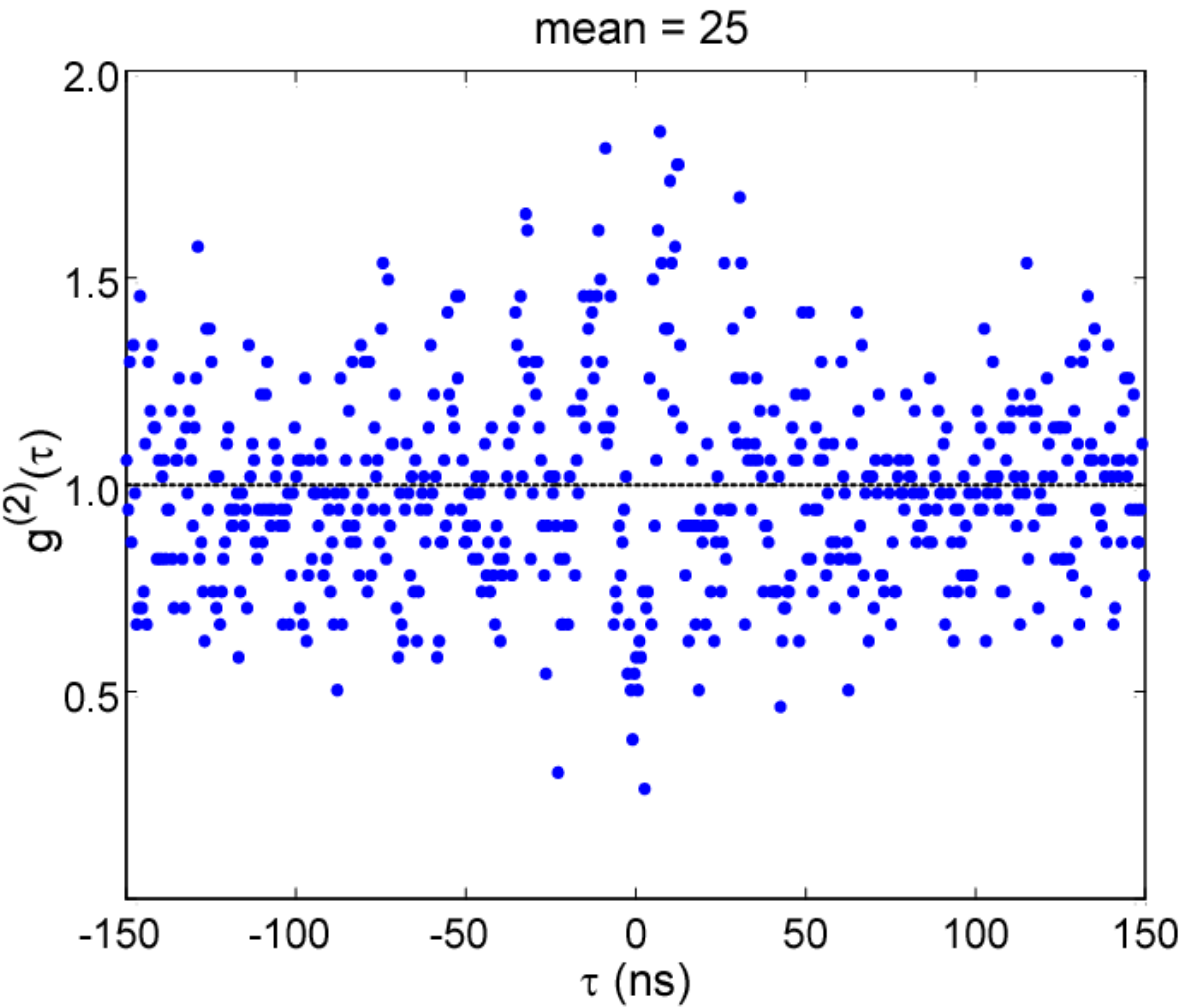

ATOMS
CAVITY
LIGHT
SIGNAL
APD1
APD2
TDC
start
stop

Experimental considerations

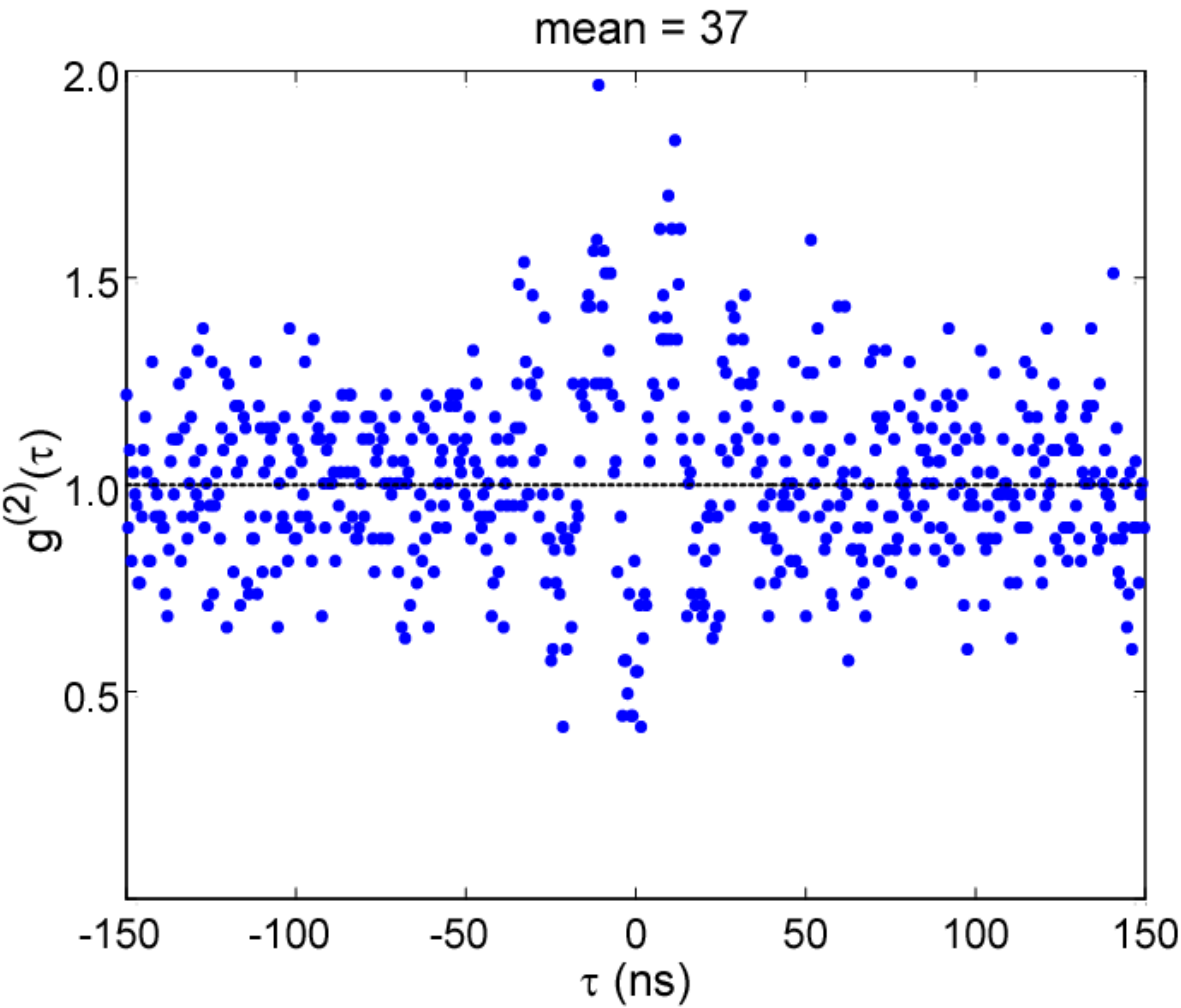
Collimated atomic beam: thermal, high velocity only a few atoms are maximally coupled.

Atomic number fluctuations are small.

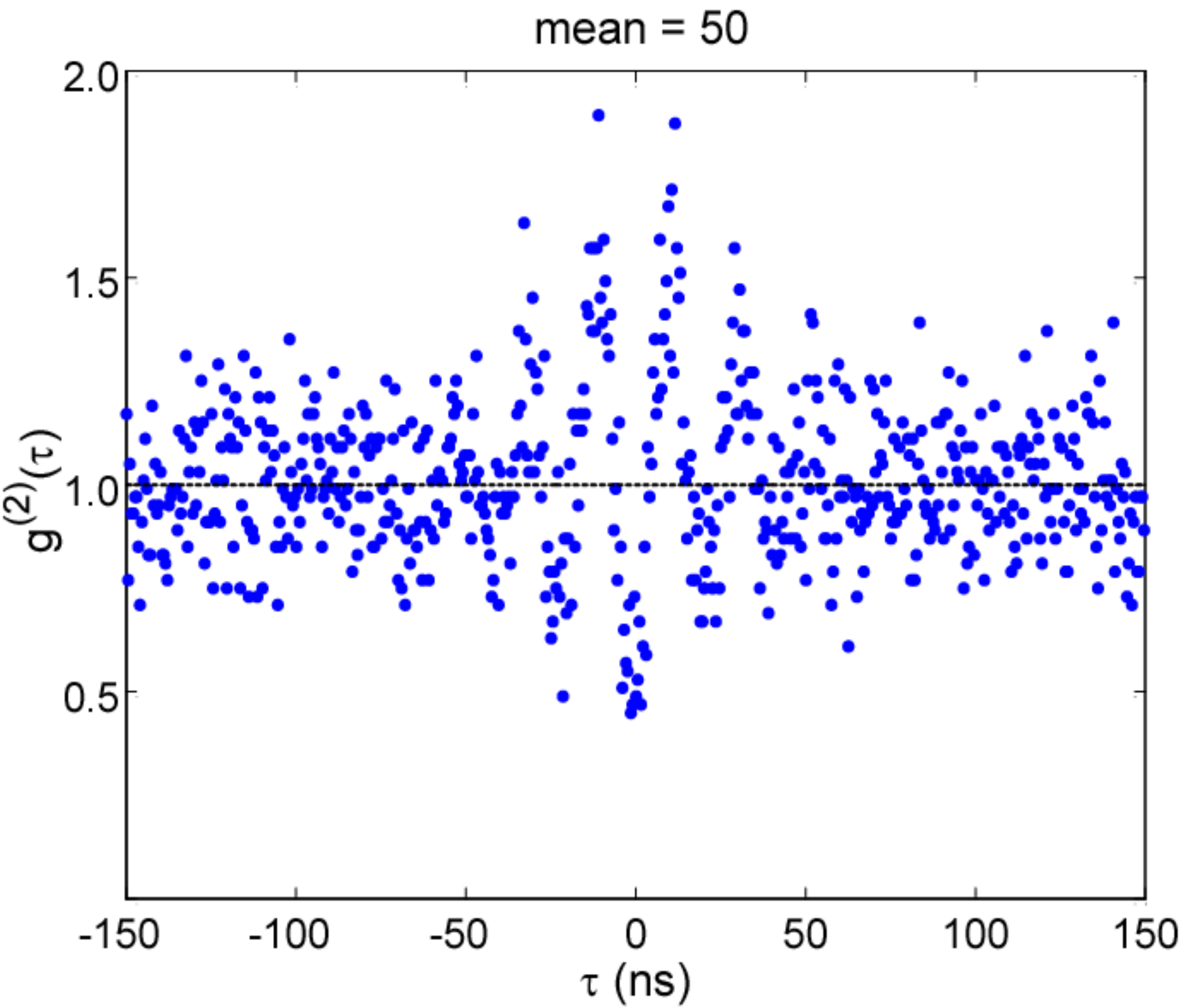

mean = 13
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

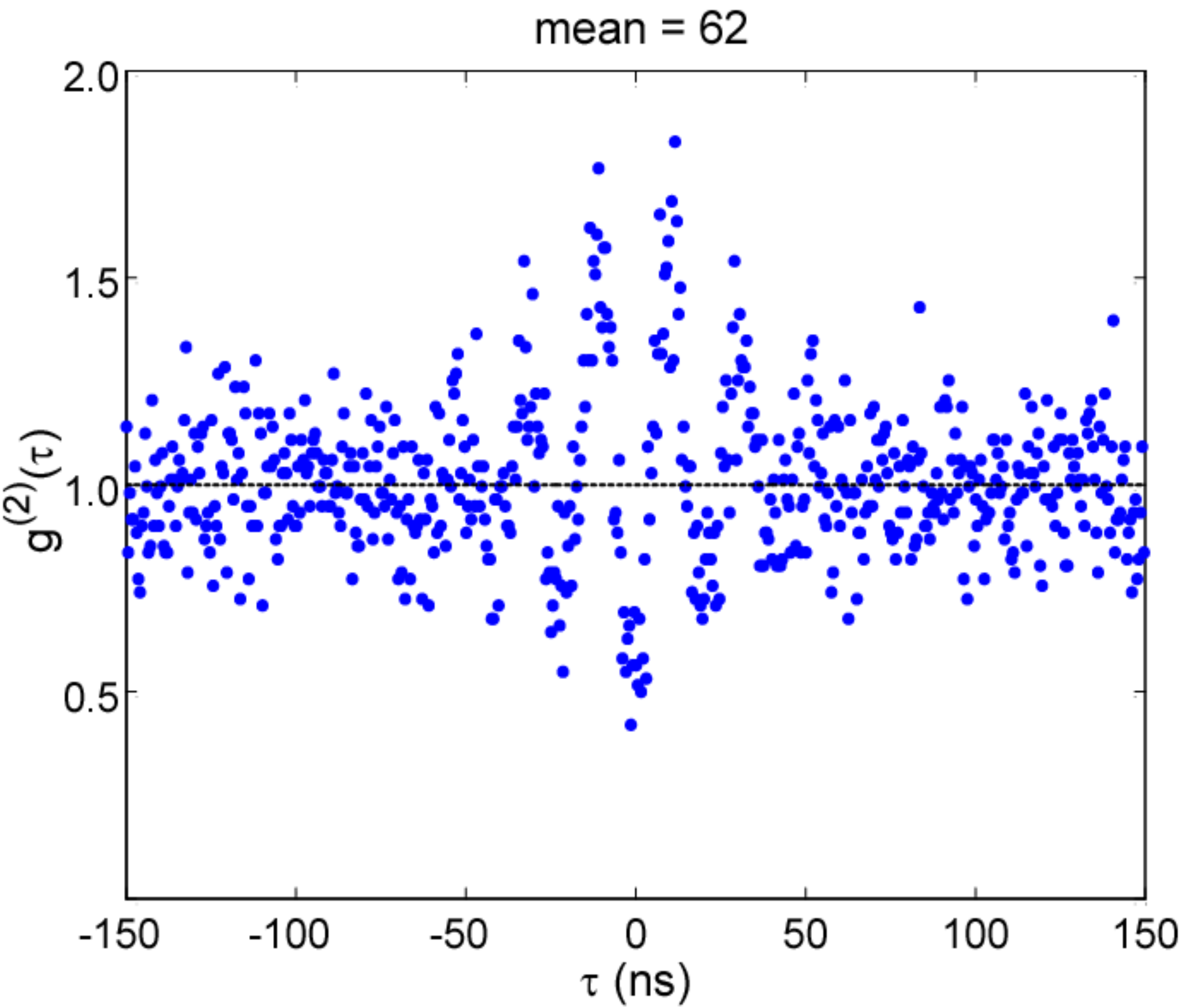


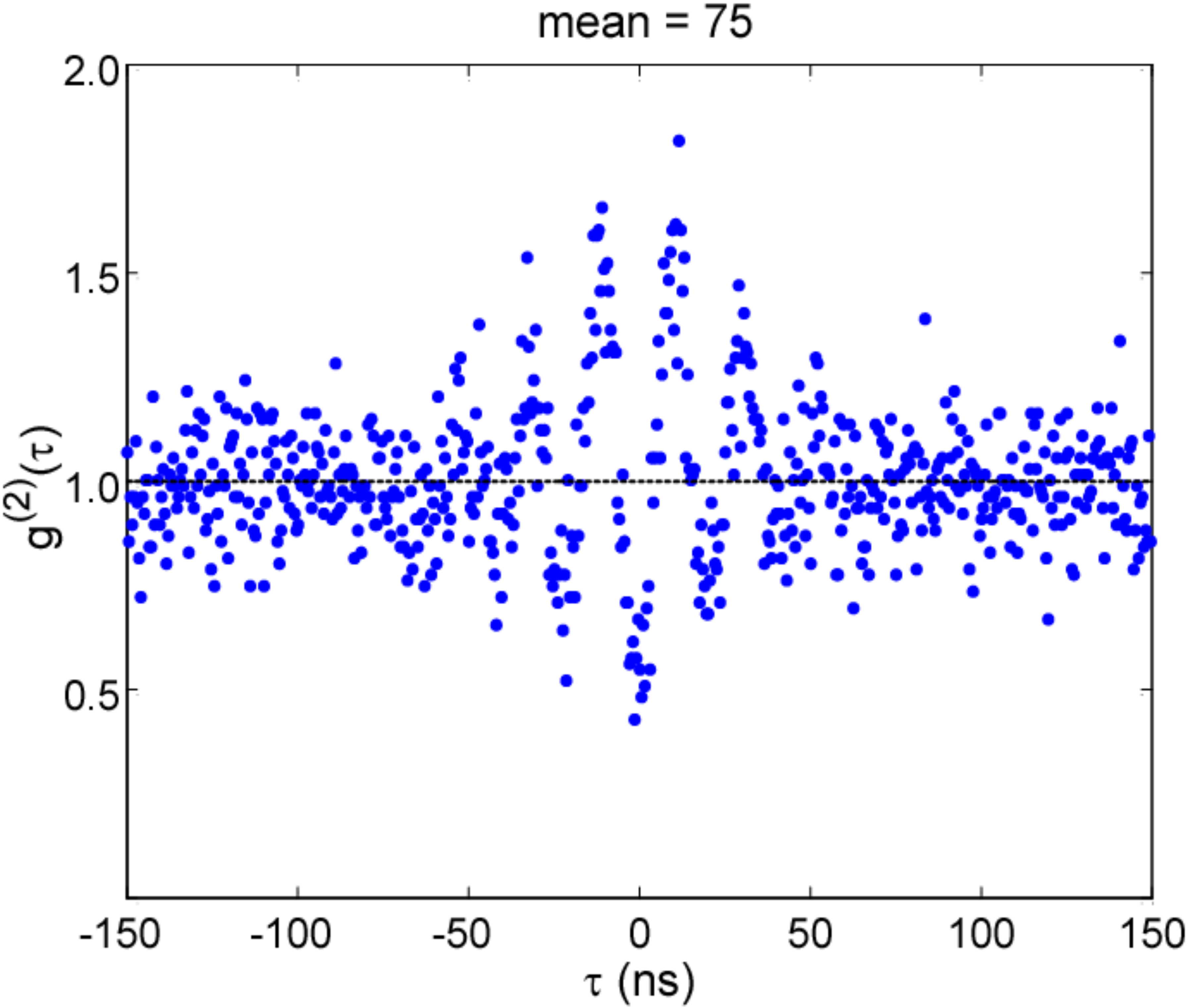
mean = 25
2.0
1.5
1.0
0.5
g(2)(τ)
-150
-100
-50
0
50
100
150
τ (ns)

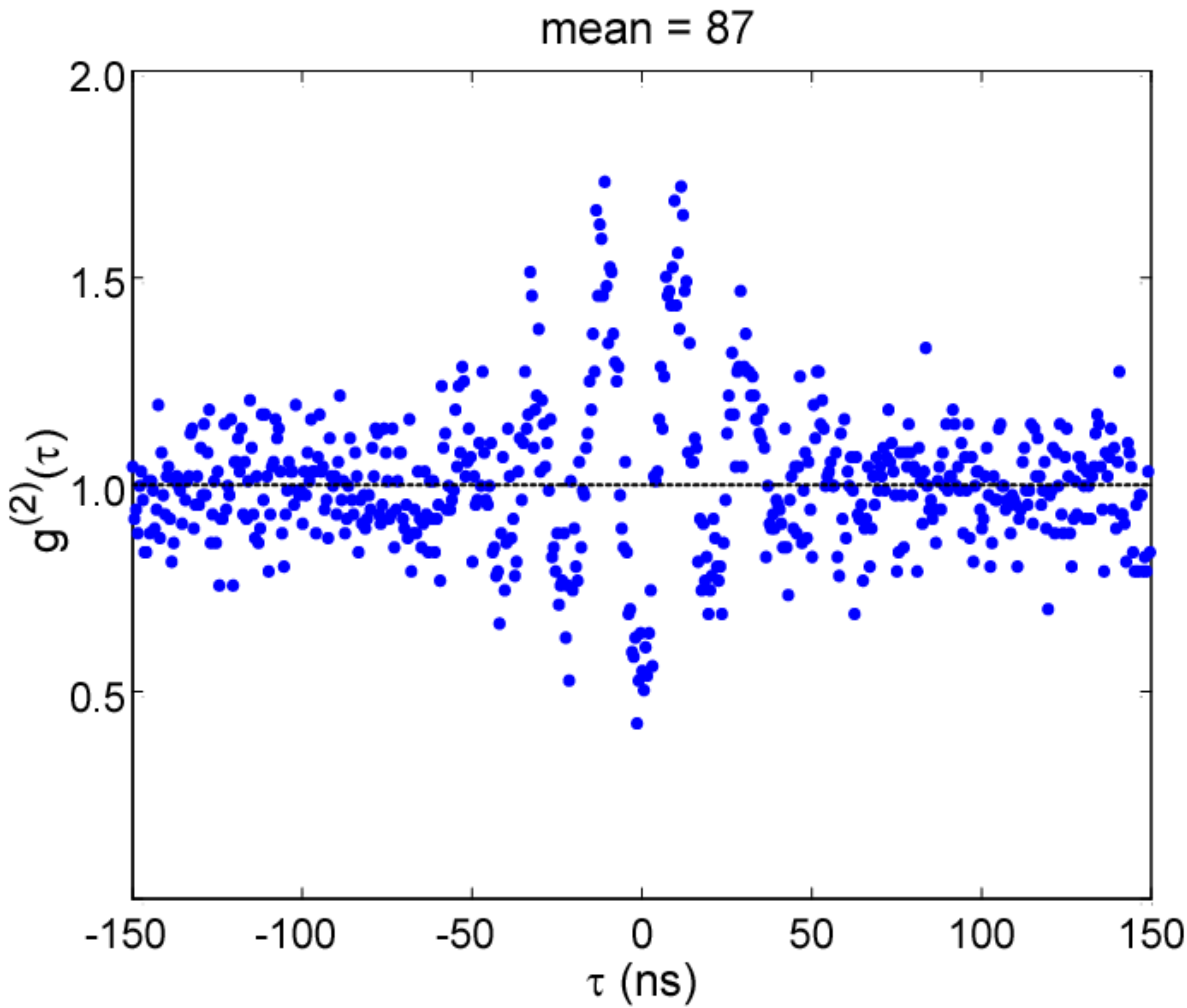


mean = 37
2.0
1.5
1.0
0.5
g(2)(τ)
-150
-100
-50
0
50
100
150
τ (ns)

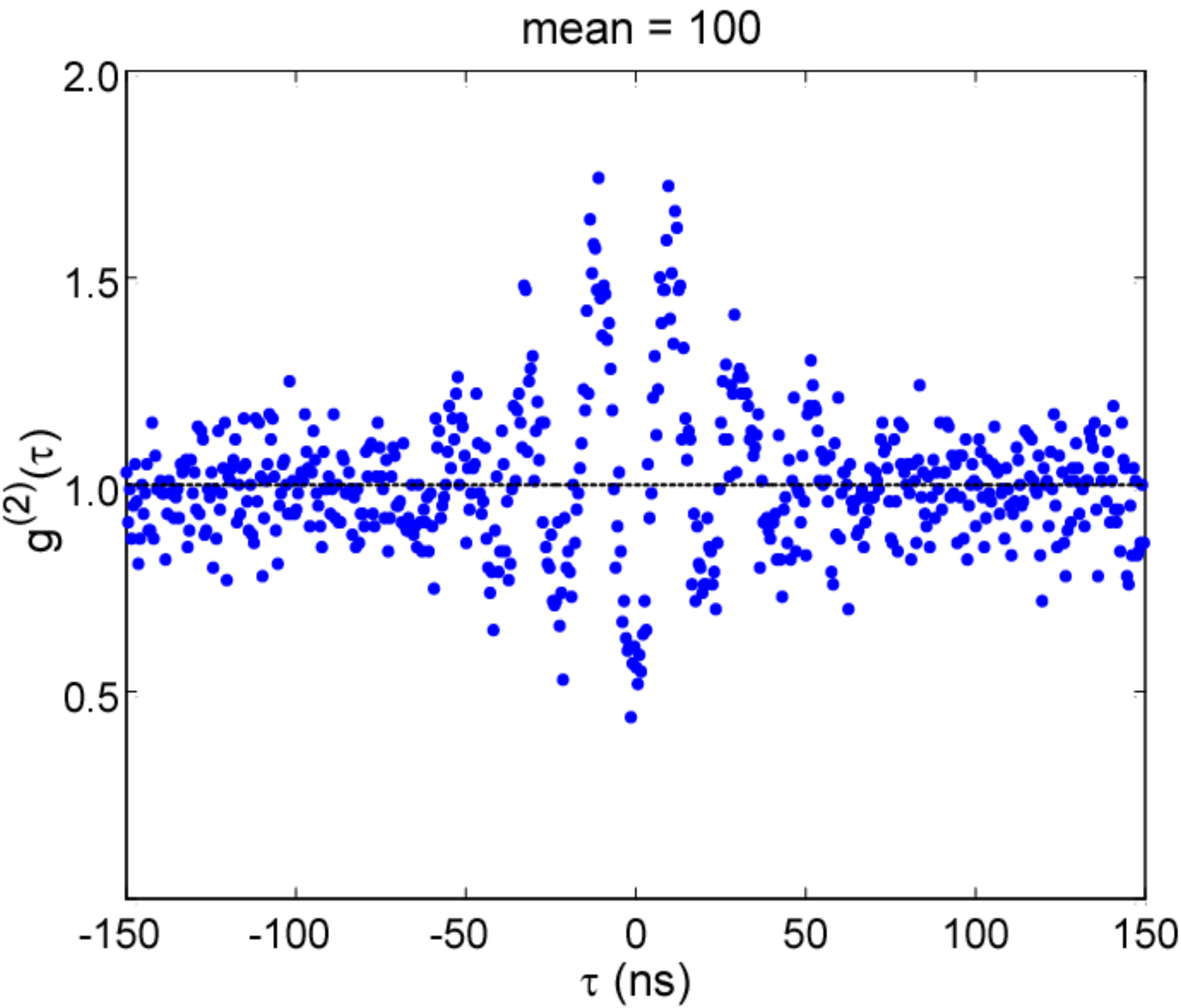

mean = 50
2.0
1.5
1.0
0.5
g(2)(τ)
-150
-100
-50
0
50
100
150
τ (ns)


mean = 62
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

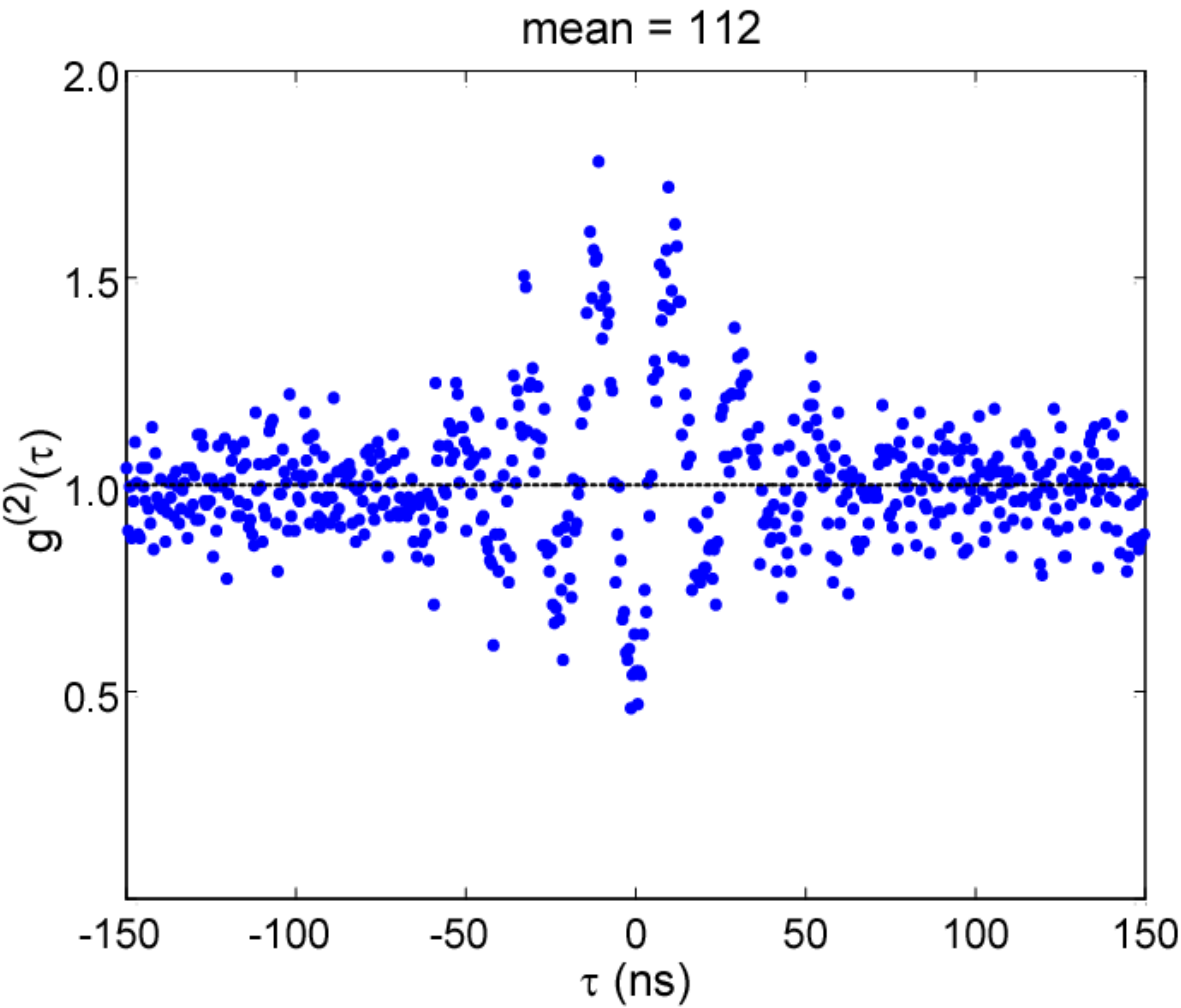

mean = 75
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

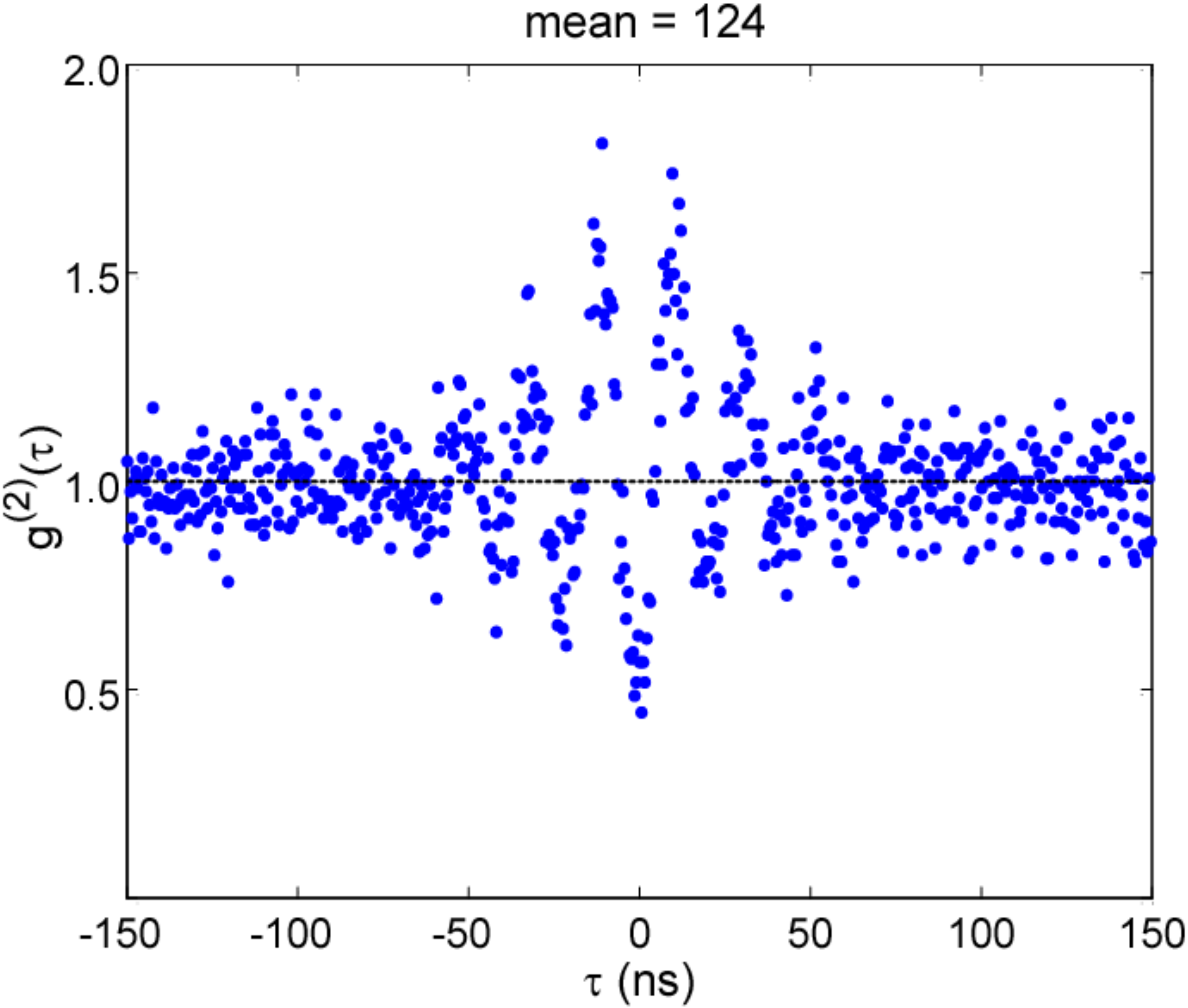


mean = 87
2.0
1.5
1.0
0.5
g(2)(τ)
-150
-100
-50
0
50
100
150
τ (ns)

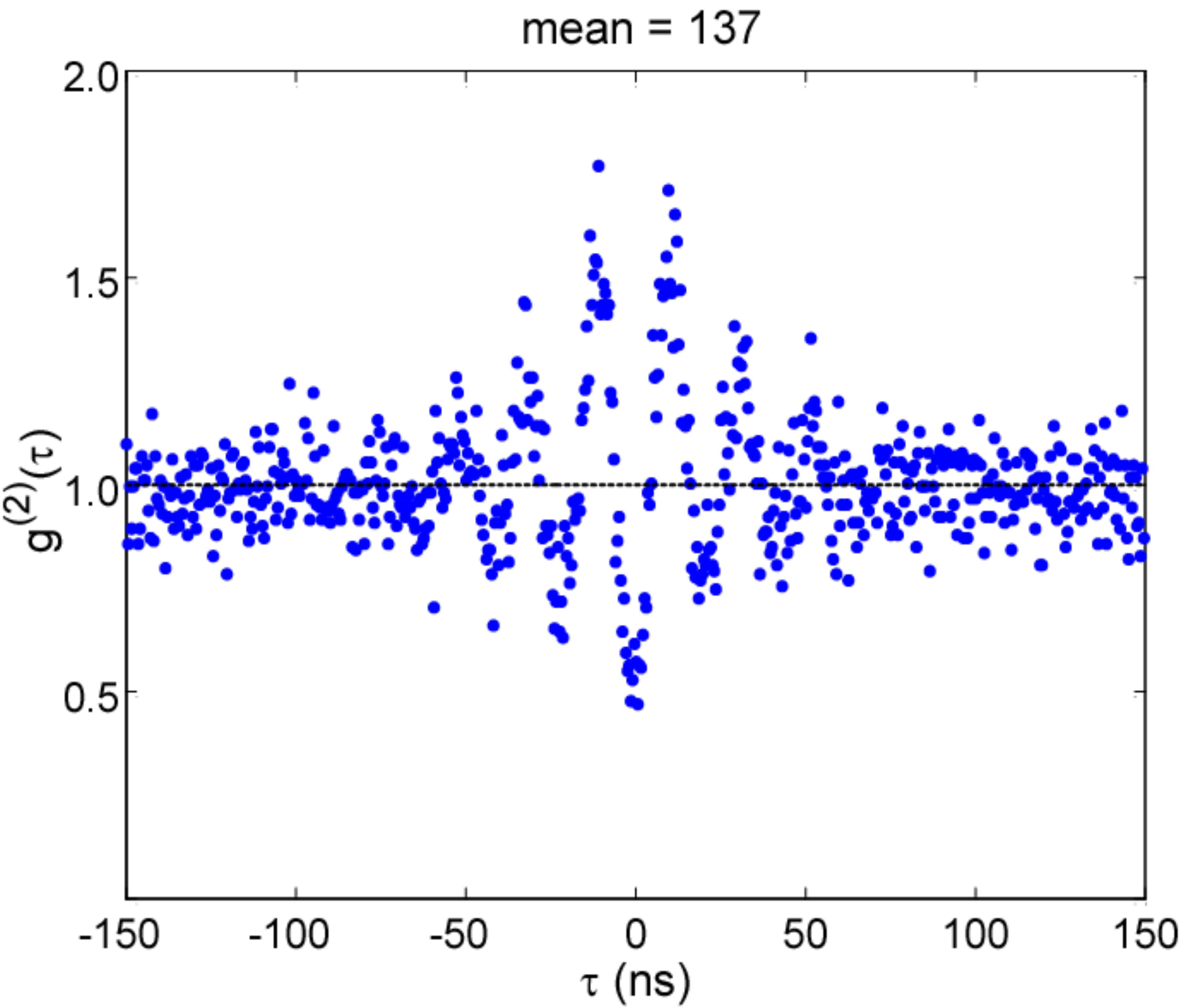


mean = 100
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

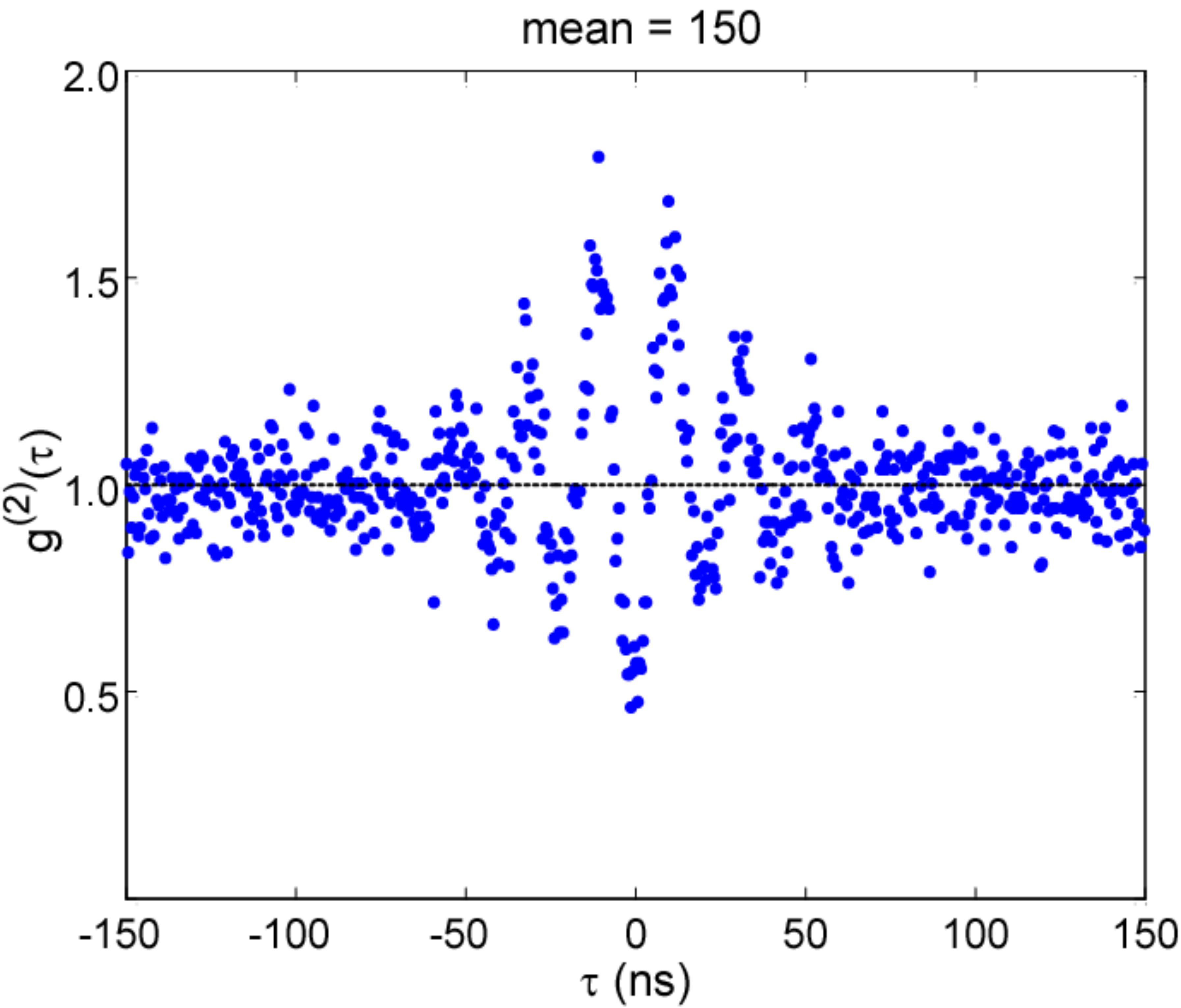

mean = 112
2.0
1.5
1.0
0.5
g(2)(τ)
-150
-100
-50
0
50
100
150
τ (ns)

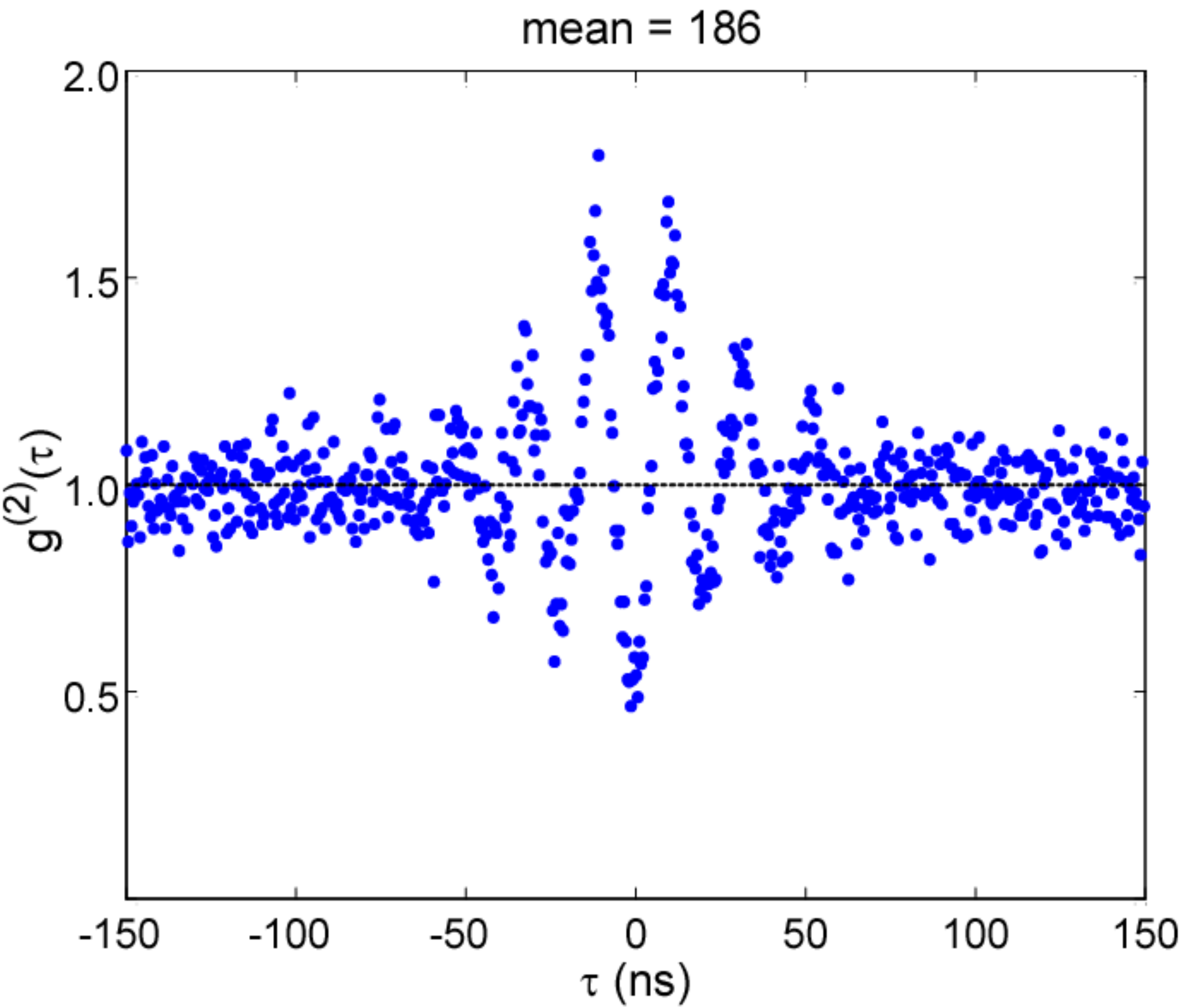


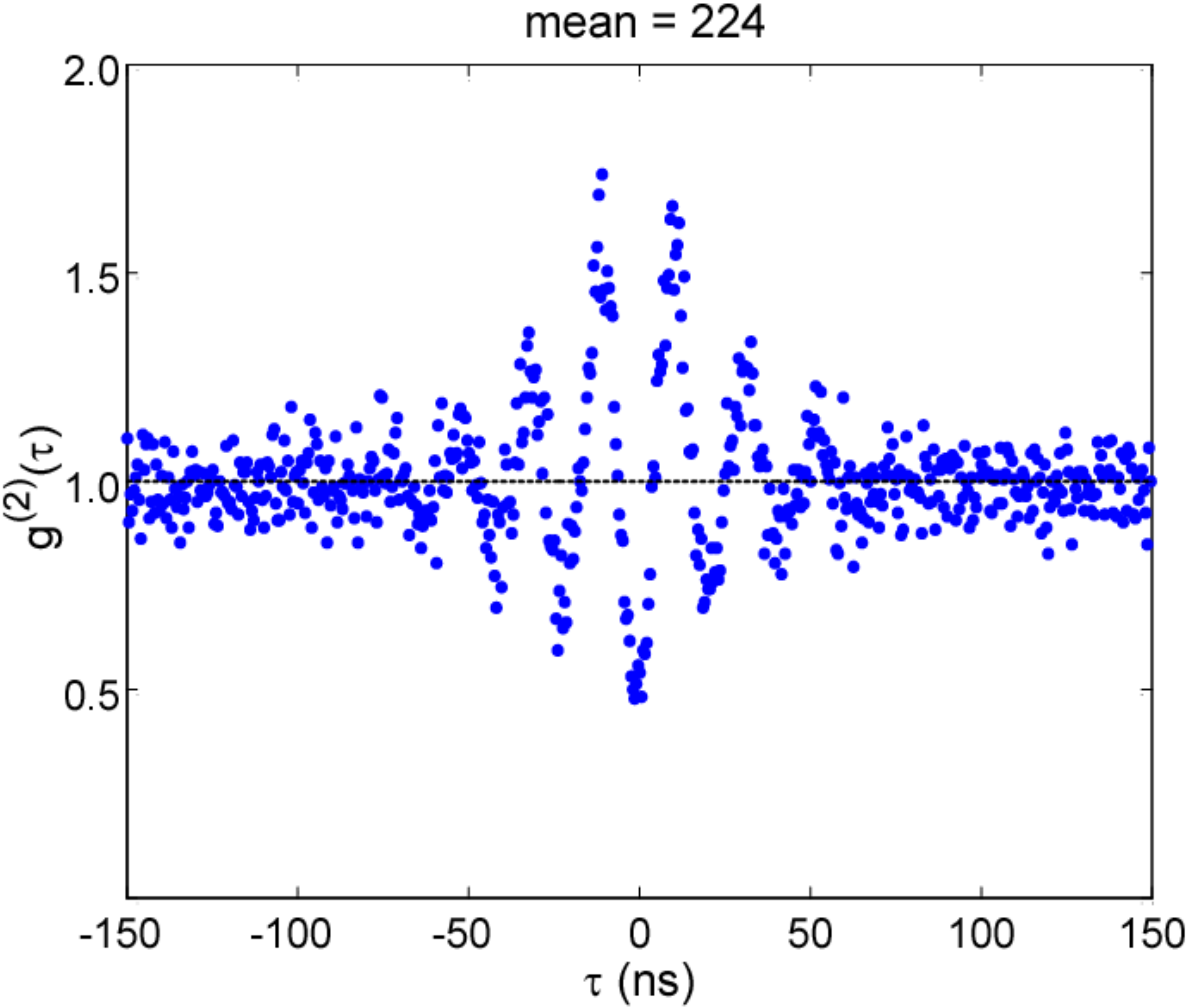
mean = 124
2.0
1.5
1.0
0.5
g(2)(τ)
-150
-100
-50
0
50
100
150
τ (ns)



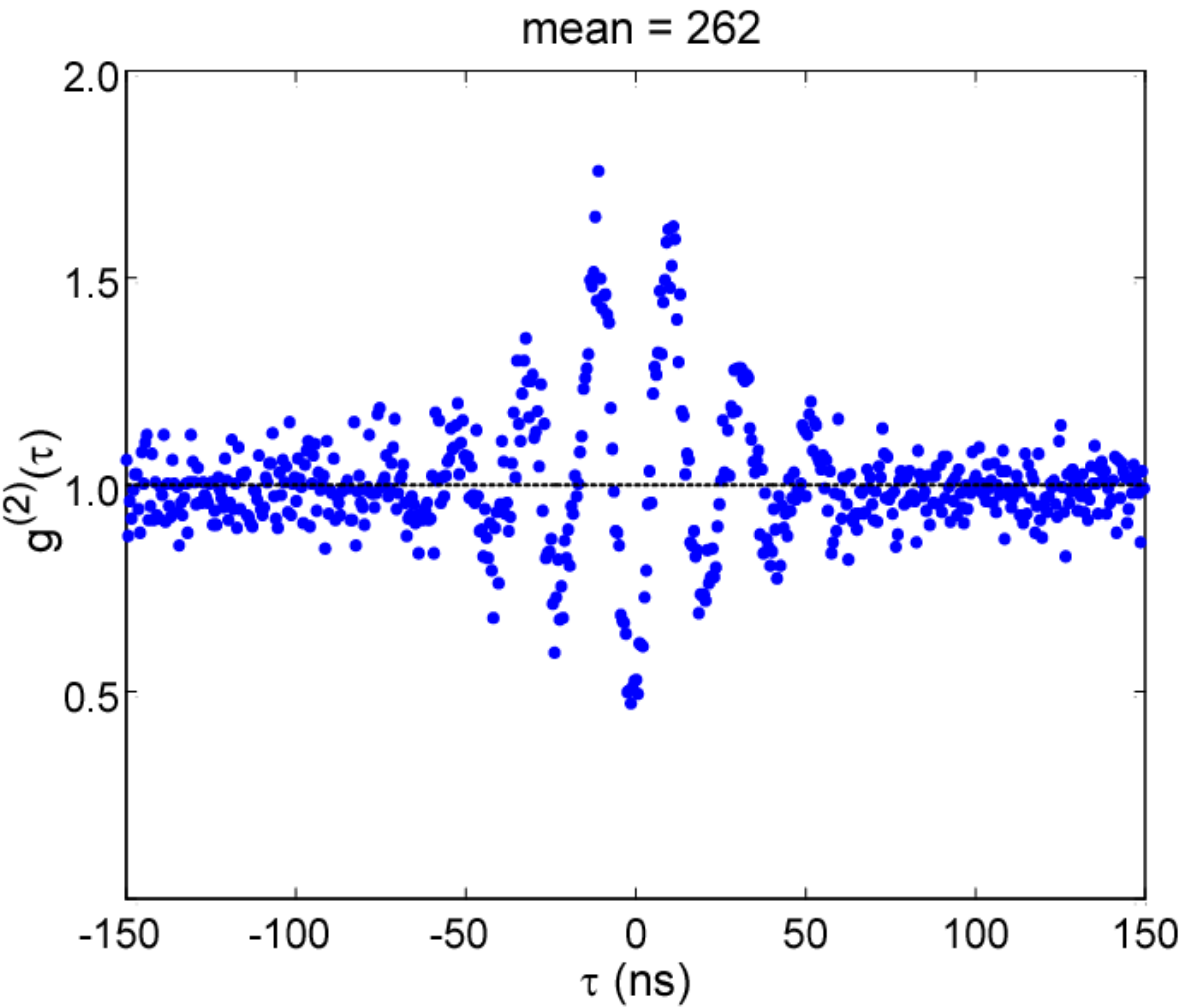
mean = 137
2.0
1.5
1.0
0.5
g^(2)(τ)
-150
-100
-50
0
50
100
150
τ (ns)


mean = 150
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

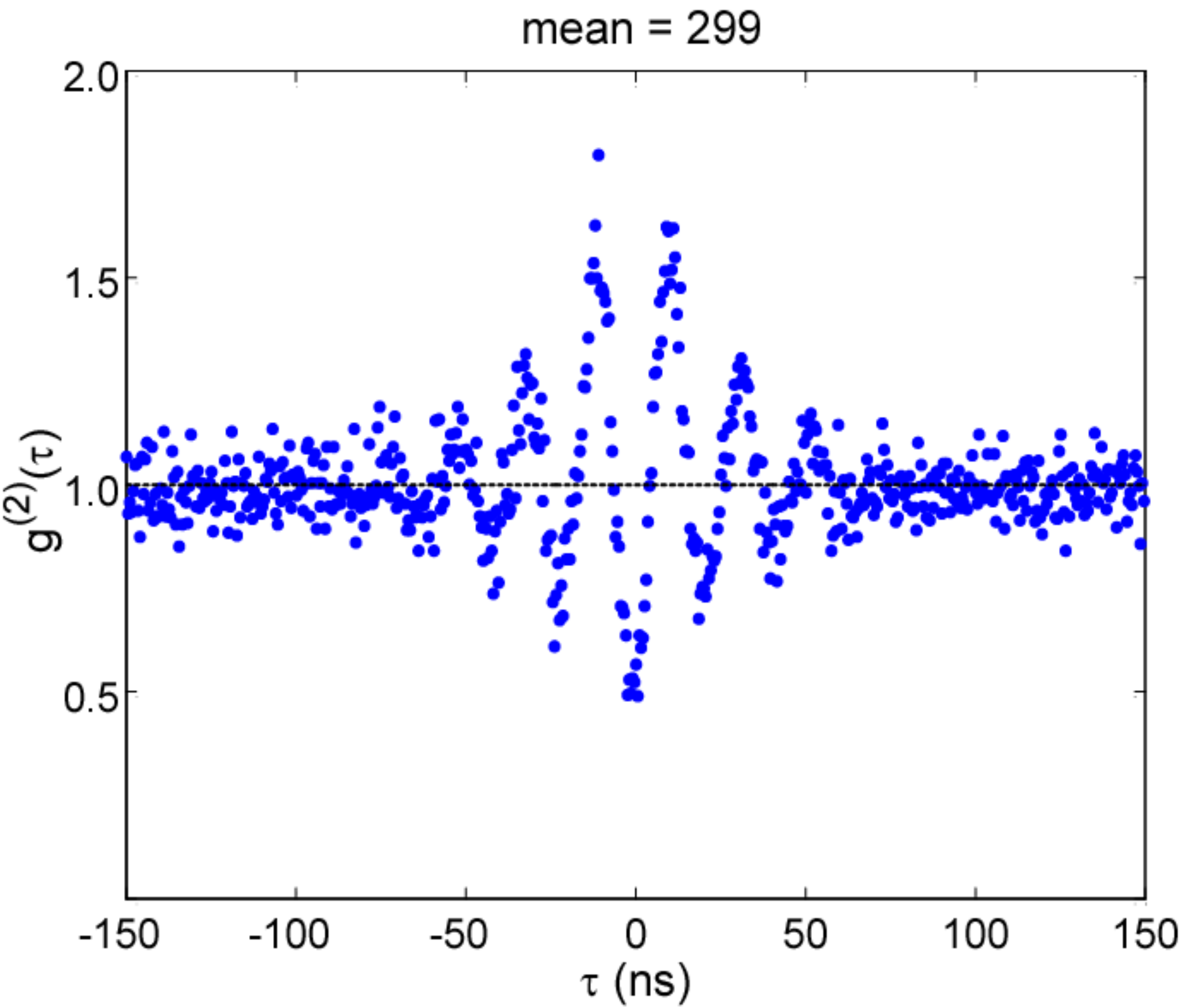

mean = 186
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)



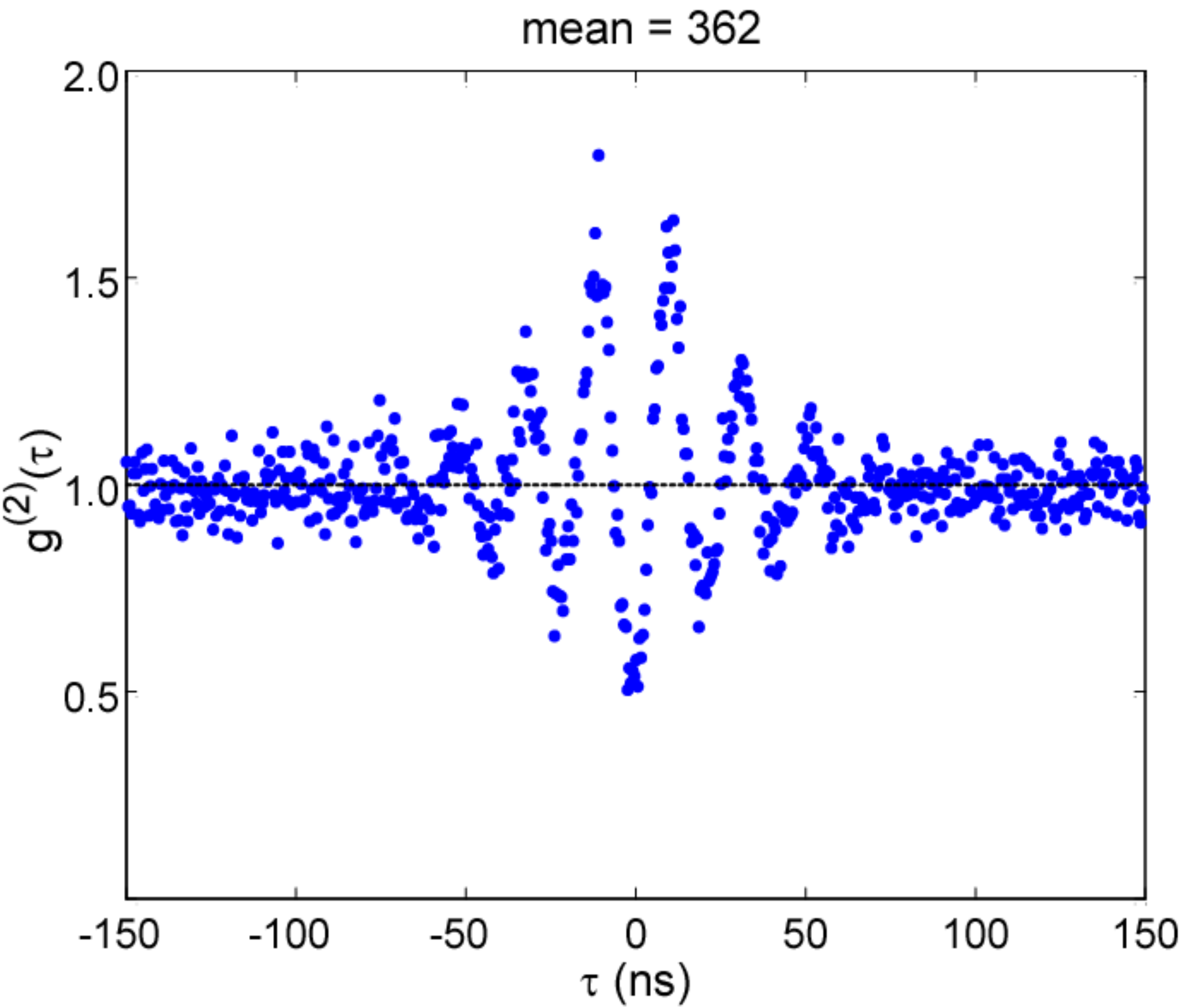
mean = 224
2.0
1.5
1.0
0.5
g(2)(τ)
-150
-100
-50
0
50
100
150
τ (ns)

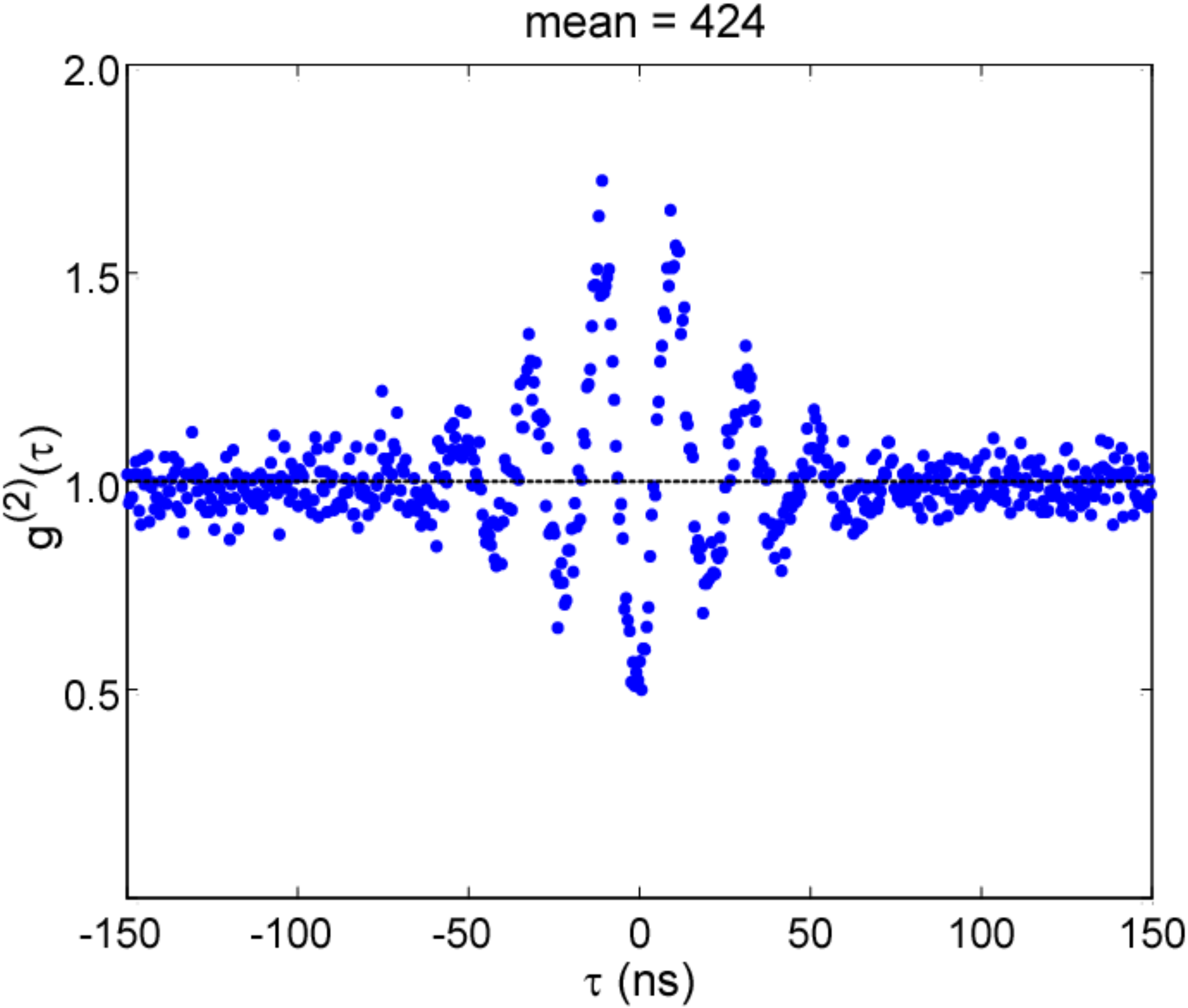


mean = 262
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

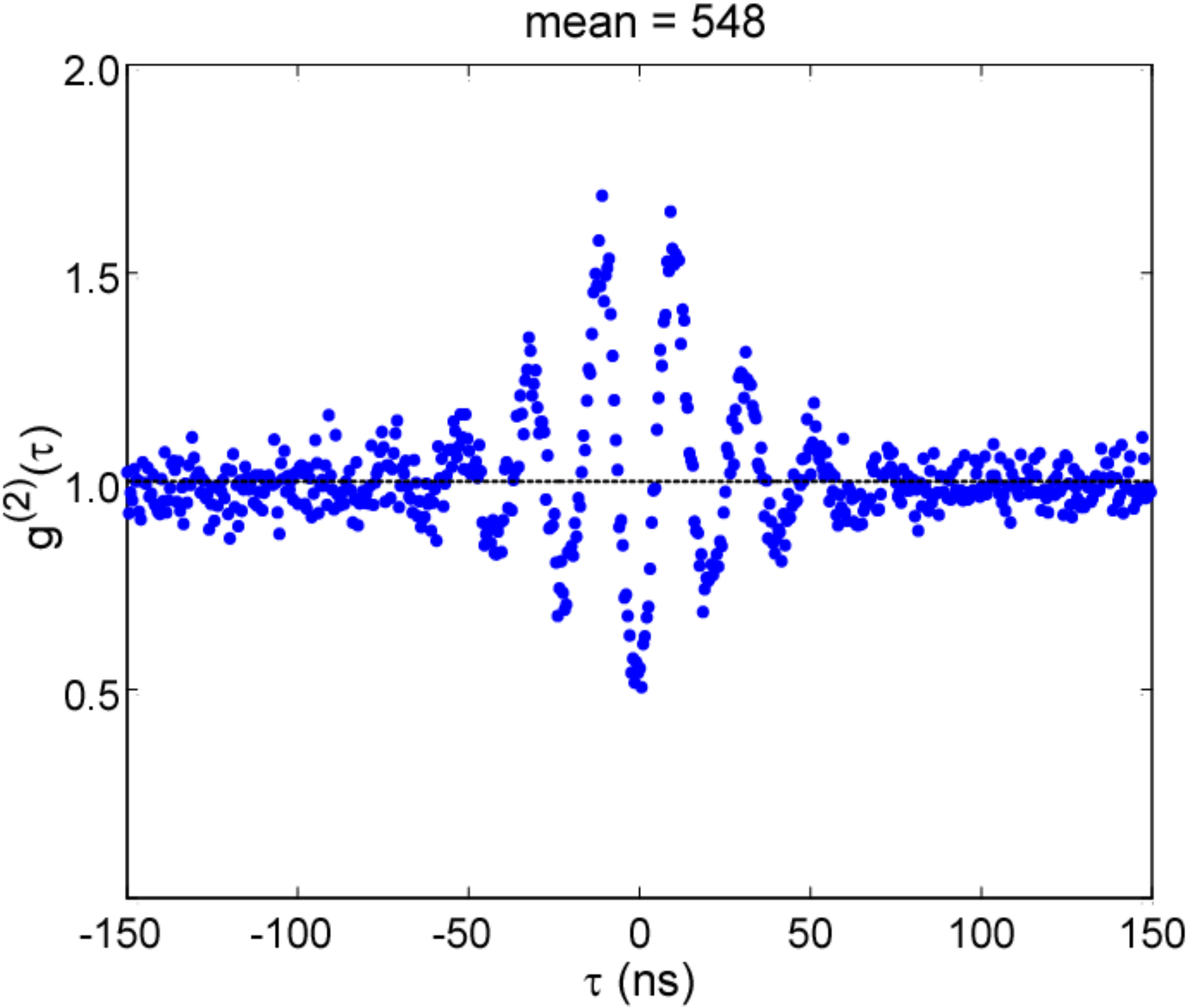


mean = 299
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

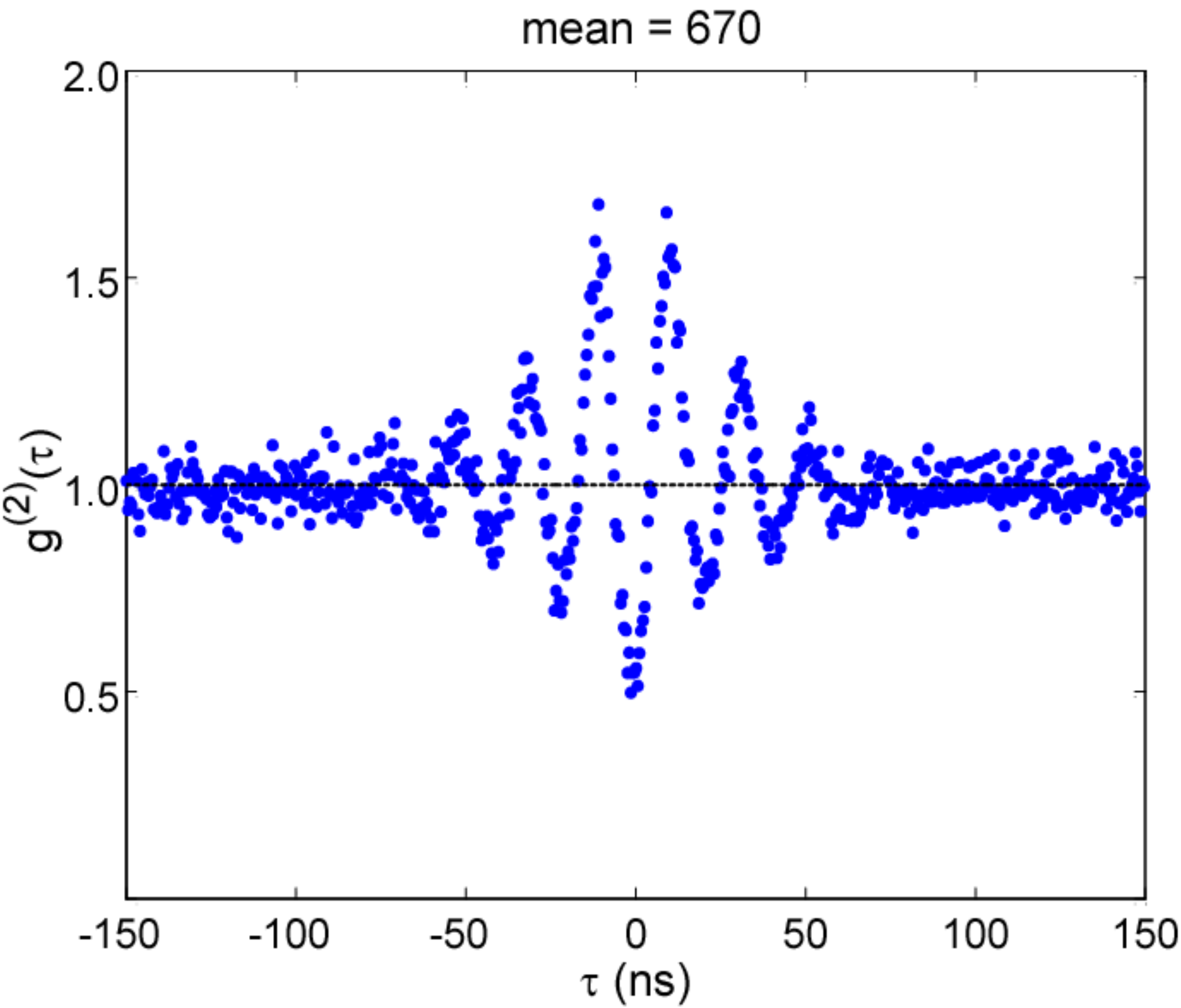

mean = 362
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)



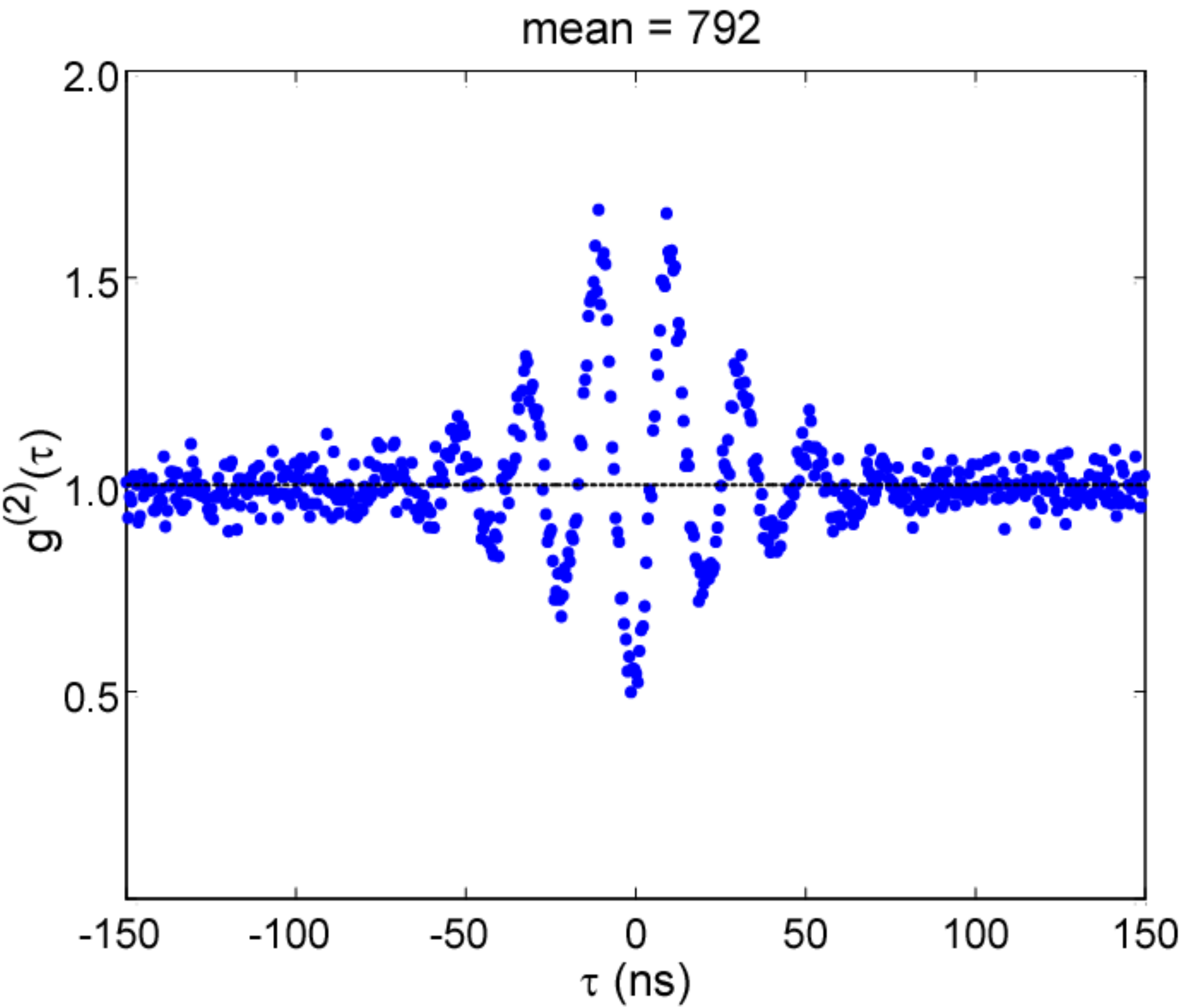
mean = 424
2.0
1.5
1.0
0.5
g(2)(τ)
-150
-100
-50
0
50
100
150
τ (ns)



mean = 548
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

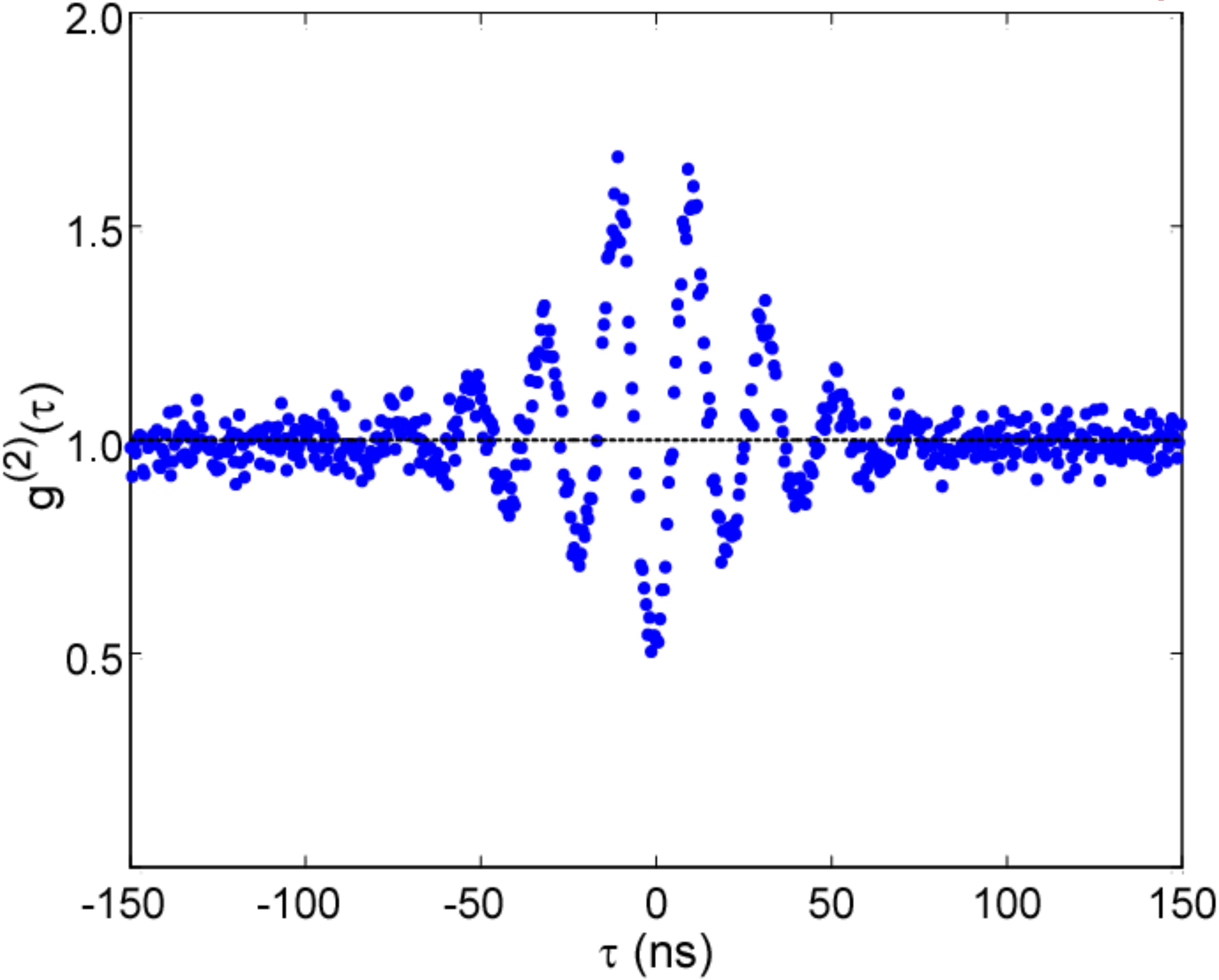


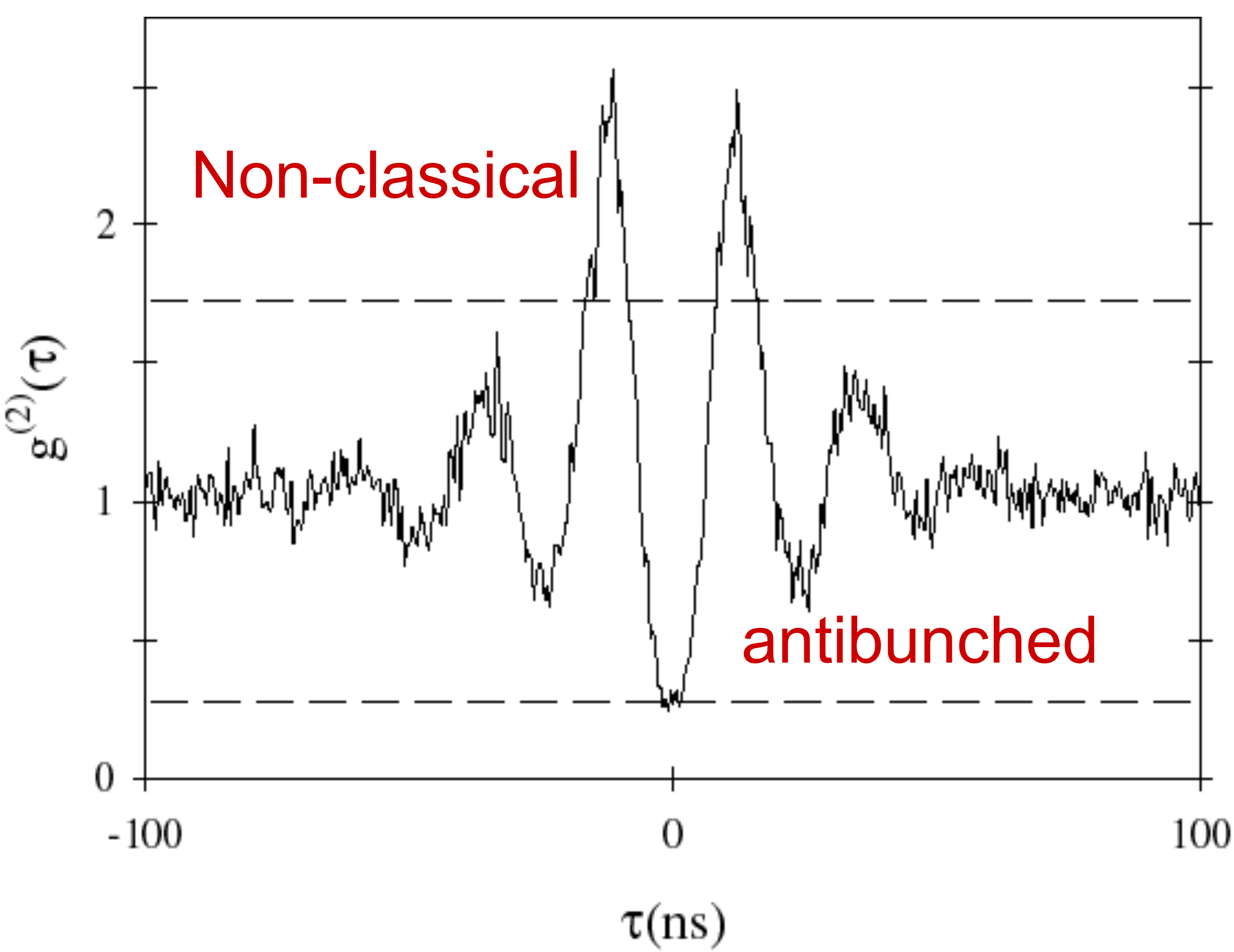
mean = 670
2.0
1.5
1.0
0.5
g(2)(τ)
-150
-100
-50
0
50
100
150
τ (ns)



mean = 792
2.0
1.5
1.0
0.5
g(2)(τ)
-150
-100
-50
0
50
100
150
τ (ns)

7 663 536 starts mean = 913 1 838 544 stops





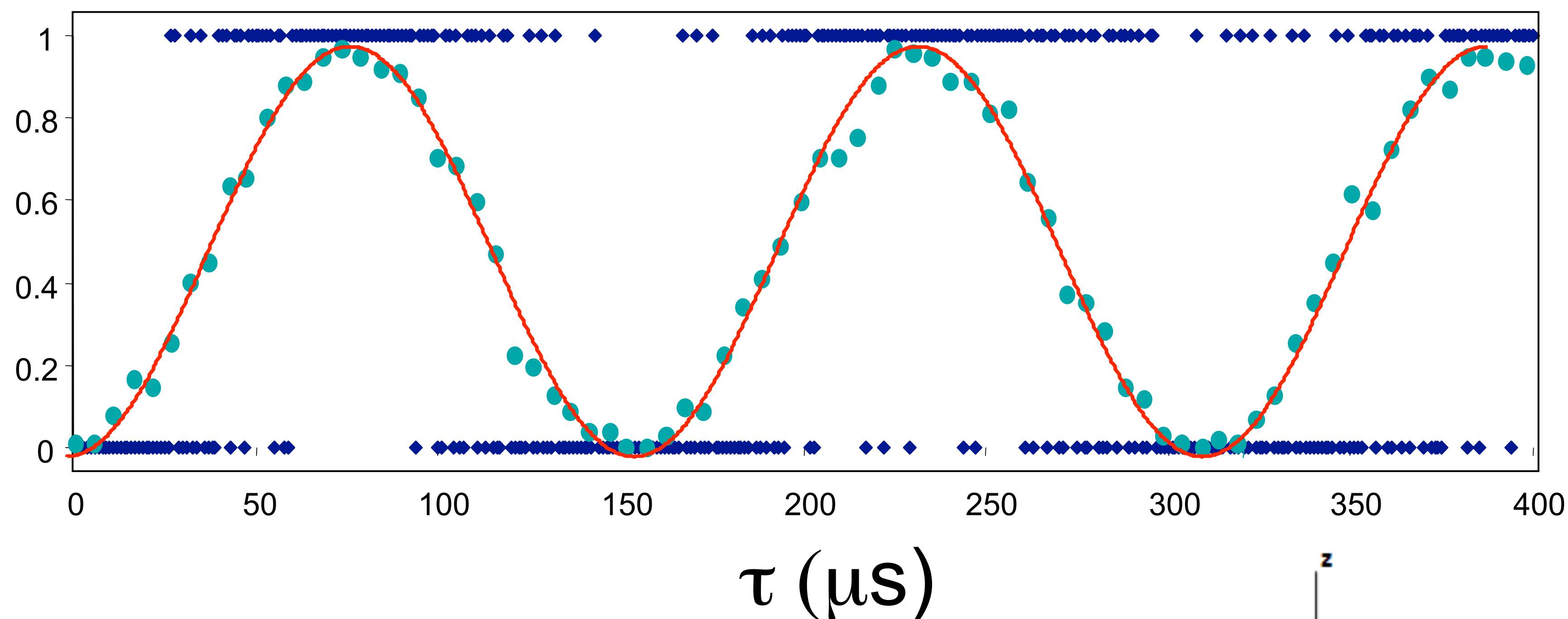
Classically $g^{(2)}(0) > g^{(2)}(\tau)$ and
also $|g^{(2)}(0)-1| > |g^{(2)}(\tau)-1|$

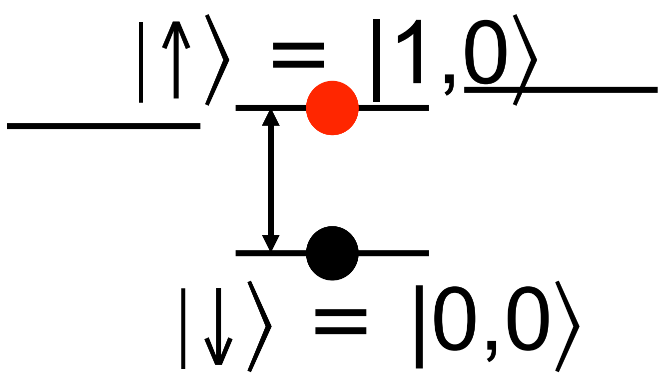
Another example
Rabi Oscillations in trapped ion system
(JQI, C. Monroe Laboratory)

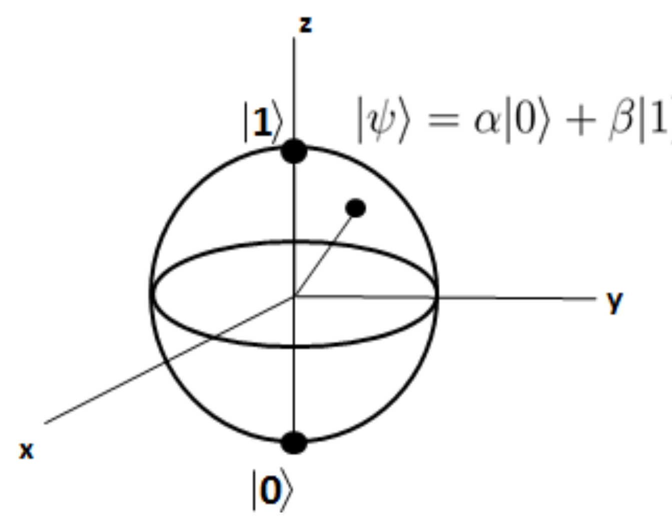
Qubit superposition (Ytterbium ion) :

Prob(↑|↓)

$$|\Psi\rangle = a_0|\uparrow\rangle + a_1|\downarrow\rangle$$







The state of the cavity QED system for N atoms is:

$$|\psi\rangle = |00\rangle + \alpha|10\rangle + \beta|01\rangle + (\alpha^2/\sqrt{2})pq|20\rangle + (\alpha\beta)q|11\rangle + (\beta^2/\sqrt{2})qr|02\rangle ,$$

The values of the coefficients are:

$$\alpha = (\mathscr{E}/\kappa)(1+2C)^{-1}, \quad \beta = -\sqrt{N}g(\gamma/2)^{-1}\alpha ,$$

$$p = 1-2C_1', \quad q = (1+2C)/(1+2C-2C_1')$$

$$r = \sqrt{1-1/N}, \qquad C_1' = C_1(1+\gamma/2\kappa)^{-1}$$

The probability of two simultaneous transmission of photons is:

$$\left|\langle 00|\hat{a}^2|\psi\rangle\right|^2 = \left|\alpha^2 pq\right|^2$$

This can be zero if *p* is zero

Back to optical cavity QED

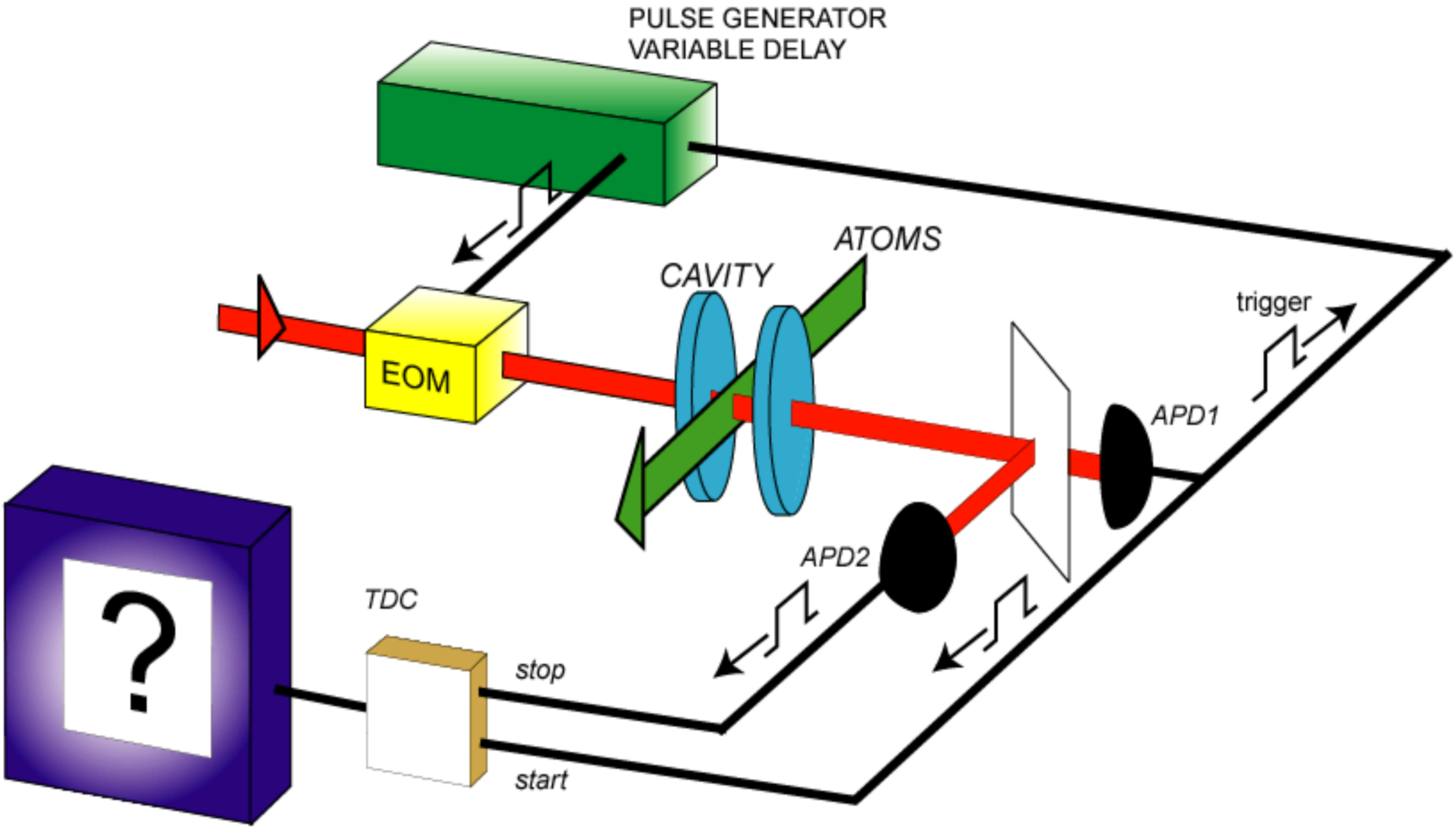
$$\left|\psi_c\right\rangle = \frac{\hat{a}\left|\psi\right\rangle}{\left\langle 00\right|\hat{a}\left|\psi\right\rangle} = \left|00\right\rangle + \beta q\left|01\right\rangle + \alpha pq\left|10\right\rangle,$$

$$g^{(2)}(\tau) = \left|1 + \left(\frac{\Delta\alpha}{\alpha}\right)\exp\left[-\frac{(\kappa + \gamma/2)}{2}\tau\right]\right.$$

$$\left.\times\left(\cos\Omega\tau + \frac{(\kappa + \gamma/2)}{2\Omega}\sin\Omega\tau\right)\ \right|^2$$

$$\left(\frac{\Delta\alpha}{\alpha}\right) = -2C_1^{'}\left[\frac{2C}{\left(1 + 2C - 2C_1^{'}\right)}\right]$$

Trigger the intensity-step with a fluctuation (photon) and measure the time evolution of the intensity as in $g^{(2)}(\tau)$. Can we feedback?



Conditional dynamics in cavity QED:

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

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

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 (f_1) — Atomic Polarization (f_2)

Use passive feedback to stabilize the wavefunction

For times when the following relation holds, we see that the state resembles a steady state.

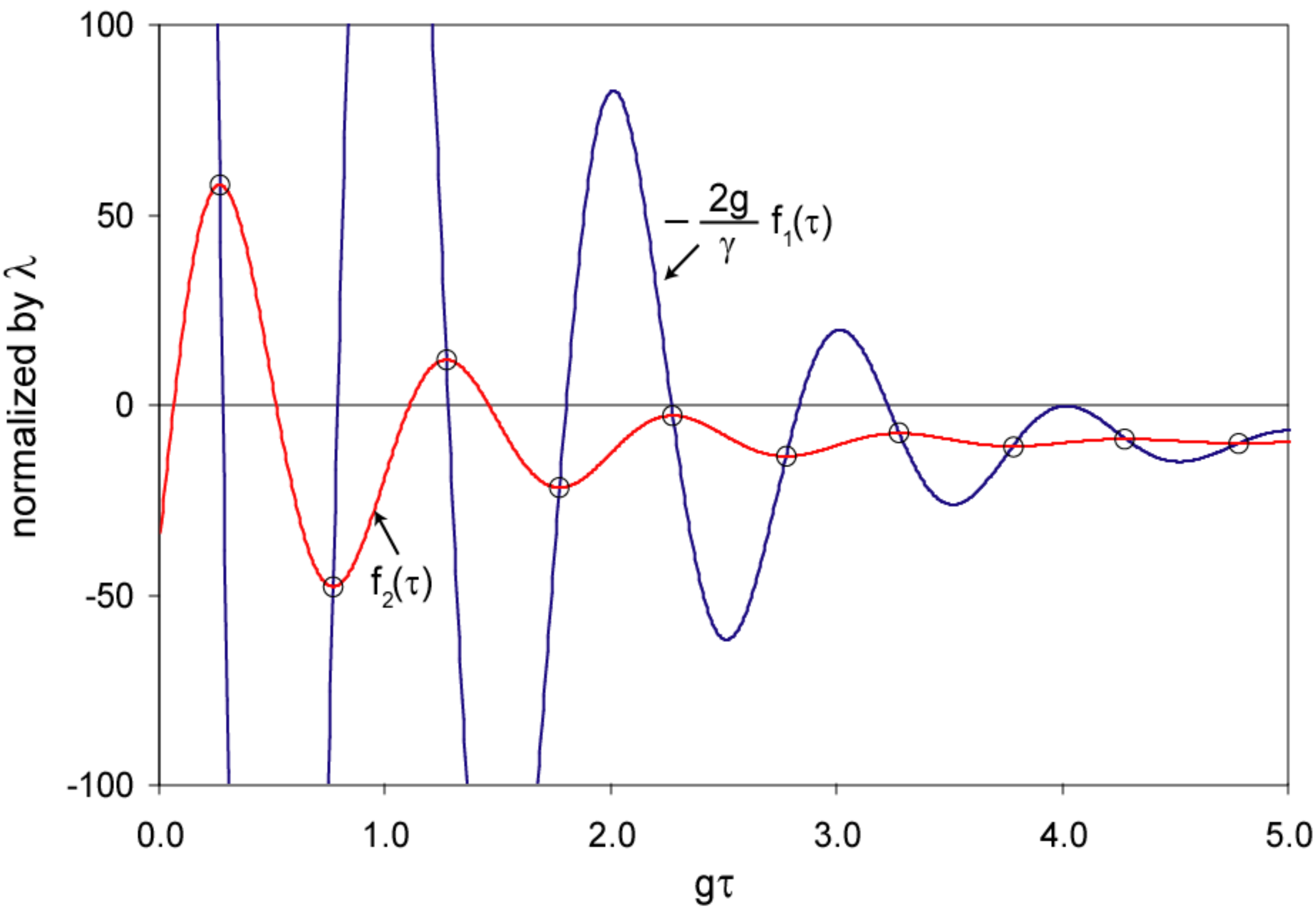
$$f_2(T) = -\frac{2g}{\gamma} f_1(T)$$

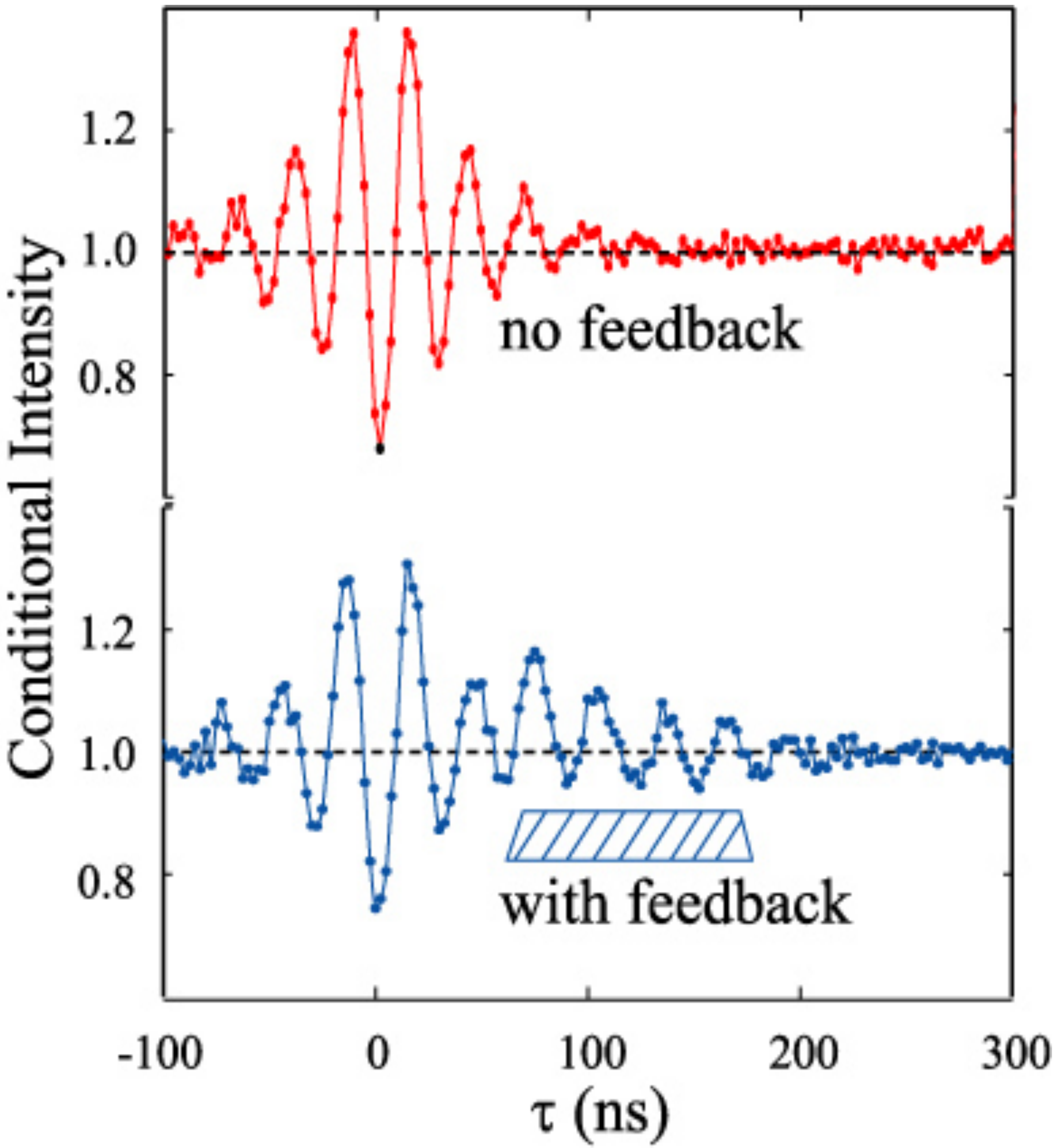
Problem: The driving field at times, T, will not stabilize the state.

Solution: Change the driving field so that it will.

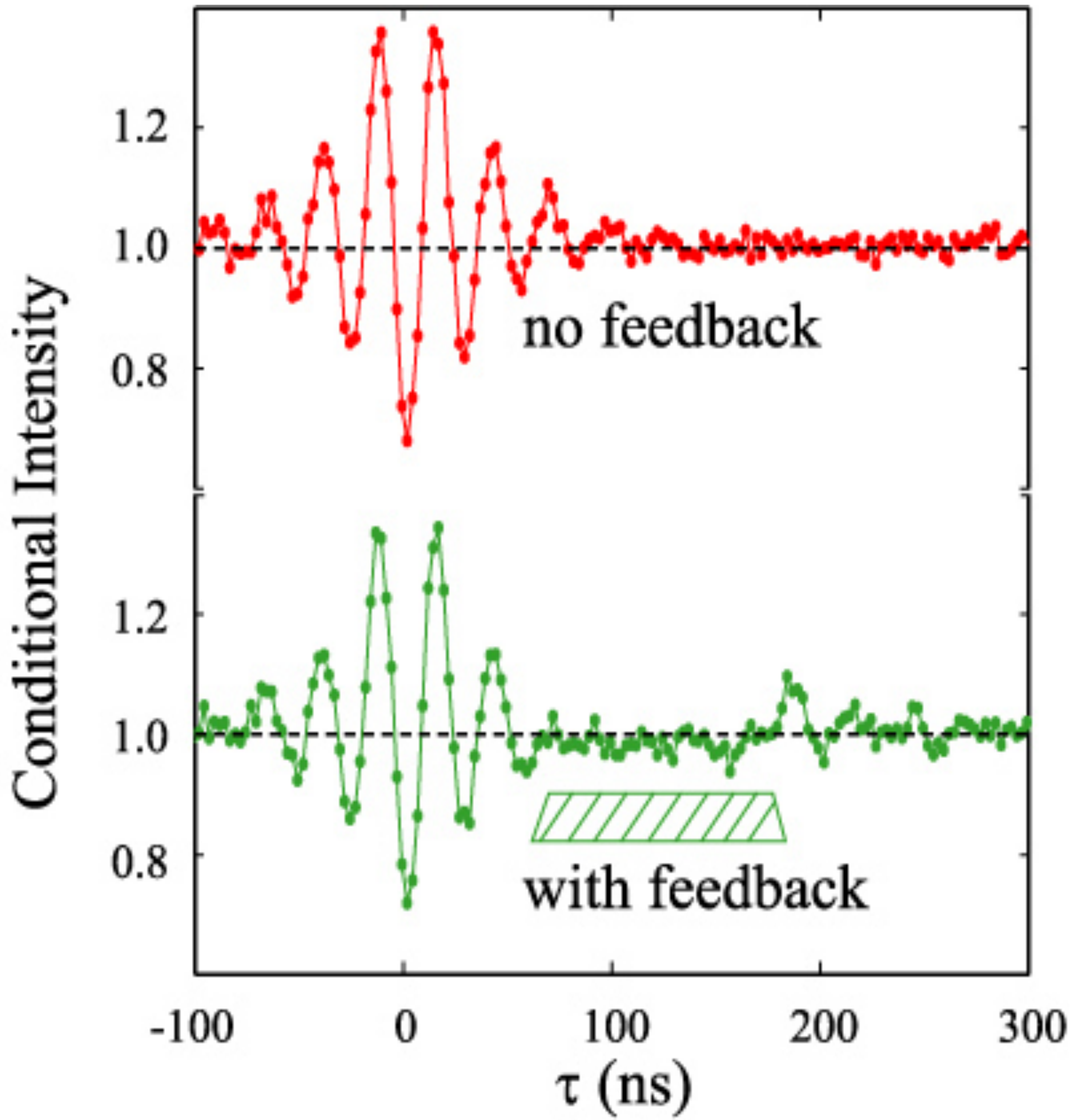
$$\frac{\text{driving intensity}(\tau > T)}{\text{driving intensity}(\tau < T)} = f_1(T)$$

Plot to find times where quantum control will work. (g, k, g)/2p = (30.0, 7.9, 6.0) MHz

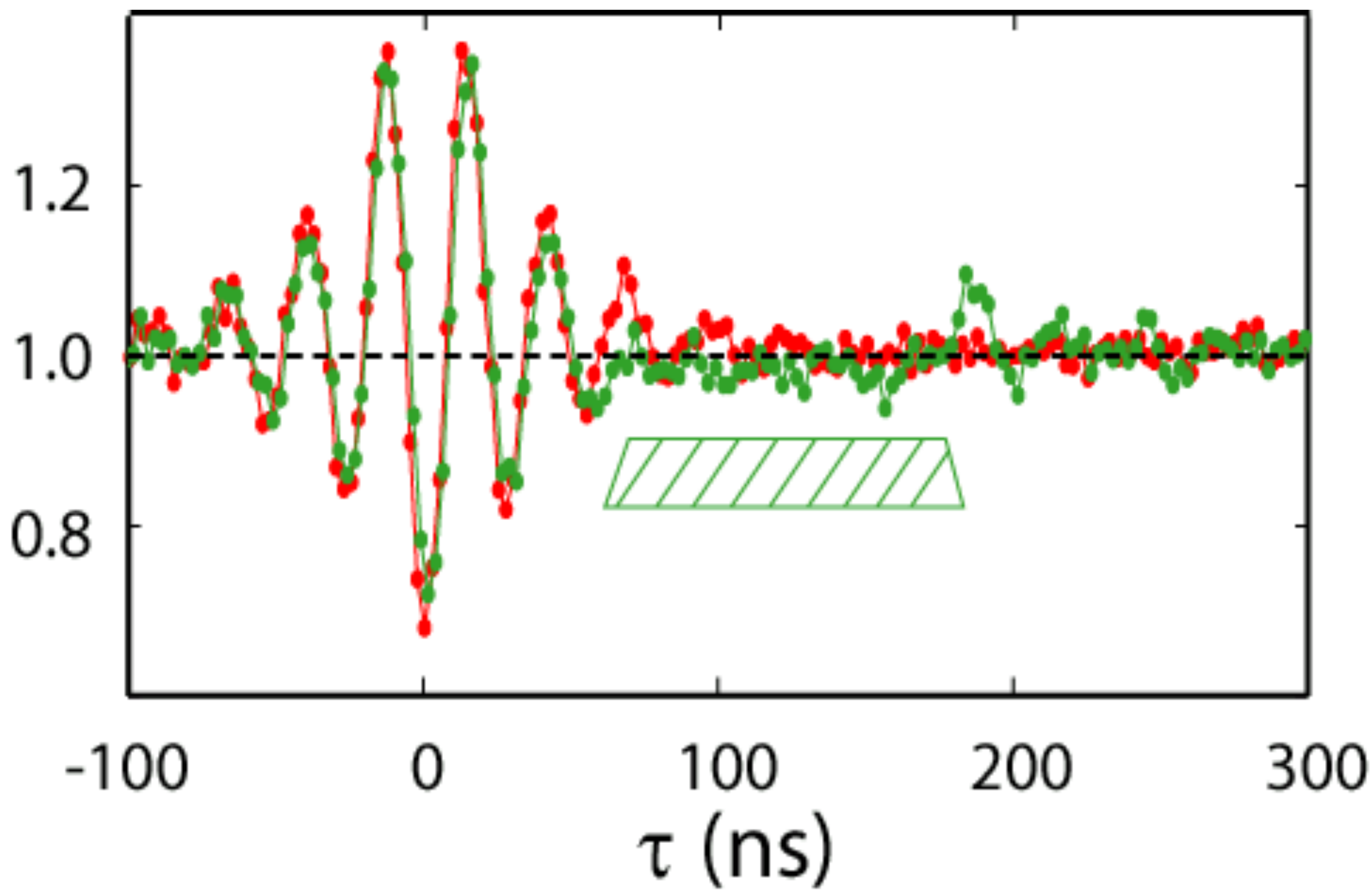




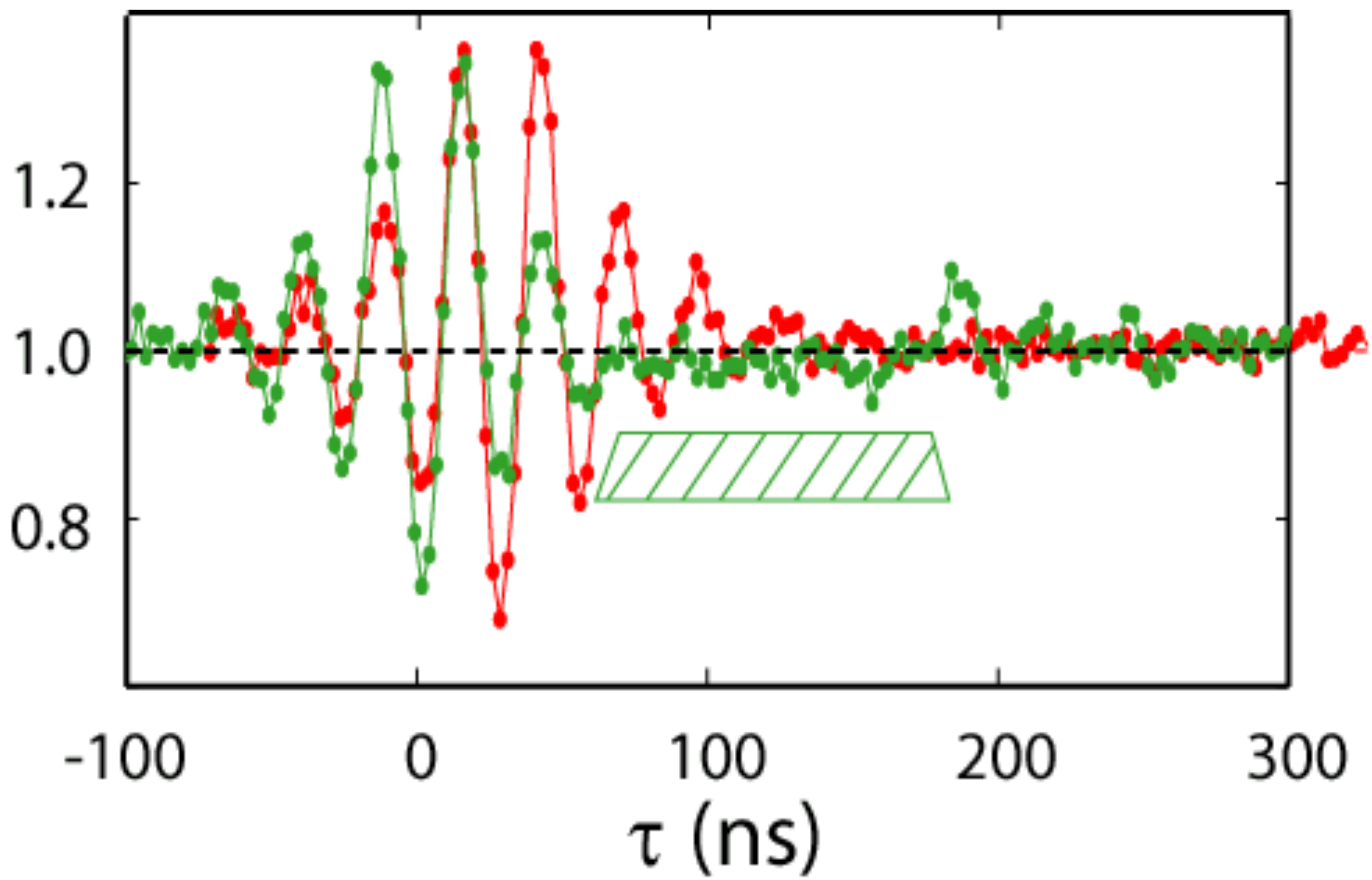
Conditional Intensity
1.2
1.0
0.8
no feedback
1.2
1.0
0.8
with feedback
-100
0
100
200
300
τ (ns)



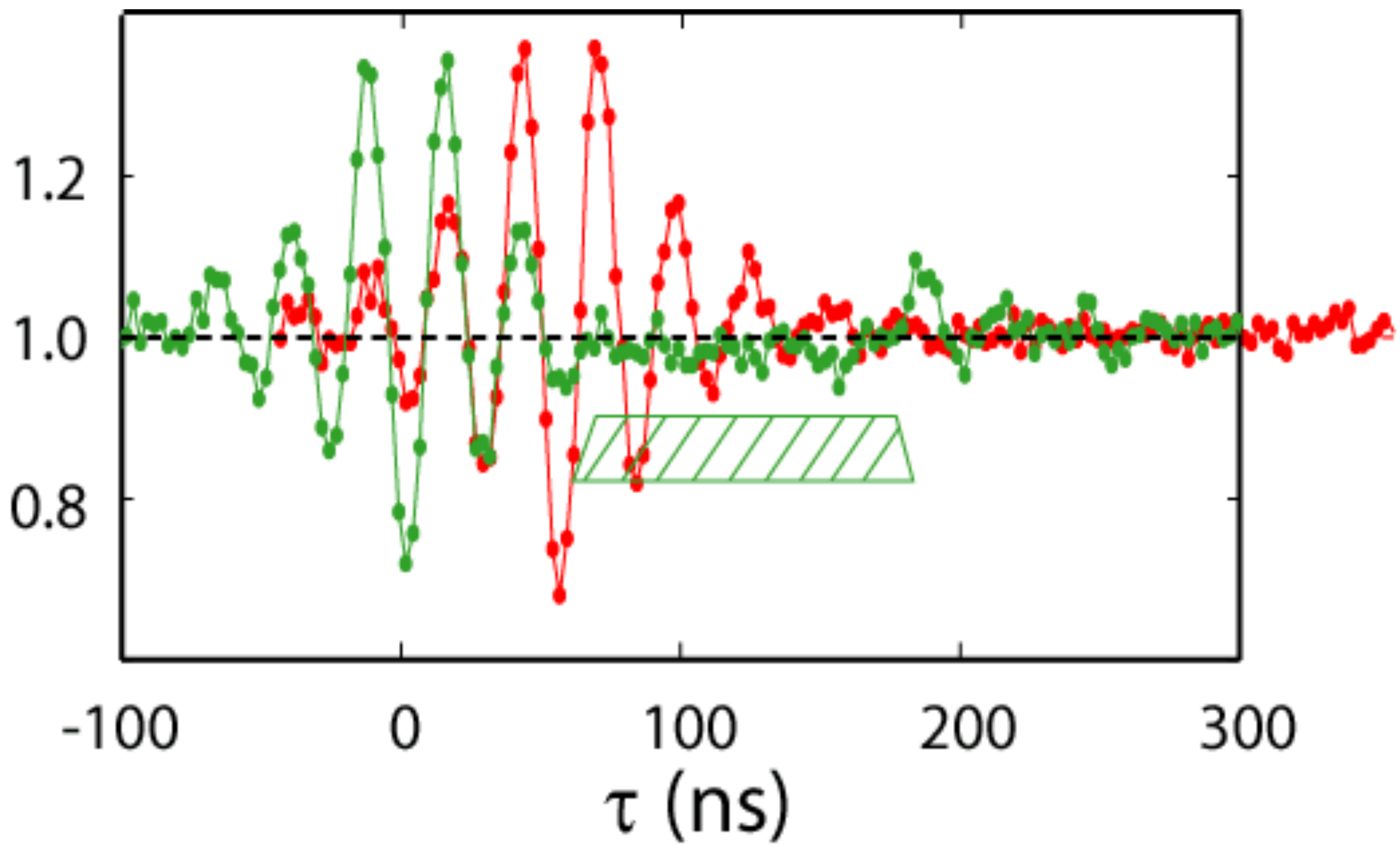
1.2
1.0
0.8
no feedback
1.2
1.0
0.8
with feedback
Conditional Intensity
-100
0
100
200
300
τ (ns)



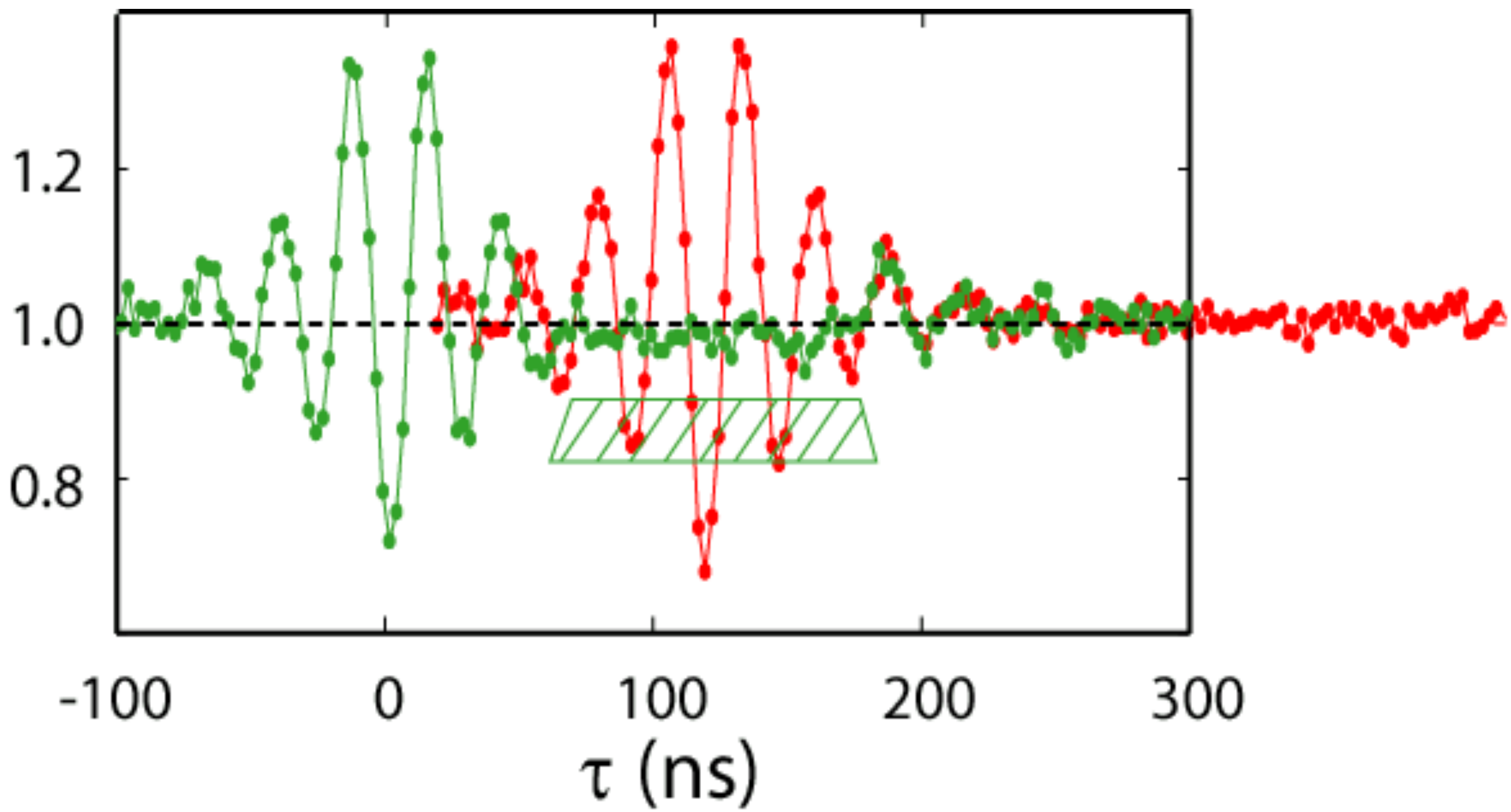
1.2
1.0
0.8
-100
0
100
200
300
τ (ns)



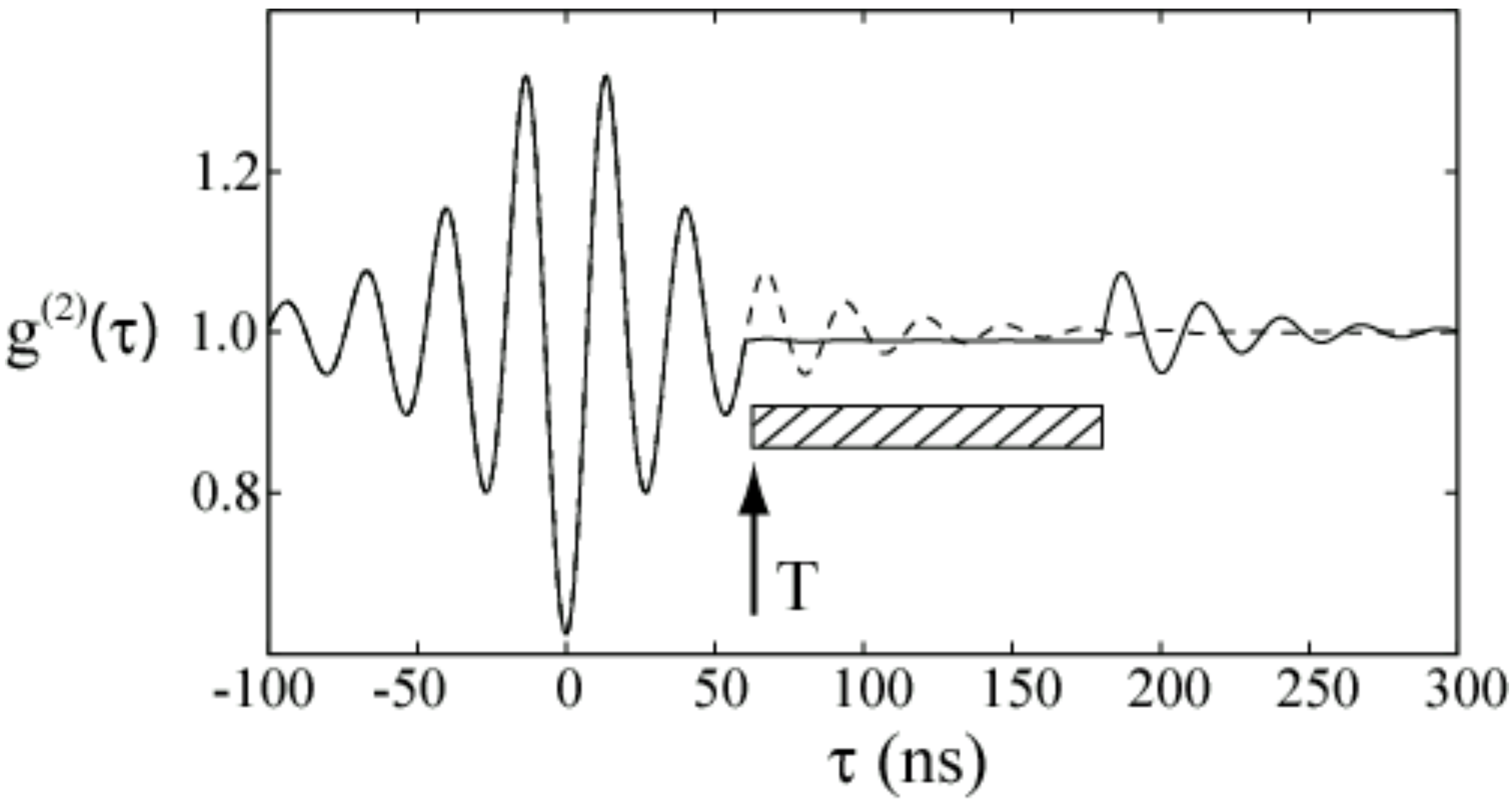
1.2
1.0
0.8
-100
0
100
200
300
τ (ns)

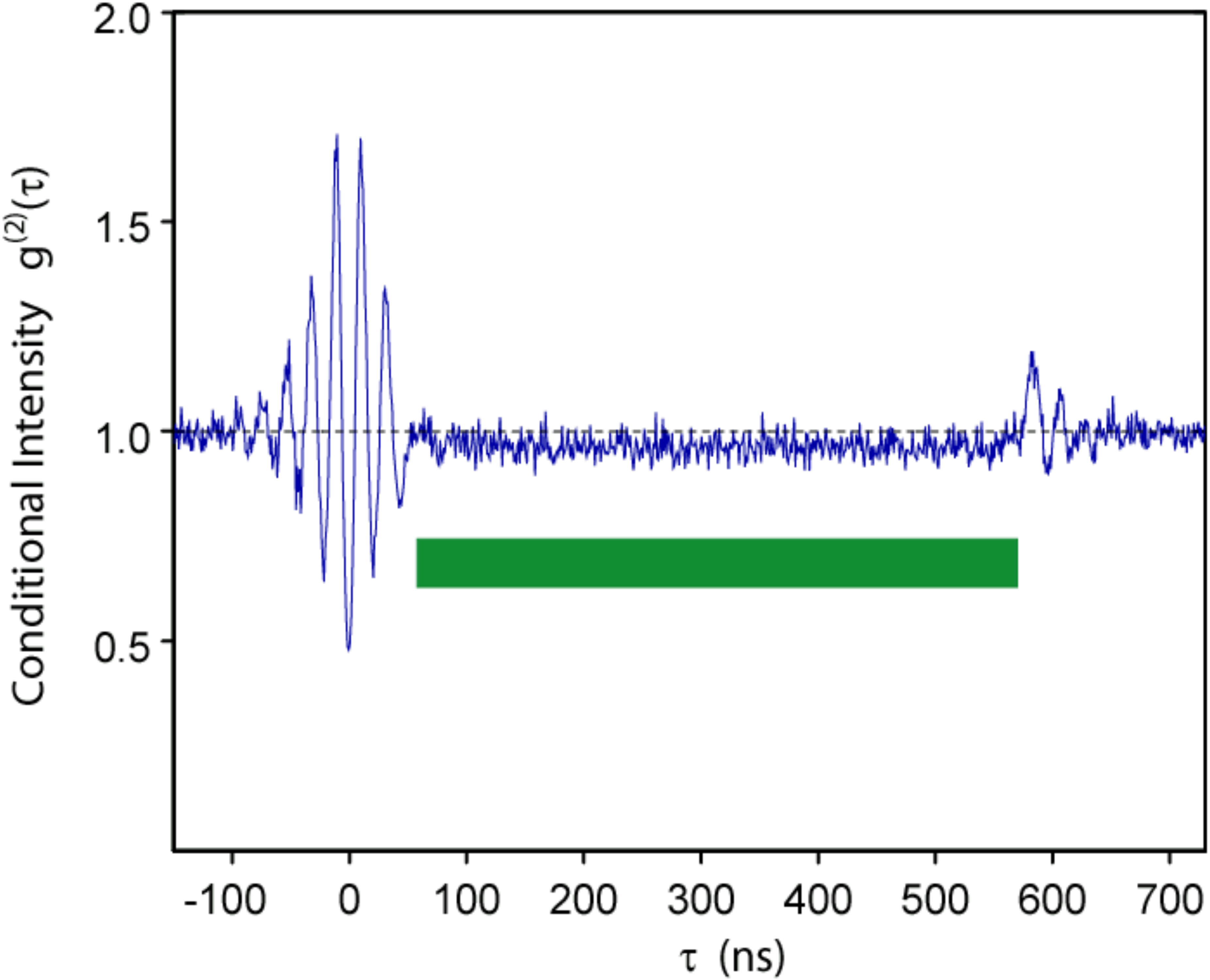


1.2
1.0
0.8
-100
0
100
200
300
τ (ns)


1.2
1.0
0.8
-100
0
100
200
300
τ (ns)

Theoretical prediction.




2.0
1.5
1.0
0.5
Conditional Intensity $g^{(2)}(\tau)$
-100
0
100
200
300
400
500
600
700
τ (ns)

How long can we hold it and then release it?

As long as we want!

How sensitive is it to detunings?

The protocol only operates on resonance.

Where is the information stored?

In the new steady state.

What is quantum about this?

The detection of the first photon.

Deterministic source?

No, we mostly create the vacuum: $|0,g> + \lambda|1,g> + \ldots$

Condition on a Click

Measure the correlation function of the Intensity and the Field:

$<I(t)\, E(t+\tau)>$

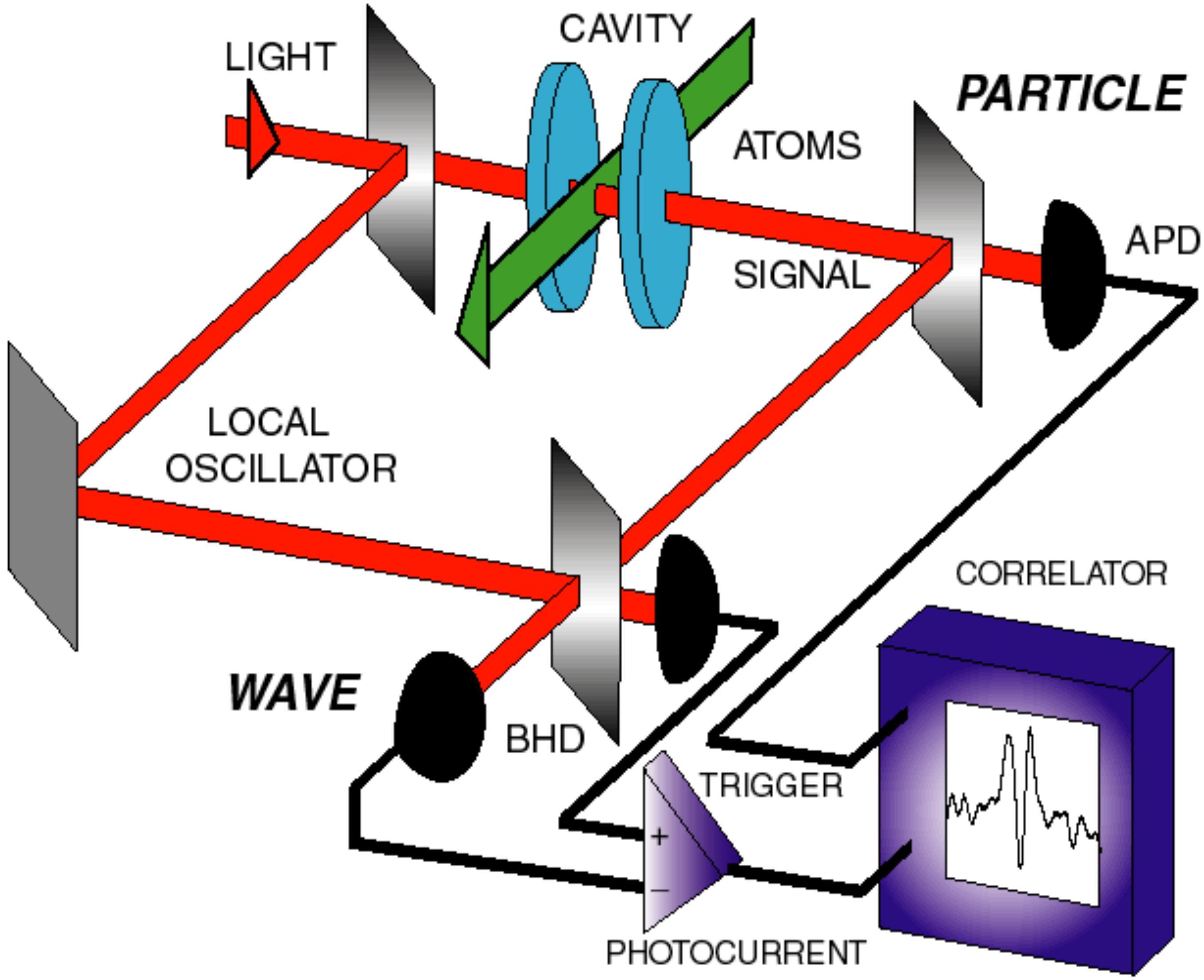
Normalized form:

$h_\theta(\tau) = <E(\tau)>_c / <E>$

From Cauchy Schwartz inequalities:

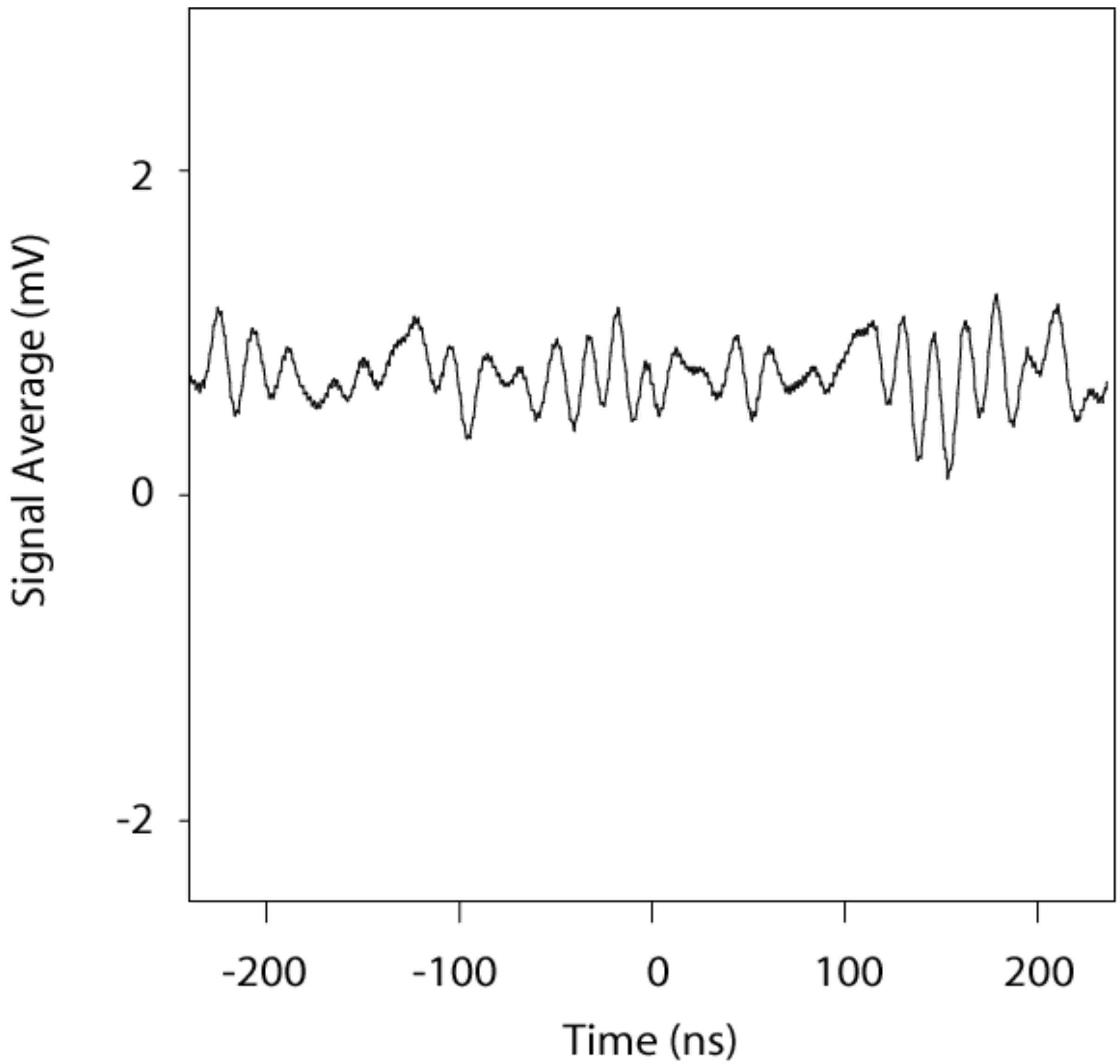
$$0 \le \bar{h}_0(0) - 1 \le 2$$

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

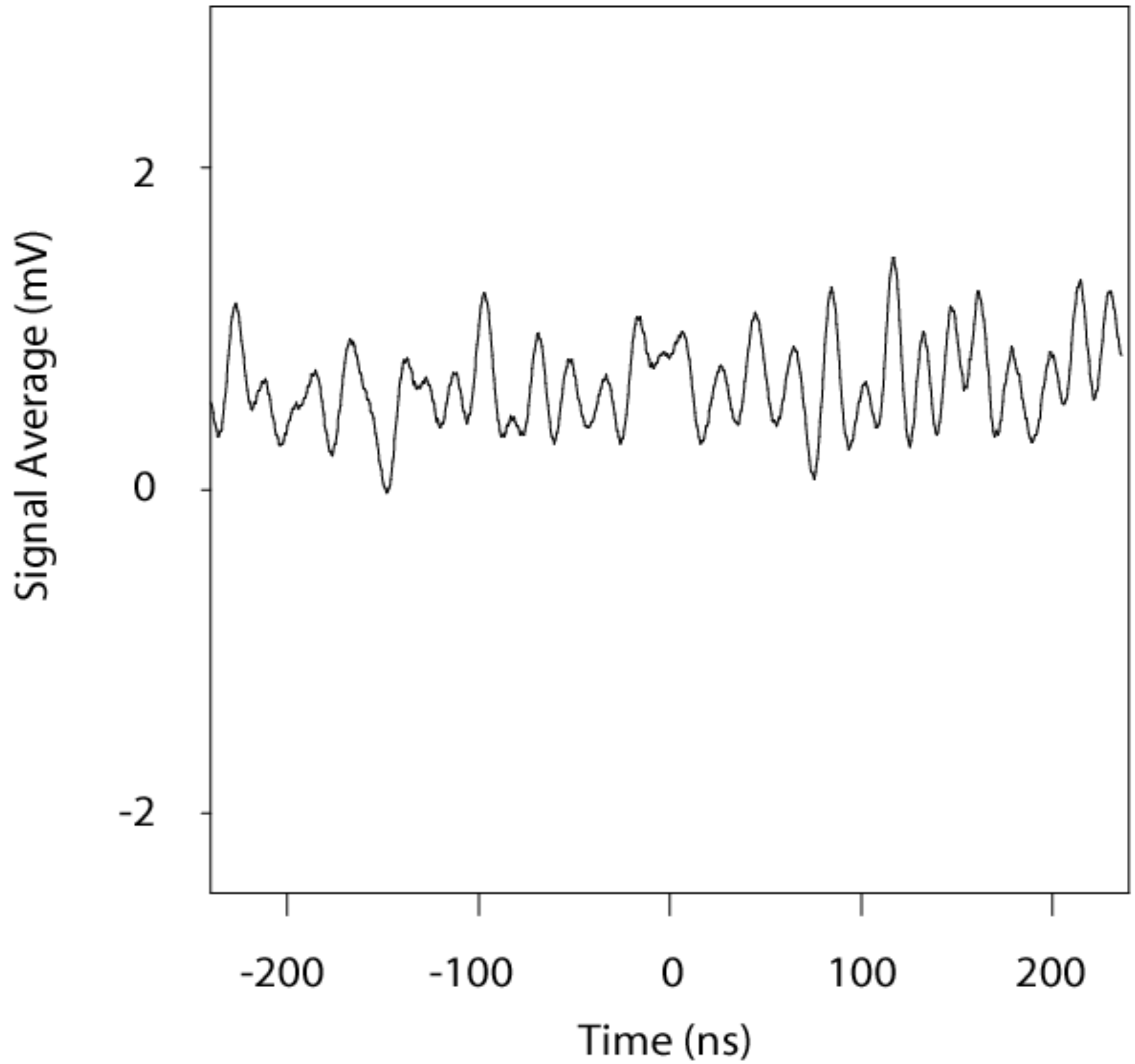


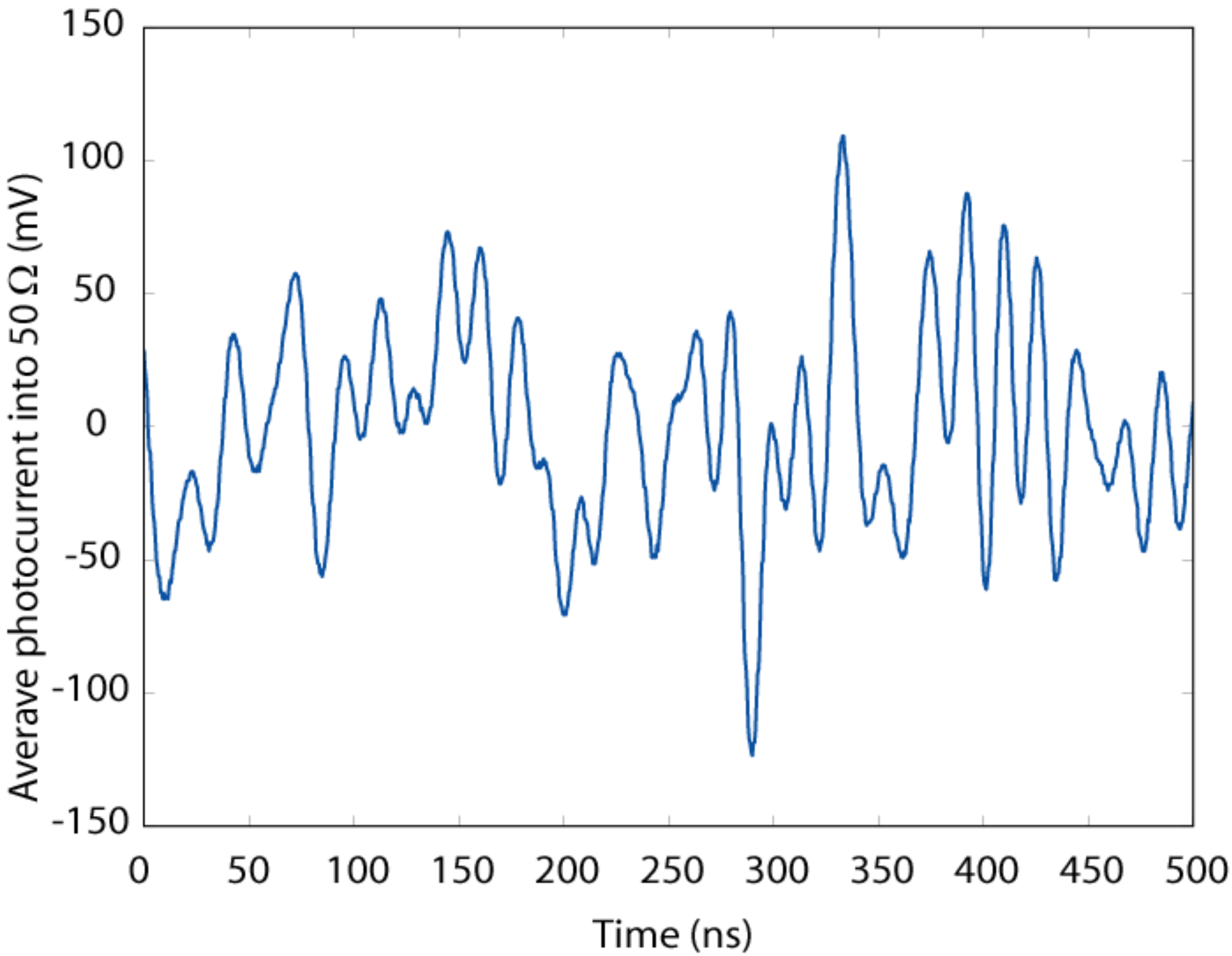
LIGHT
CAVITY
ATOMS
PARTICLE
APD
SIGNAL
LOCAL
OSCILLATOR
CORRELATOR
WAVE
BHD
TRIGGER
+
–
PHOTOCURRENT

Photocurrent average with random conditioning

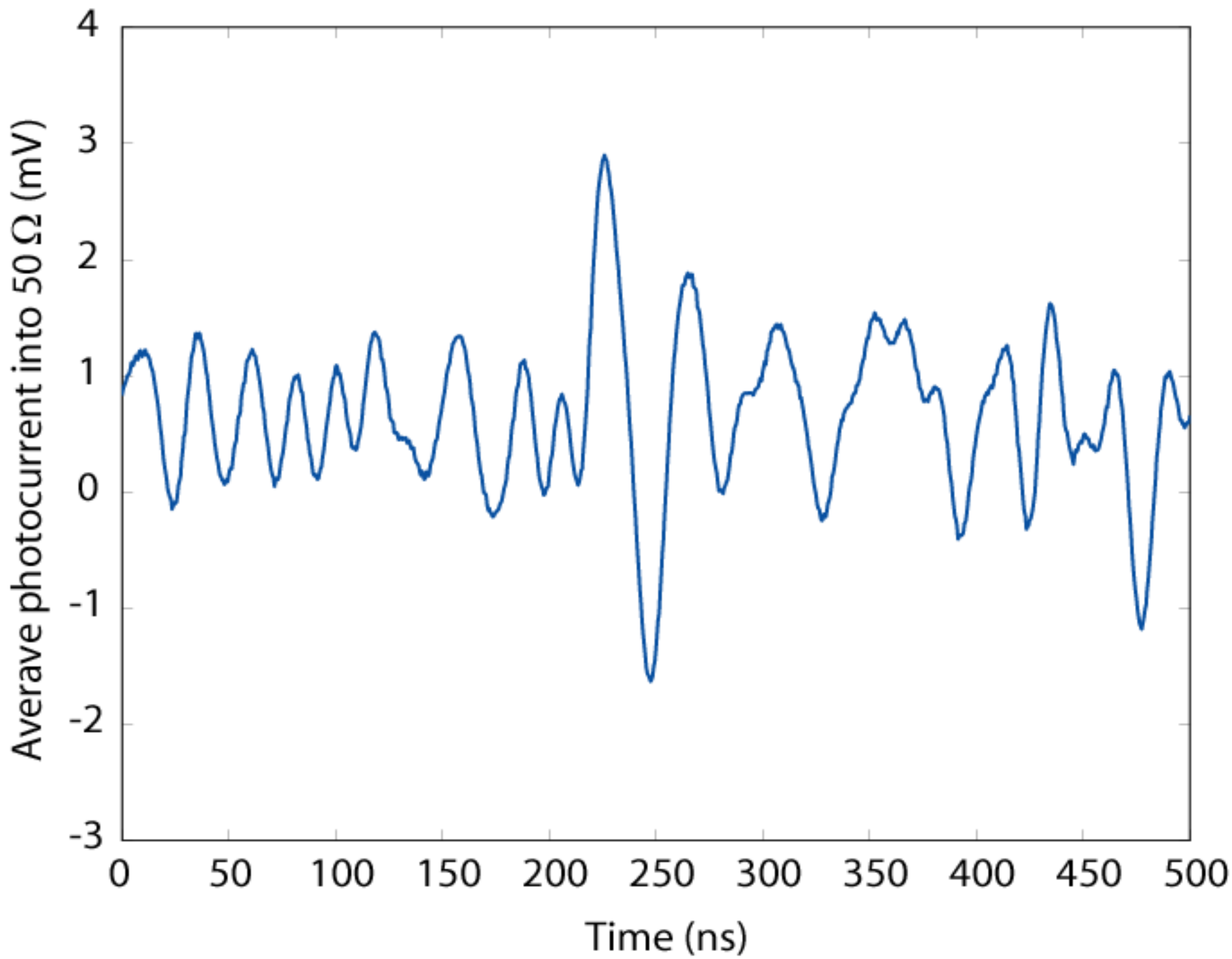


Conditional photocurrent with no atoms in the cavity.

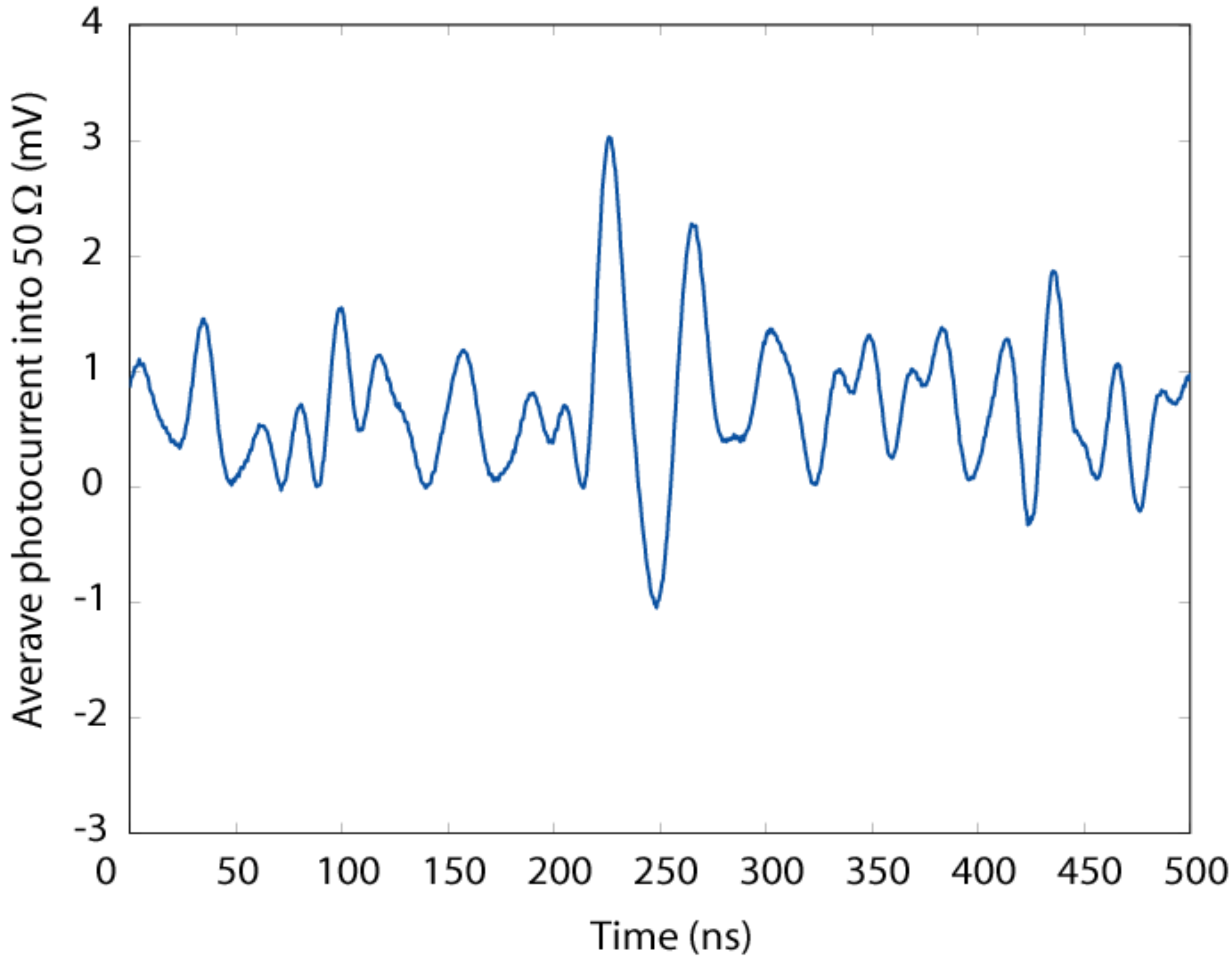




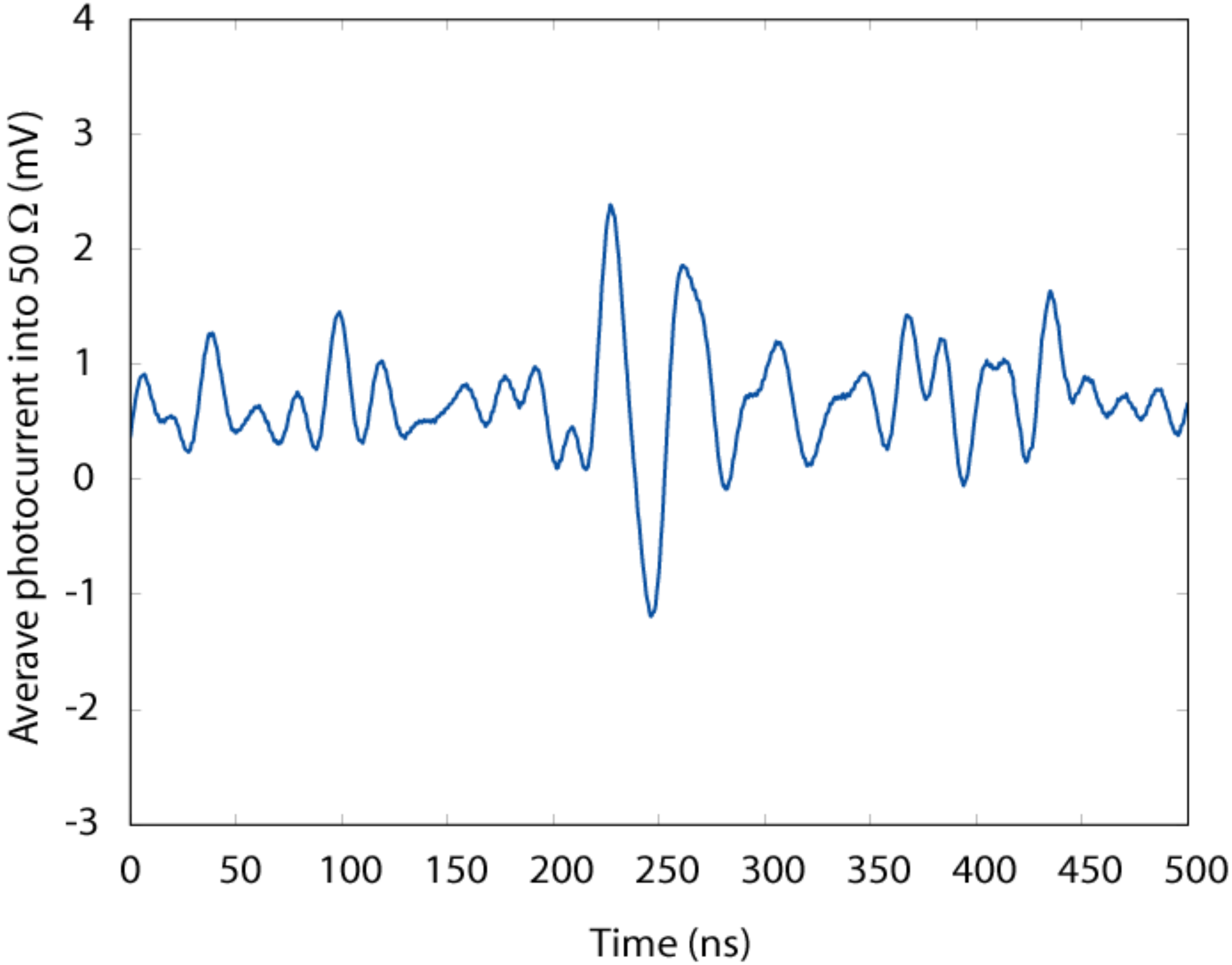
After 1 average



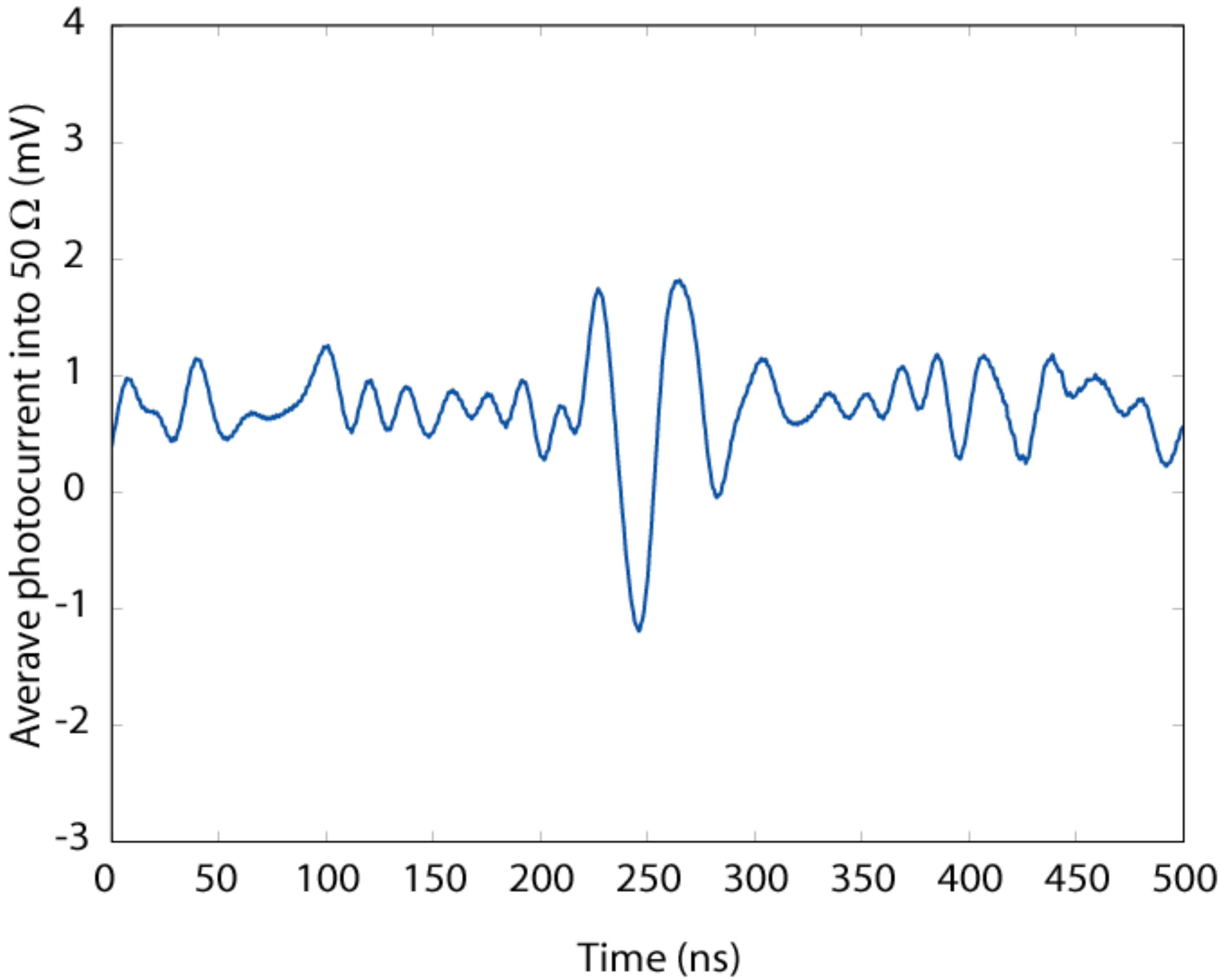
After 6,000 averages



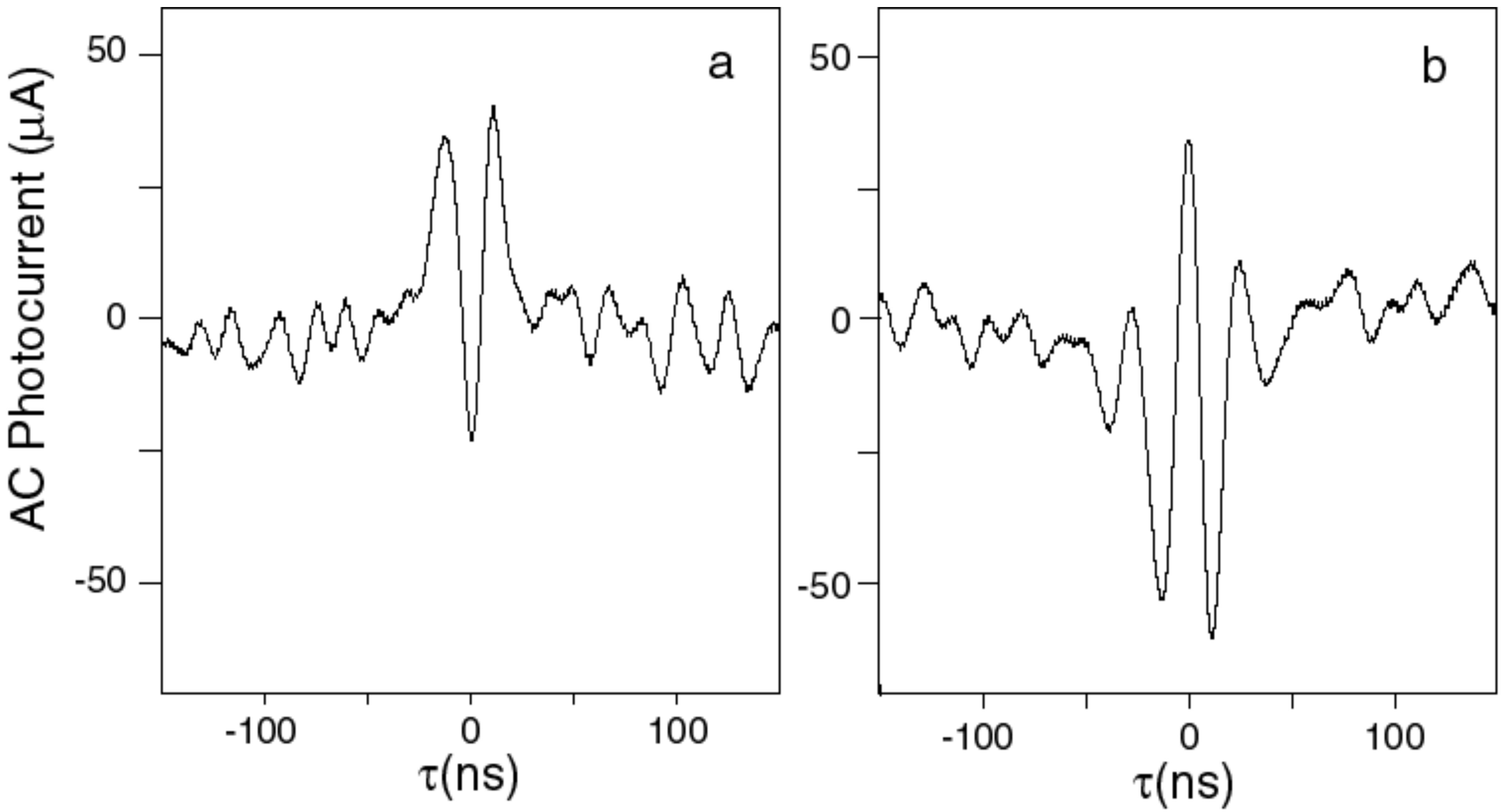
After 10,000 averages



After 30,000 averages

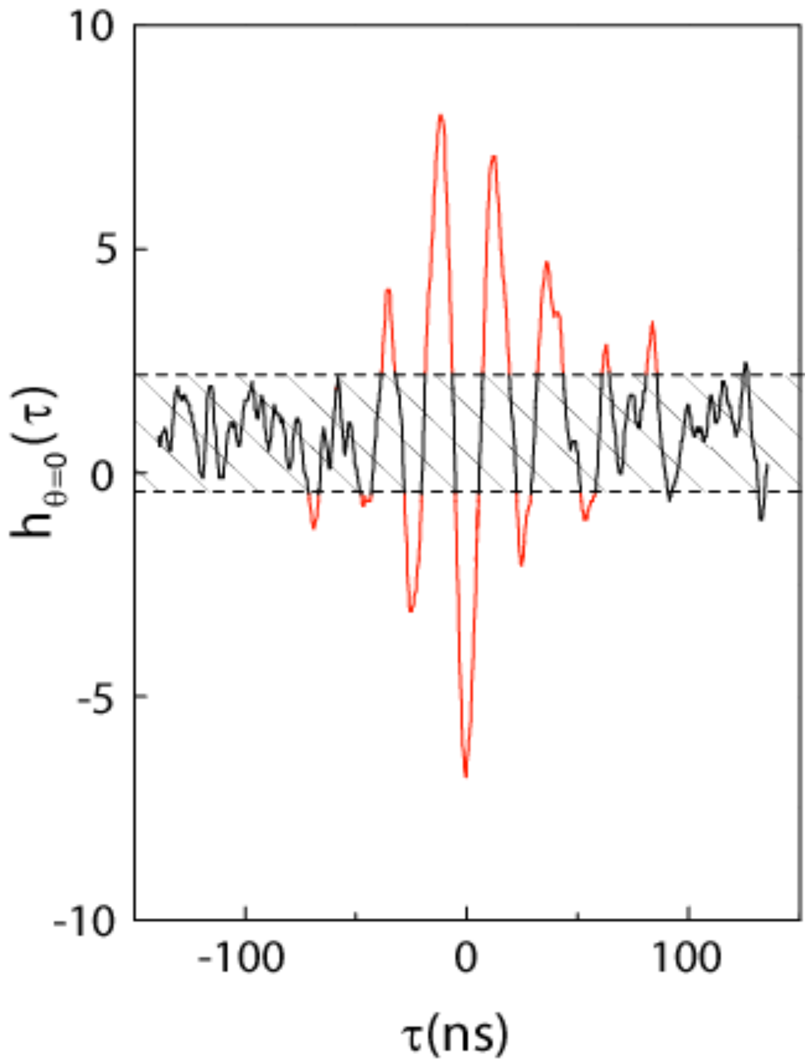


After 65,000 averages



Flip the phase of the Mach-Zehnder by 146°

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.

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

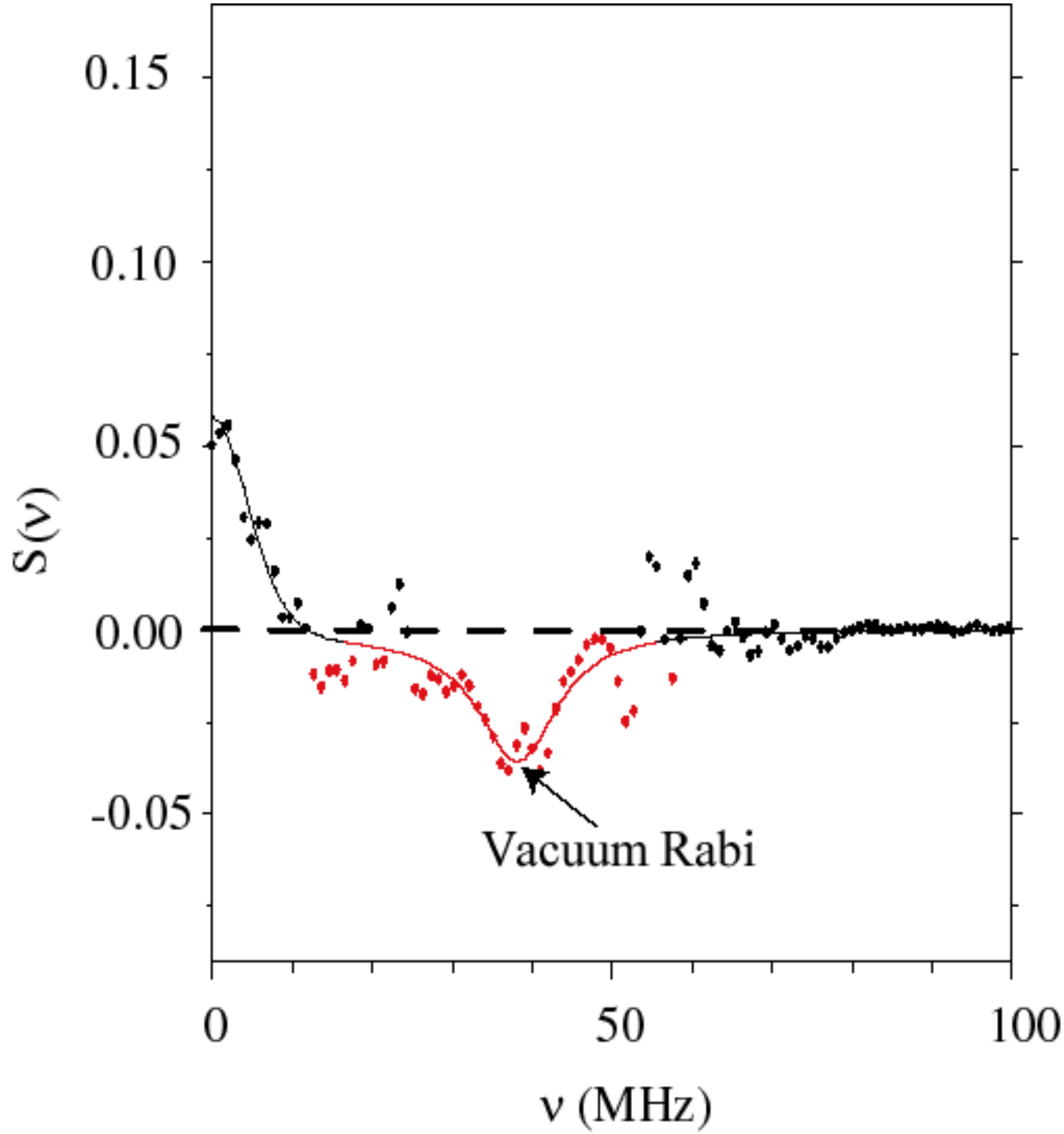
The conditional field prepared by the click is:

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

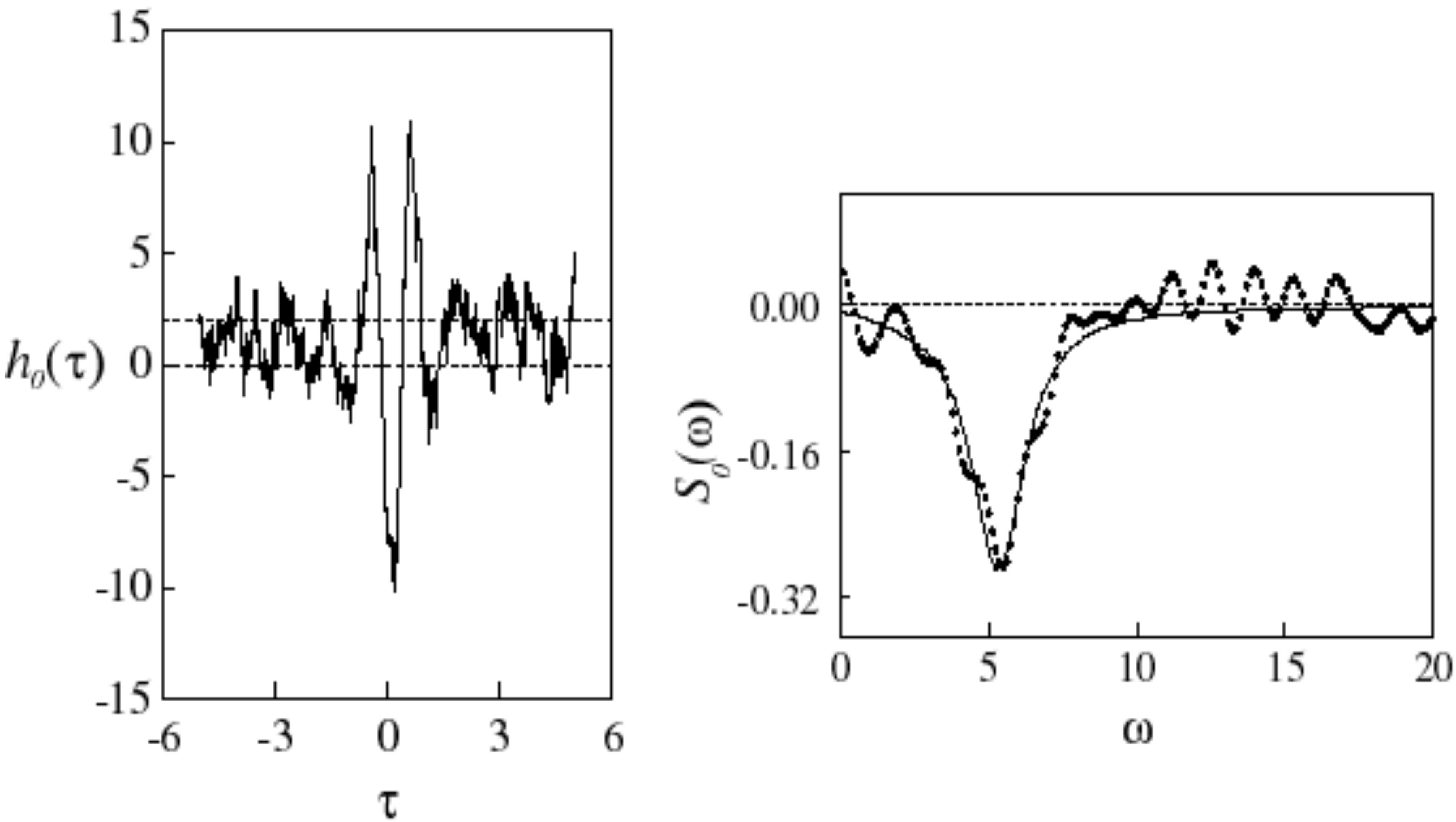
We measure the field of a fraction of a photon!

Fluctuations are very important.

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

- 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 (need of shaping the LO temporal mode) of the dynamical evolution of the electromagnetic field state.

Summary:

1. Review of correlations in quantum optics.
2. Cavity QED with two level atoms.
3. Quantum optics in optical cavity QED.

Gracias