Quantum Feedback in cavity QED

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SUNYSB

SUNY Stony Brook Quantum Optics group:
(Moving to University of Maryland College Park at the end of the summer)

http://funk.physics.sunysb.edu/lab/index.html

Students:
- Dr. Joseph Reiner
- Dr. Wade Smith
- Matthew Terraciano
- Frank Dimler

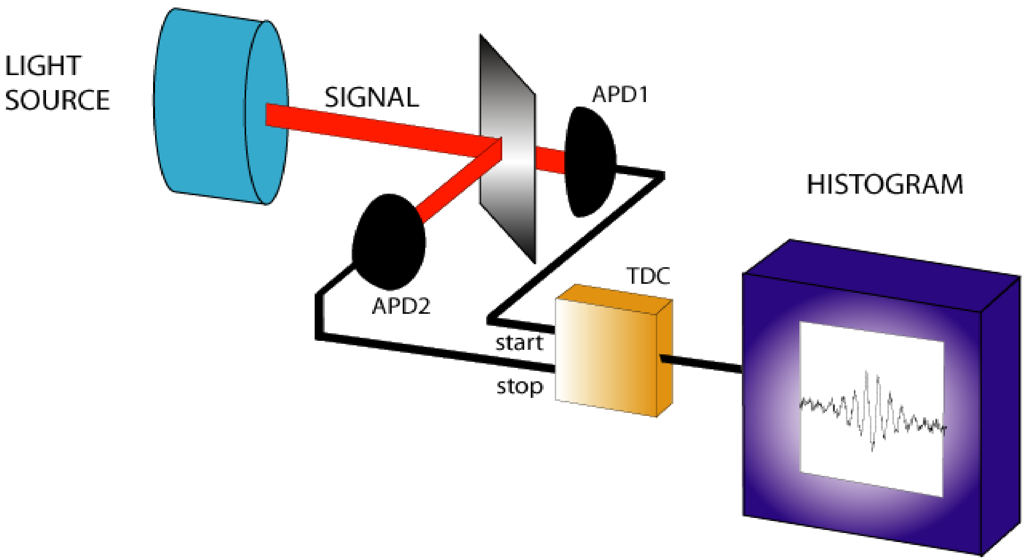
Collaborators

Prof. Howard Wiseman, Griffith University, Brisbane, Australia.

Visiting Students: Jin Wang Australia, Stefan Kuhr Germany.

Supported by NSF and NIST

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

The correlation is largest at equal time

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

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:

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

Cavity QED

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

ATOMS + CAVITY MODE

Non perturbative regime: Coupling > dissipation

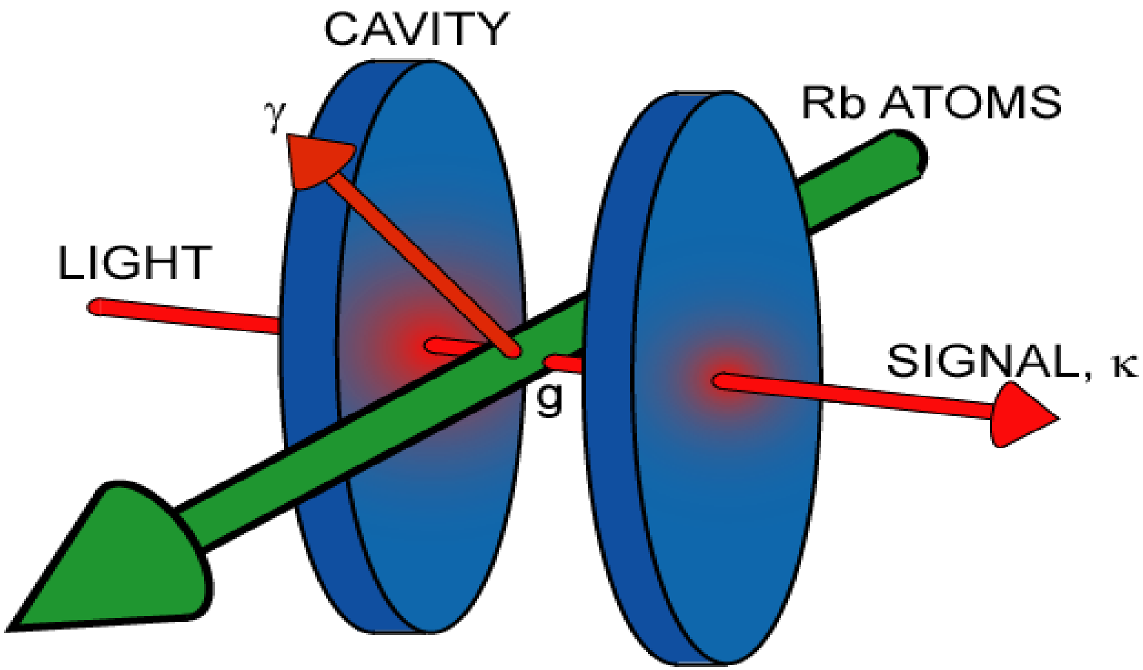
Dipole coupling between the atom and the cavity.

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

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

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

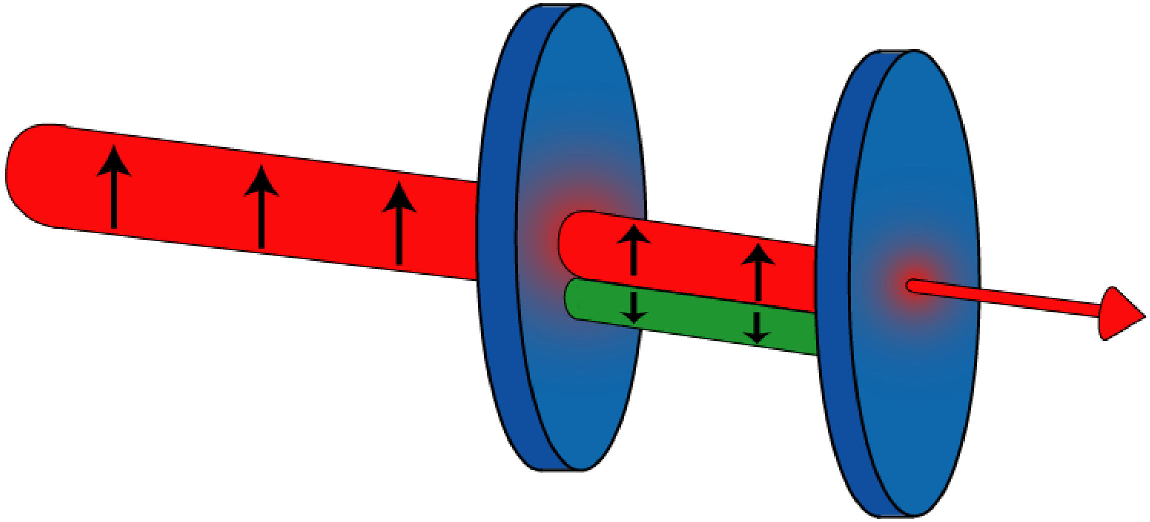
Cavity QED System



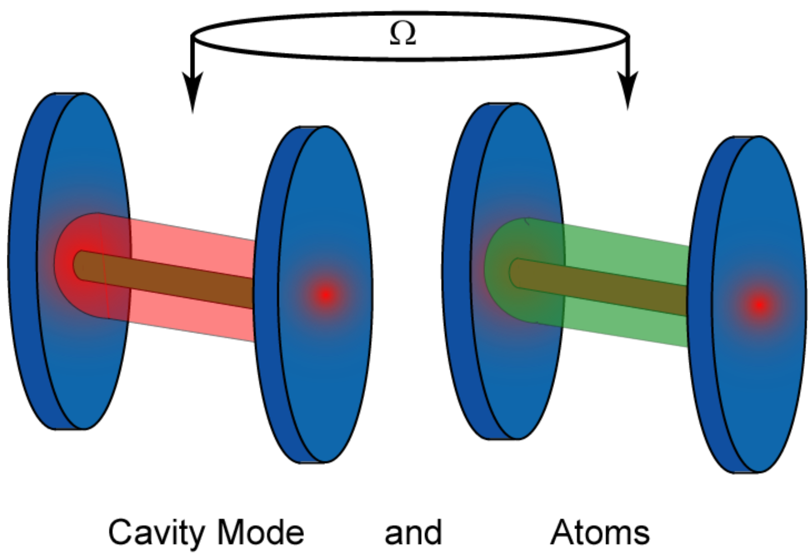
Cavity length ≈ 850 μm

$$\left(\frac{g}{2\pi}, \frac{\kappa}{2\pi}, \frac{\gamma}{2\pi}\right) \approx (5.1,\ 3.7,\ 6.0)\,\mathrm{MHz}$$

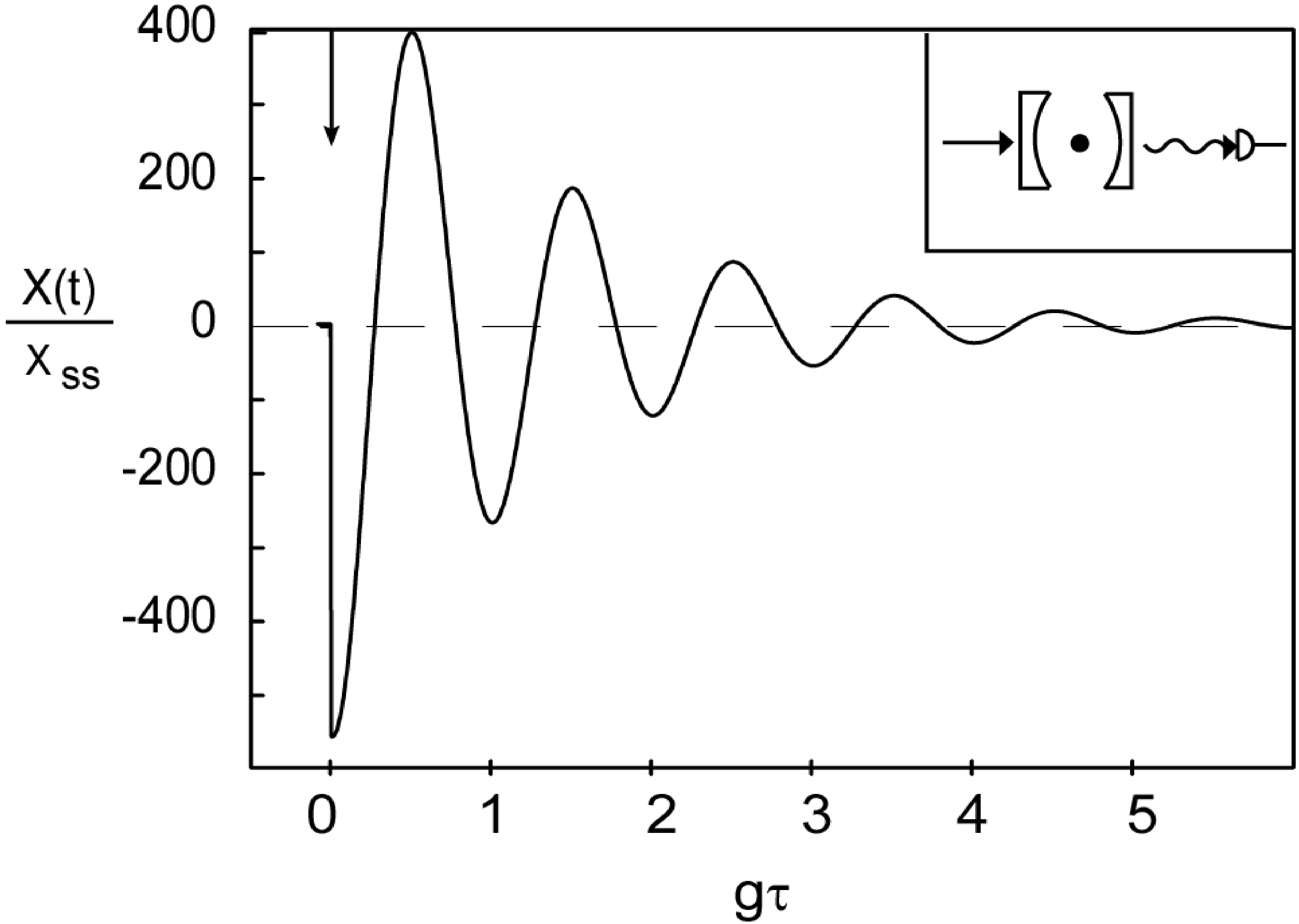
Steady State:



Exchange of Excitation:



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



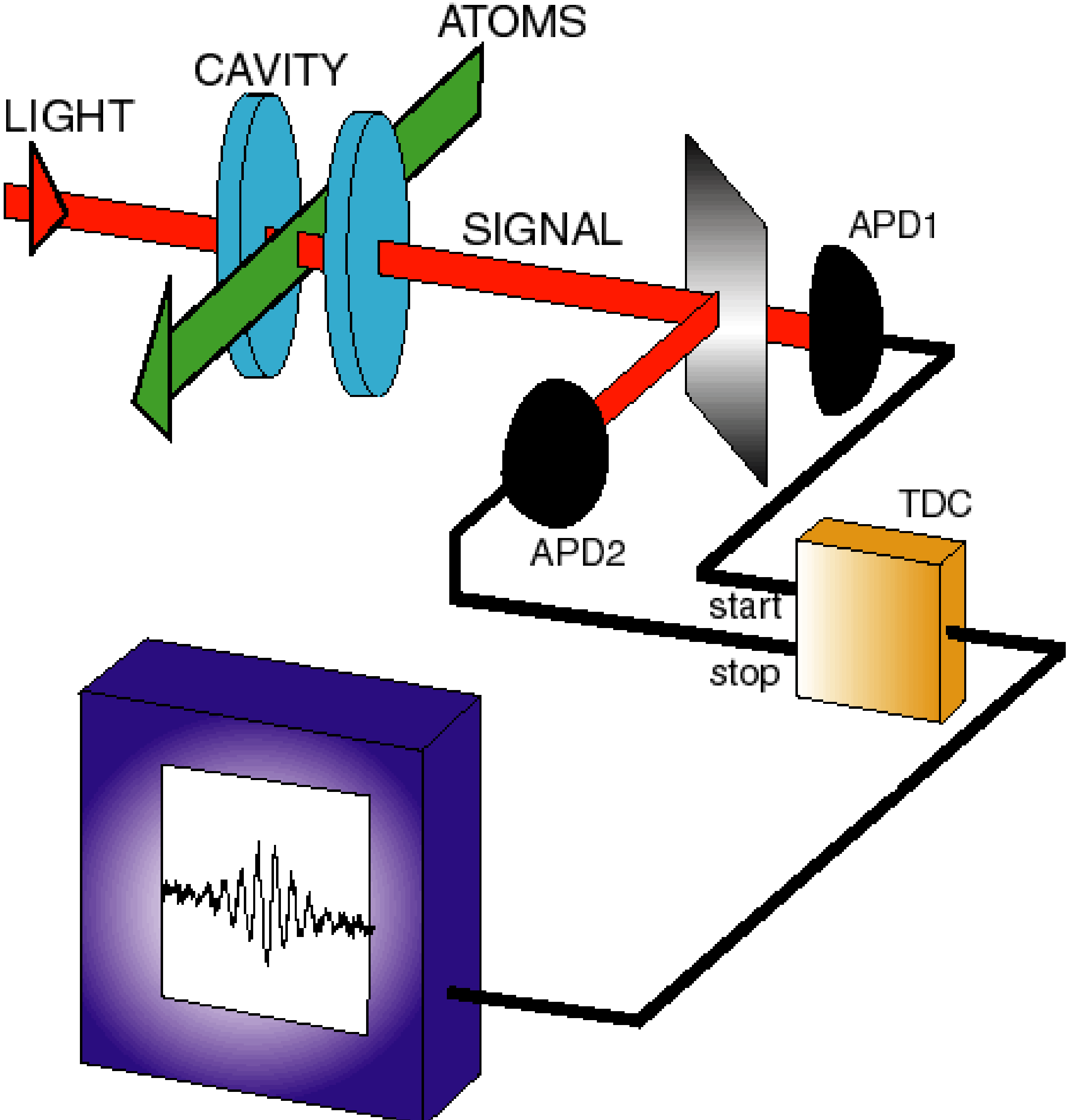
Each escape of a photon creates a very large disturbance.

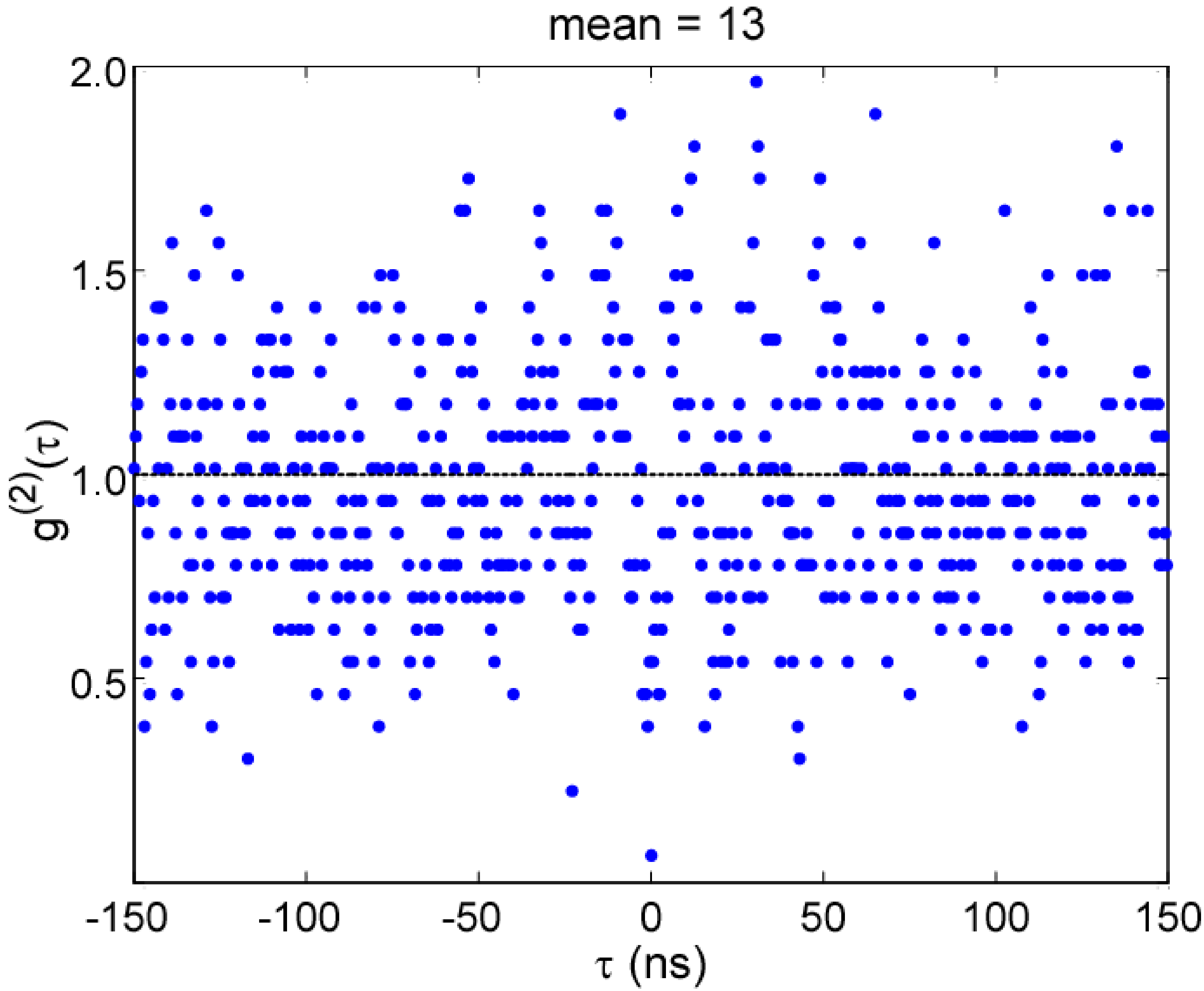
We want to monitor that disturbance or fluctuation.

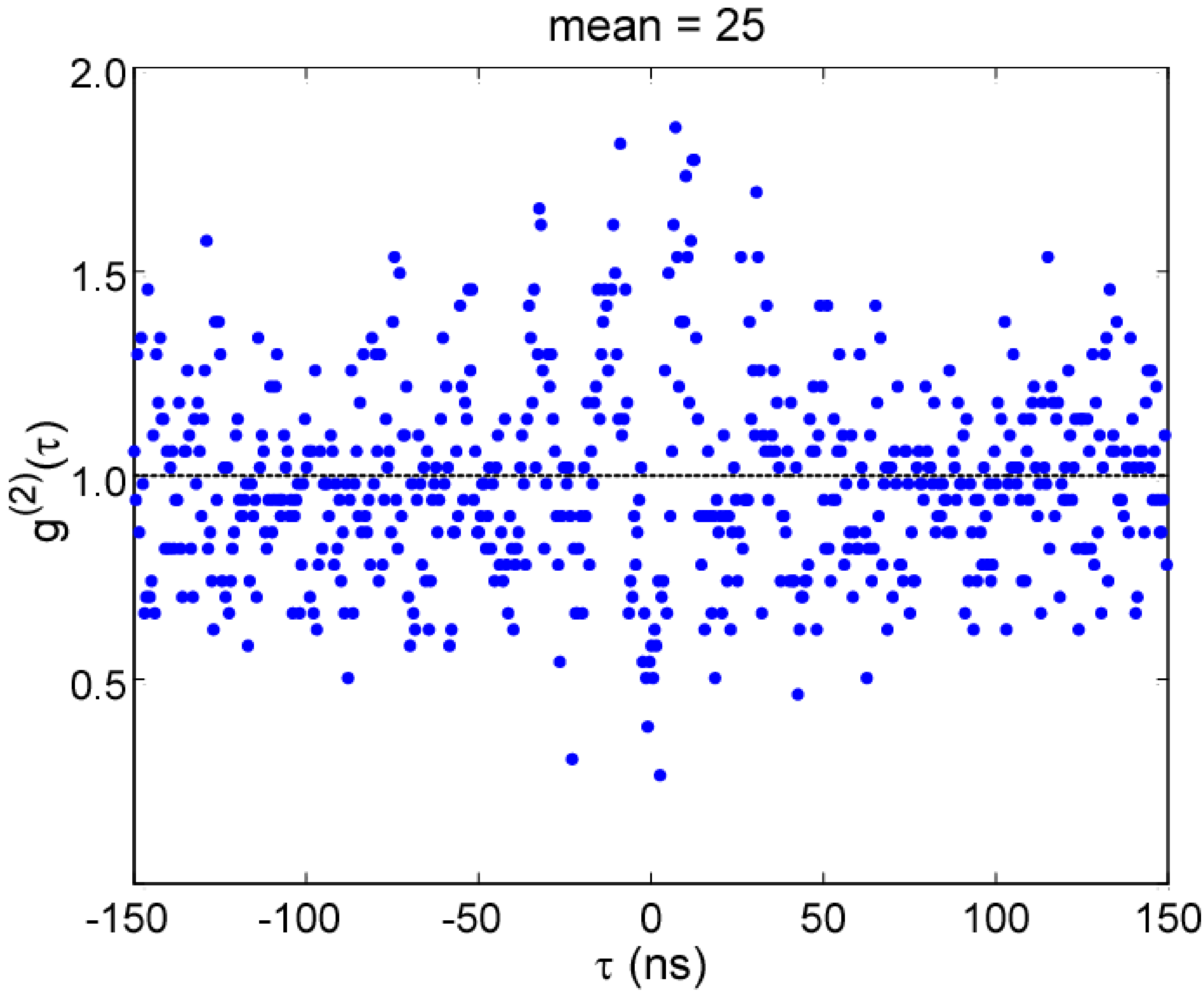
But we can only get one photon at best every time there is a disturbance.

We have to average the conditional intensity.

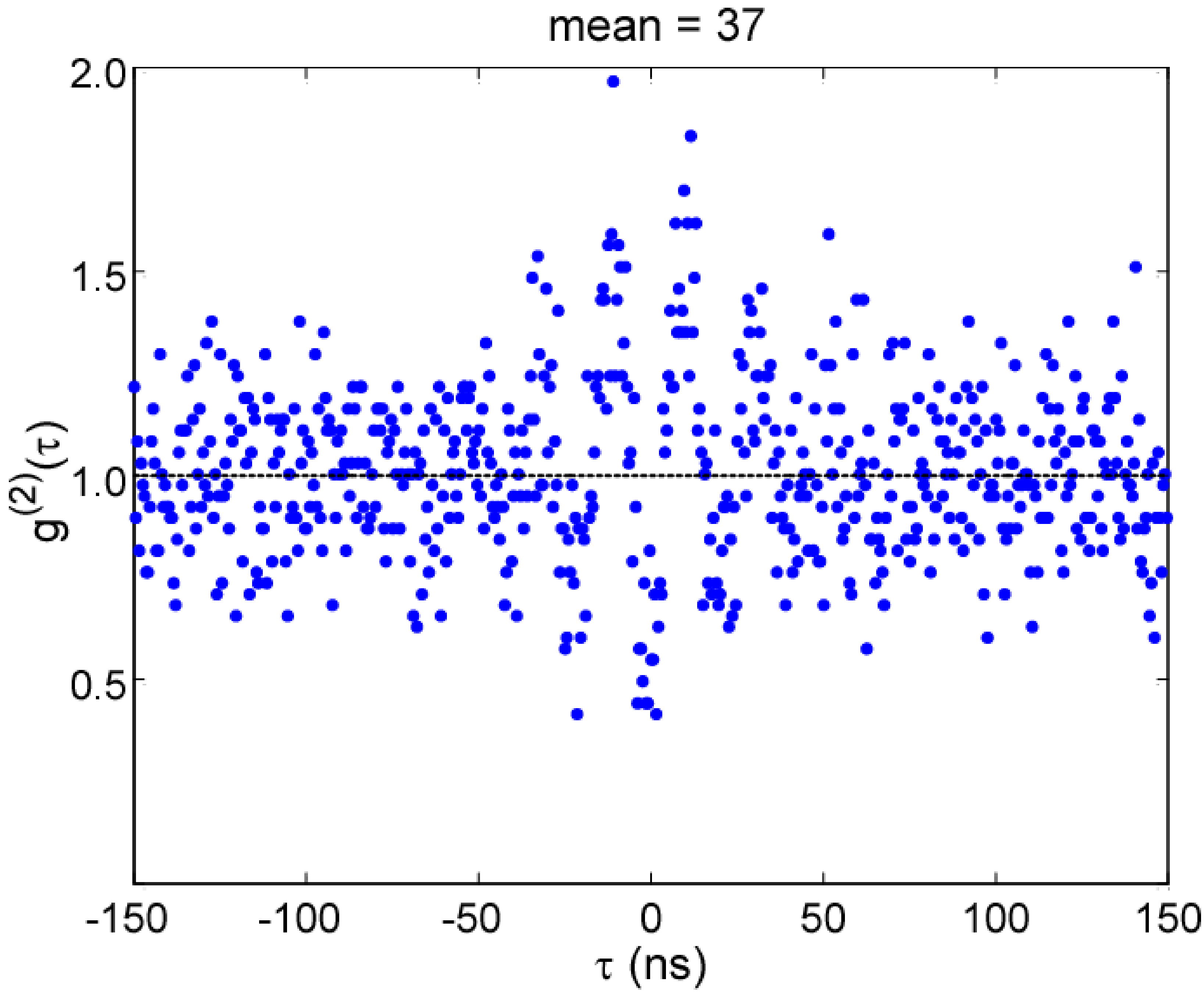
How does the data look in the lab?


ATOMS
CAVITY
LIGHT
SIGNAL
APD1
APD2
TDC
start
stop

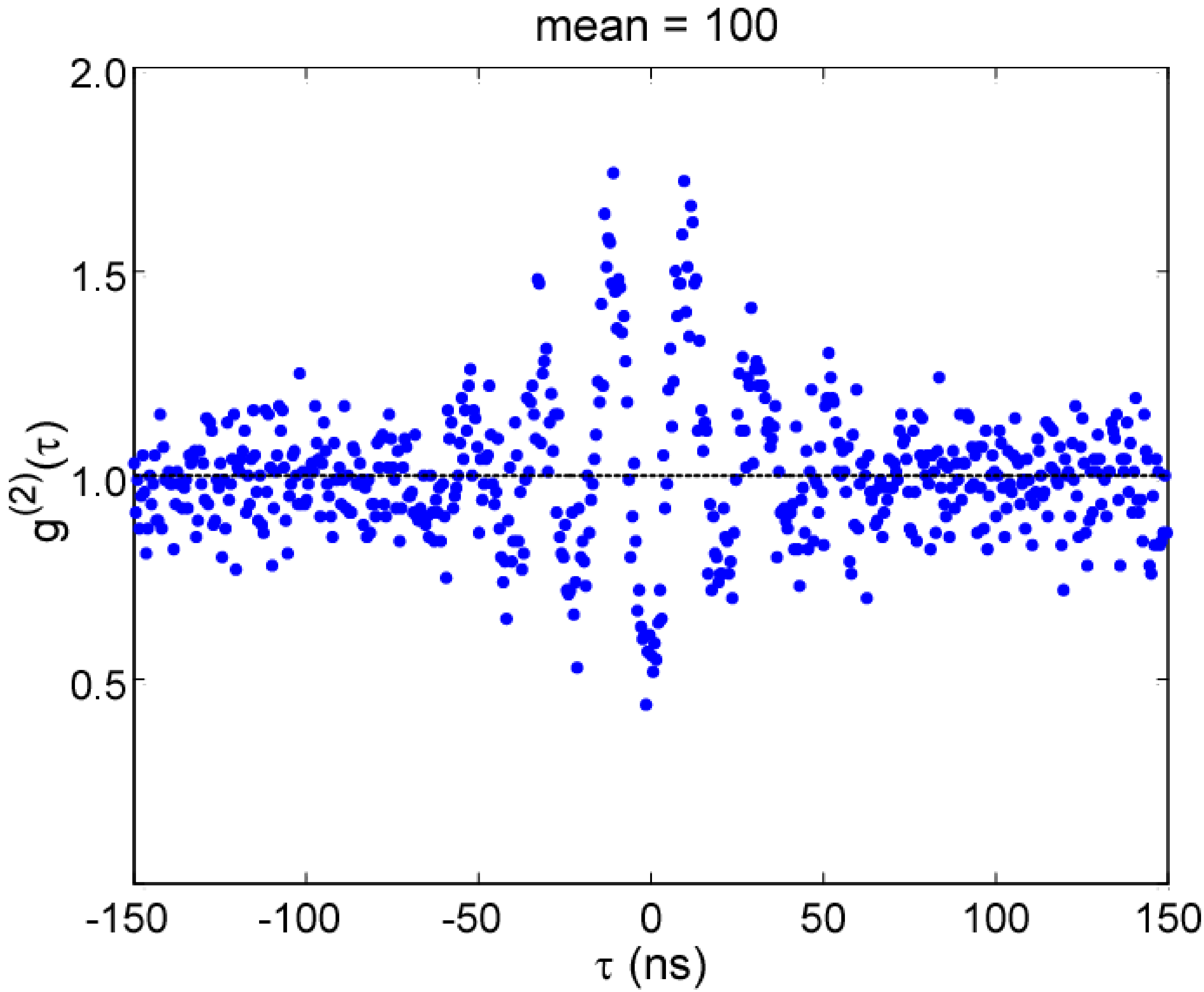

mean = 13
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)



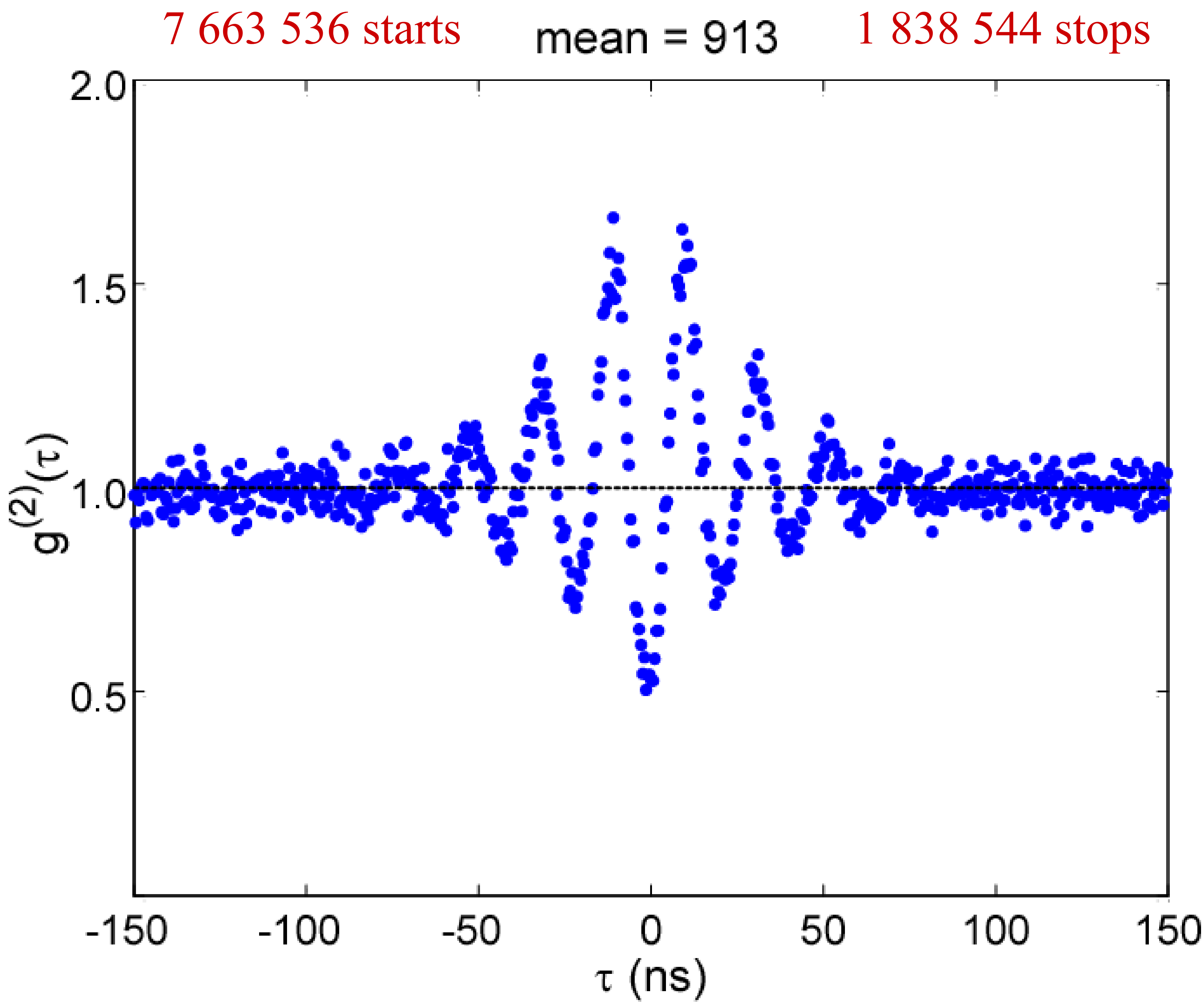
mean = 25
2.0
1.5
1.0
0.5
g(2)(τ)
-150
-100
-50
0
50
100
150
τ (ns)



mean = 37
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

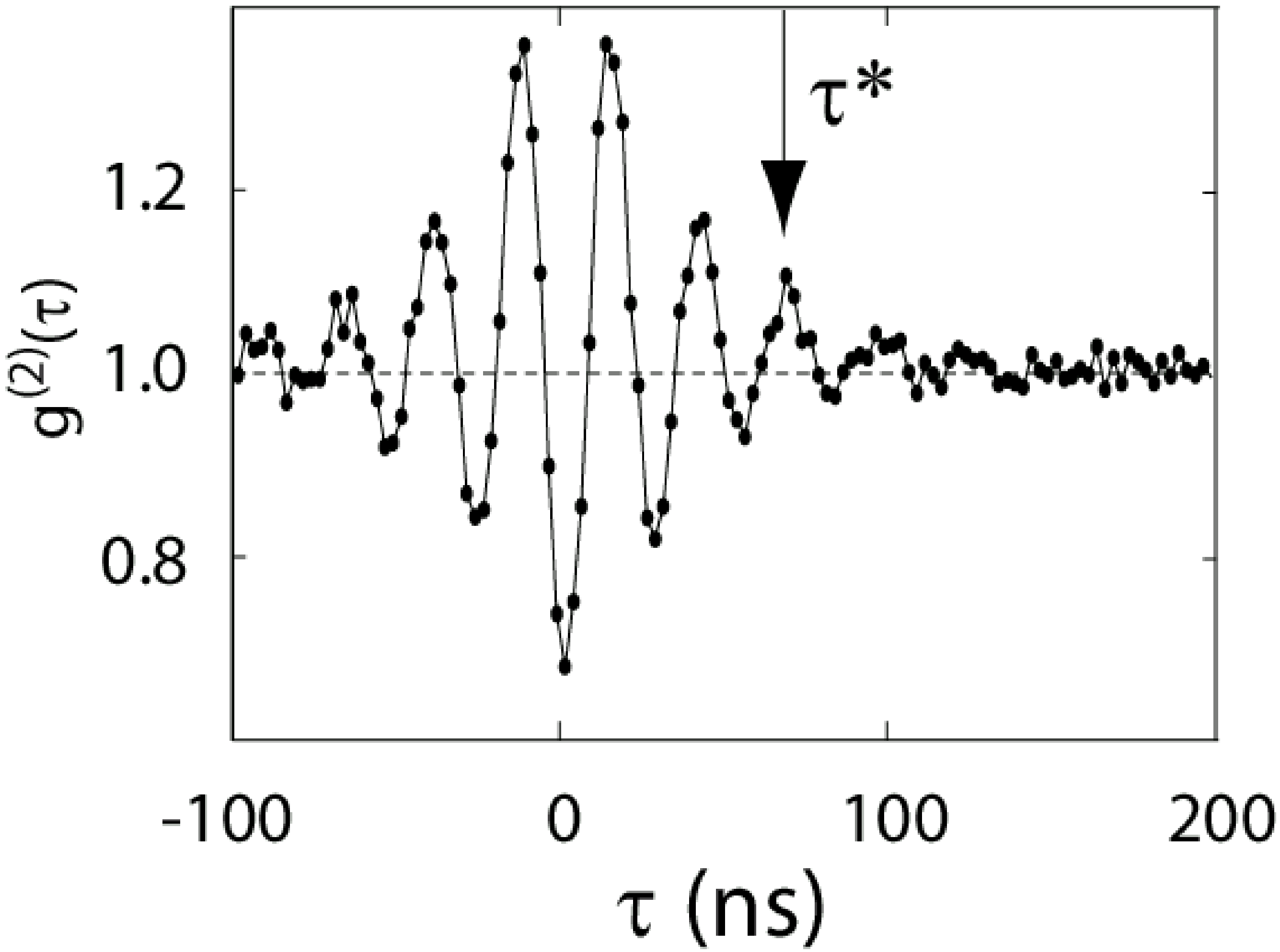


mean = 100
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)


7 663 536 starts
mean = 913
1 838 544 stops
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

Non-classical

antibunched

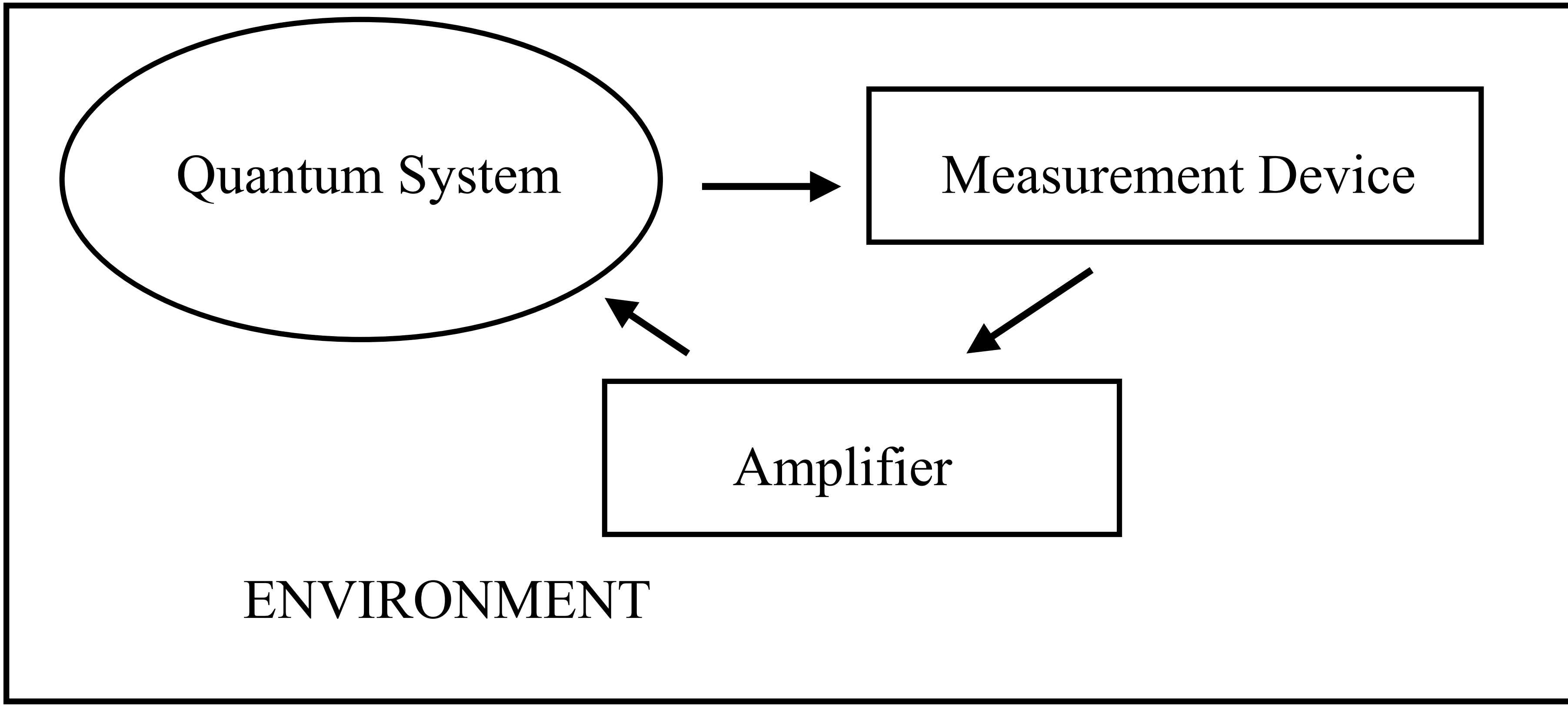


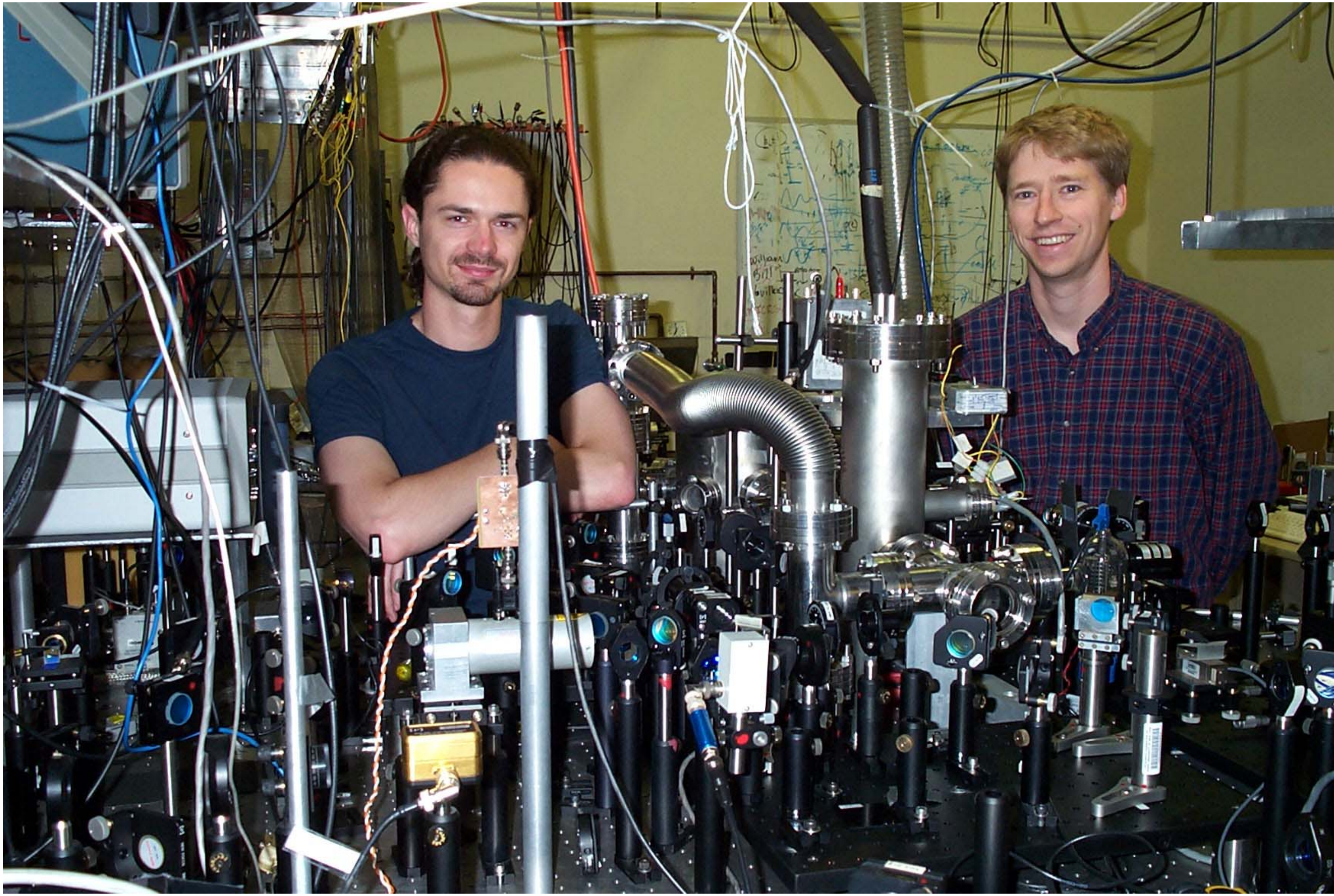
Classically $g^{(2)}(0) > g^{(2)}(\tau)$ and also $|g^{(2)}(0)-1| > |g^{(2)}(\tau)-1|$

Conditioned measurements in the language of correlation functions allow the study of the dynamics of the system.

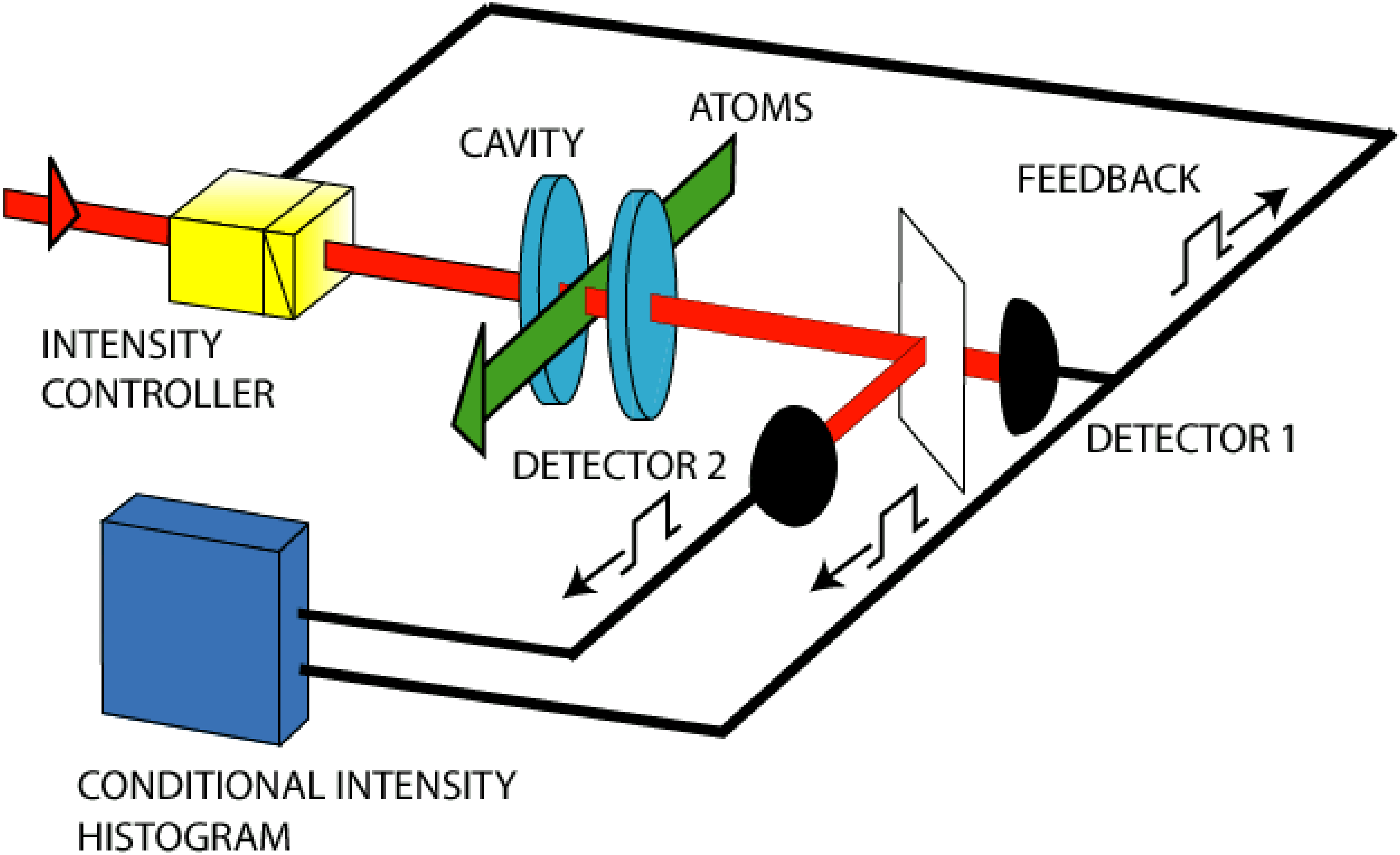
Quantum conditioning, with photodetections, provides the most ideal times for controlling the evolution of the system.

Feedback on a single photodetection.

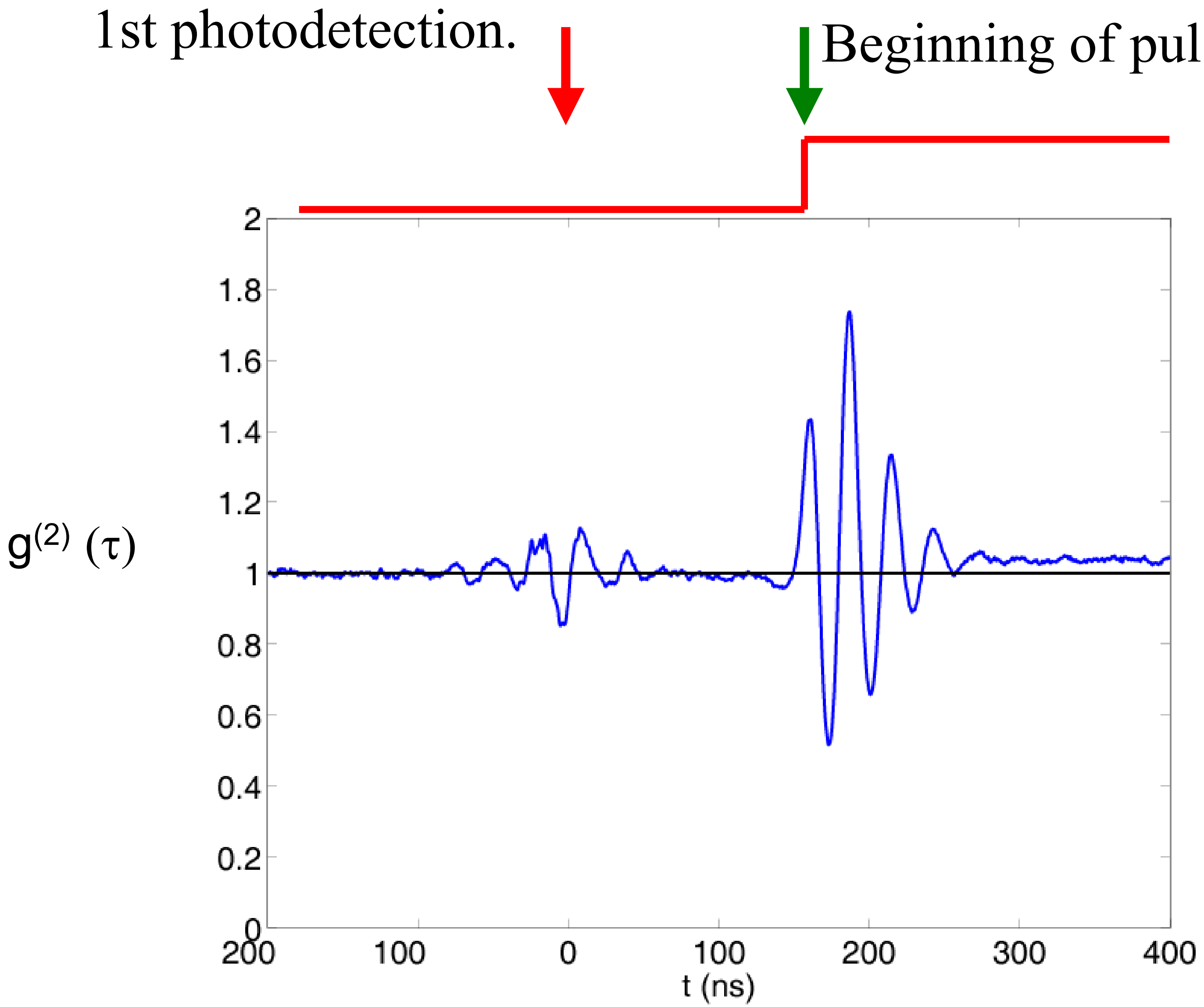

Quantum System
Measurement Device
Amplifier
ENVIRONMENT



Wade Smith and Joe Reiner


ATOMS
CAVITY
FEEDBACK
INTENSITY
CONTROLLER
DETECTOR 1
DETECTOR 2
CONDITIONAL INTENSITY
HISTOGRAM

Conditional intensity and step:



We have to satisfy three conditions:

Amplitude

Sign of the step (parity)

Time of the step

We only have one bit of information, a click.

We have good knowledge of the dynamics.

Conditional dynamics of the system wavefunction

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

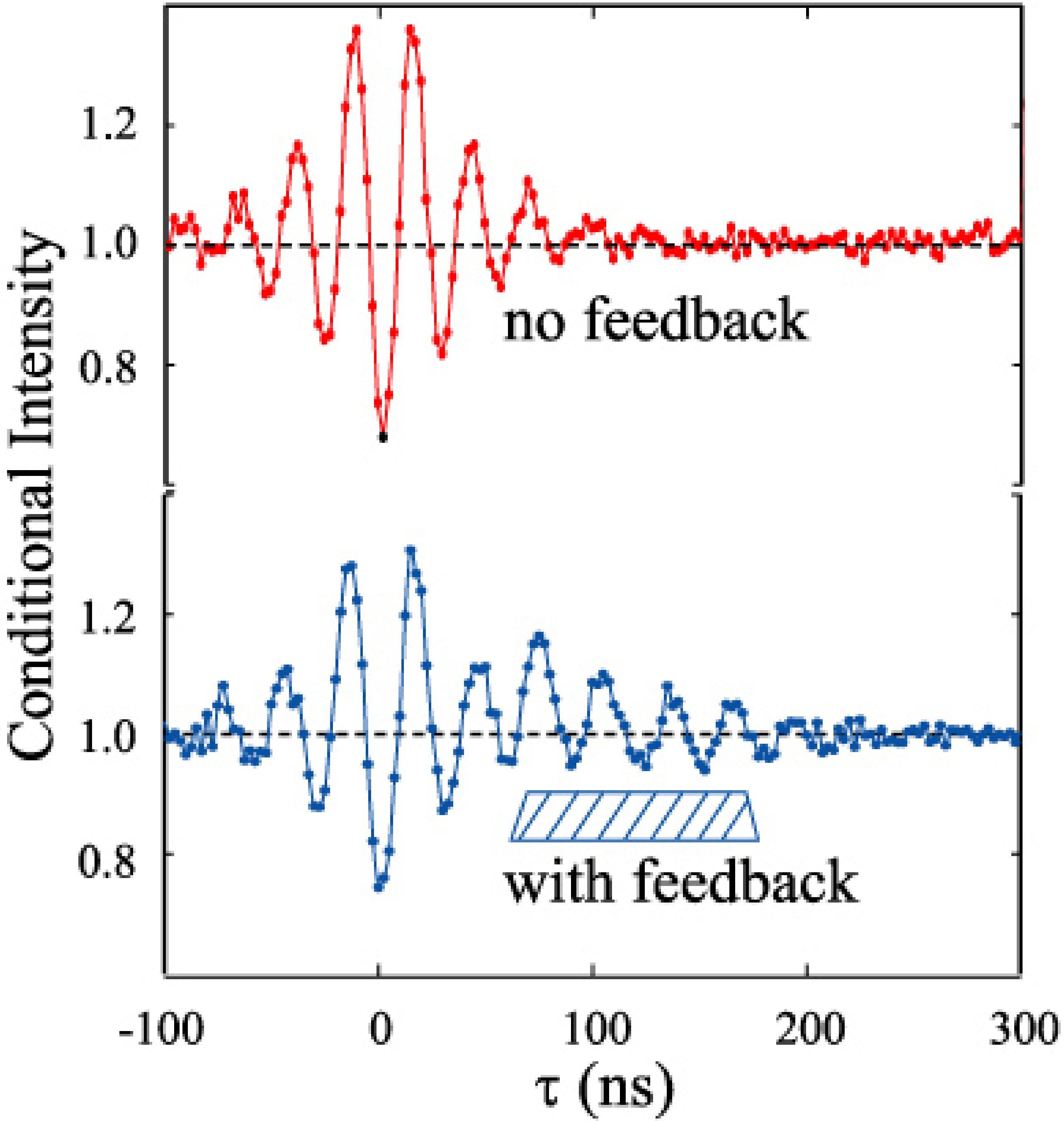
$$\lambda = \langle \hat{a} \rangle, \quad p = p(g,\kappa,\gamma) \text{ and } q = q(g,\kappa,\gamma)$$

$$\hat{a}\left|\Psi_{ss}\right\rangle \Rightarrow \left|\Psi_{collapse}\right\rangle = \left|0,g\right\rangle + \lambda pq\left|1,g\right\rangle - \frac{2g\lambda q}{\gamma}\left|0,e\right\rangle$$

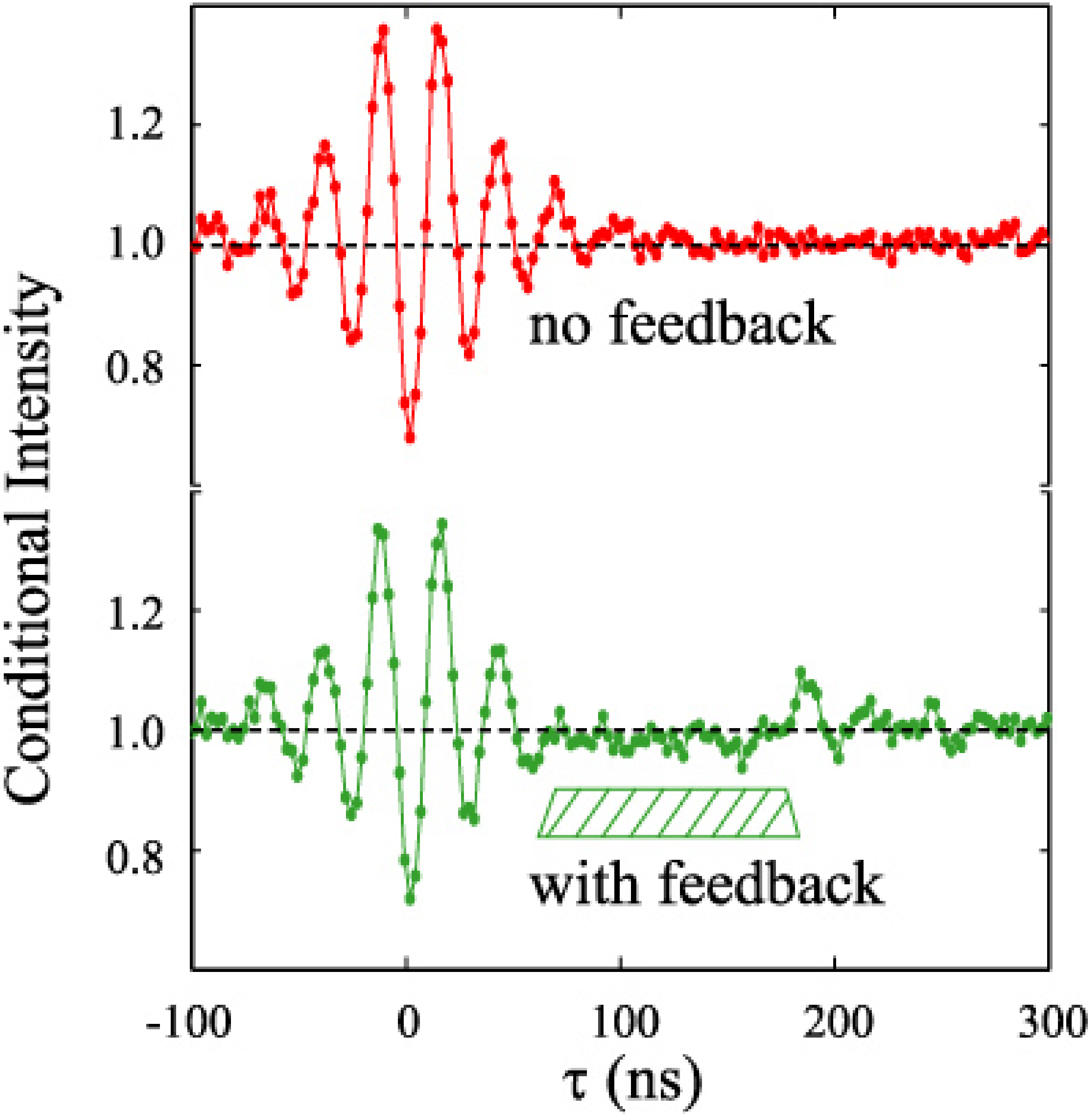
$$\left|\Psi(\tau)\right\rangle = \left|0,g\right\rangle + \lambda\left[f_1(\tau)\left|1,g\right\rangle + f_2(\tau)\left|0,e\right\rangle\right] + O\left(\lambda^2\right)$$

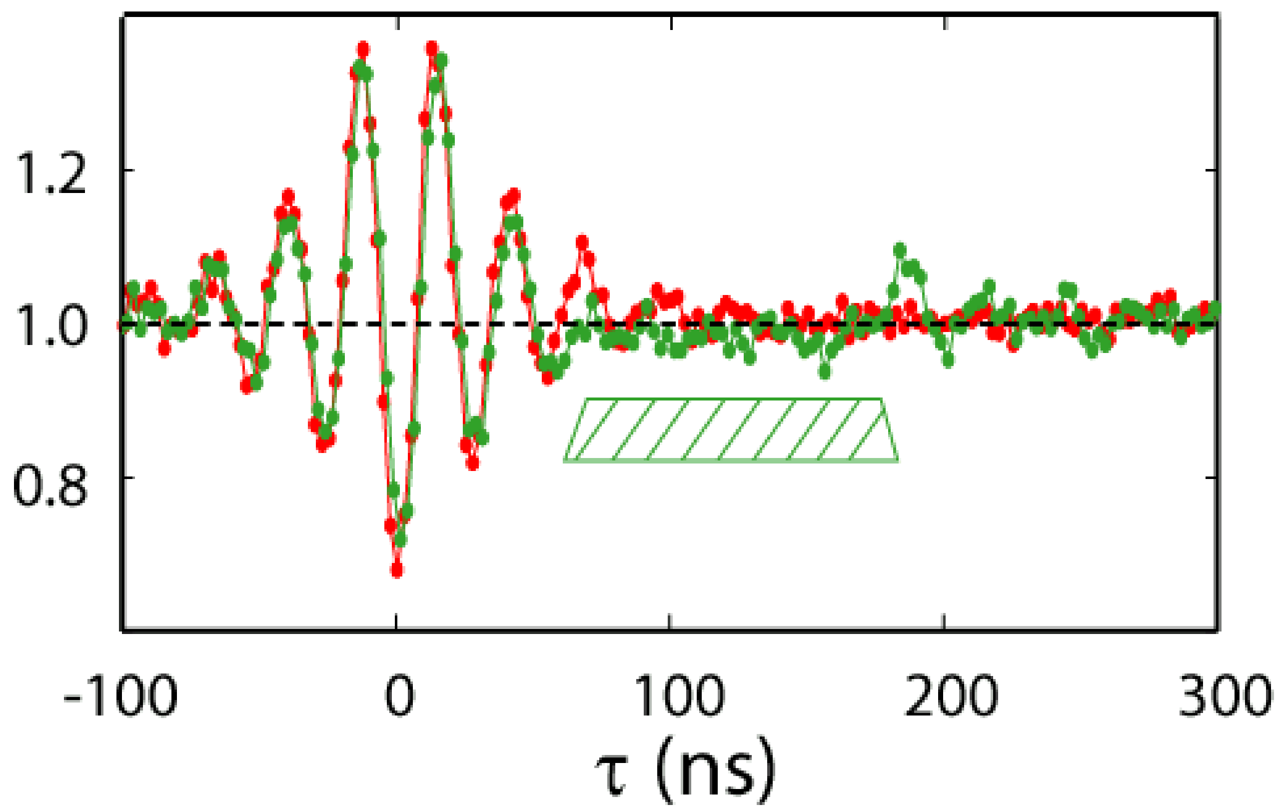
Field (f_1) — Atomic Polarization (f_2)

Same coefficients when $\quad f_2(T) = -\frac{2g}{\gamma} f_1(T)$

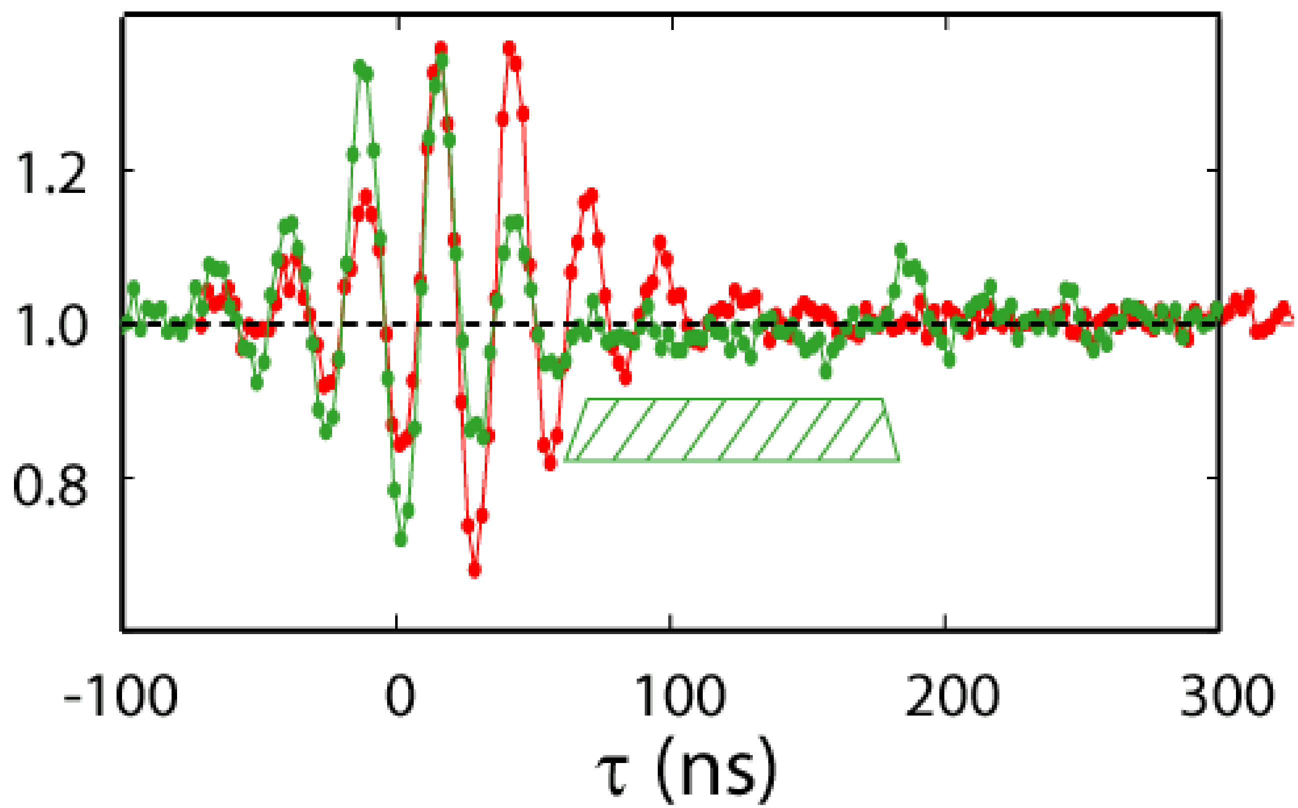


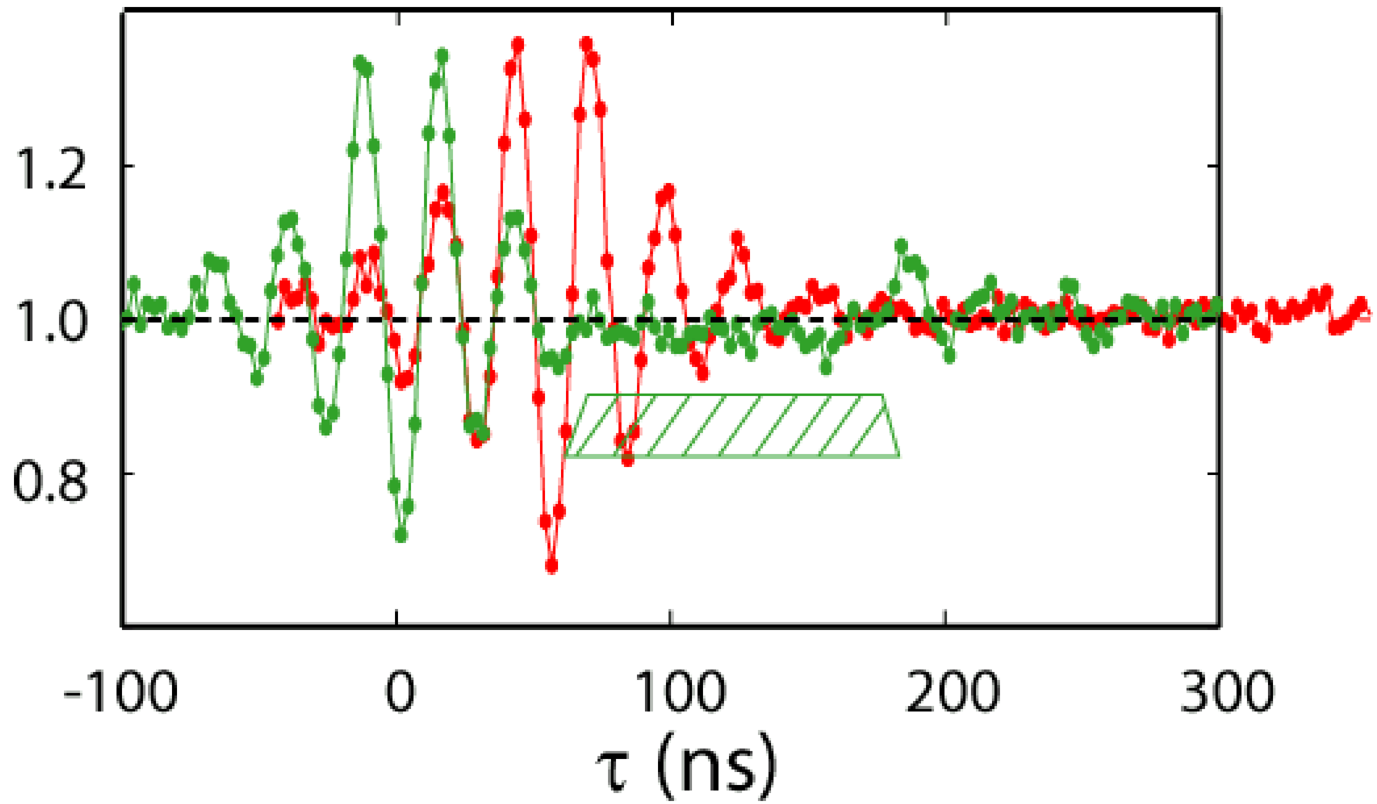
Conditional Intensity
1.2
1.0
0.8
no feedback
with feedback
-100
0
100
200
300
τ (ns)


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)

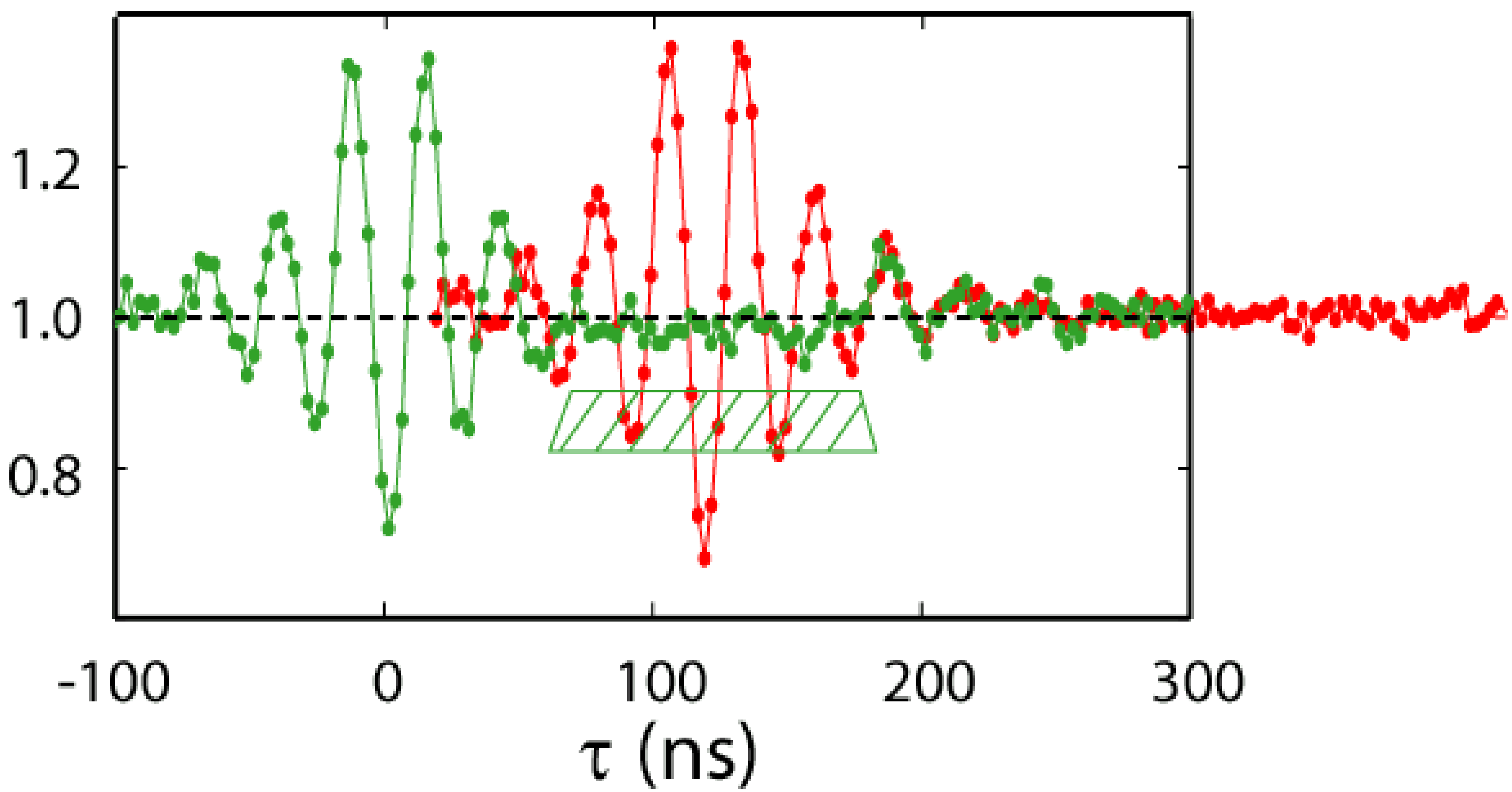


1.2
1.0
0.8
-100
0
100
200
300
τ (ns)


1.2
1.0
0.8
-100
0
100
200
300
τ (ns)

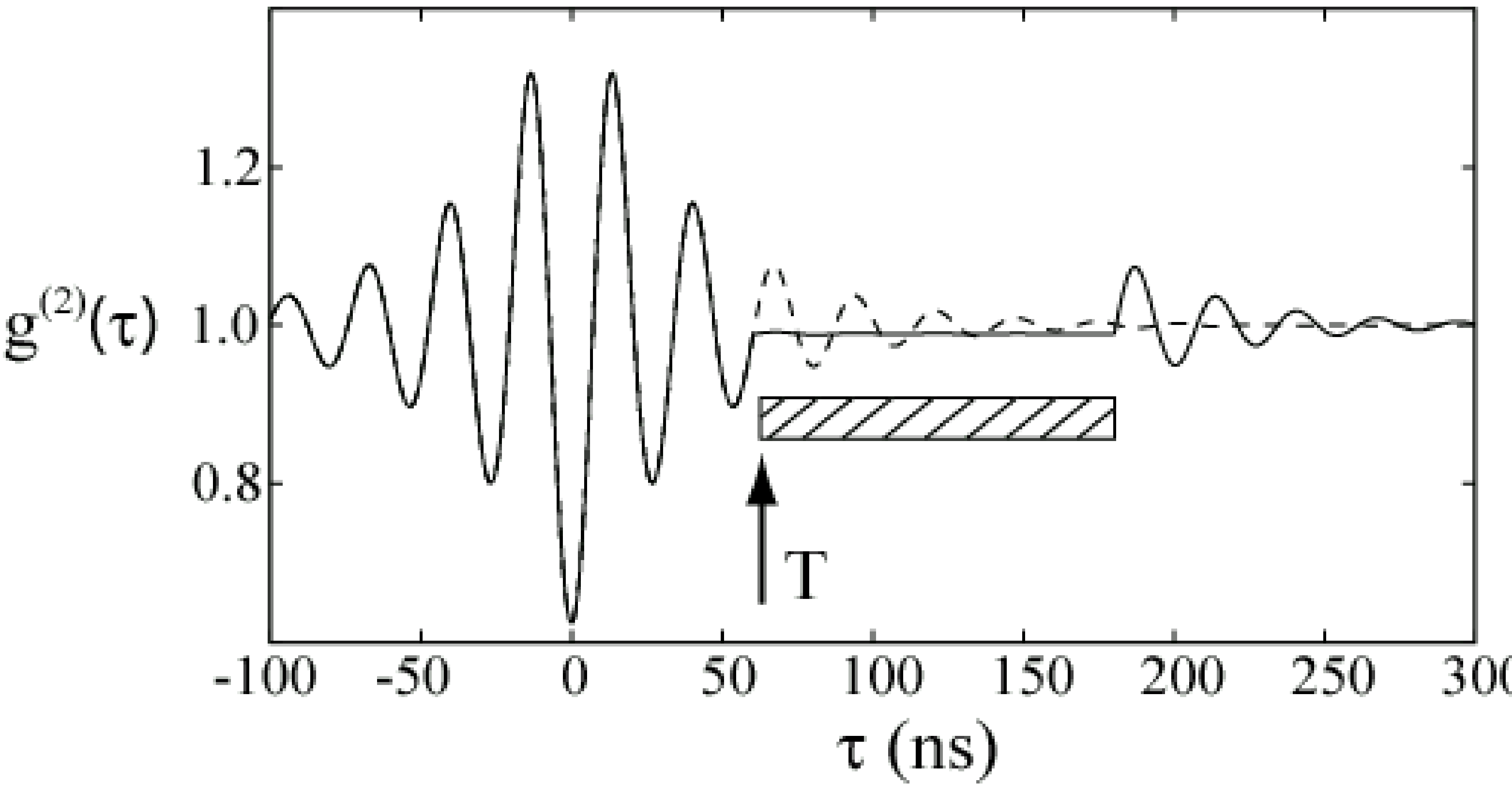


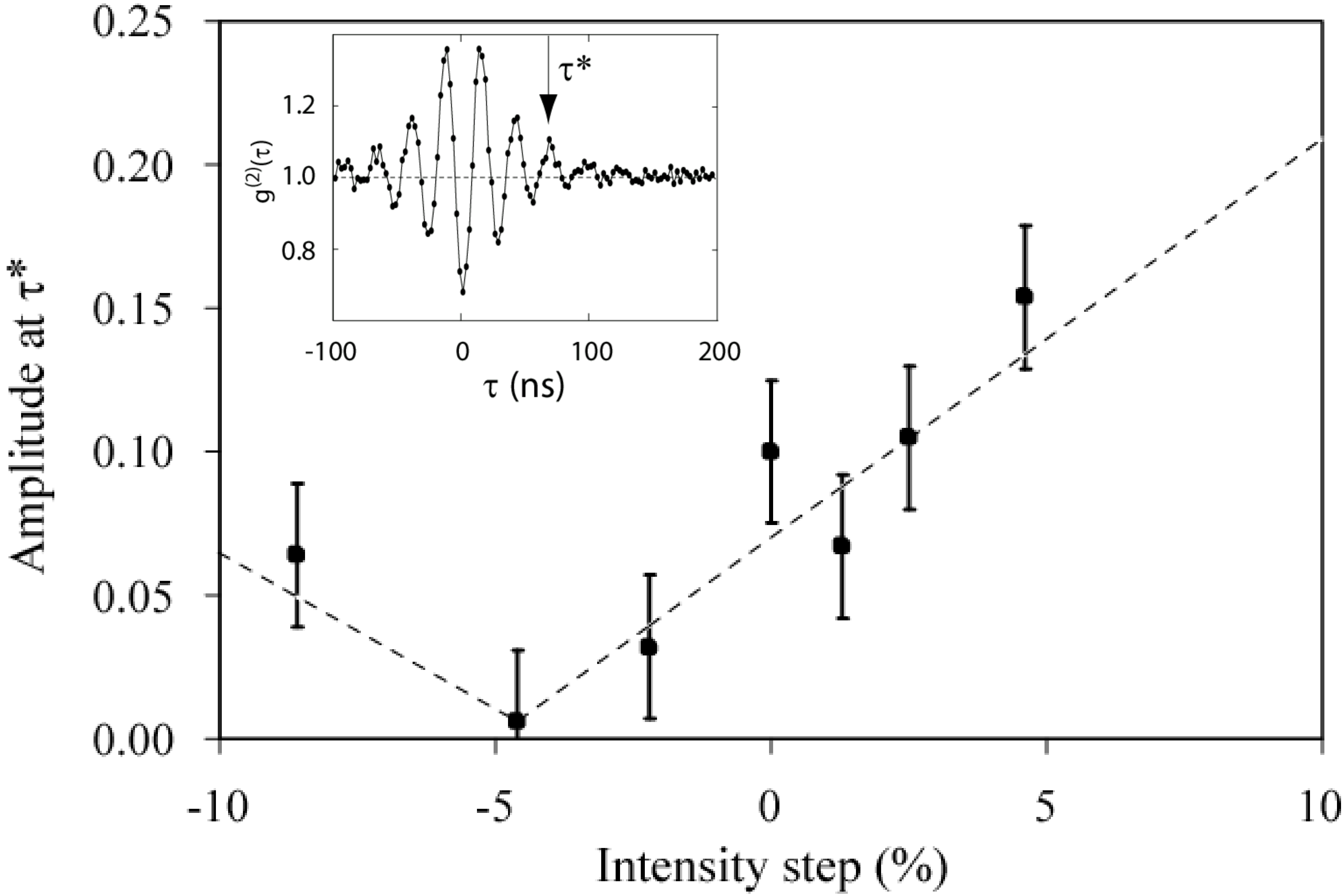
1.2
1.0
0.8
-100
0
100
200
300
τ (ns)



1.2
1.0
0.8
-100
0
100
200
300
τ (ns)

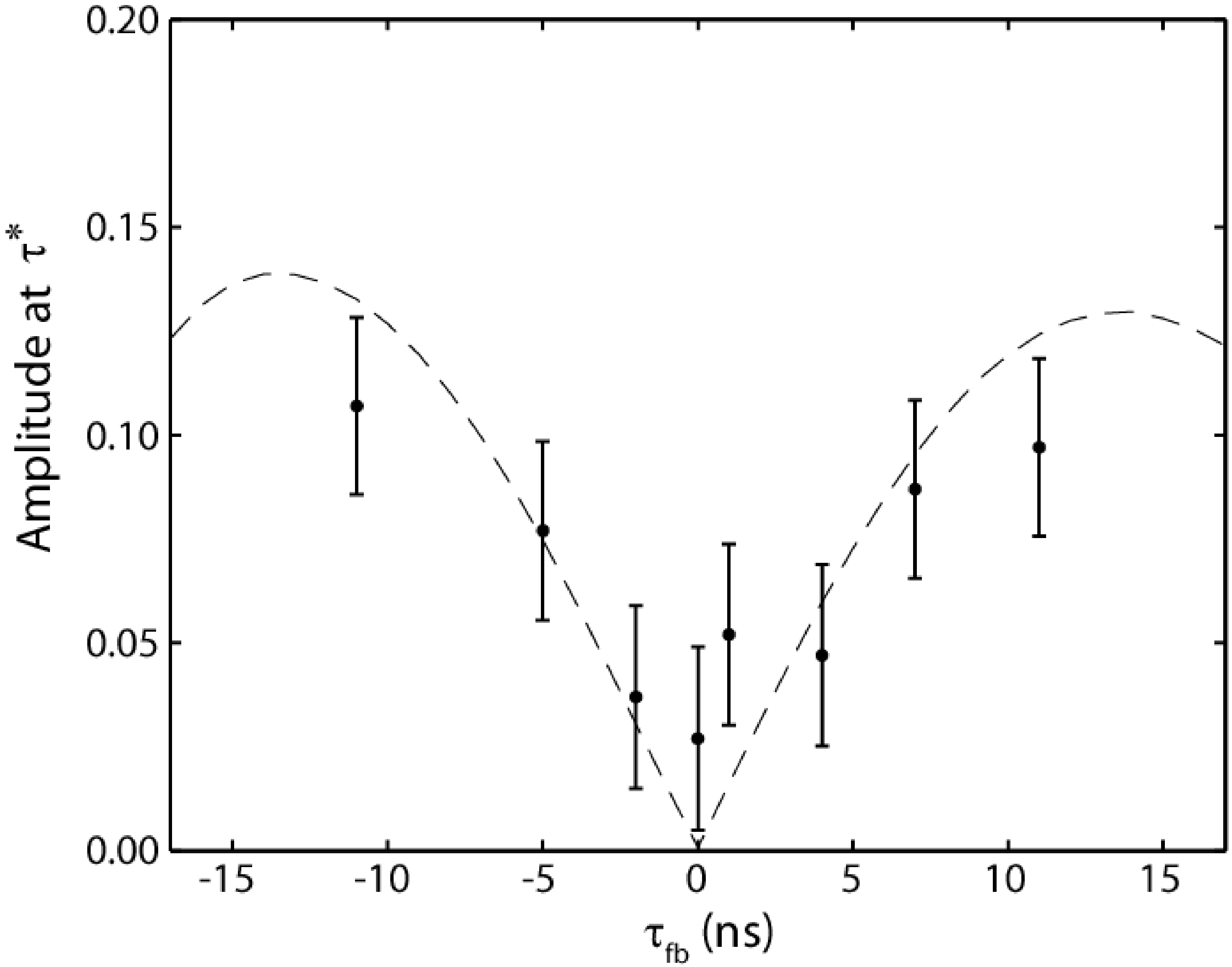
Theoretical prediction.





0.25
0.20
0.15
0.10
0.05
0.00
Amplitude at τ*
-10
-5
0
5
10
Intensity step (%)
τ*
1.2
1.0
0.8
g(2)(τ)
-100
0
100
200
τ (ns)

Systematically study amplitude



Questions:

How long can we hold the system and then release it?

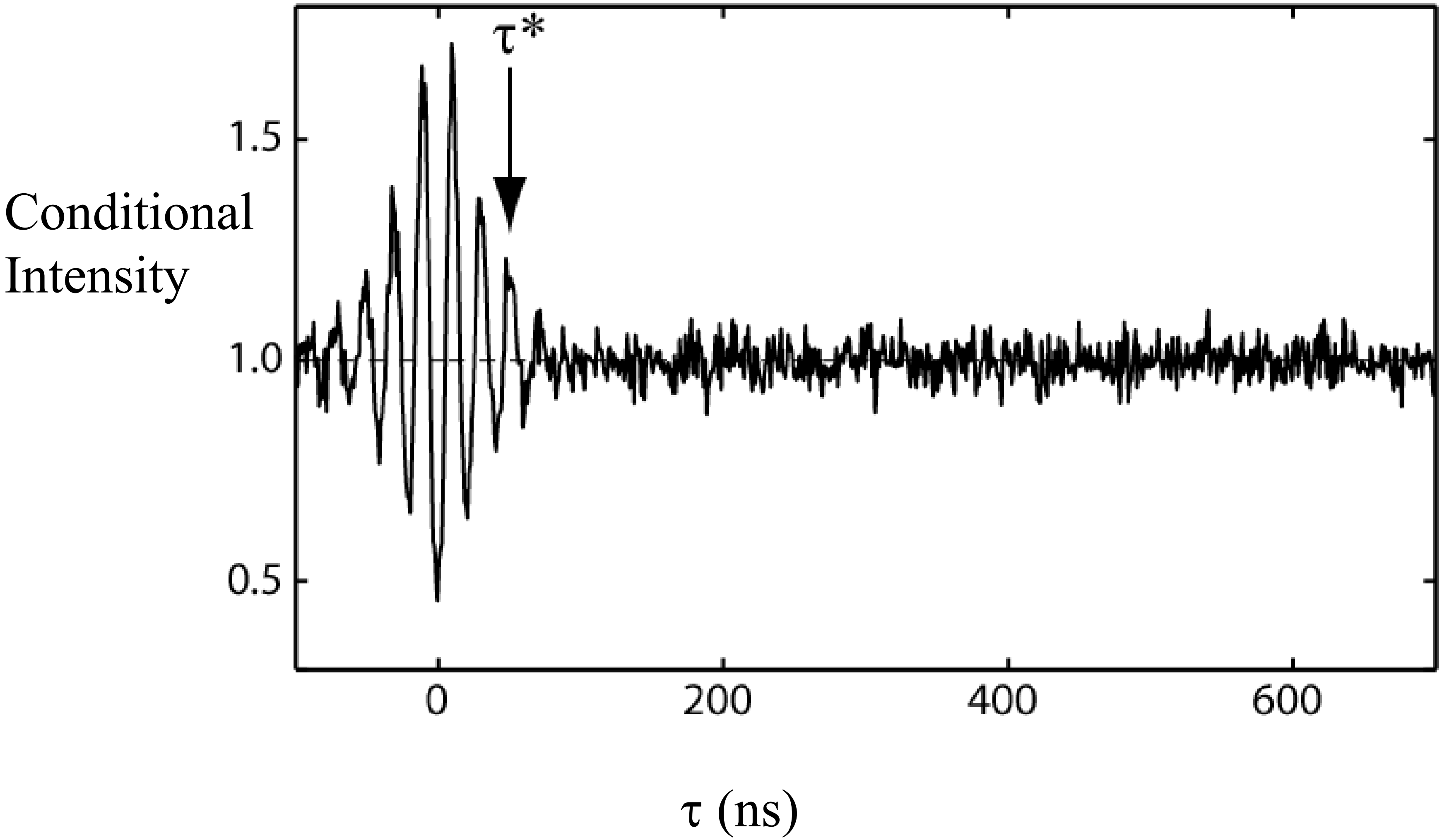
How sensitive is it to atomic detuning?

Where is the information stored?

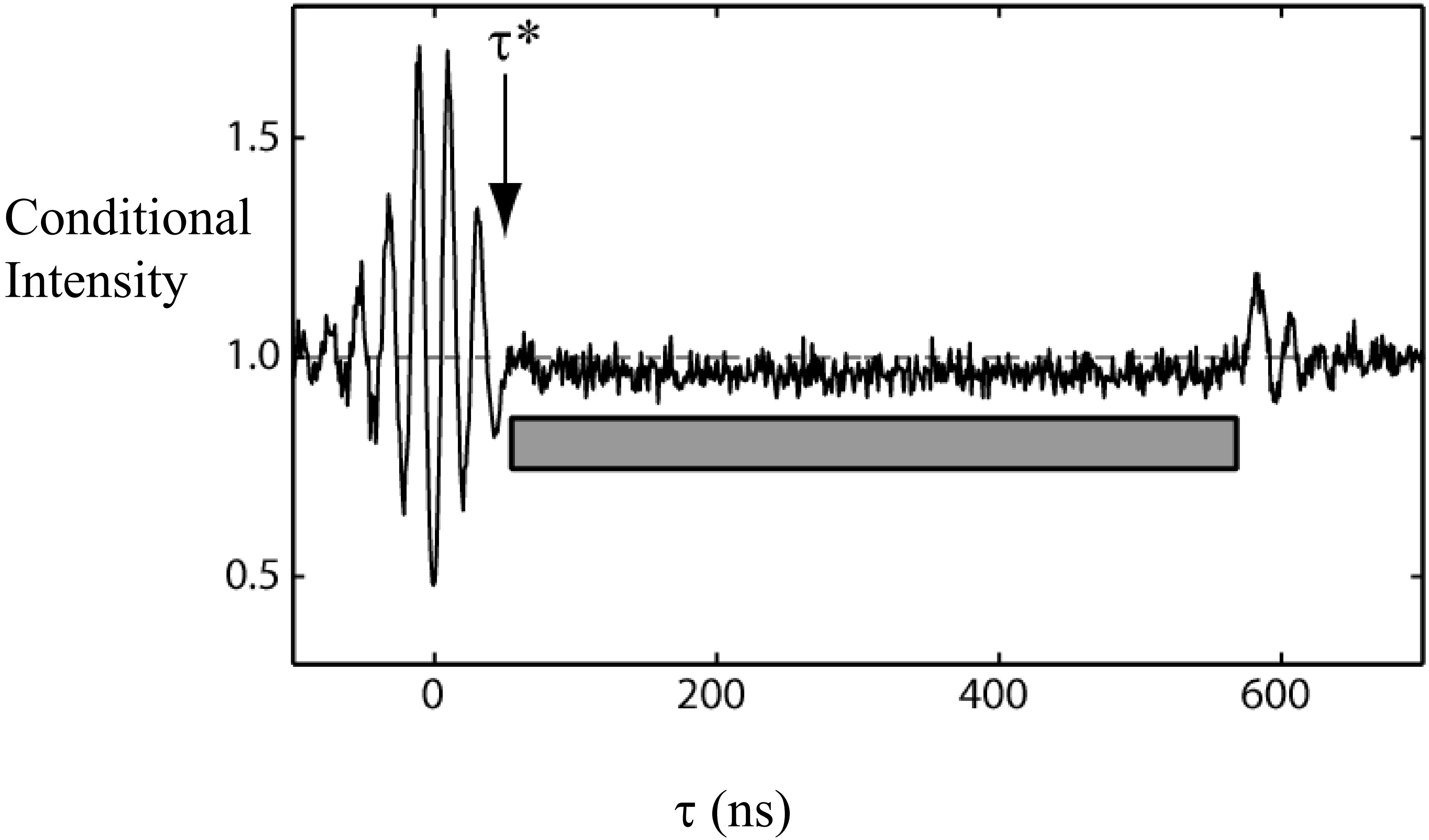
What is quantum about this?

Deterministic source?

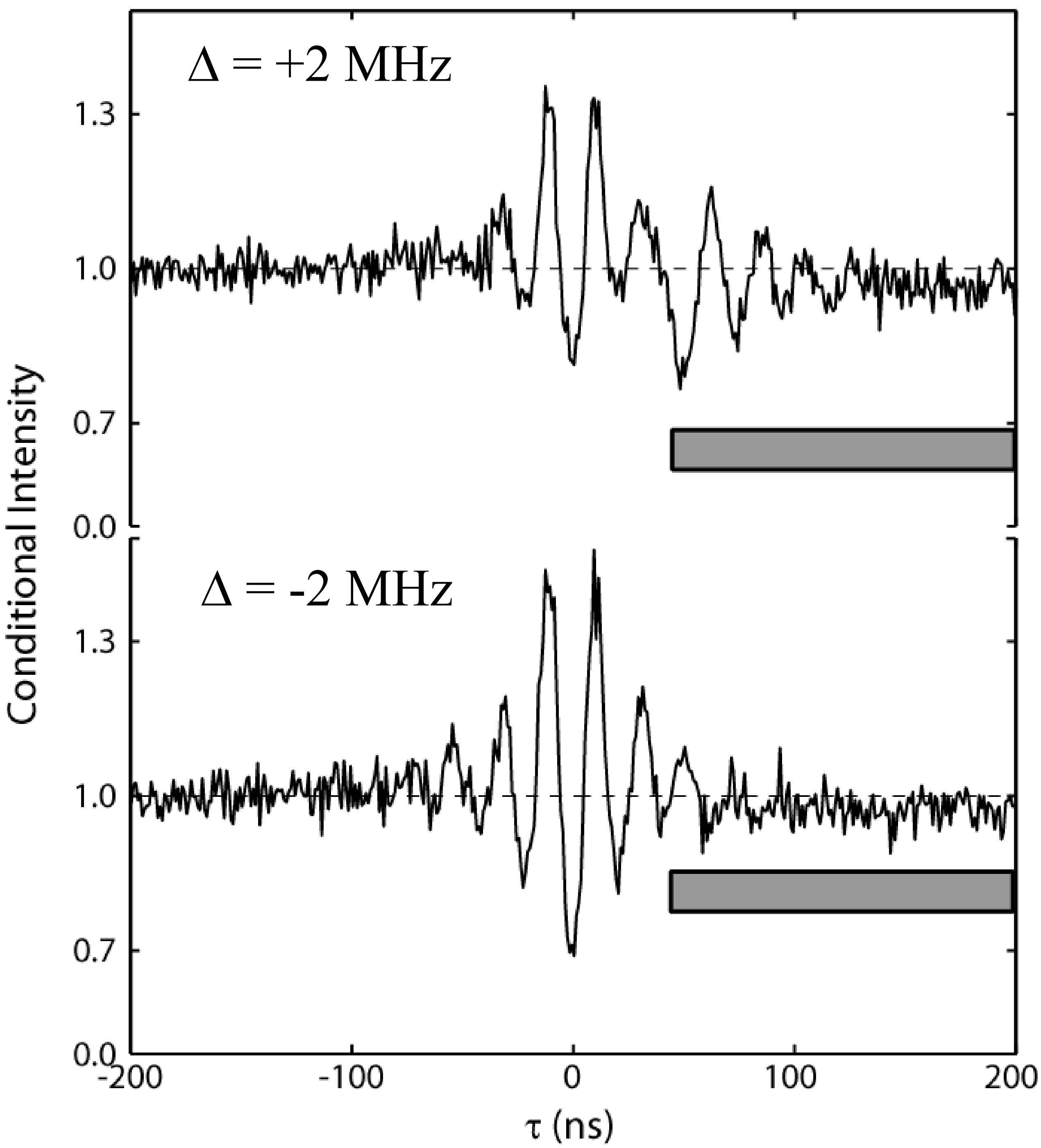
Intensity correlation without feedback



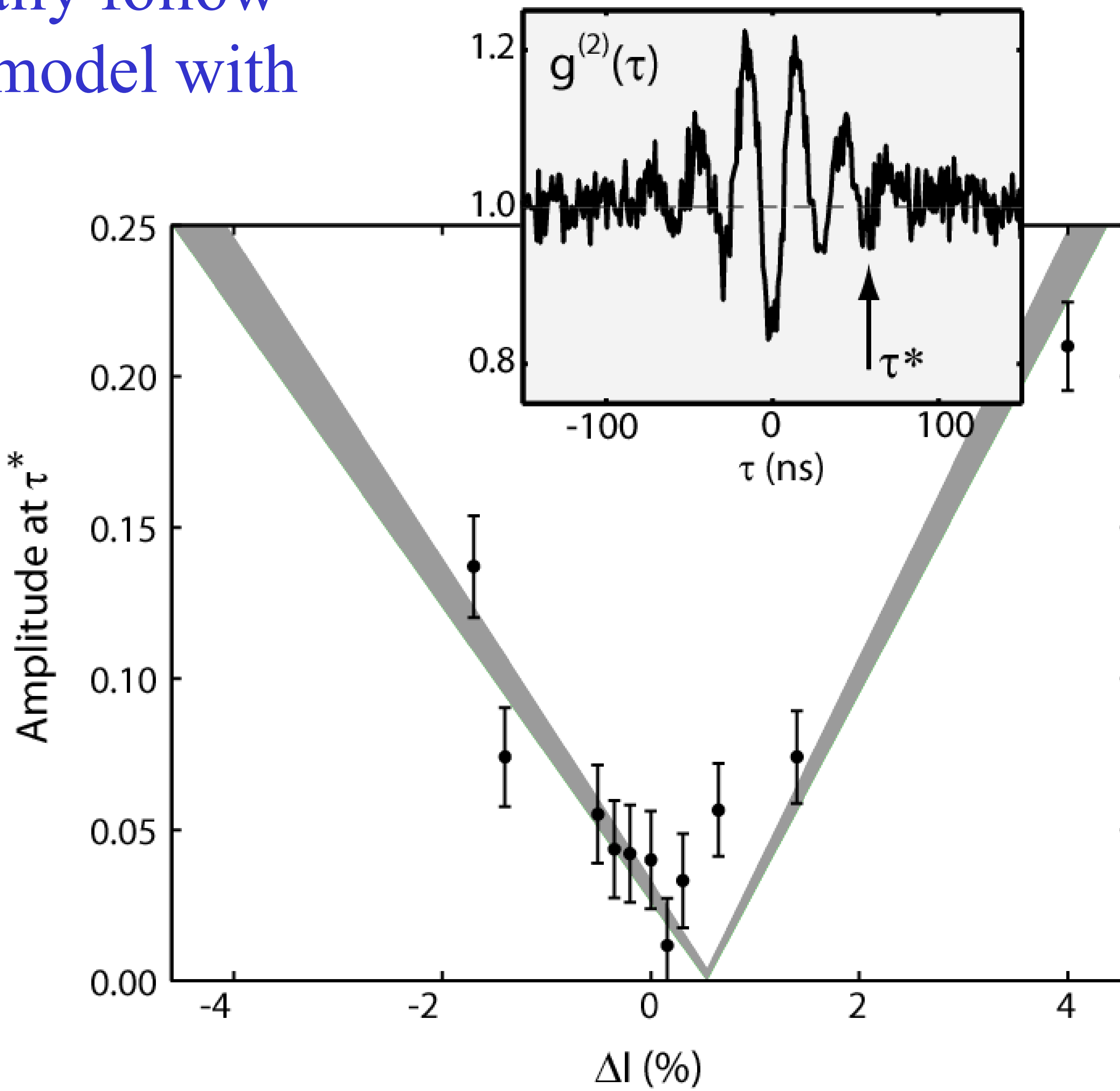
Intensity correlation with feedback



Feedback in a detuned system



Systematically follow amplitude, model with detuning



Answers:

How long can we hold the system and then release it?
As long as we want!

How sensitive is it to detunings?
With our protocol we only operate well on resonance.

Where is the information stored?
New steady state.

What is quantum about this?
The detection of the first photon.

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

Summary:

Knowledge of the conditional state for a continuously monitored cavity QED system → Quantum feedback protocols

We trigger on a fluctuation (photon detection) and change the drive at a particular delay after detection. Weak driving field manipulation.

The initiation is with a fluctuation, the feedback is just as for any driven coupled oscillators.