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the lectures pdfs are available at:

https://www.physics.umd.edu/rgroups/amo/orozco/results/2022/Results22.htm

Correlations in Optics and Quantum Optics; A series of lectures about correlations and coherence. November 2022

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BOS.QT

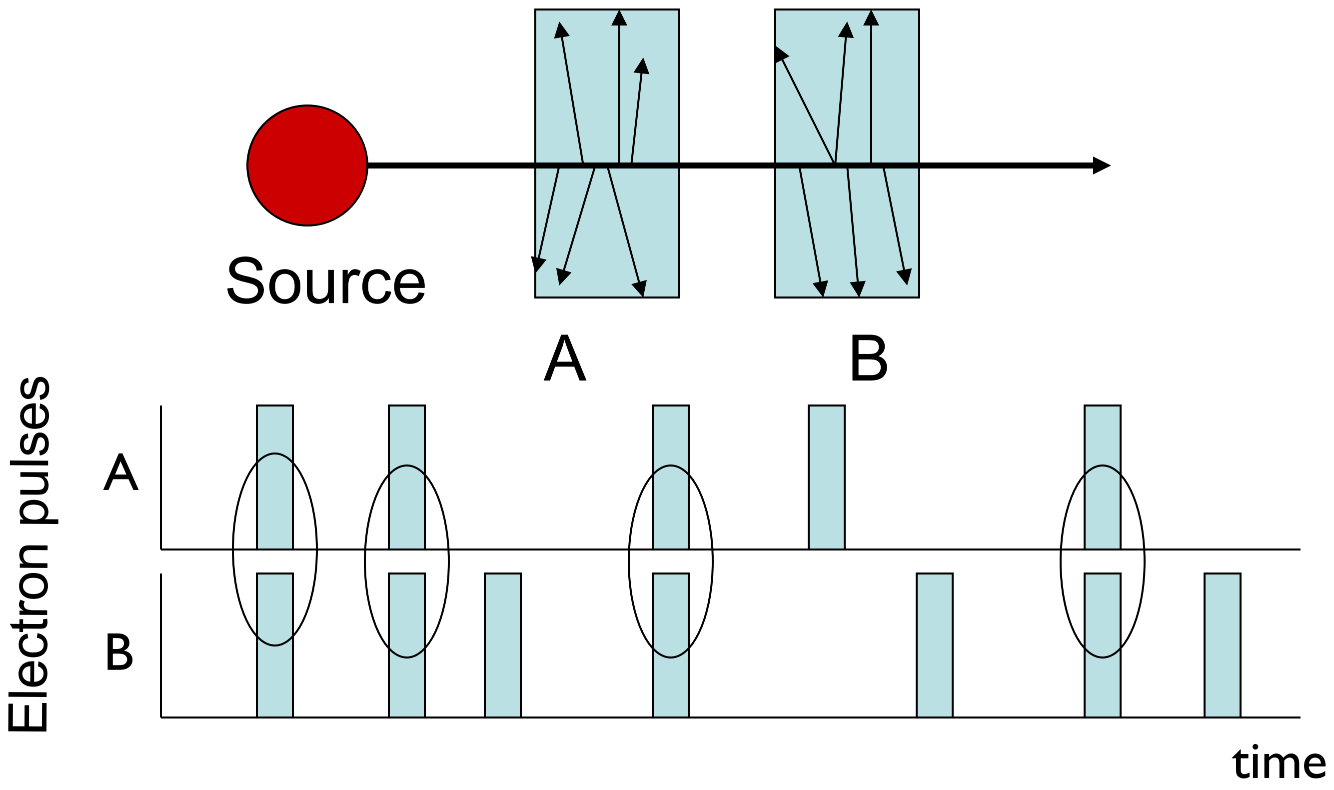
Lesson 8

Tentative list of topics to cover:

- From statistics and linear algebra to power spectral densities
- Historical perspectives and examples in many areas of physics
- Correlation functions in classical optics (field-field; intensity-intensity; field-intensity) part iii
- Optical Cavity QED
- Correlation functions, quantum examples
- Correlations and conditional dynamics for control
- Correlations of the field and intensity
- From Cavity QED to waveguide QED.

Conditional measurements:
Make a measurement only when you know there is something to measure.
Make measurements in coincidence.

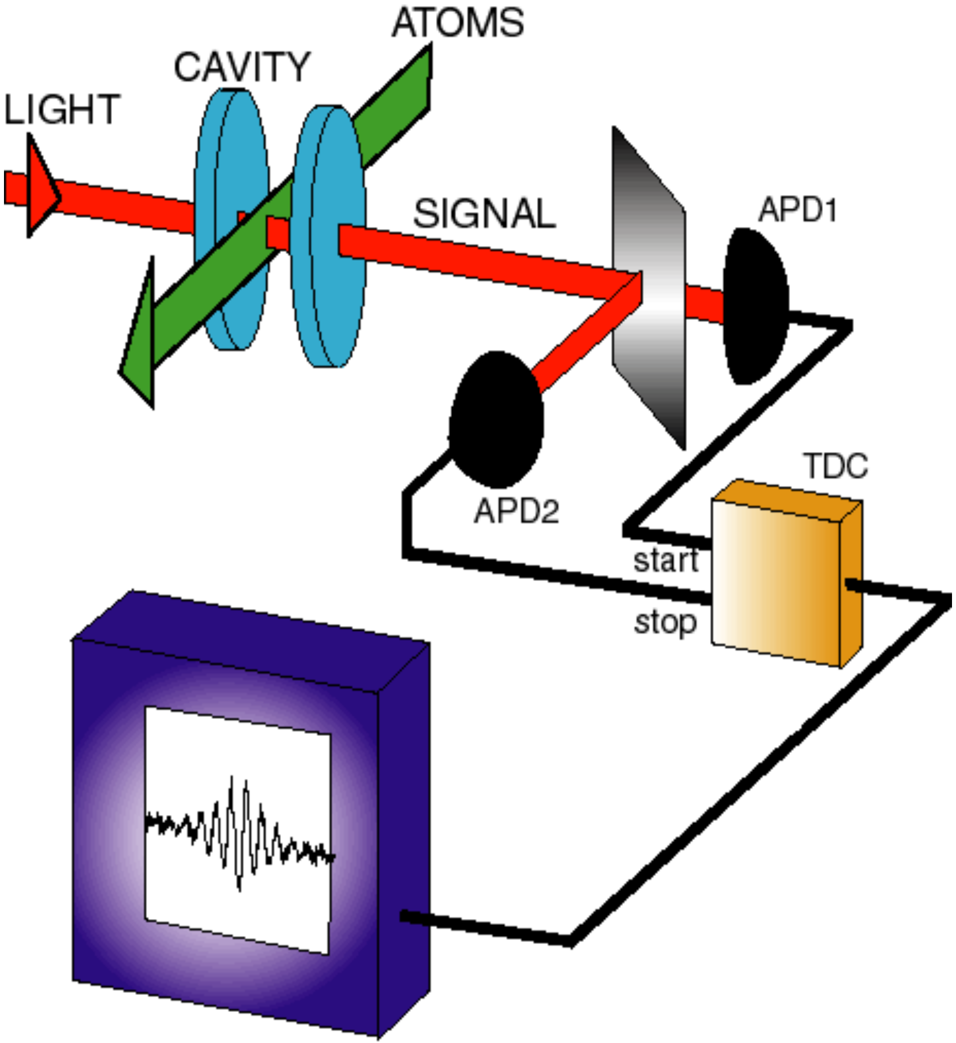
Example:
Calibration of a high energy detector.
(Geiger in 1910)

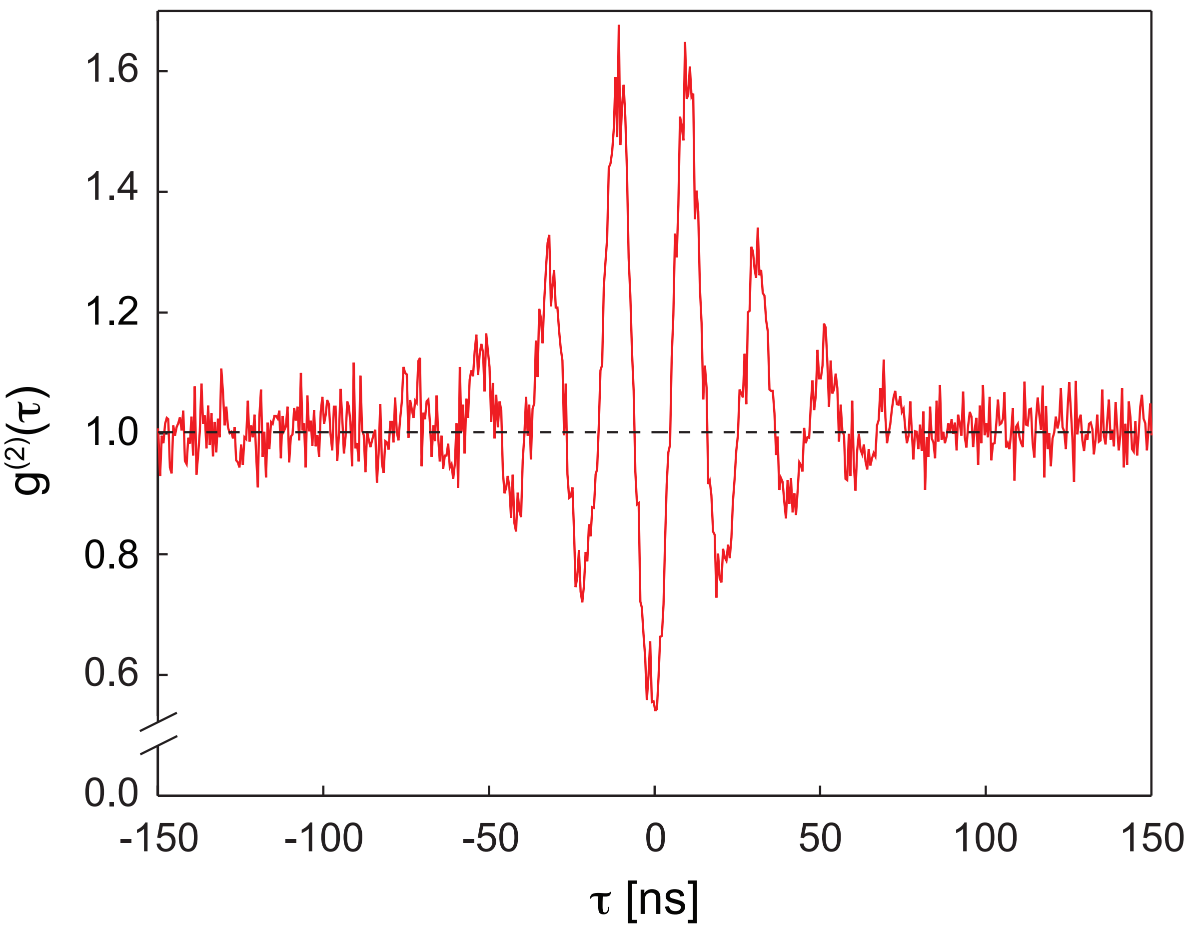


4 coincidences out of 5 A detections; efficiency of B=4/5

It is not necessary to know the efficiency of A!

Feedback in Cavity QED


ATOMS
CAVITY
LIGHT
SIGNAL
APD1
APD2
TDC
start
stop



1.6
1.4
1.2
1.0
0.8
0.6
0.0
-150
-100
-50
0
50
100
150
g(2)(τ)
τ [ns]

Conditional evolution of the state for N atoms

Steady state

$$|\psi_{ss}\rangle = |0, G\rangle + \lambda\left(|1, G\rangle - \frac{2g\sqrt{N}}{\gamma}|0, E\rangle\right)$$

$$+ \lambda^2\left(\zeta_0 \frac{1}{\sqrt{2}}|2, G\rangle - \theta_0 \frac{2g\sqrt{N}}{\gamma}|1, E\rangle\right) + \ldots.$$

Detection of a photon

$$\hat{a}|\psi_{ss}\rangle/\sqrt{\langle\hat{a}^\dagger\hat{a}\rangle_{ss}},$$

Conditional state

$$|\psi_c(\tau)\rangle = |0, G\rangle + \lambda\left(\zeta(\tau)|1, G\rangle - \theta(\tau)\frac{2g\sqrt{N}}{\gamma}|0, E\rangle\right)$$

$$+ O(\lambda^2).$$

$$\lambda = \langle\hat{a}\rangle = \frac{\varepsilon}{\kappa}\left(\frac{1}{1+2C}\right)$$

Algorithm

Conditional state

$$|\psi_c(\tau)\rangle = |0, G\rangle + \lambda\left(\zeta(\tau)|1, G\rangle - \theta(\tau)\frac{2g\sqrt{N}}{\gamma}|0, E\rangle\right) + O(\lambda^2).$$

If we choose a time $\tau = T$ such that

$\zeta(T) = \theta(T)$ to order λ we get a steady state with a new λ'

$$|\psi_c(T)\rangle \simeq |0, G\rangle + \lambda'\left(|1, G\rangle - \frac{2g\sqrt{N}}{\gamma}|0, E\rangle\right)$$

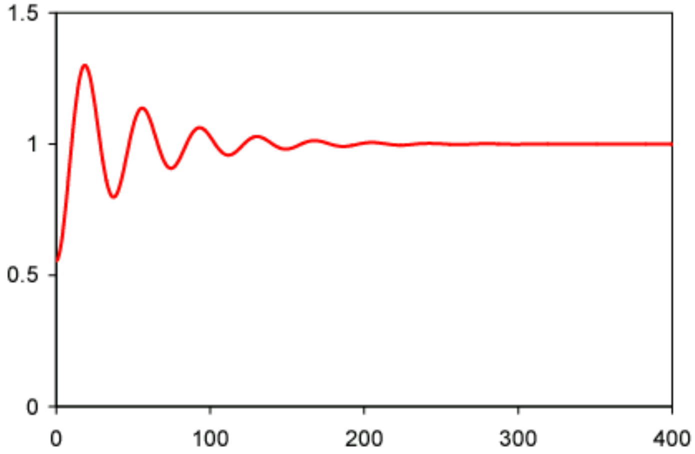
Then in the presence of feedback the correlation function is not symmetric, but it is still correctly calculated by:

$$g^{(2)}(\tau) \simeq \frac{|\langle 1, G|\psi_{\mathrm{c+fb}}(\tau)\rangle|^2}{|\langle 1, G|\psi_{\mathrm{ss}}\rangle|^2} = [\zeta_{\mathrm{fb}}(\tau)]^2$$

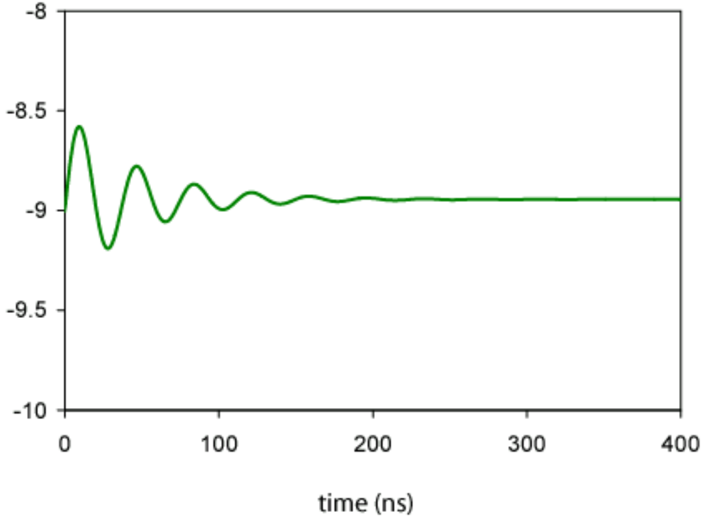
The time T is close to the time when the field fluctuation crosses the mean. This way of stabilizing the conditional state is possible because it is a pure quantum state with two real parameters (θ and ζ) and two control parameters: the change in the drive λ'- λ and the timing of the change T.

$$\lambda = \langle \hat{a} \rangle = \frac{\varepsilon}{\kappa}\left(\frac{1}{1+2C}\right)$$

Field ~ $\zeta(\tau)$



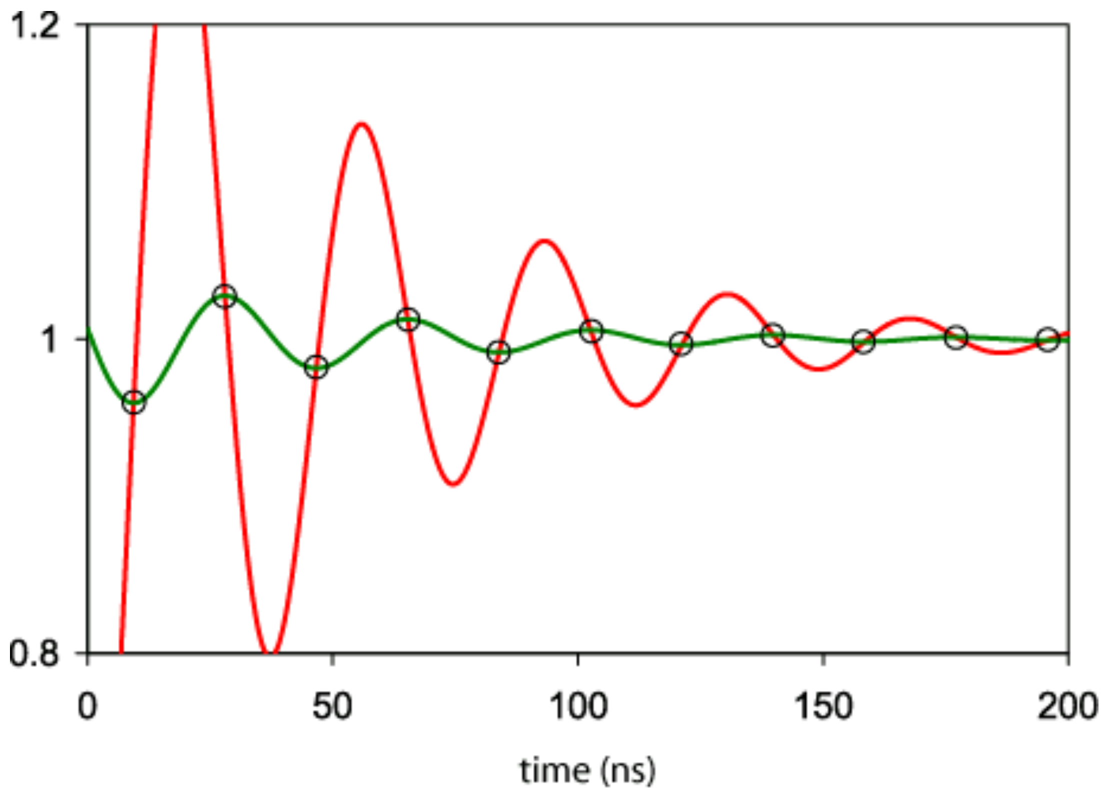
Atomic polarization ~ $\theta(\tau)$



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

$$\lambda(t > T) = f_1(T)\lambda(t < T)$$

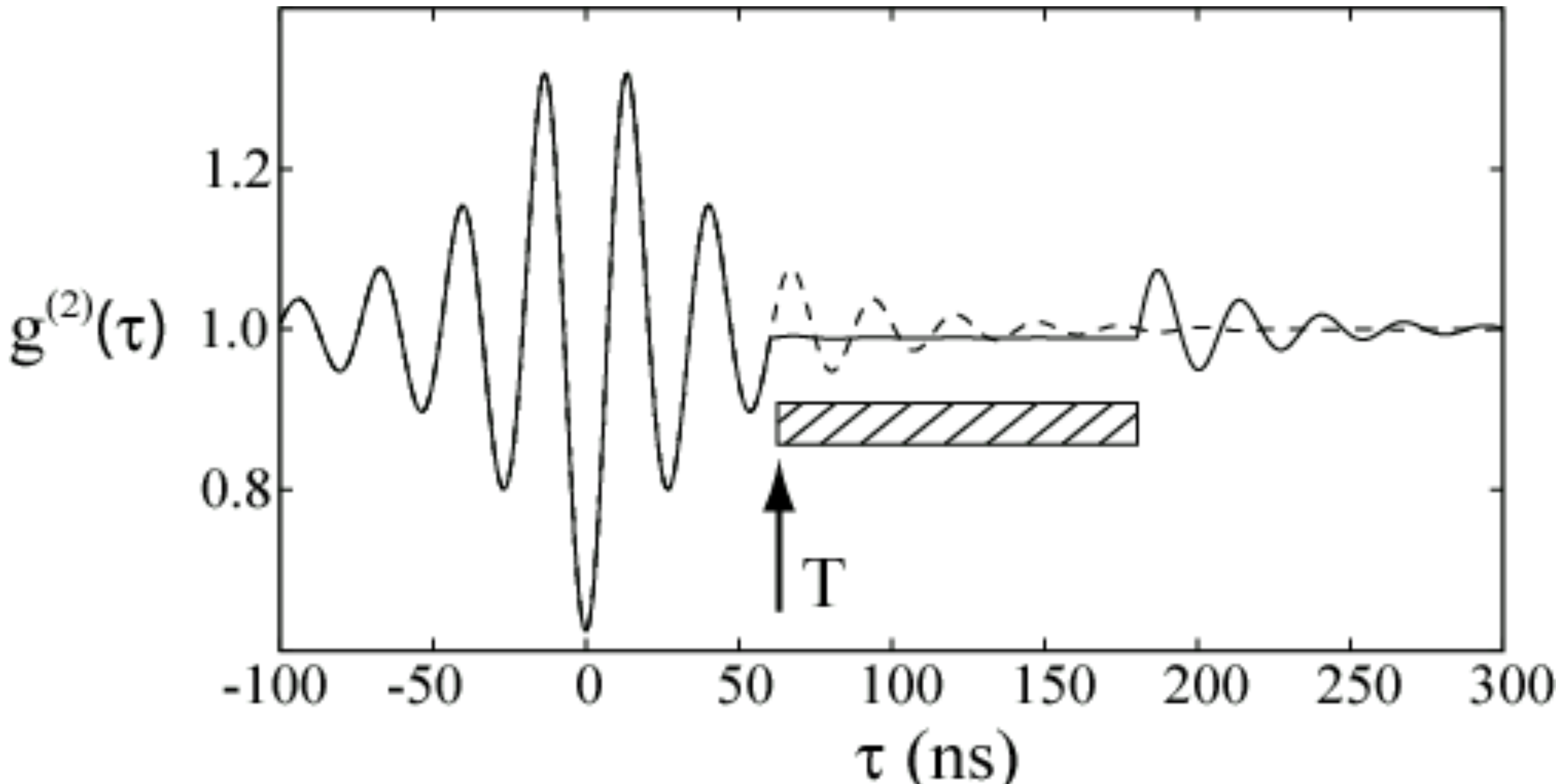
$\zeta(\tau)$ [field red]
$\theta(\tau)$ [atoms green]



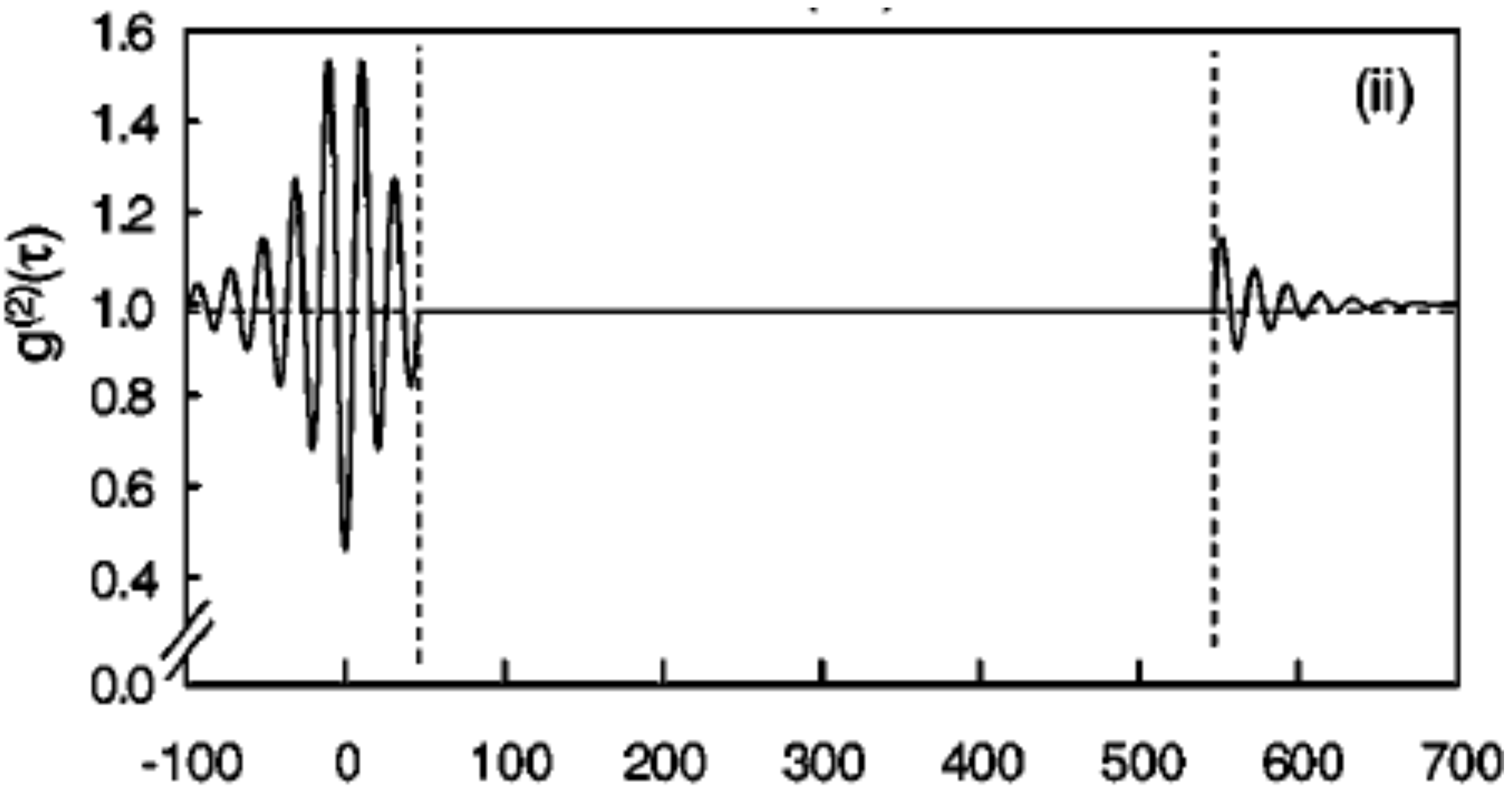
Crossing at:

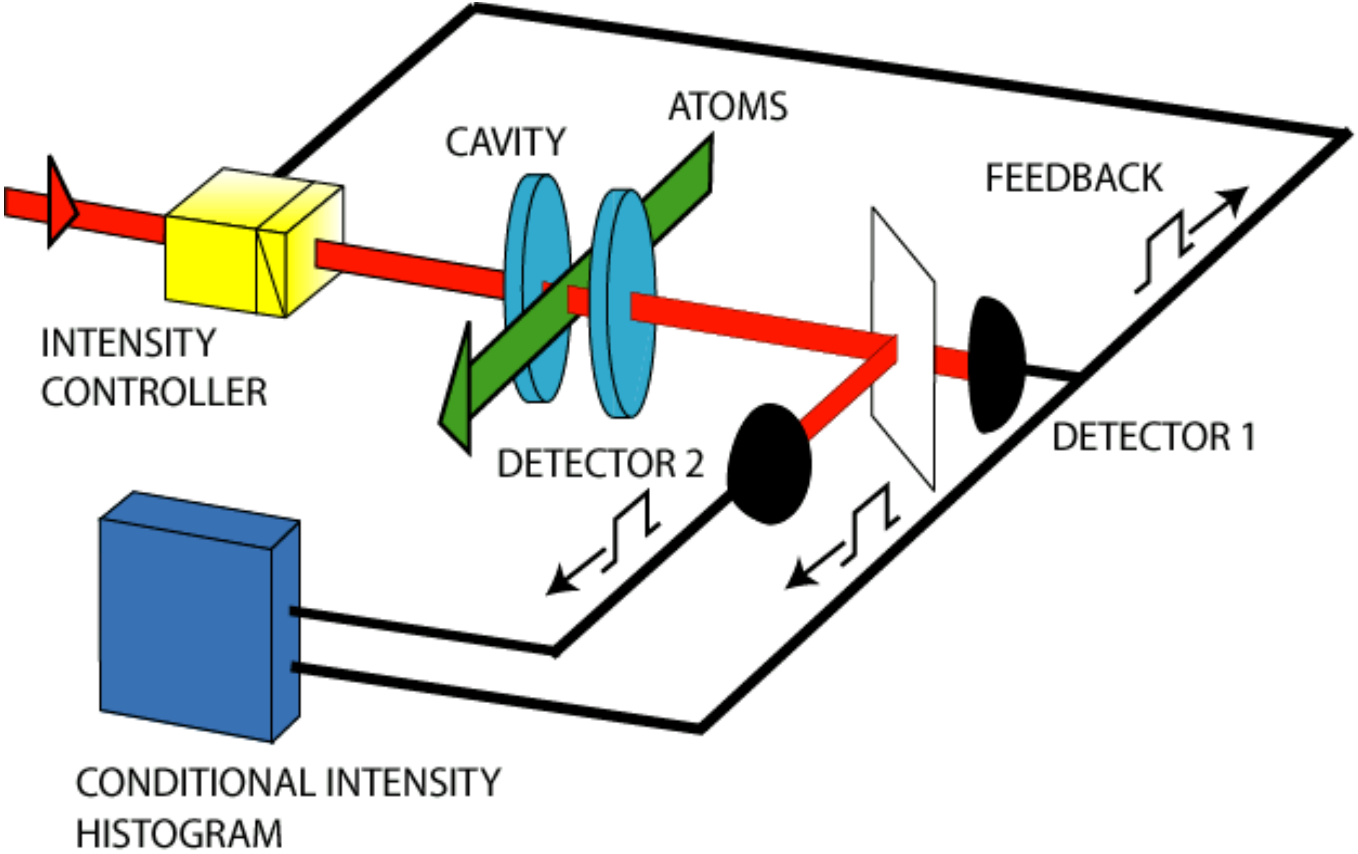
$$\Omega T = n\pi - \tan^{-1}\left(\frac{1+2C}{2C\left(\frac{2\kappa+\gamma}{4\Omega}\right) + \frac{4\kappa^2-\gamma^2-16\Omega^2}{16\Omega\kappa}} \right)$$

Theoretical prediction.

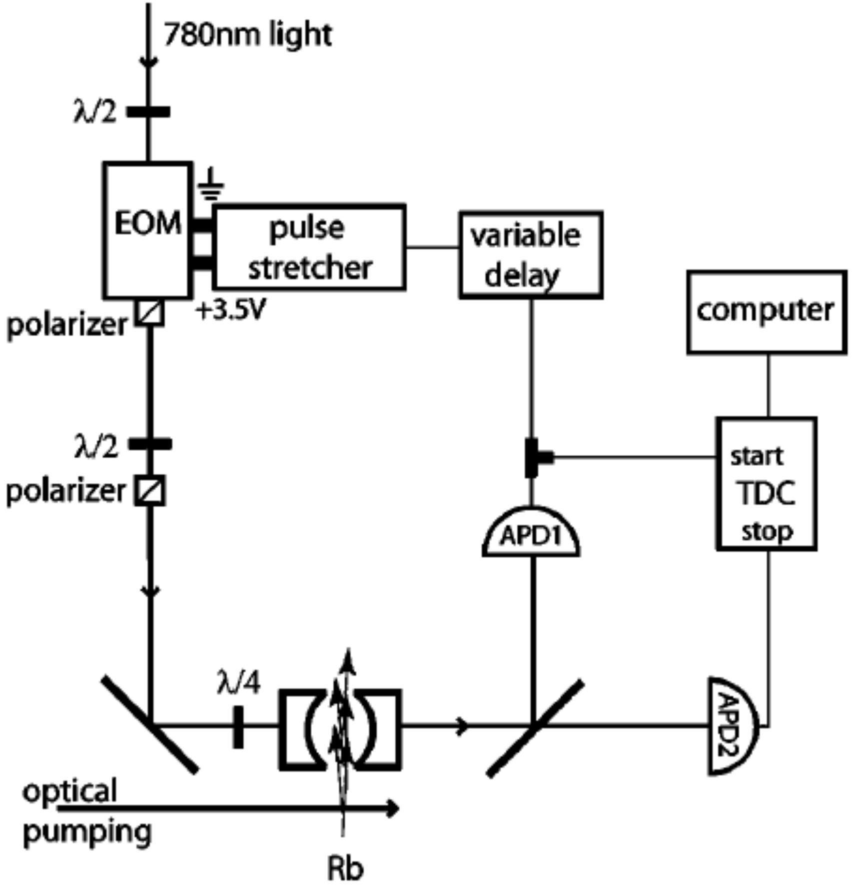


Capture and release

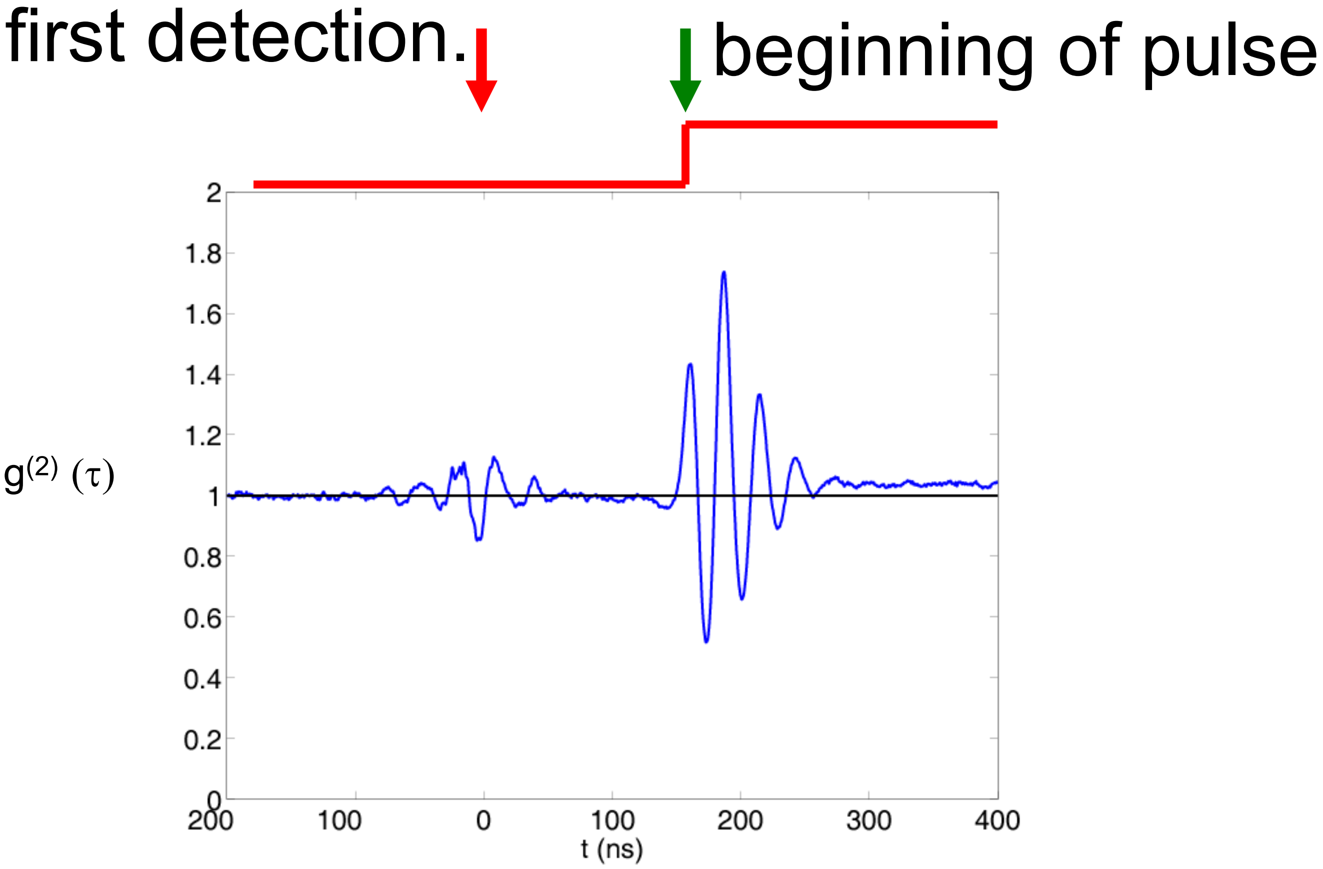


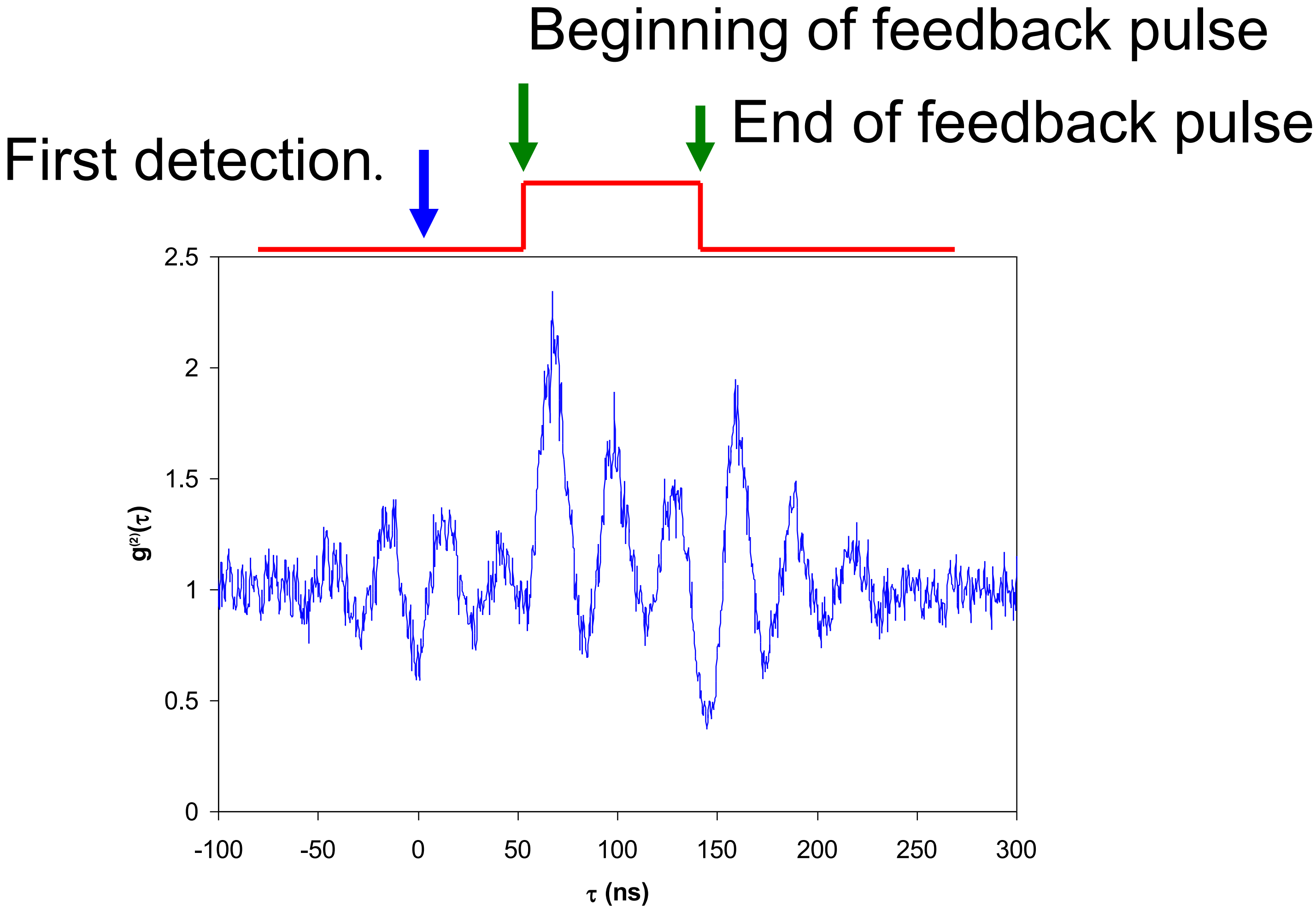

ATOMS
CAVITY
FEEDBACK
INTENSITY
CONTROLLER
DETECTOR 2
DETECTOR 1
CONDITIONAL INTENSITY
HISTOGRAM

Implementation



Conditional intensity and step:

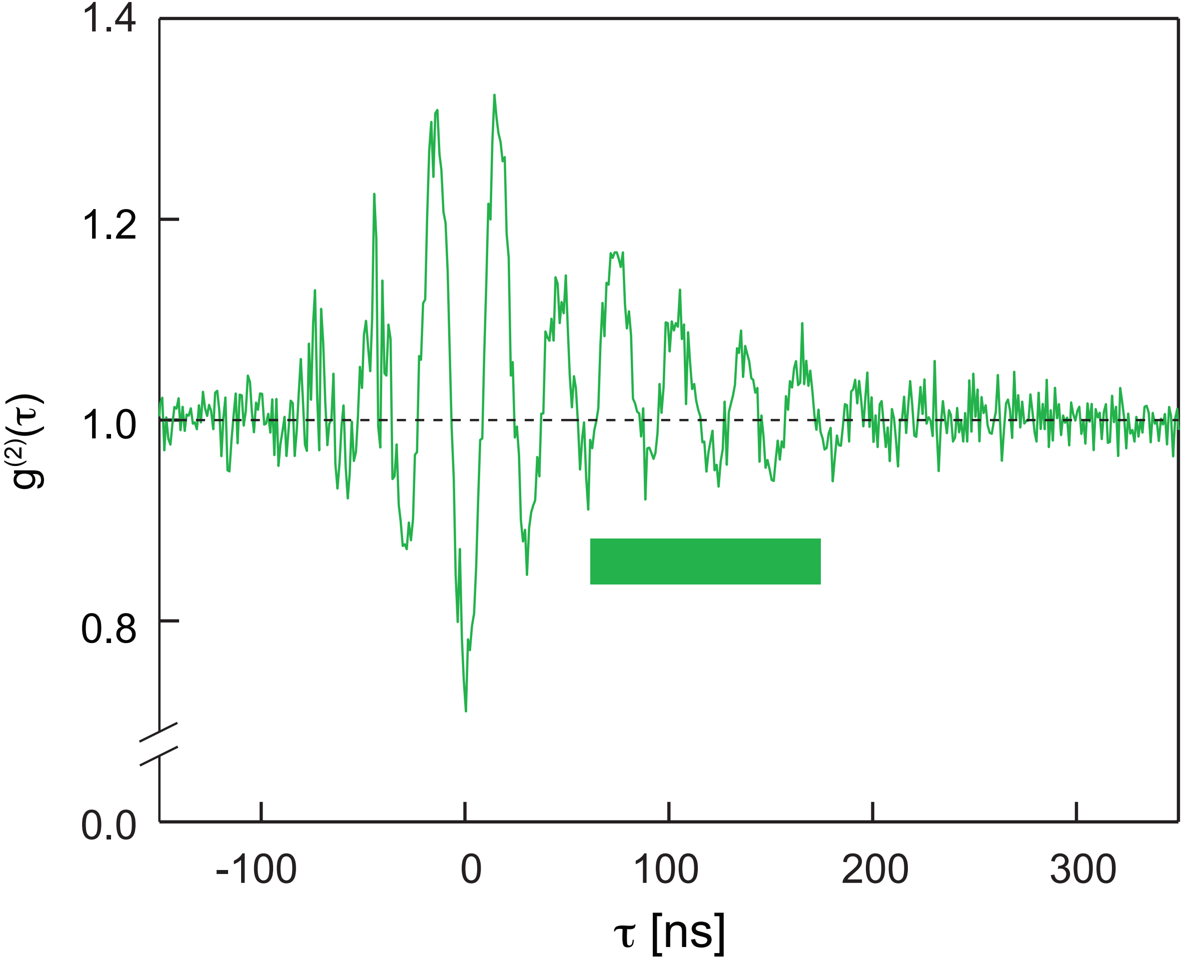


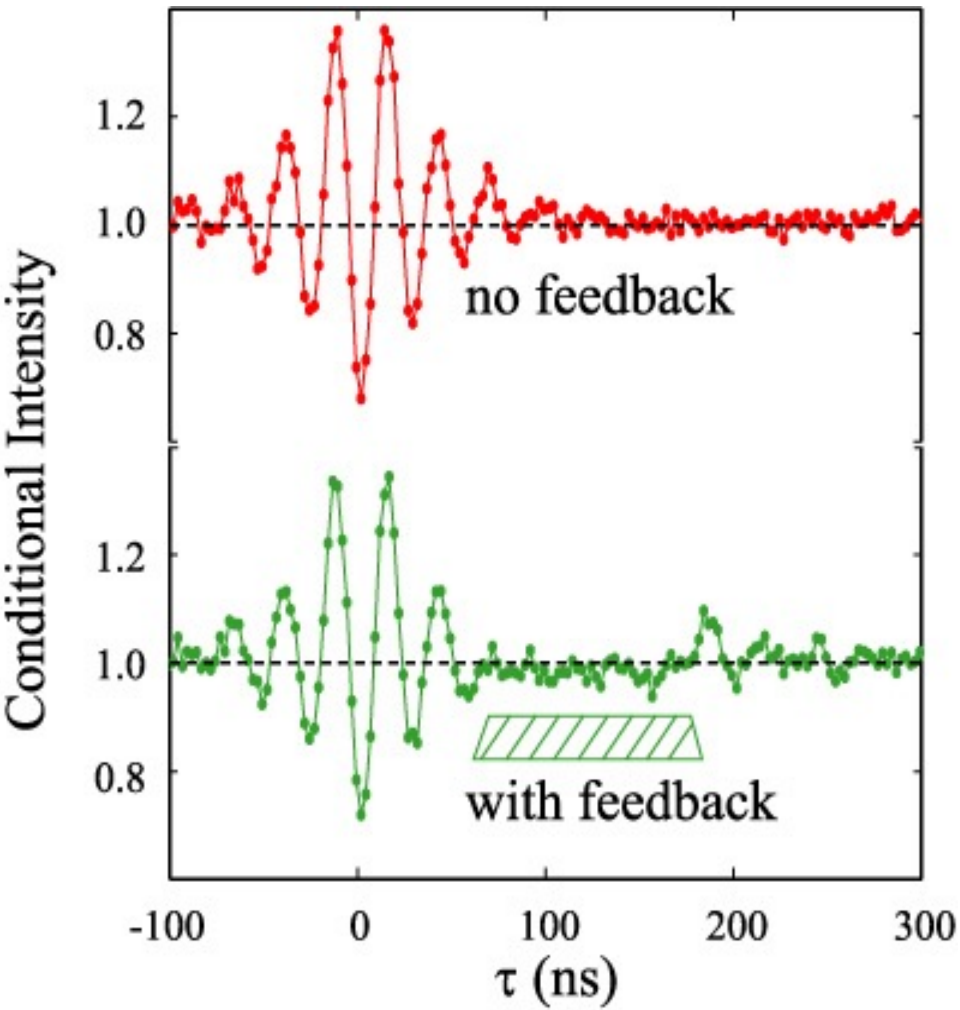

Beginning of feedback pulse
End of feedback pulse
First detection.
g(2)(τ)
τ (ns)
2.5
2
1.5
1
0.5
0
-100
-50
0
50
100
150
200
250
300

Three conditions:
Amplitude
Parity
Push time

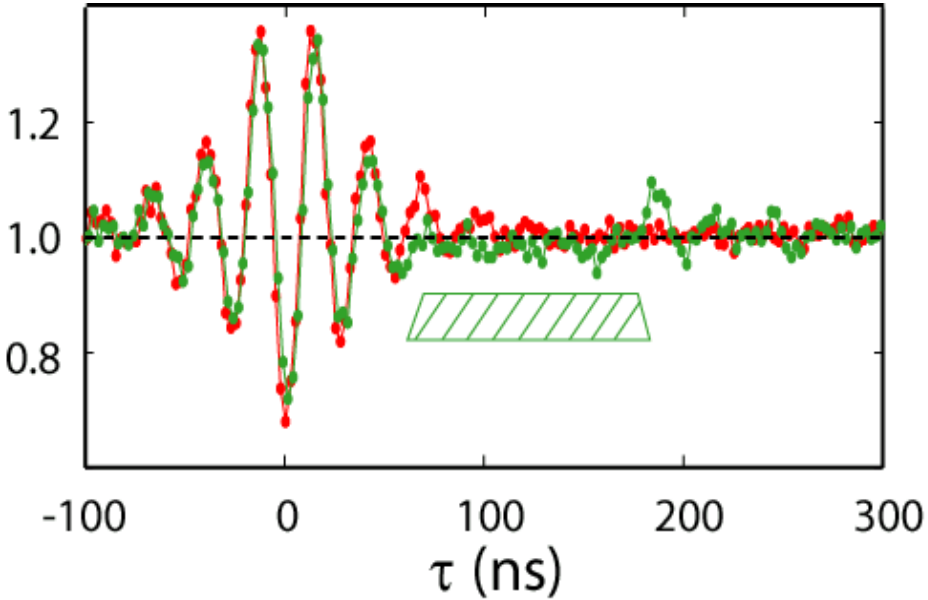
We only have one information bit, one click
But we have a very good understanding of dynamics.

With feedback to maintain oscillation

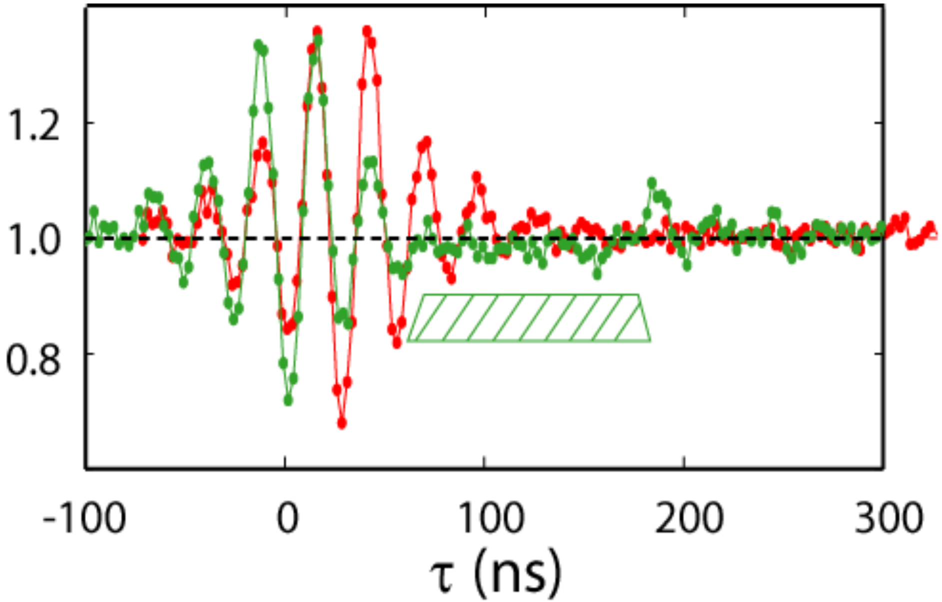




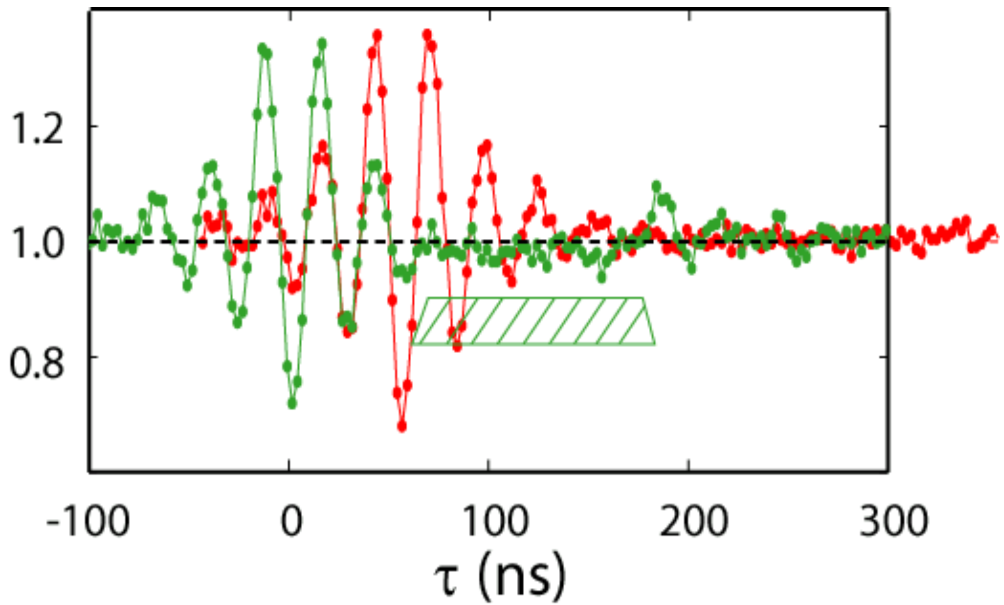
Conditional Intensity
1.2
1.0
0.8
no feedback
with feedback
-100
0
100
200
300
τ (ns)



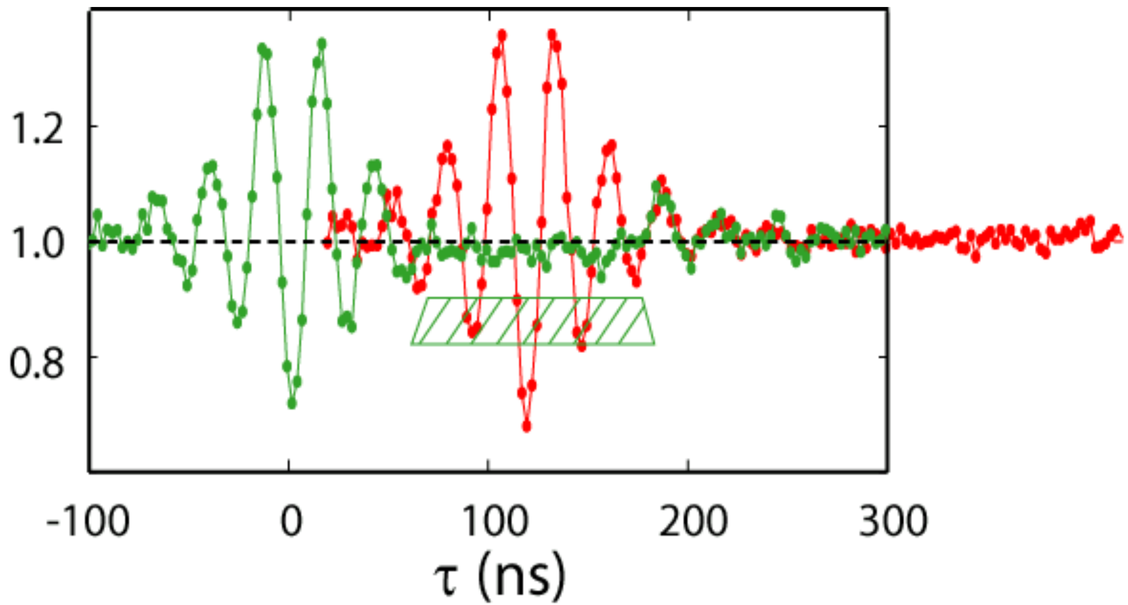
1.2
1.0
0.8
-100
0
100
200
300
τ (ns)



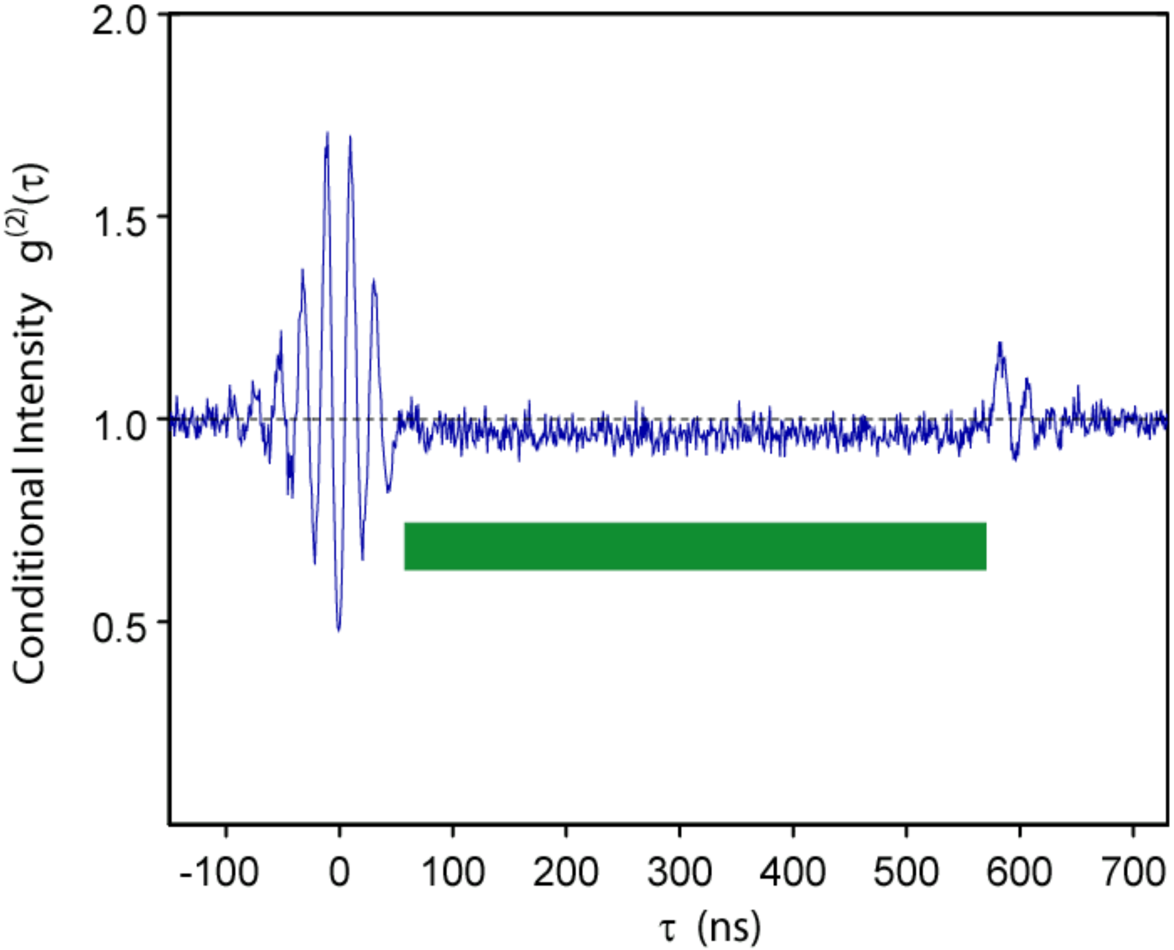
1.2
1.0
0.8
-100
0
100
200
300
τ (ns)



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)

Capture and release of oscillation



How long can we maintain the system?
As much as we want

Where is the information?
There is a new steady state.

What is quantum about this?
The detection of the first photon that triggers the conditional evolution.

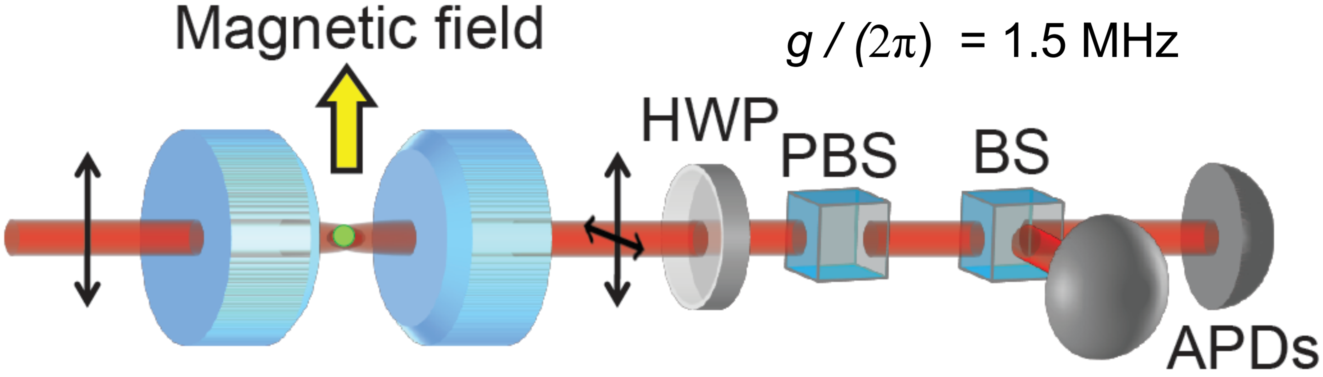
A second example, ground state quantum beats

Detection of Coherence

$\gamma / (2\pi) = 6.0 \times 10^6\ s^{-1}$

$\kappa / (2\pi) = 3.2 \times 10^6\ s^{-1}$

$g / (2\pi) = 1.5$ MHz

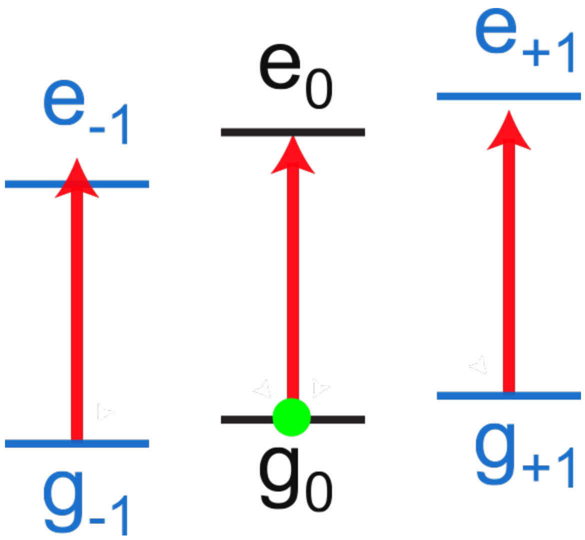


Drive vertical polarization (π)

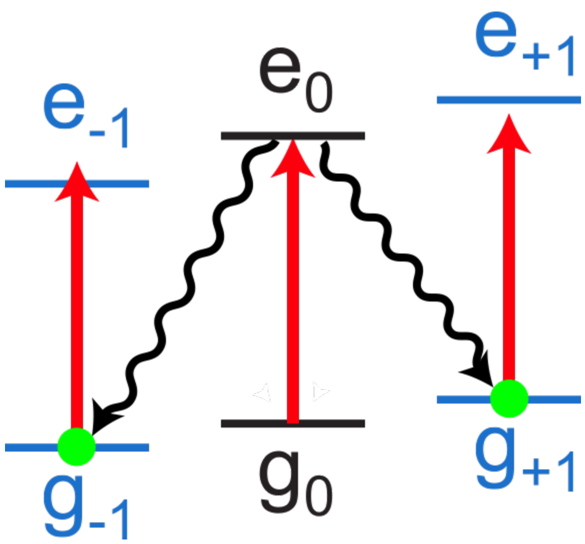
Look at horizontal polarization with HWP slightly rotated.

^{85}Rb atoms

Spontaneous emission is important

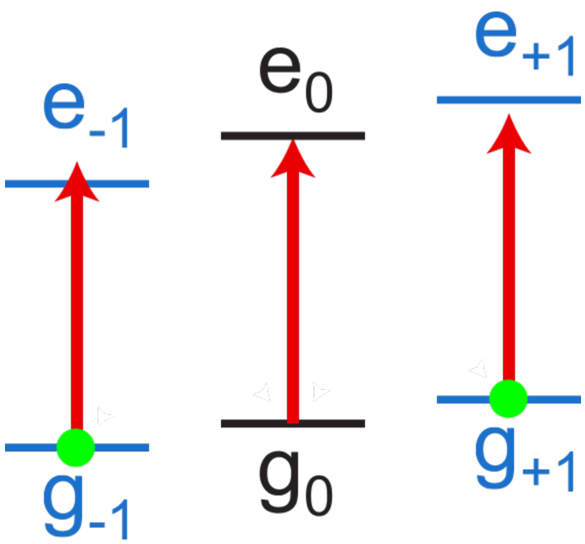


Atom prepared in ground state

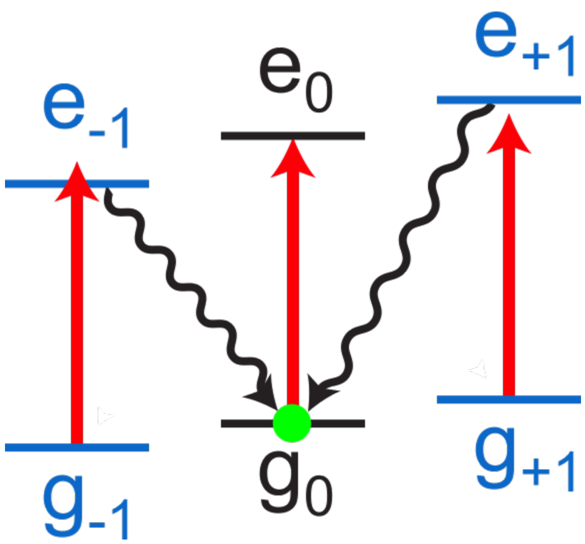


Click!

Detection of one horizontal photon ensures superposition



Continue resonant π drive



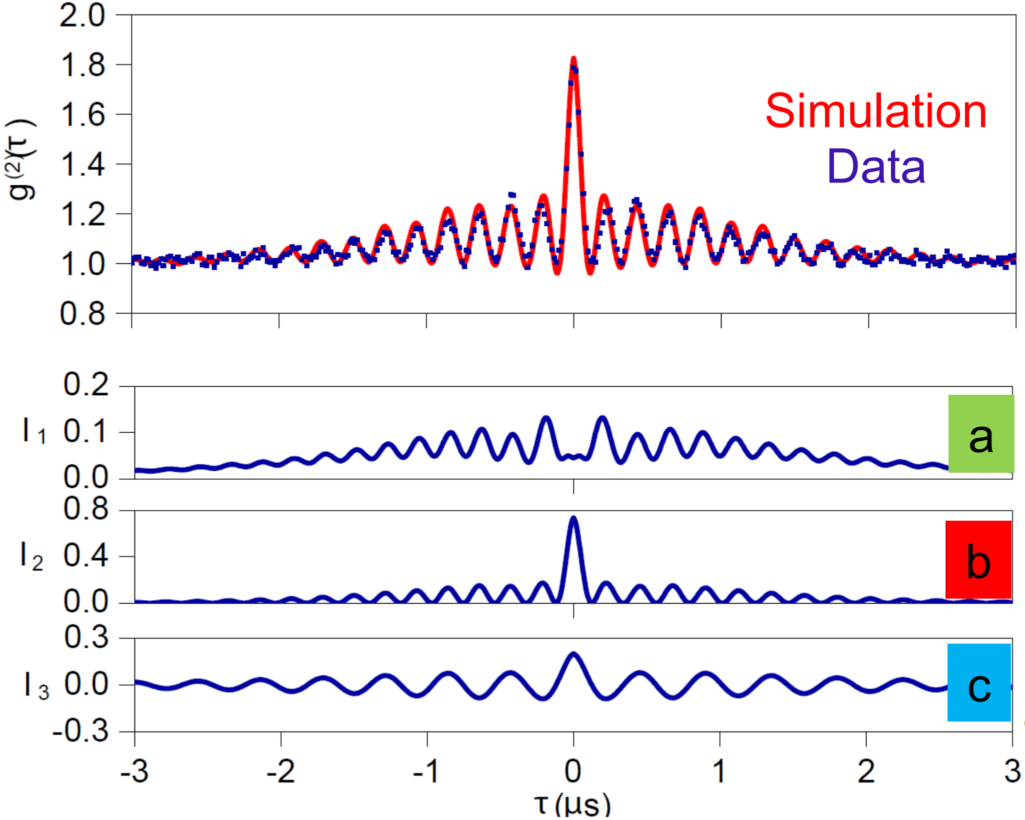
Click!

Detection of second horizontal photon puts the atom where it started erasing all which path information: Quantum Eraser.

$$g^{(2)}(\tau) = \langle a^\dagger(t) a^\dagger(t+\tau) a(t+\tau) a(t) \rangle \qquad a = \sum_{i=1}^{N} \sigma_i + b$$

coherent background

N-atom atomic emission



Single-atom $g_A^{(2)}(\tau)$

$\langle \sigma_i^\dagger(t) \sigma_i^\dagger(t+\tau) \sigma_i(t+\tau) \sigma_i(t) \rangle$

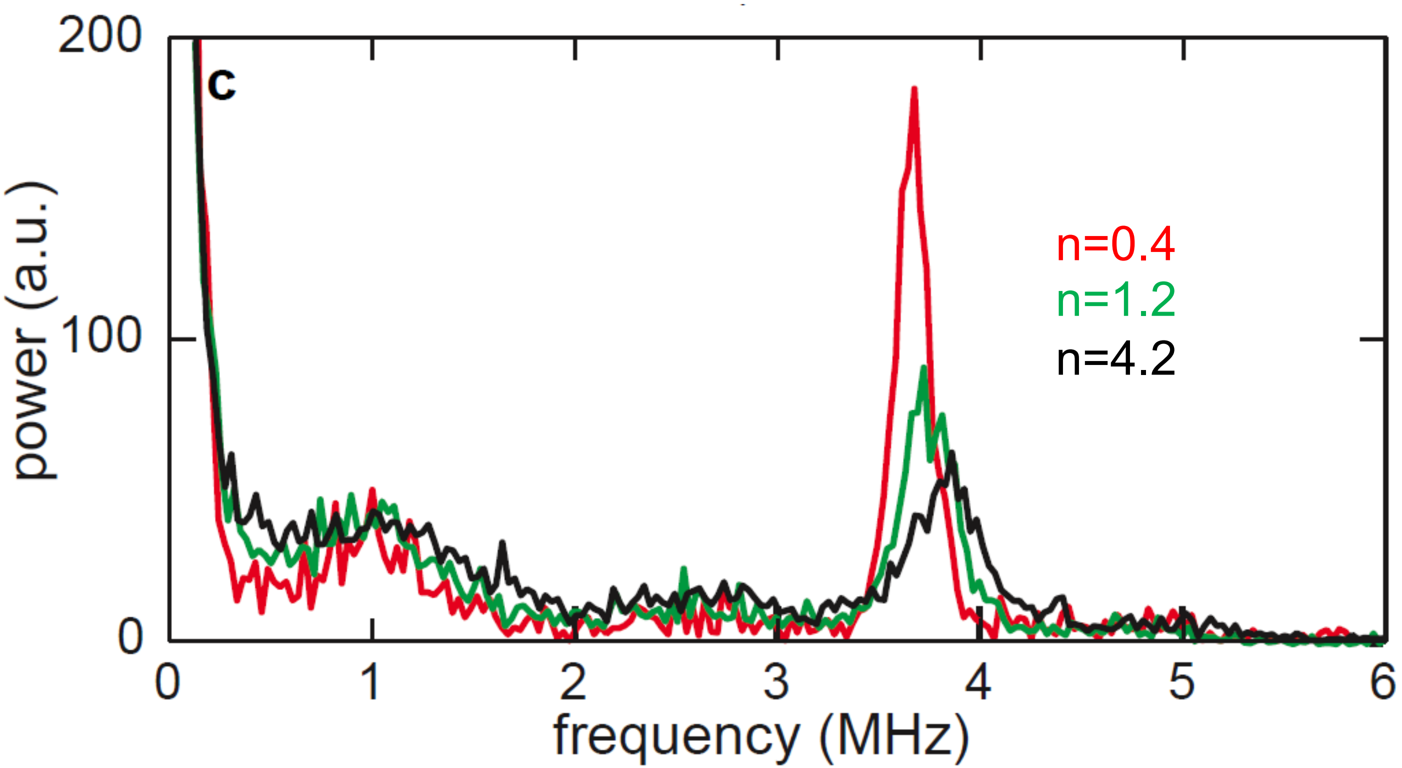
Multi-atom $|g_A^{(1)}(\tau)|^2$

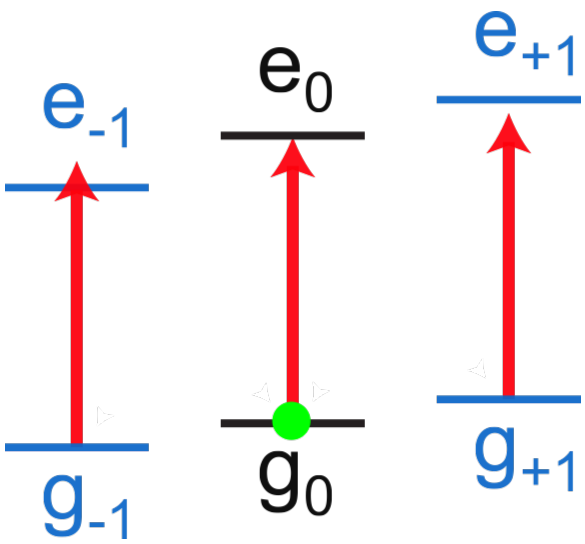
$\langle \sigma_j^\dagger(t) \sigma_i^\dagger(t+\tau) \sigma_j(t+\tau) \sigma_i(t) \rangle$

Homodyne $\mathrm{Re}\left(g_A^{(1)}(\tau)\right)$

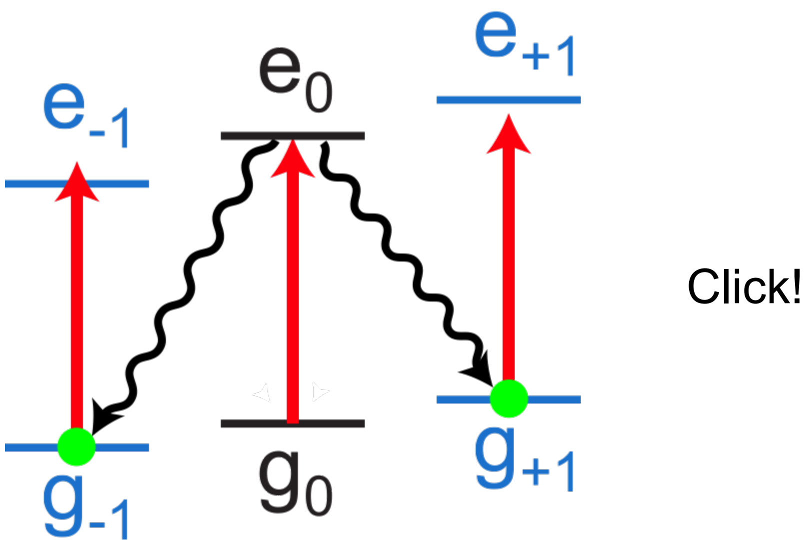
$\langle b^\dagger(t) \sigma_i^\dagger(t+\tau) b(t+\tau) \sigma_i(t) \rangle + \text{c.c.}$

Not just a shift, but also a broadening and decay of amplitude with increasing drive

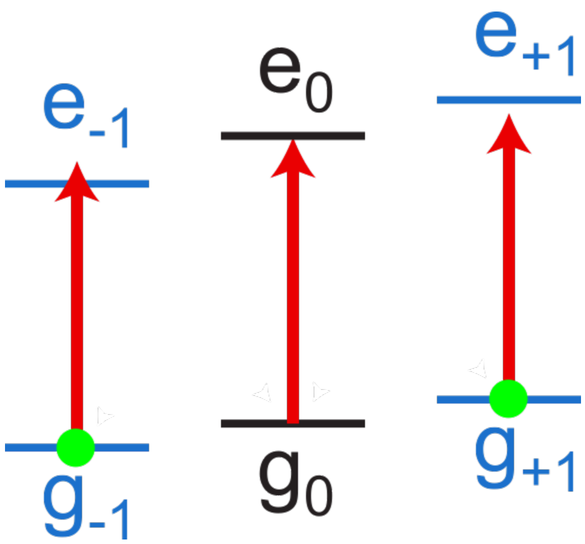




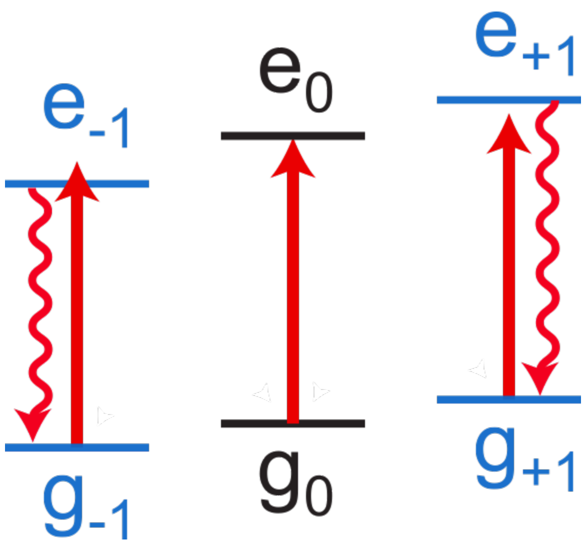
Atom prepared in ground state



Detection of horizontal photon ensures superposition

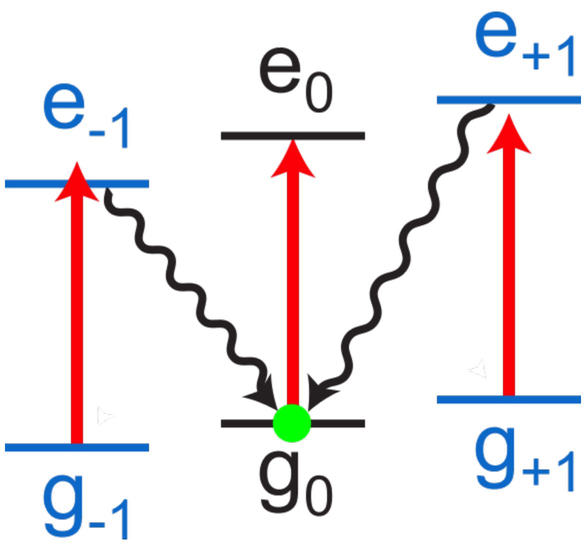


Continue resonant π drive



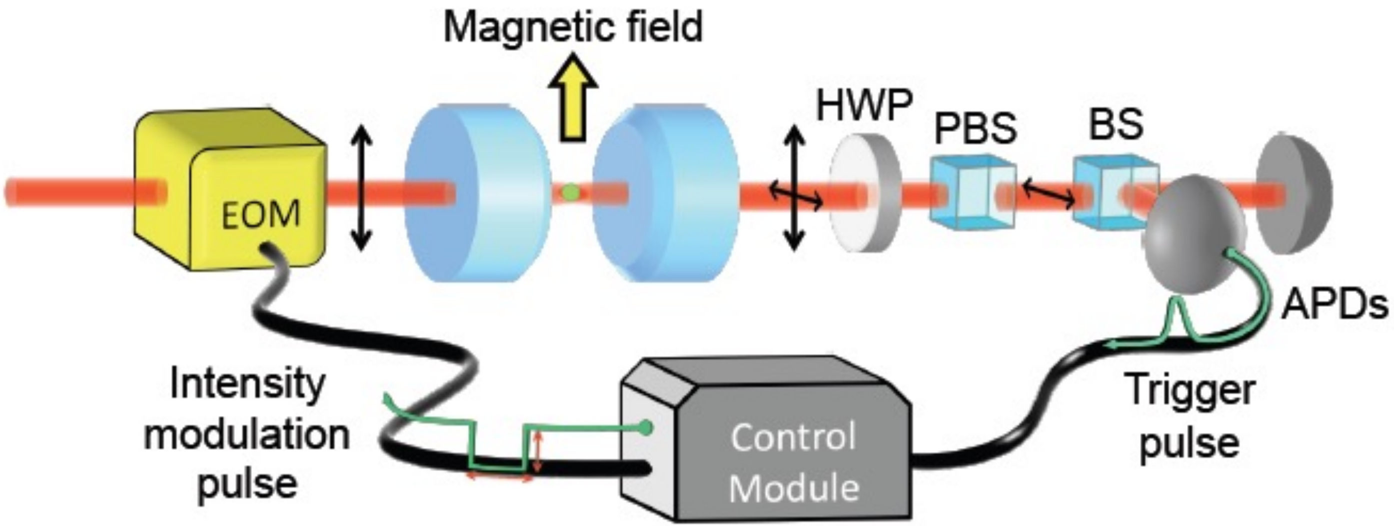
Click, Click not detected

Rayleigh Scattering, interruptions, phase shifts!

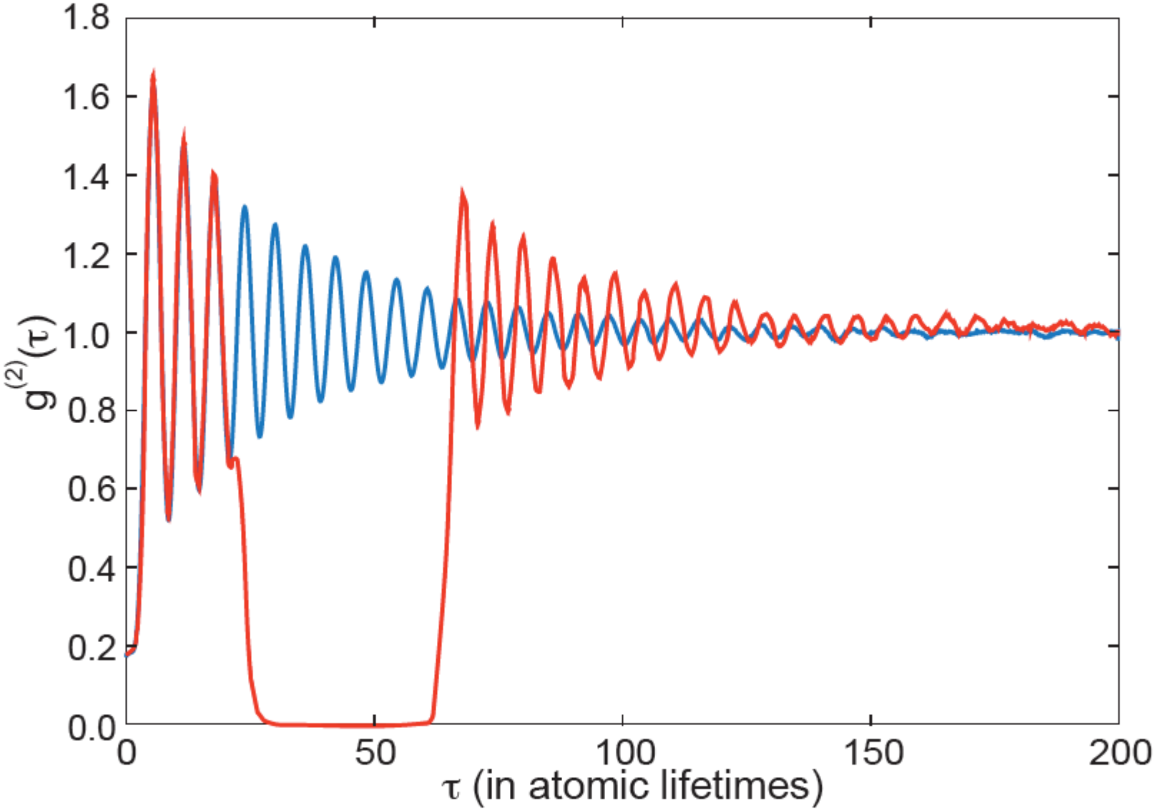


Detection of second horizontal photon

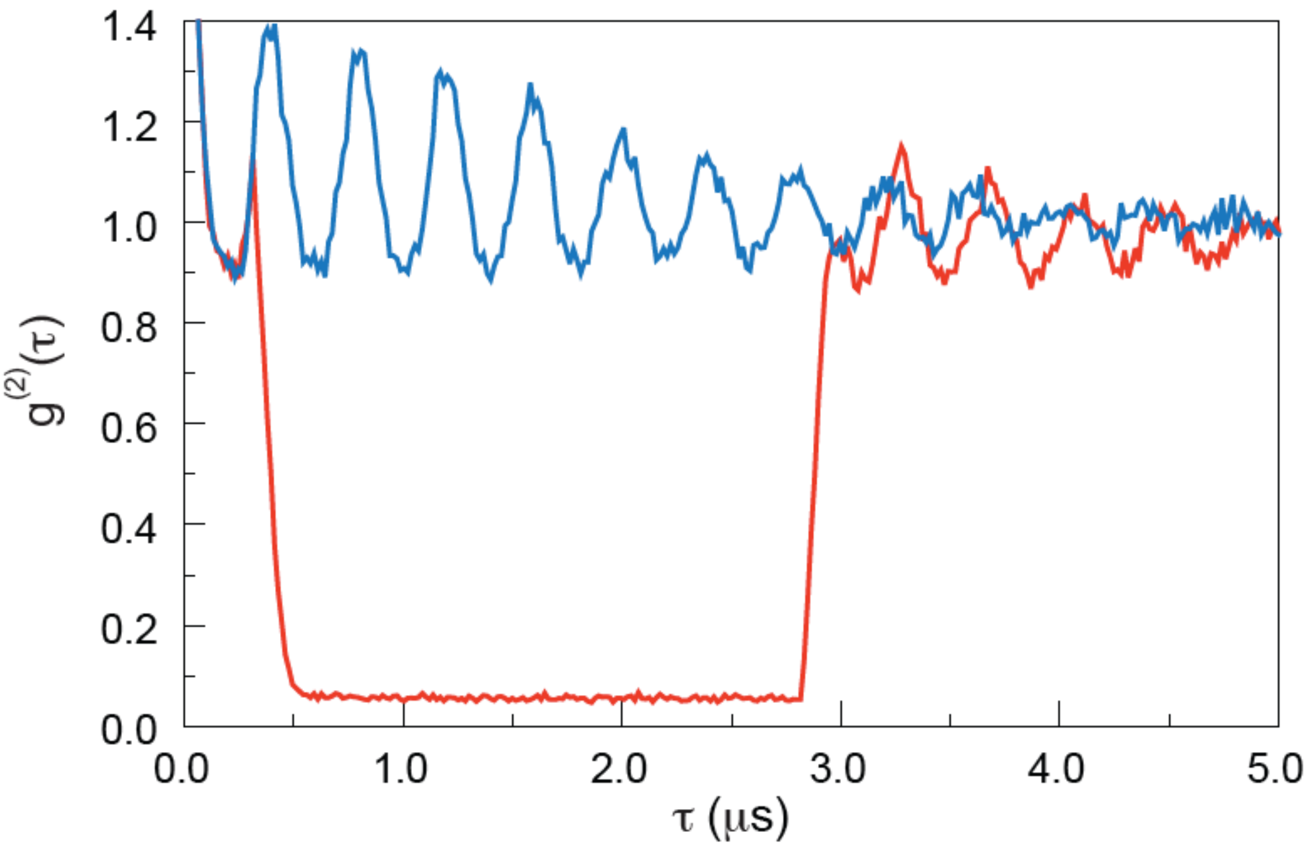
Feedback on a click!



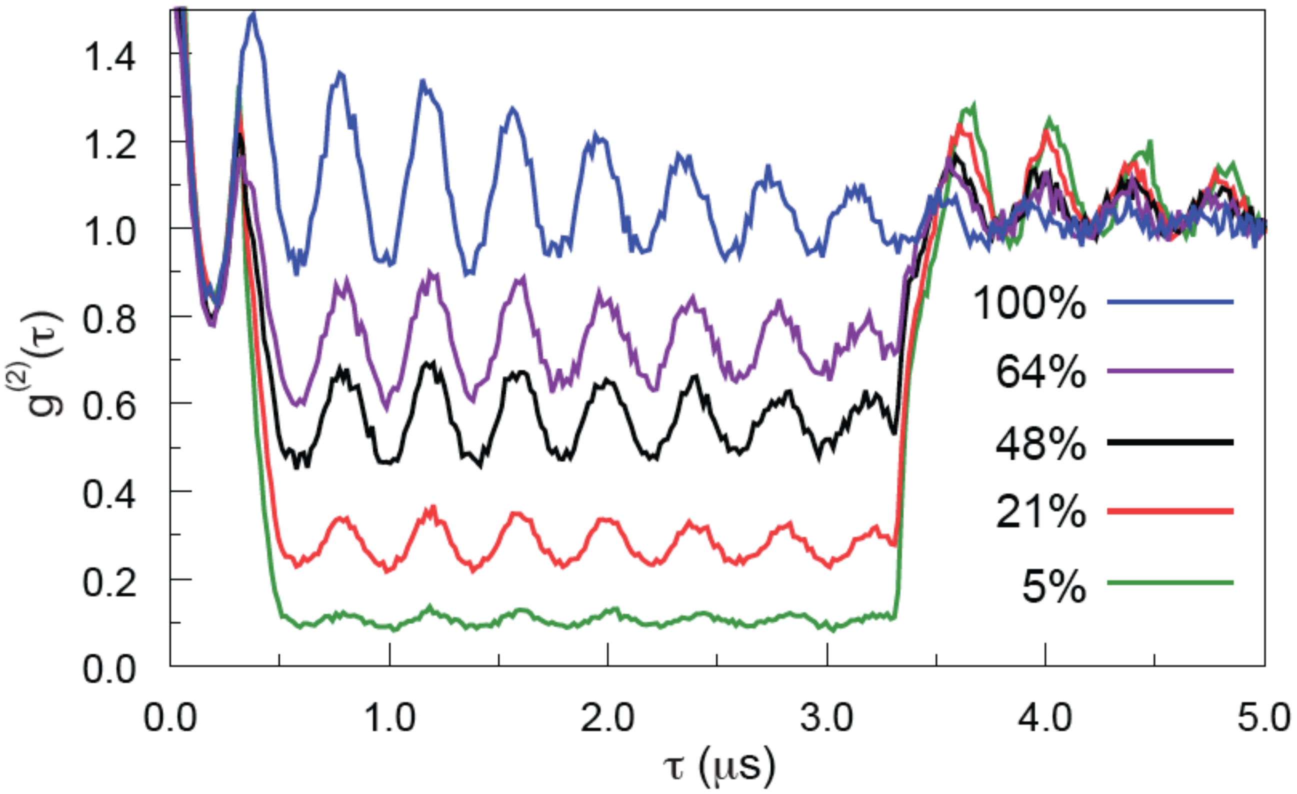
Turn off drive (simulation)



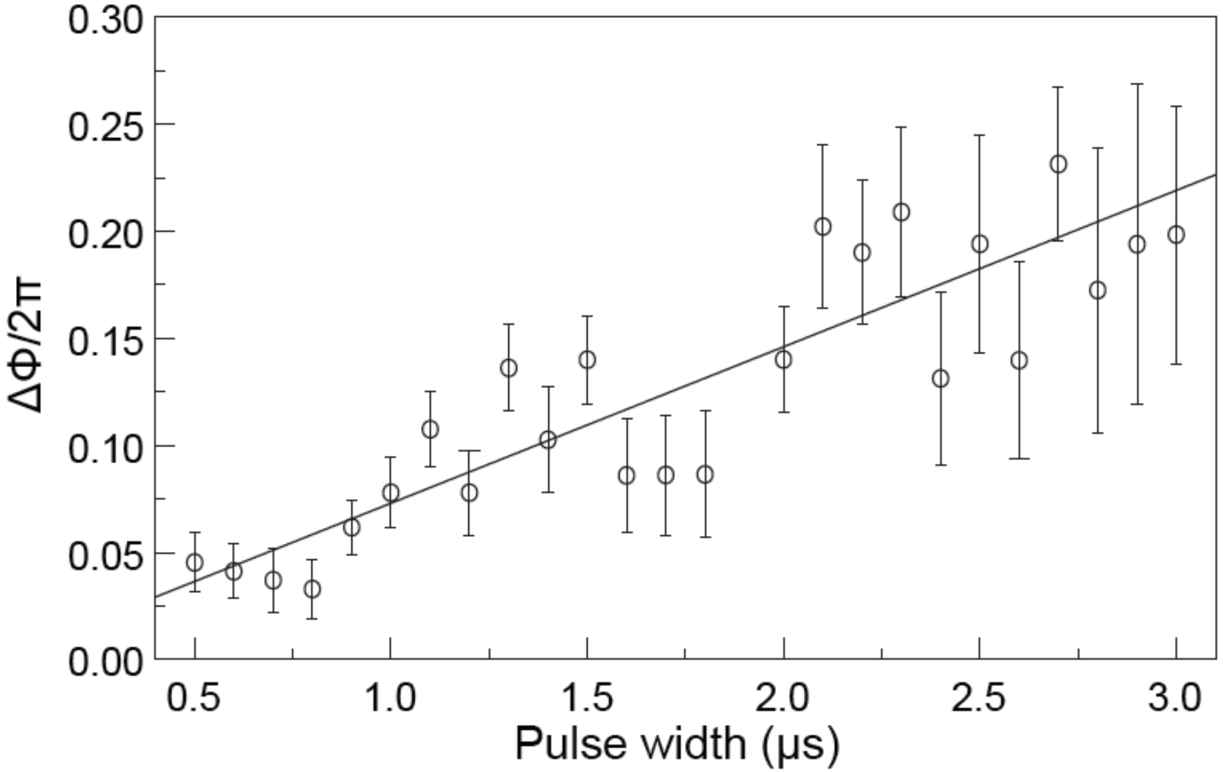
Turn off drive (experiment)



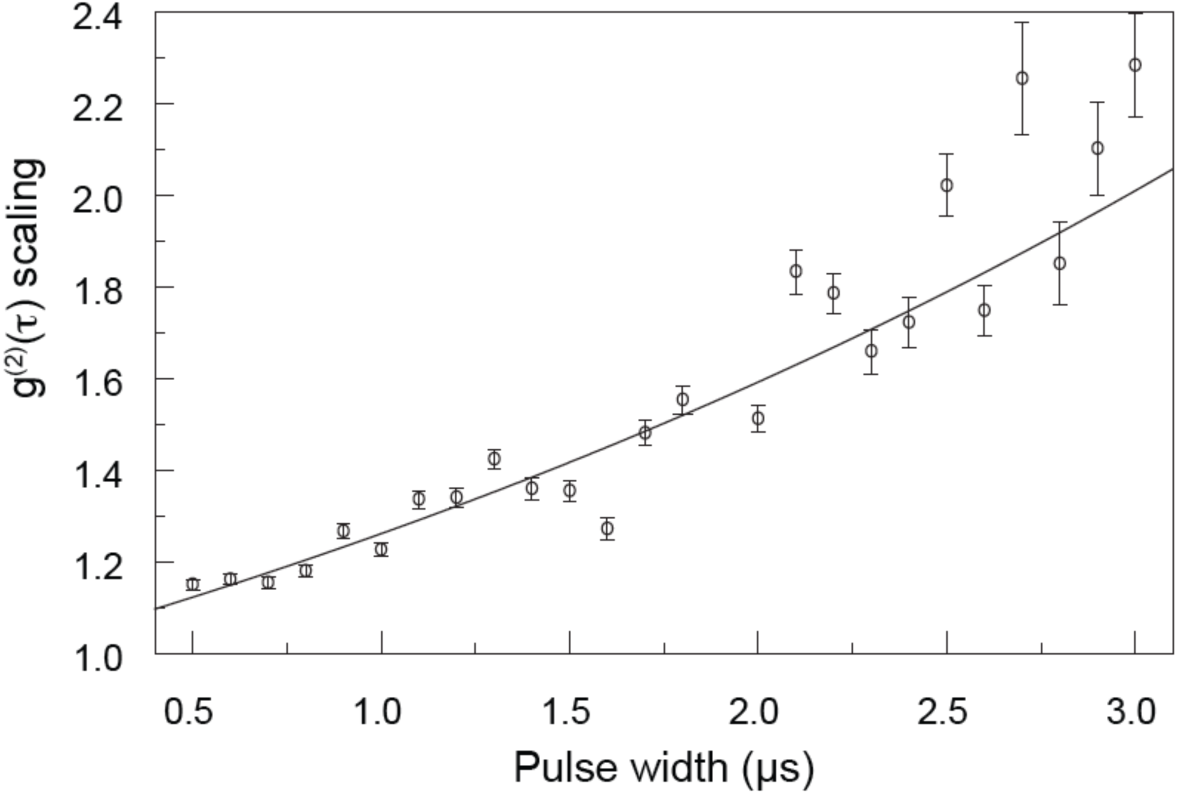
Partial turn off drive (experiment)



Phase shift



Scaling of correlation when turning back on



Spontaneous emission prepares quantum beats from the ground state. Long coherence.

However, too much spontaneous emission can destroy the quantum beats, frequency shift and decoherence .

Start of a feedback protocol: Turn off the drive after the first click and let the coherence evolve in the dark!, just as Norman Ramsey taught us!

Bibliography

W. P. Smith, J. E. Reiner, L. A. Orozco, S. Kuhr, H. M. Wiseman, "Capture and release of a conditional state of a cavity QED system by quantum feedback," Phys. Rev. Lett. **89**, 133601, (2002).

J. E. Reiner, W. P. Smith, L. A. Orozco, H. M. Wiseman, and Jay Gambetta, "Quantum feedback in a weakly driven cavity QED system, " Phys. Rev. A. **70**, 023819, (2004).

A. D. Cimmarusti, C. A. Schroeder, B. D. Patterson, L. A. Orozco, P. Barberis-Blostein, and H. J. Carmichael, "Control of conditional quantum beats in cavity QED: amplitude decoherence and phase shifts," New J. Phys. **15,** 023002 (2013).

Thanks