# Current issues in coherence for small laser sources

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with the support of : Région Provence-Alpes-Côte d'Azur

# Coworkers

At the INLN

Experiments Tao Wang (Ph.D. Student)

Région Provence-Alpes-Côte d'Azur

B. Benzimoun (Intern, Univ. Clermont-Ferrand)

At CNR (Italy)

Numerics G.P. Puccioni – Firenze (Italy)

Consiglio Nazionale delle Ricerche
Institute for Complex Systems
*Istituto dei Sistemi Complessi*

# Outline of talk

0. General Introduction and Overview of the Problem

I. Coherence in Macroscopic Lasers

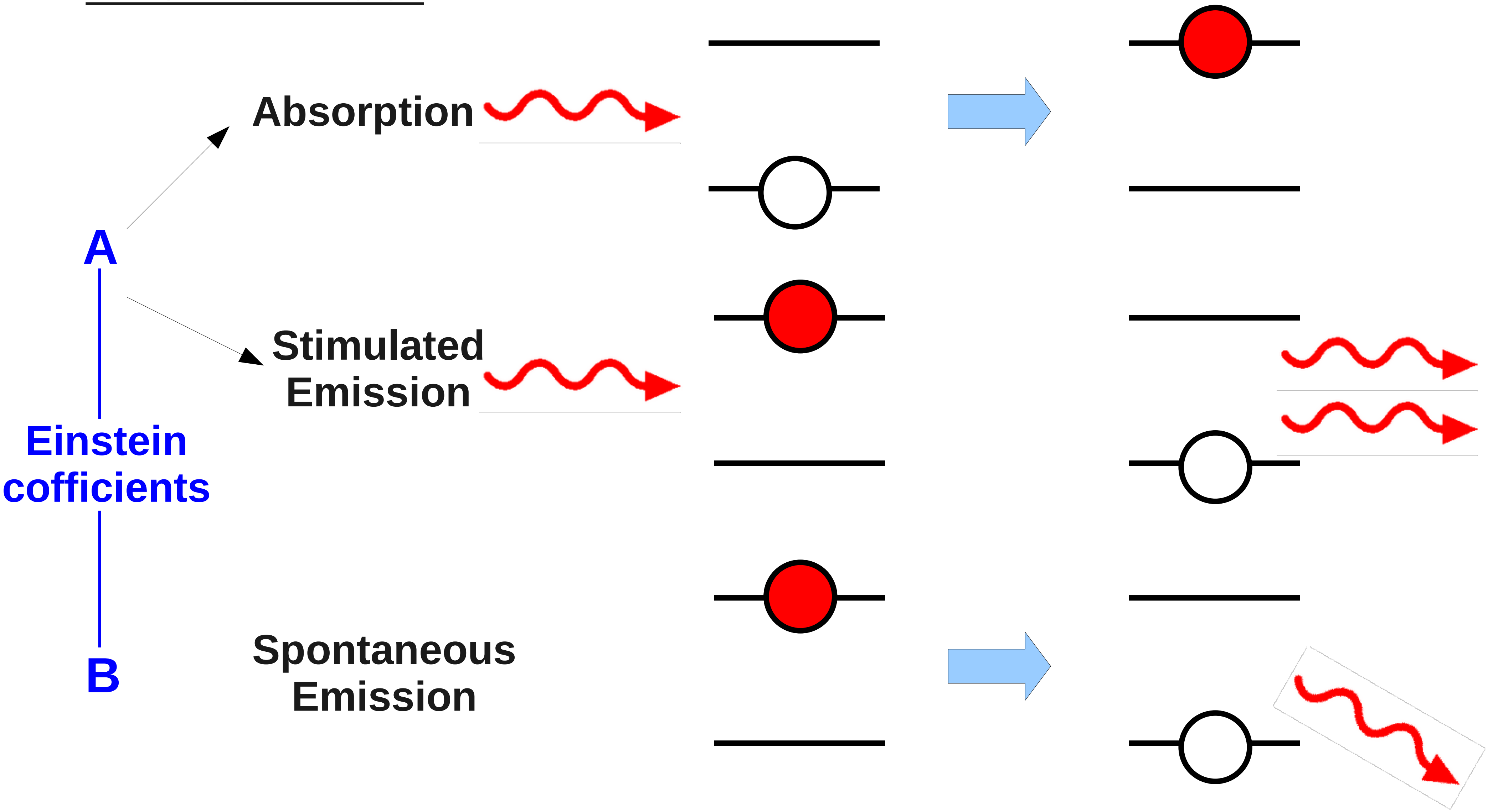
II. Coherence in Micro- and Nanolasers

III. Statistical Mixture of Thermal and Coherent light

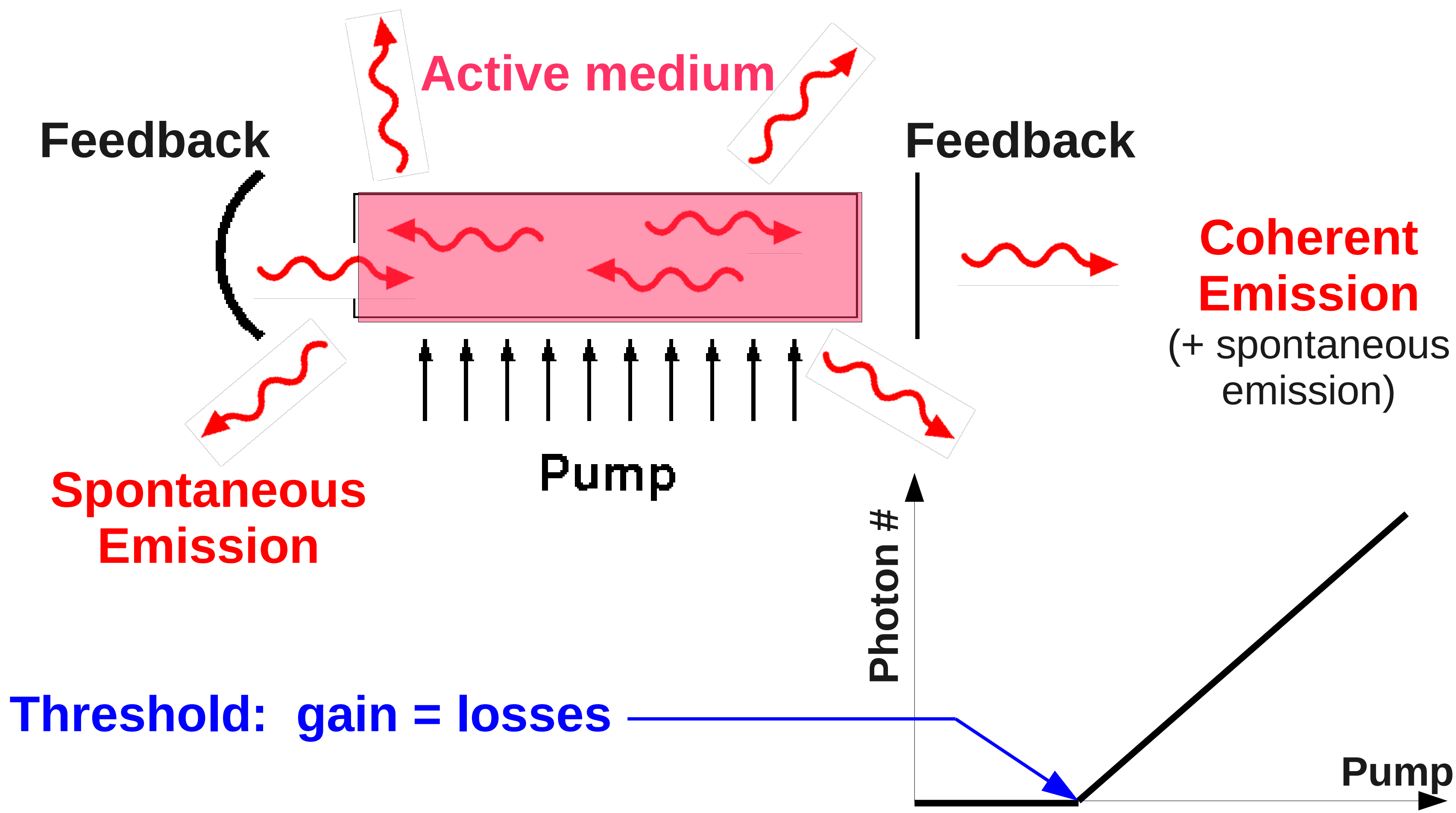
IV. Oscillations in Coherence Function

V. Additional Remarks

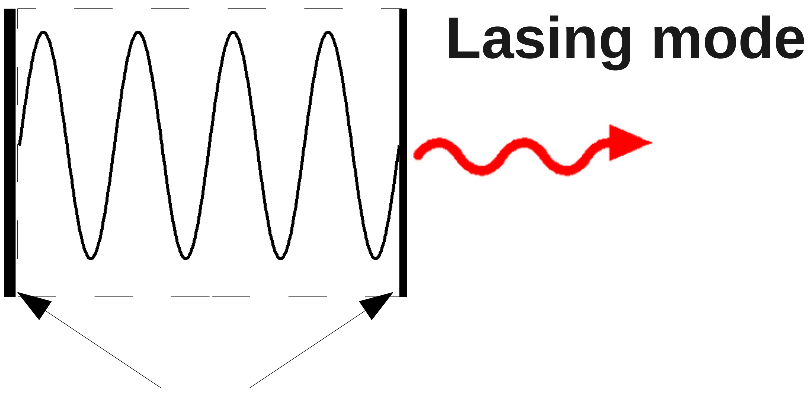
## Brief reminder

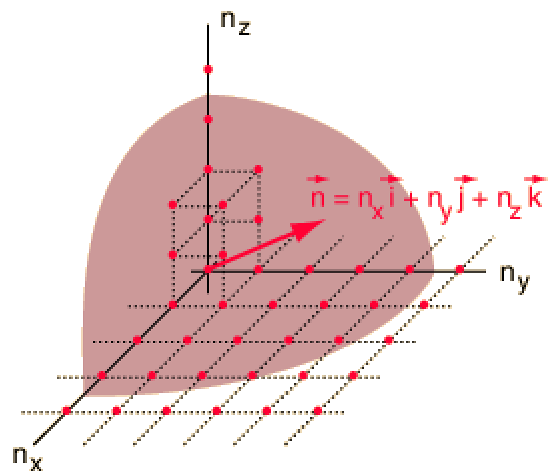


## Brief reminder



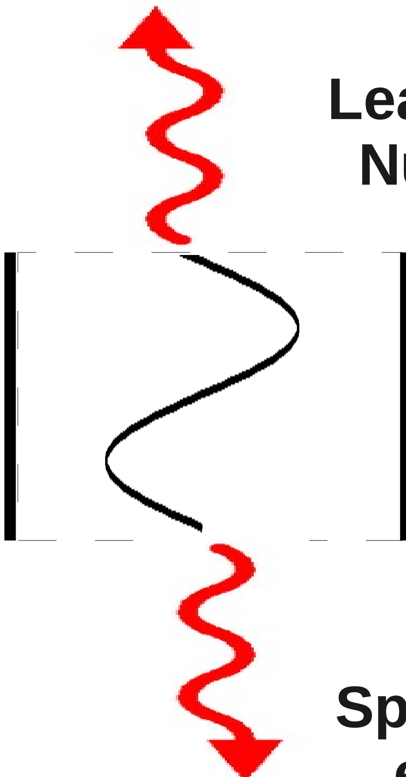
# Cavity modes



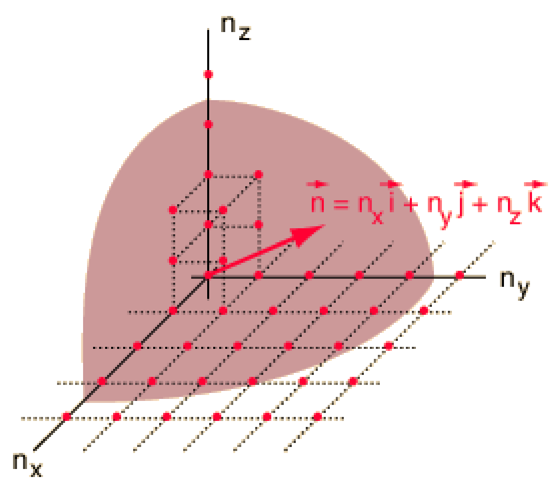
# What is a laser?

## Cavity modes



Leaky modes
Numerous!

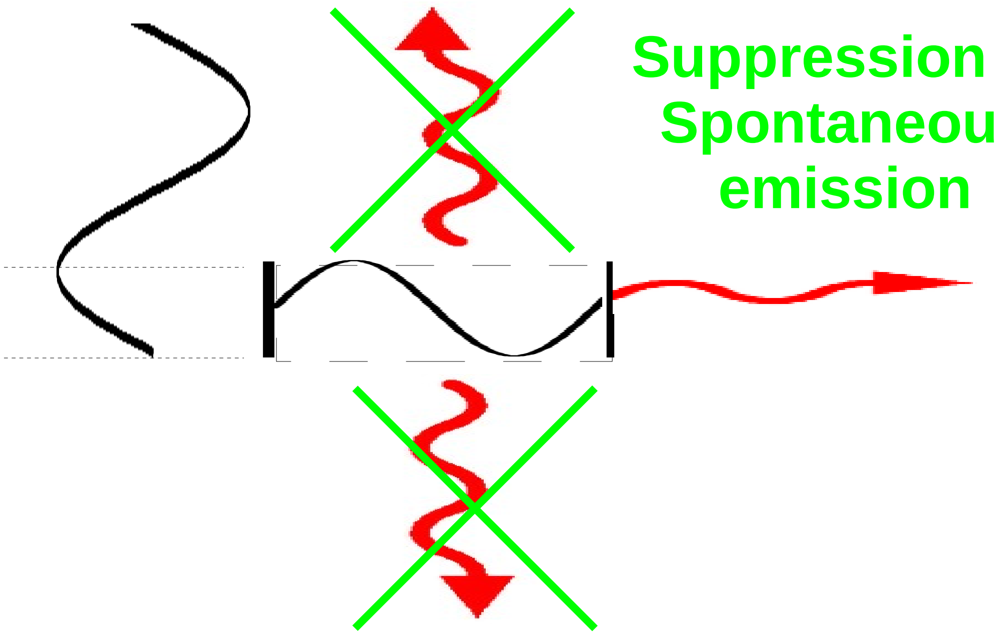
→ **High losses**




Spontaneous emission

“Macroscopic” laser
$> 10^5$ modes
$\beta < 10^{-5}$

## Nanolaser



Suppression of Spontaneous emission

Coherent Emission + Spontaneous Emission

Limit: 1 mode

$\beta = 1$

# I. Coherence in Macroscopic Lasers

## Experiments (and theory)

**He-Ne $\lambda$ = 6328 Å**

**Cavity volume ~ 1 $cm^3$**
**$\beta < 10^{-8}$**

# Statistics of Light

Estratto da *Rendiconti della Scuola Internazionale di Fisica «E. Fermi»* - XLII Corso 1967

## Photocount Distributions and Field Statistics.

F. T. ARECCHI

*CISE Laboratories - Segrate (Milano)*
*Istituto di Fisica dell'Università - Milano*

**Thermal light photocount statistics: G**
**Laser light photocount statistics: L**
**Superposition of thermal and laser light: S**

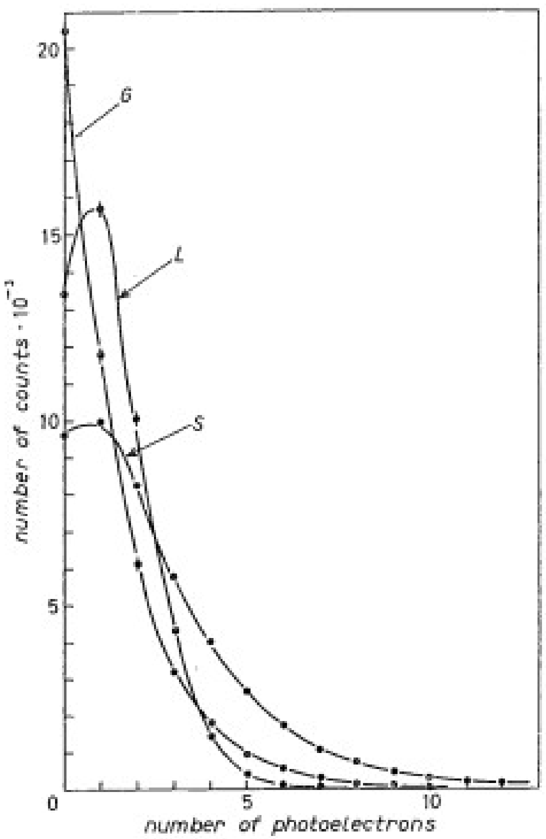



Fig. 2. – Photocount distributions of a Gaussian field, a laser field, and a field made by the superposition of the two (nonlinear method); *G*, gaussian light; *L*, laser light; and *S*, superposed light. The three curves are not normalized.

# Statistics of Light

Estratto da *Rendiconti della Scuola Internazionale di Fisica «E. Fermi»* - XLII Corso 1967

## Photocount Distributions and Field Statistics.

F. T. ARECCHI

*CISE Laboratories - Segrate (Milano)*
*Istituto di Fisica dell'Università - Milano*

**Evolution of the statistical photon mixture**

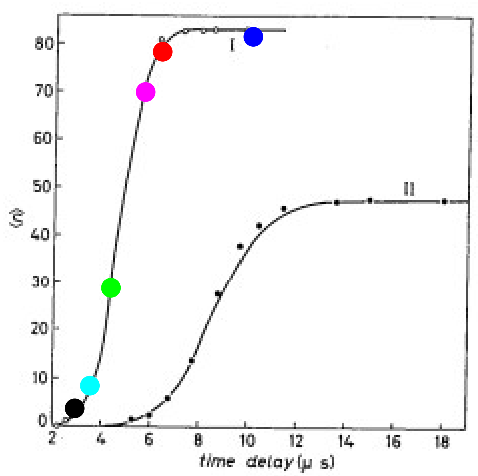



Fig. 23. – Evolution of the mean value ⟨$n$⟩ of the statistical distribution $p(n, T, \tau)$. The solid lines represent the theoretical curves which best fit the experimental points (o, •). The experimental points related to curve I) have been obtained by the statistical distributions of Fig. 22.

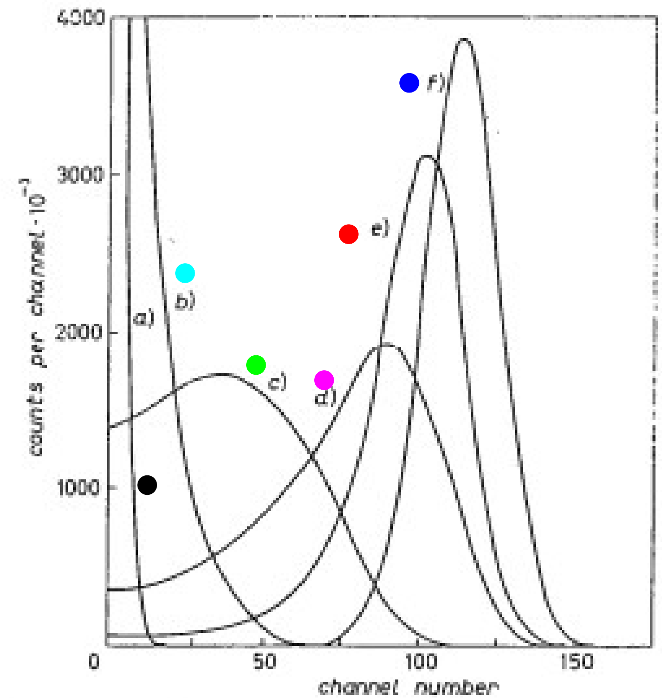



Fig. 22. – Experimental statistical distributions with different time delays obtained on a laser transient. The solid lines connect the experimental points which are not shown to make clearer the figure. All distributions are normalized to the same area *a*) 2.6 μs; *b*) 3.7 μs; *c*) 4.3 μs; *d*) 5 μs; *e*) 5.6 μs; *f*) 8.8 μs.

# Moment distributions

Estratto da *Rendiconti della Scuola Internazionale di Fisica « E. Fermi » - XLII Corso* 1967

## Photocount Distributions and Field Statistics.

F. T. ARECCHI

*CISE Laboratories - Segrate (Milano)*
*Istituto di Fisica dell'Università - Milano*

$$H_2 = \frac{\langle n(n-1)\rangle}{\langle n\rangle^2} - 1, \tag{6.28}$$

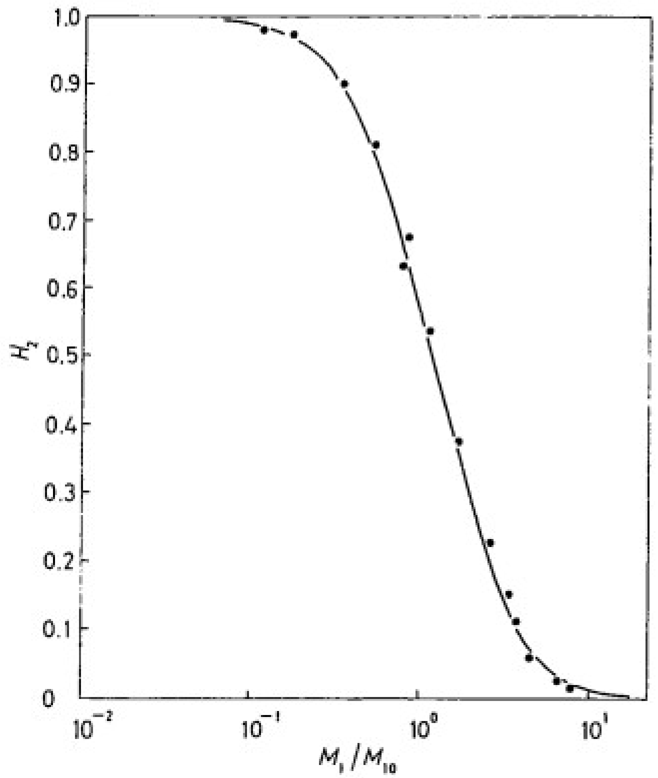



Fig. 17. – Measured and theoretical values of the reduced second-order factorial moment $H_2$ as a function of the normalized intensity $M_1/M_{10}$ in the threshold region. —— Theory; • experimental point.

Estratto da *Rendiconti della Scuola Internazionale di Fisica «E. Fermi»* - XLII Corso 1967

# Photocount Distributions and Field Statistics.

F. T. Arecchi

*CISE Laboratories - Segrate (Milano)*
*Istituto di Fisica dell'Università - Milano*

$$H_3 = \frac{\langle n(n-1)(n-2)\rangle}{\langle n\rangle^3} - 1, \qquad (6.29)$$

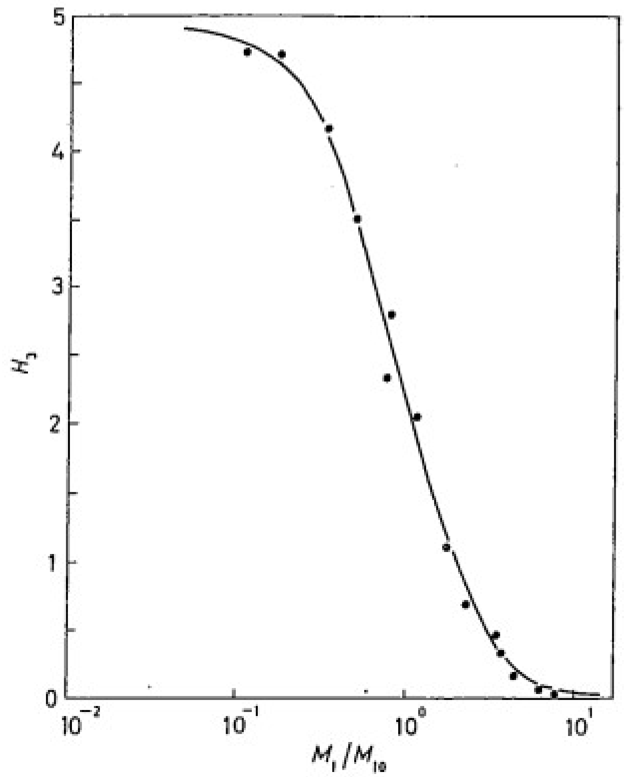



Fig. 18. – Measured and theoretical values of the reduced third-order factorial moment $H_3$ as a function of the normalized intensity $M_1/M_{10}$ in the threshold region. —— Theory, • experimental point.

# II. Coherence in Micro- and Nanolasers

## Experiments and theory

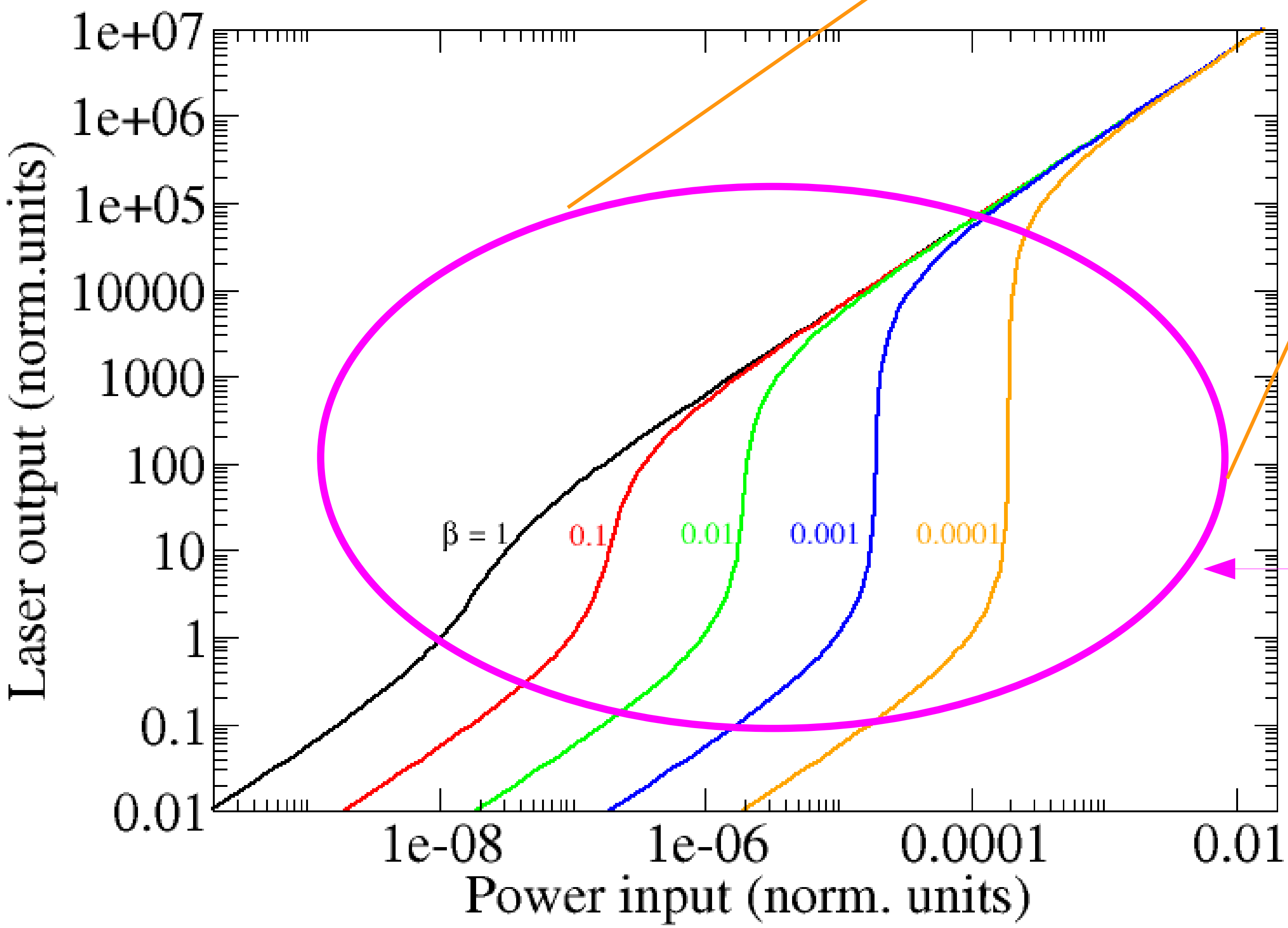
**0.8 μm < λ < 1.5 μm**

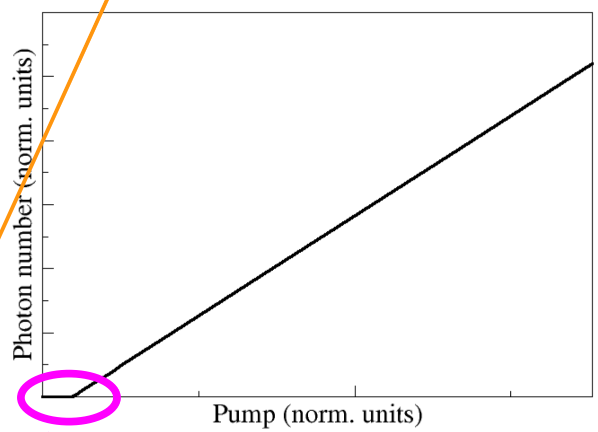
**Cavity volume < 10 μm$^3$**

**$\beta > 10^{-4}$**

## Threshold representation

Coherence?



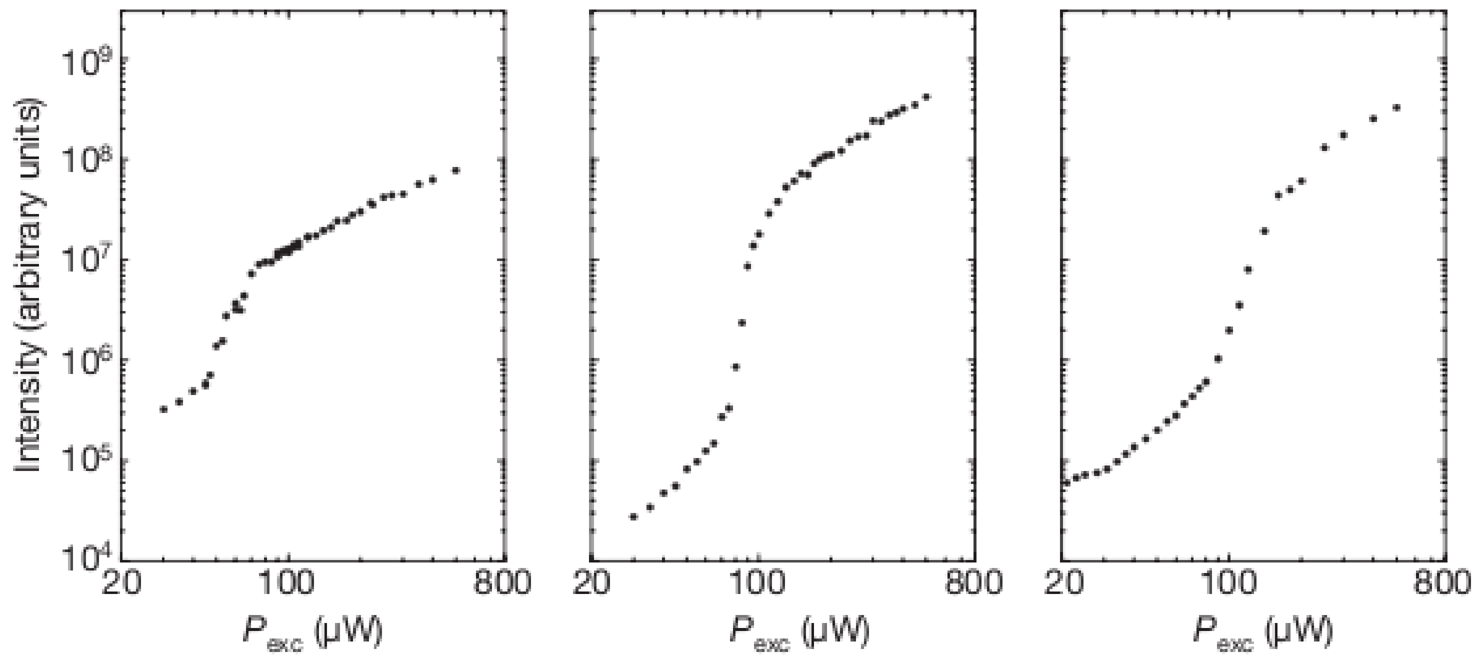

"Threshold"

# Power curves for small lasers

Vol 460 | 9 July 2009 | doi:10.1038/nature08126

## Direct observation of correlations between individual photon emission events of a microcavity laser

J. Wiersig[1]†, C. Gies[1], F. Jahnke[1], M. Aßmann[2], T. Berstermann[2], M. Bayer[2], C. Kistner[3], S. Reitzenstein[3], C. Schneider[3], S. Höfling[3], A. Forchel[3], C. Kruse[1], J. Kalden[1] & D. Hommel[1]




| | | | |
|---|---|---|---|
| Size | "small" | "medium" | "large" |
| | d = 1.5 μm | d = 5 μm | d = 8 μm |
| Q | 1850 | 9000 | 19000 |

# Correlations in small lasers

Vol 460 | 9 July 2009 | doi:10.1038/nature08126

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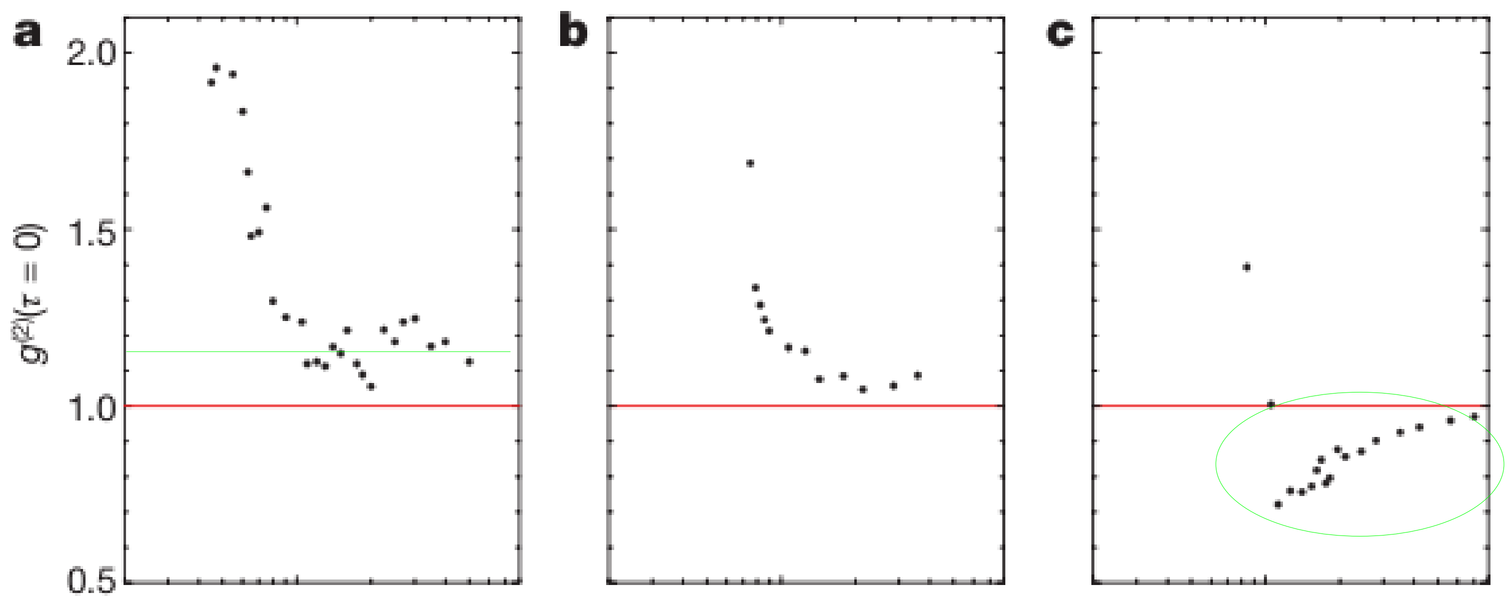


| | | | |
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| Size | "small" | "medium" | "large" |
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# Correlations in small lasers

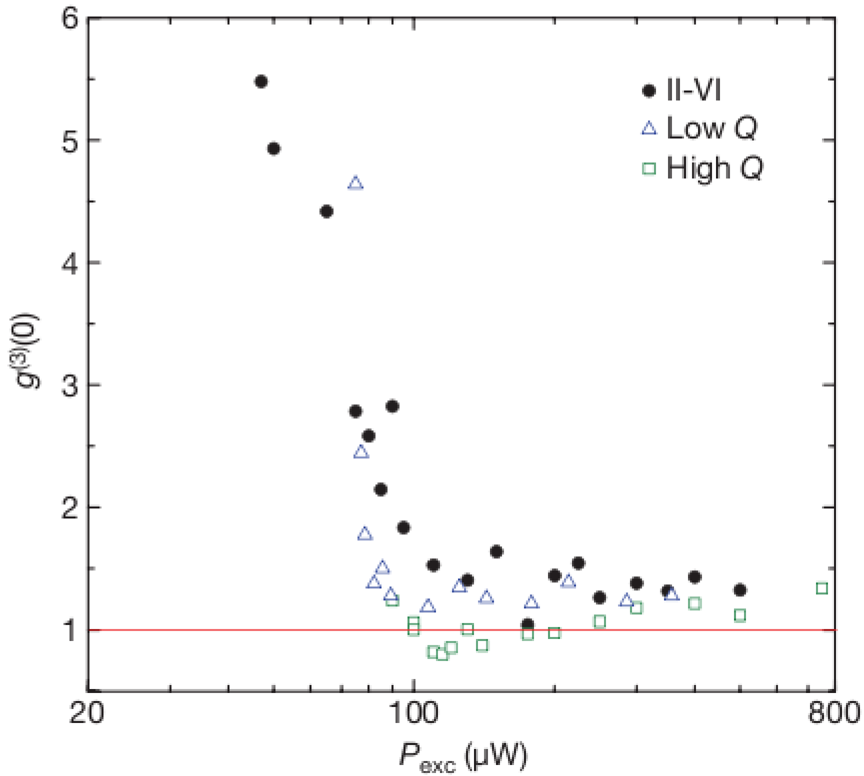



**Figure 5 | Measured third-order correlation function $g^{(3)}(0)$.** Characterization of the simultaneous arrival of three photons as a function of excitation power, for the three different micropillar samples studied in this paper. For the II-VI and low-$Q$ resonators, the time resolution was increased to about 20 ps. These two samples show values close to the theoretical prediction, $g^{(3)}(0) = 6$, at lowest excitation powers. The $k$th-order correlation functions for a thermal source of radiation are readily obtained from the factorial moments of the Planck distribution, $\langle n(n-1)\cdots(n-k+1)\rangle = k!\langle n\rangle^k$, to give $g^{(k)}(0) = k!$, corresponding to the number of permutations of indistinguishable photons.

**For the larger laser the $g^{(3)}(0)$ function does not match the theoretically expected values**

**Coherence?**

Wiersig et al., Nature **460**, 245 (2009)

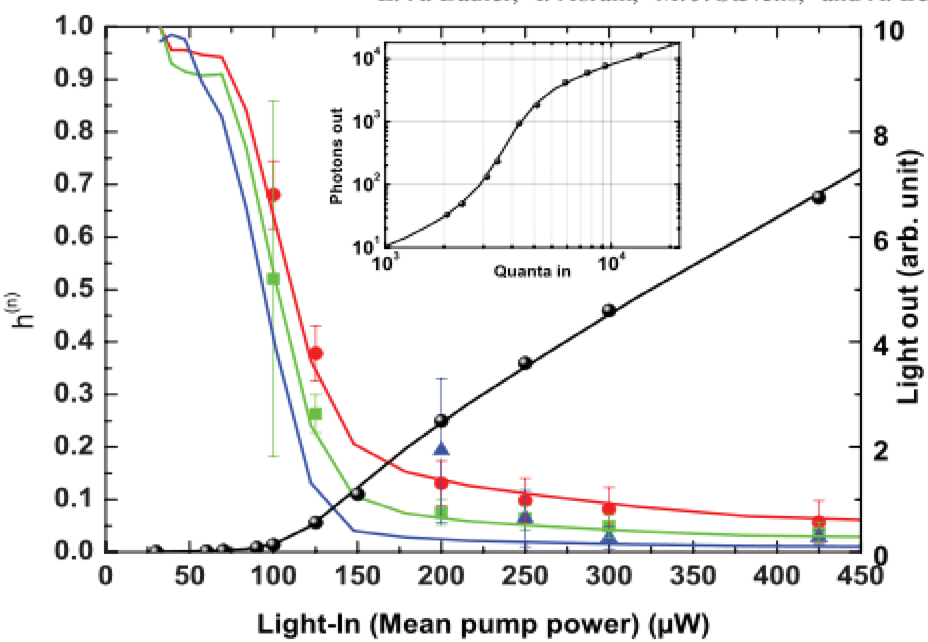
# Correlations in small lasers

RAPID COMMUNICATIONS

PHYSICAL REVIEW A **84**, 061802(R) (2011)

**Higher-order photon correlations in pulsed photonic crystal nanolasers**

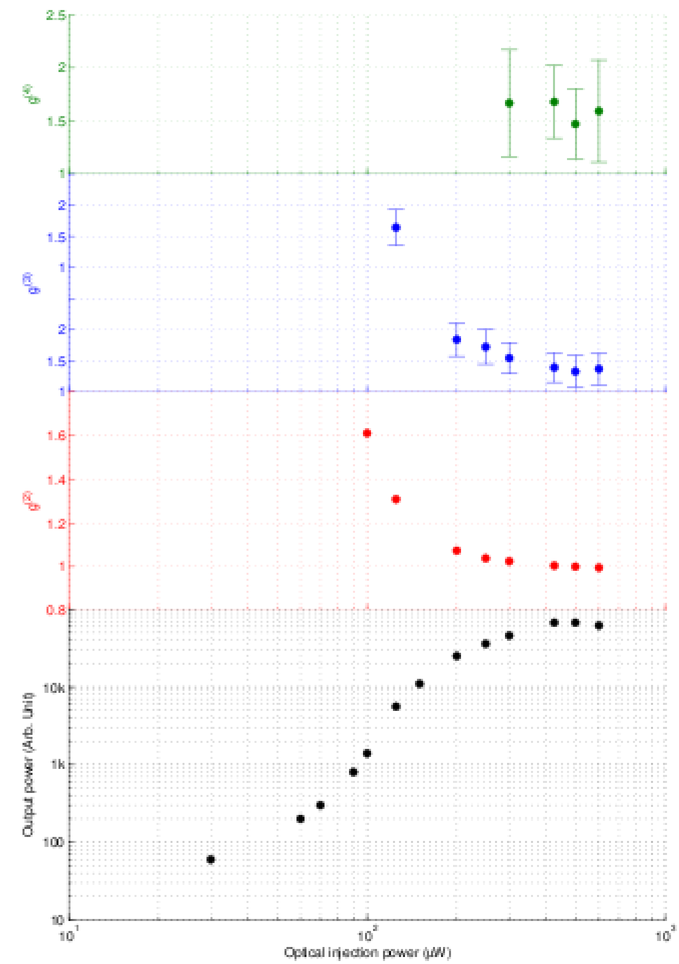
D. Elvira,[1] X. Hachair,[1] V. B. Verma,[2] R. Braive,[1] G. Beaudoin,[1] I. Robert-Philip,[1] I. Sagnes,[1] B. Baek,[2] S. W. Nan
E. A. Dauler,[3] I. Abram,[1] M. J. Stevens,[2] and A. Beveratos[1,*]




Blue

Green

FIG. 3. (Color online) Right-hand axis: Experimental (black dots) and calculated (black line) light-in–light-out curve. Left-hand axis: Experimental (red circles, green squares, and blue triangles for $n = 2,3,4$, respectively) and calculated (continuous lines of the corresponding colors) values of $h^{(n)}$ as functions of pump power. The fit of the $h^{(n)}$ data has no free parameters. Inset: Theoretical light-in–light-out curve in log-log scale. The experimental points have been normalized by the fit parameters.




Courtesy of X. Hachair

# Correlations in small lasers

PRL **98,** 043906 (2007) PHYSICAL REVIEW LETTERS week ending 26 JANUARY 2007

## Photon Statistics of Semiconductor Microcavity Lasers

S. M. Ulrich,[1,*] C. Gies,[2] S. Ates,[1] J. Wiersig,[2] S. Reitzenstein,[3] C. Hofmann,[3] A. Löffler,[3]
A. Forchel,[3] F. Jahnke,[2] and P. Michler[1]

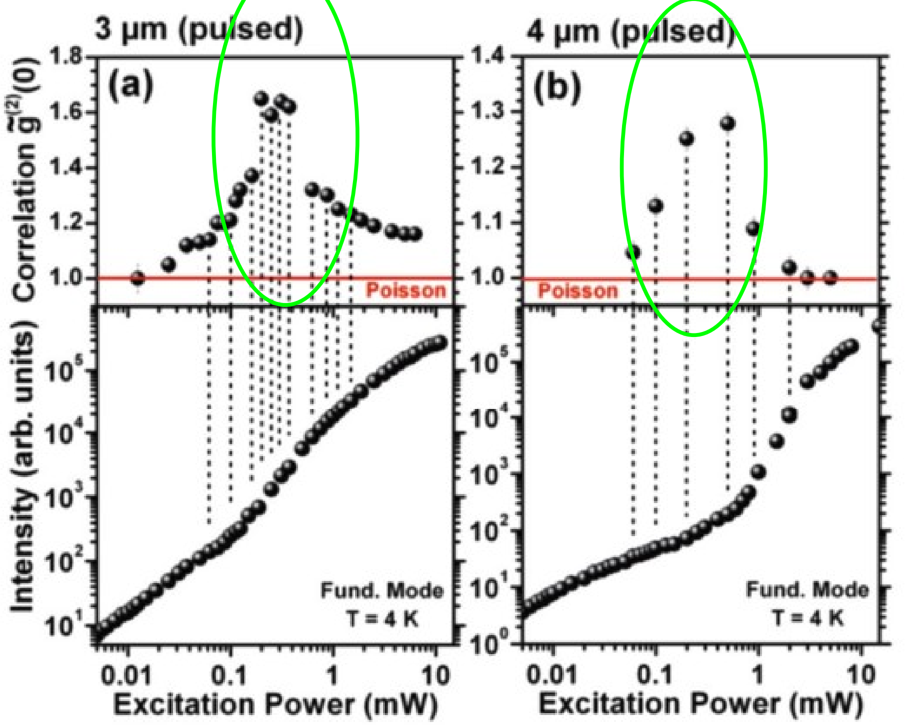



FIG. 3 (color online). (a),(b) Integrated intensities (bottom) for the 3 (4 $\mu$m) pillars under nonresonant pulsed excitation. Strong photon bunching $\tilde{g}^{(2)}(0) > 1$ is found from corresponding correlation measurements (top) over a broadened regime around the threshold.

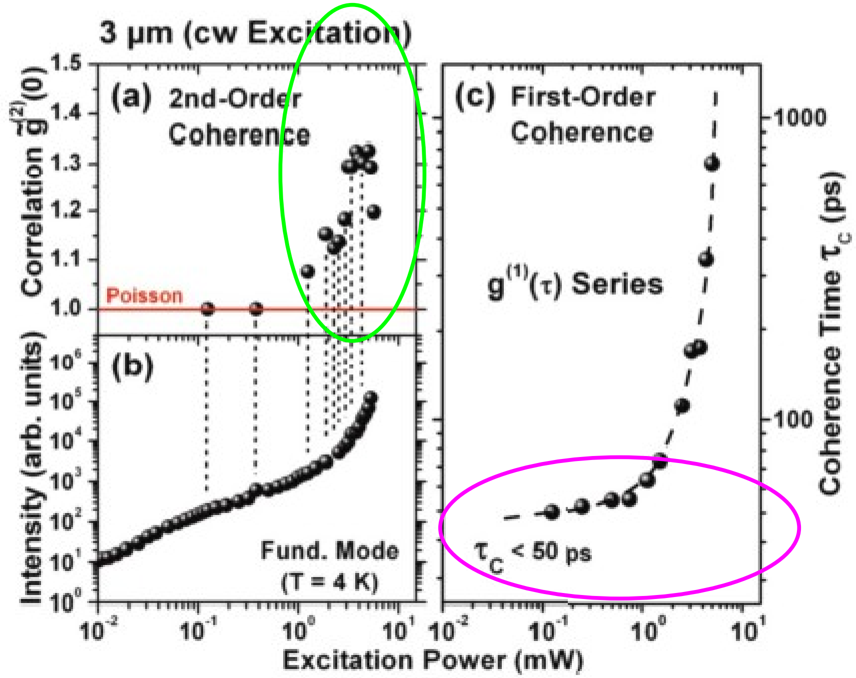



FIG. 4 (color online). (a) $\tilde{g}^{(2)}(\tau = 0)$ autocorrelation results derived from the 3 $\mu$m pillar fundamental mode under cw excitation [see series in Fig. 2(a)], together with the corresponding mode emission intensity (b). (c) First-order $g^{(1)}(\tau)$ series, revealing a strong $\tau_c$ coherence decrease in the low excitation limit.

# Correlations in small lasers

## Summary

- **$g^{(1)}(t)$** **shows very short coherence time**
- **$g^{(2)}(0)$** **remains above 1**
  **drops below 1**
  **shows strong photon bunching (g(2) > 1)**
- **$g^{(3)}(0)$** **for larger, high Q, laser inconsistent with theoretical values for thermal light**
  **1.5 $\mu$m nanolaser: unsatisfactory convergence**
- **$g^{(4)}(0)$** **“constant” value (1.5 - 2)**

# III. Statistical mixture

# of thermal and coherent light

# Does it hold for nano- and microlasers?

# Statistical mixture

PHYSICAL REVIEW B **81**, 165314 (2010)

## Ultrafast tracking of second-order photon correlations in the emission of quantum-dot microresonator lasers

Marc Aßmann, Franziska Veit, and Manfred Bayer Christopher Gies and Frank Jahnke
Stephan Reitzenstein, Sven Höfling, Lukas Worschech, and Alfred Forchel

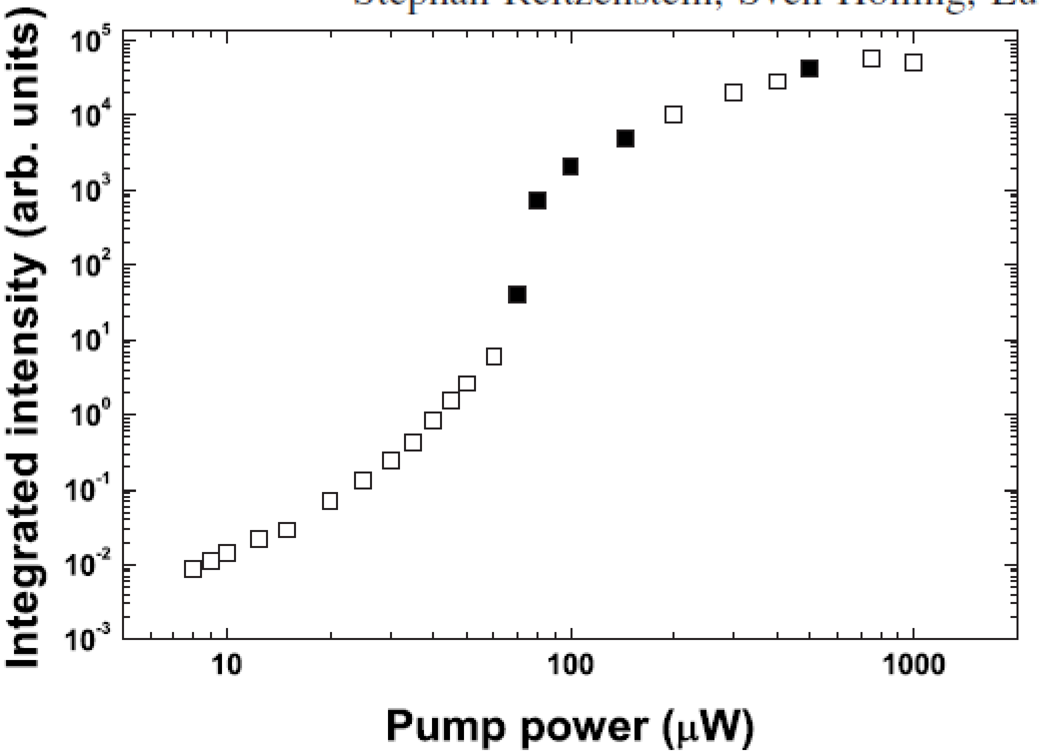
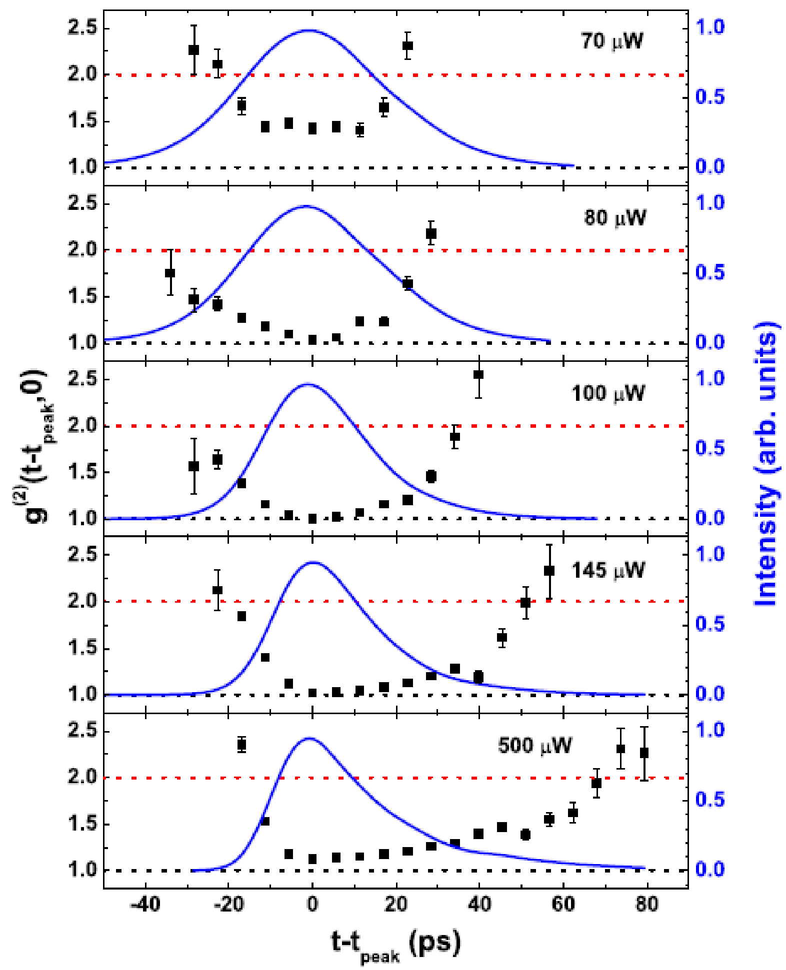



FIG. 1. Integrated intensity of the 6 $\mu$m pillar's fundamental mode under nonresonant pulsed excitation. Above threshold, saturation effects become apparent. Filled squares mark the data sets shown in Fig. 2.



# Statistical mixture

PHYSICAL REVIEW B **81**, 165314 (2010)

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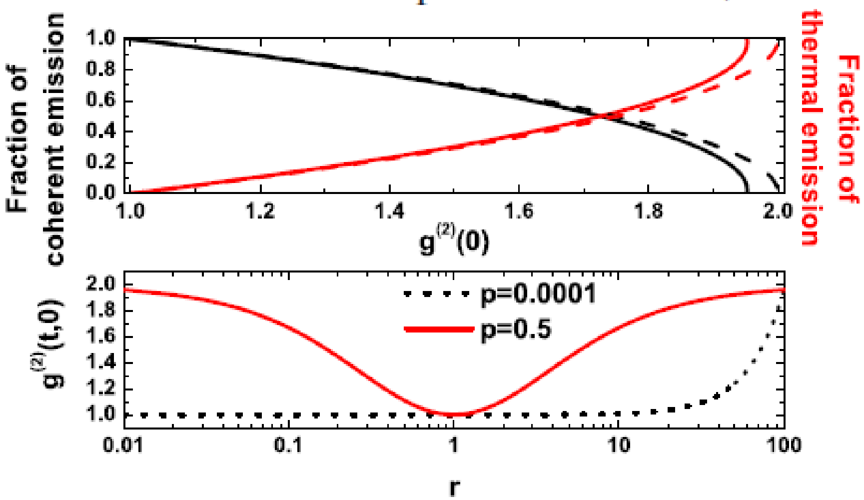
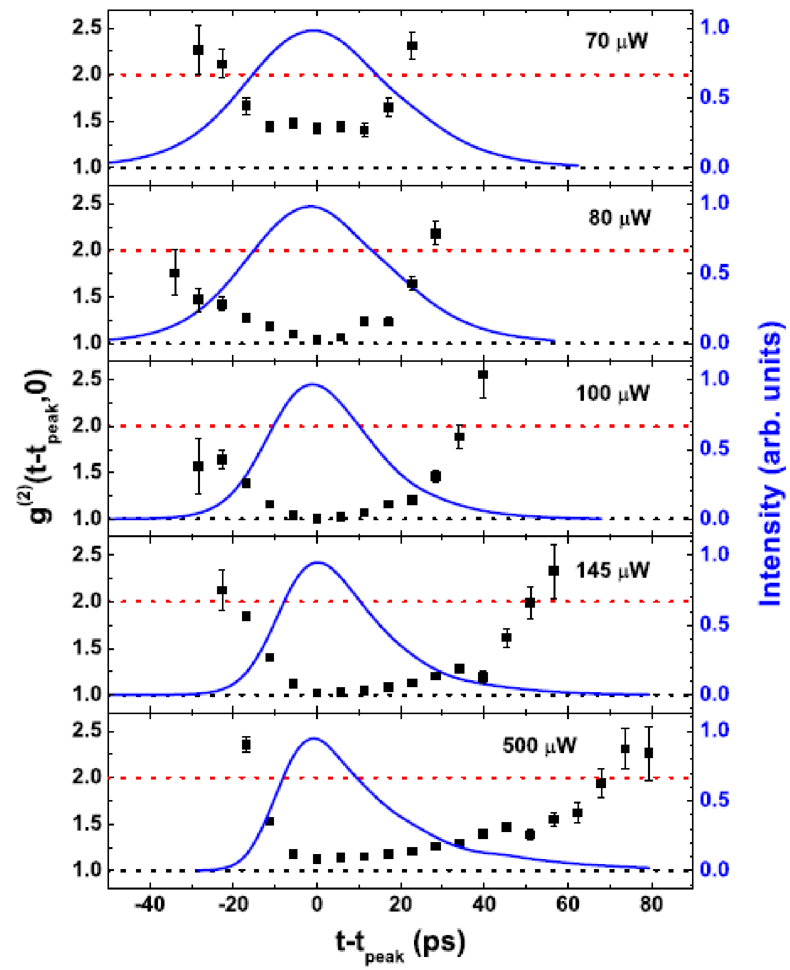



FIG. 3. (Color online) Upper panel: relative fractions of coherent and thermal emission at a fixed $g^{(2)}(t,0)$ as given by a two-mode model (solid lines) compared to the ideal case for infinitely small sampling time (dashed lines). Small deviations occur at high thermal fractions. Lower panel: effect of jitter on the measured $g^{(2)}(t,0)$ for a coherent light pulse depending on the ratio $r$ of the mean photon count rates at the pulse positions connected by the jitter and the relative frequency $p$ of jitter occurrence. While frequent jitter (solid red line) has the same effects for pulse positions with high and low intensity, rare events (dotted black line) only affect regions with low mean photon count rate (high $r$).



# Statistical mixture

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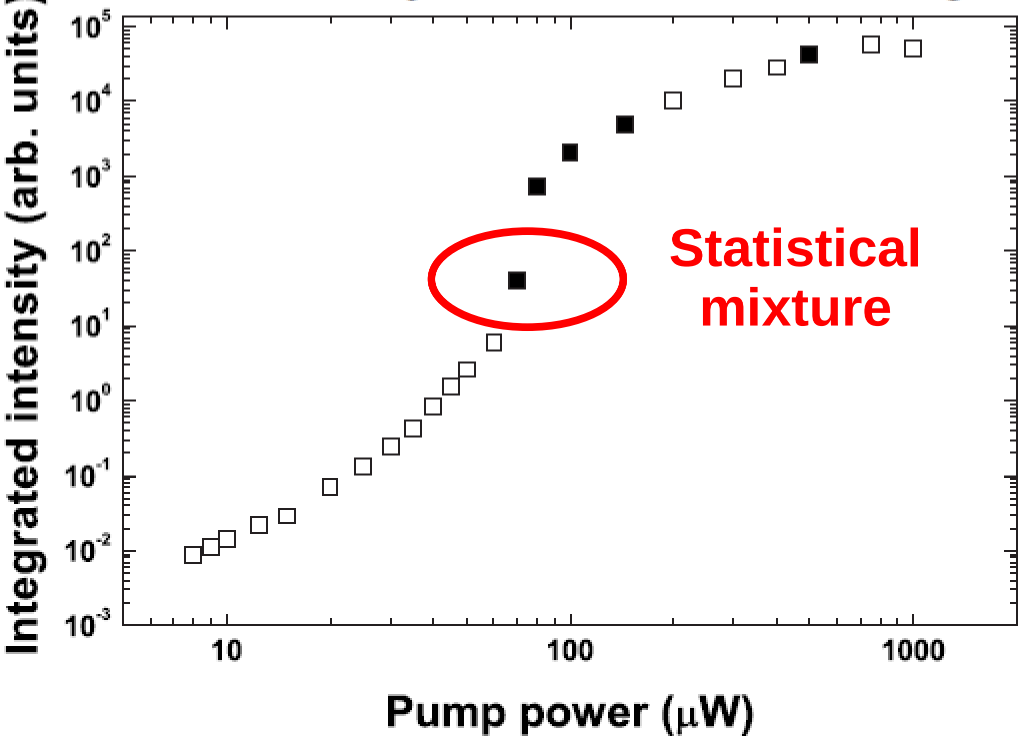


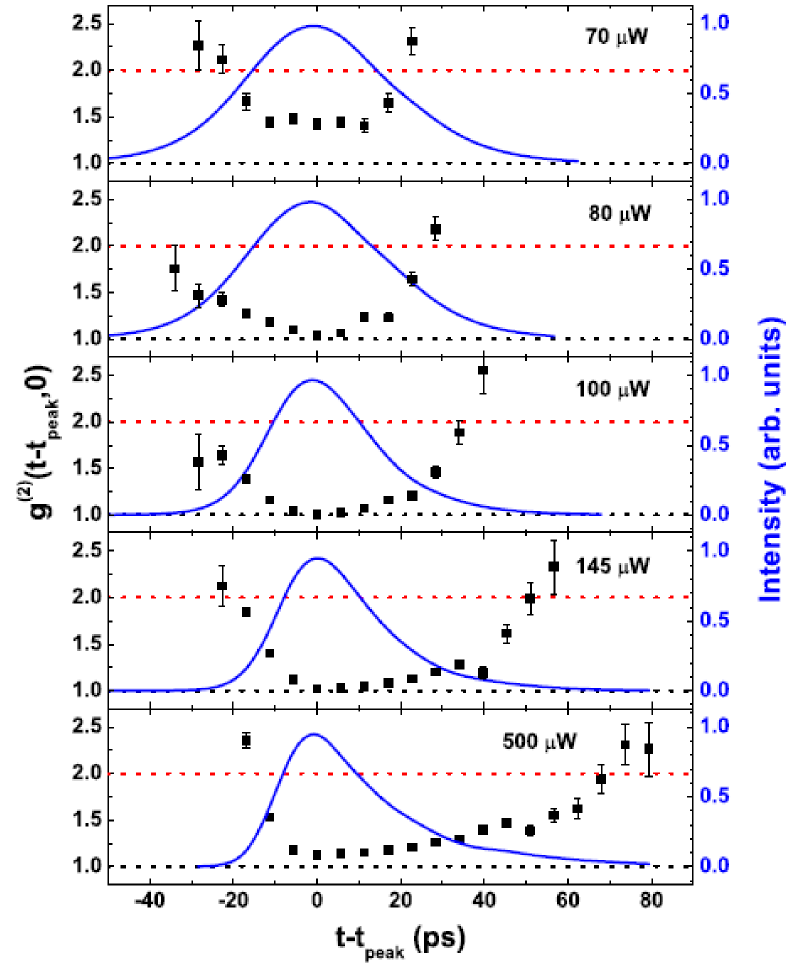




FIG. 1. Integrated intensity of the 6 $\mu$m pillar's fundamental mode under nonresonant pulsed excitation. Above threshold, saturation effects become apparent. Filled squares mark the data sets shown in Fig. 2.

# Interferometric measurements

PHYSICAL REVIEW A **88**, 013801 (2013)

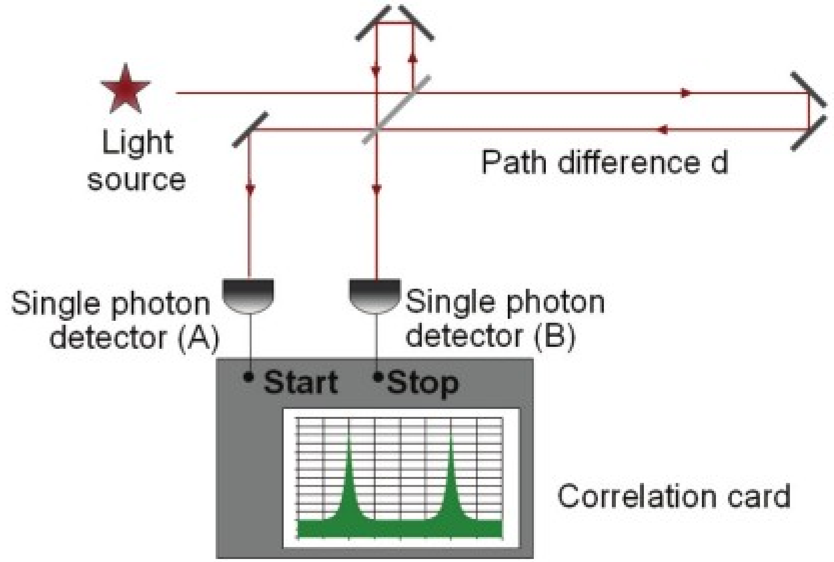
**Theory of interferometric photon-correlation measurements: Differentiating coherent from chaotic light**

A. Lebreton, I. Abram, R. Braive, I. Sagnes, I. Robert-Philip,* and A. Beveratos

## Measure average correlation in a scanning Michelson interferometer

$$\hat{E}_A^*(t) = E_0^* \frac{a^\dagger(t+d/c) - a^\dagger(t)}{\sqrt{2}},$$
$$\hat{E}_B^*(t) = E_0^* \frac{a^\dagger(t+d/c) + a^\dagger(t)}{\sqrt{2}}, \quad + \text{h.c.} \quad (4)$$

$$\langle \hat{E}_A^*(t) E_A(t) \rangle = \frac{I_1}{2}\{1 - 2\,\mathrm{Re}[g^{(1)}(d/c)]\},$$
$$\langle \hat{E}_B^*(t) E_B(t) \rangle = \frac{I_1}{2}\{1 + 2\,\mathrm{Re}[g^{(1)}(d/c)]\}, \quad (5)$$




Compute normalized correlation:

$$g^{(2X)}(\tau, d/c) = \langle \hat{E}_A^*(0) \hat{E}_B^*(\tau) \hat{E}_B(\tau) \hat{E}_A(0) \rangle, \quad (6)$$

Technique borrowed from
Photon-correlation Fourier Spectroscopy
X. Brockmann *et al.*, Opt. Expr. **14**, 6333 (2006)

# Interferometric measurements

PHYSICAL REVIEW A **88**, 013801 (2013)

## Theory of interferometric photon-correlation measurements: Differentiating coherent from chaotic light

A. Lebreton, I. Abram, R. Braive, I. Sagnes, I. Robert-Philip,* and A. Beveratos

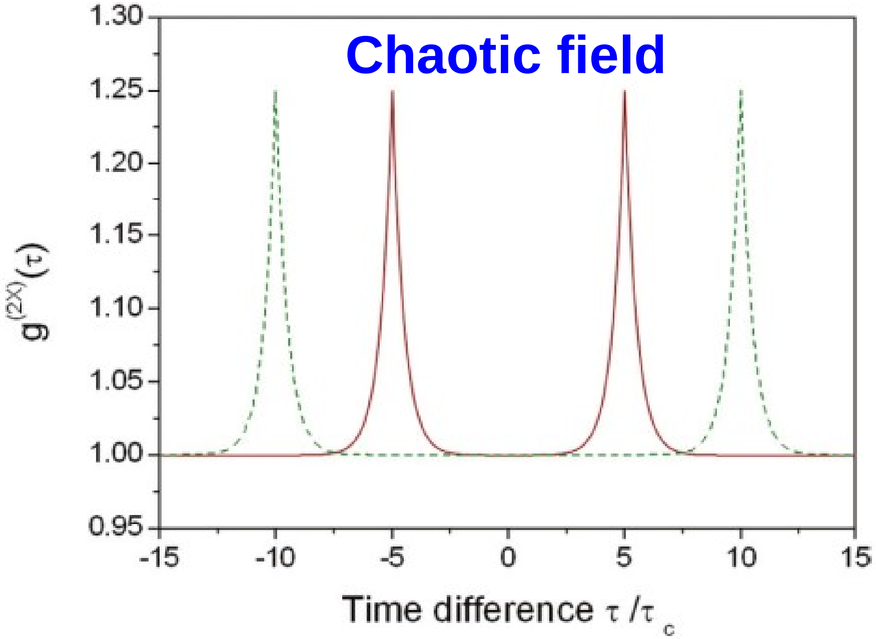



FIG. 2. (Color online) Interferometric second-order intensity cross-correlation function for a chaotic field $g^{(2X)}_{\text{chaotic}}(\tau,d/c)$ at the output ports of an unbalanced Michelson (or Mach-Zehnder) interferometer with pathlength difference $d = 5c\tau_c$ (continuous red curve) and $d = 10c\tau_c$ (dashed green curve).

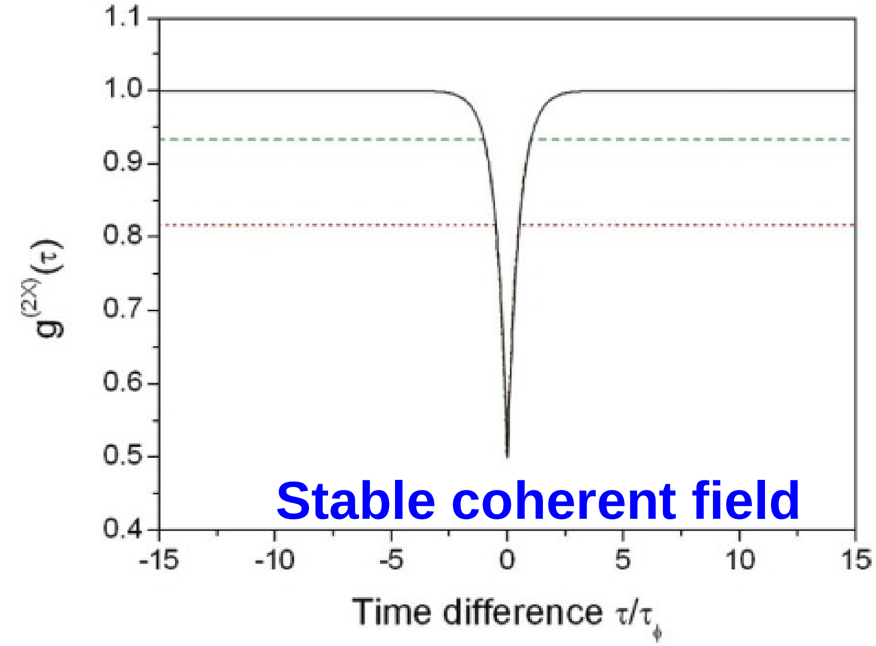



FIG. 3. (Color online) Interferometric second-order intensity cross-correlation function for a stable coherent wave $g^{(2X)}_{\text{coh}}(\tau,d/c)$ at the output ports of an unbalanced Michelson (or Mach-Zehnder) interferometer with pathlength difference $d = 0.5c\tau_\phi$ (dotted red curve), $d = c\tau_\phi$ (dashed green curve), and $d \gg c\tau_c$ (continuous black curve).

# Interferometric measurements

PHYSICAL REVIEW A **88**, 013801 (2013)

**Theory of interferometric photon-correlation measurements: Differentiating coherent from chaotic light**

A. Lebreton, I. Abram, R. Braive, I. Sagnes, I. Robert-Philip,* and A. Beveratos

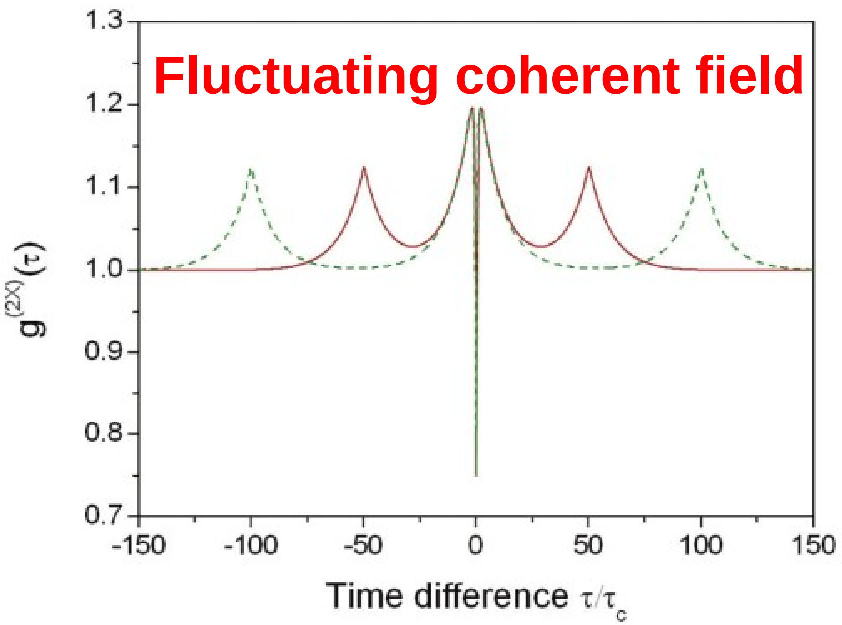



FIG. 4. (Color online) Interferometric second-order intensity cross-correlation function for a coherent field with intensity fluctuations $g^{(2X)}_{\text{amp-fluct}}(\tau,d/c)$ at the output ports of an unbalanced Michelson (or Mach-Zehnder) interferometer with pathlength difference $d = 50c\tau_c = 5c\tau_{\text{int}}$ (continuous red curve), $d = 100c\tau_c = 10c\tau_{\text{int}}$ (dashed green curve). The characteristic time of the intensity fluctuations is taken to be $\tau_{\text{int}} = 10\tau_c$.

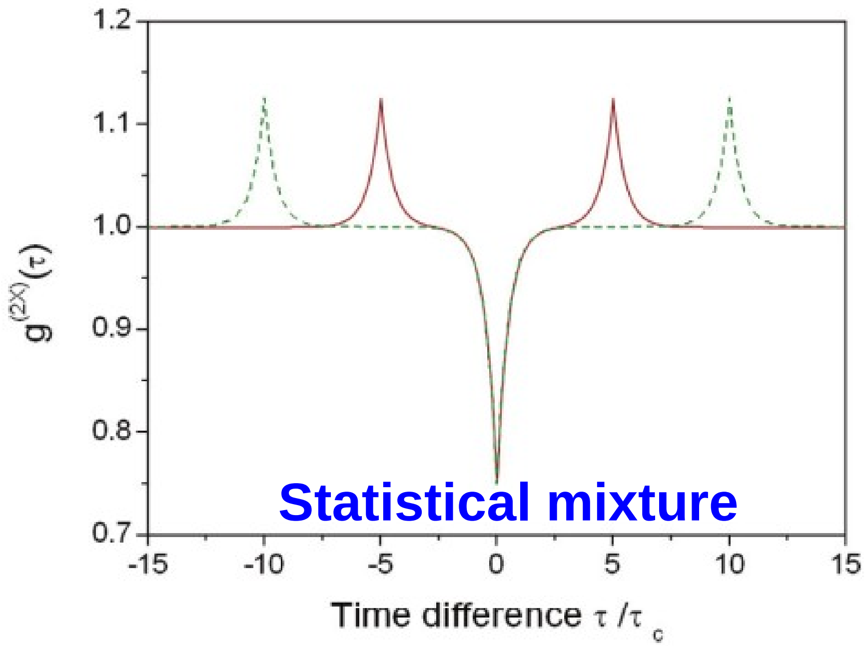



FIG. 5. (Color online) Interferometric second-order intensity cross-correlation function for a 50:50 "mixture" of coherent and chaotic light $g^{(2X)}_{\text{mix}}(\tau,d/c)$ at the output ports of an unbalanced Michelson (or Mach-Zehnder) interferometer with pathlength difference $d = 5c\tau_c$ (continuous red curve), $d = 10c\tau_c$ (dashed green curve), and $\tau_\phi = \tau_c$.

# Interferometric measurements

PRL **110,** 163603 (2013) PHYSICAL REVIEW LETTERS week ending 19 APRIL 2013

## Unequivocal Differentiation of Coherent and Chaotic Light through Interferometric Photon Correlation Measurements

A. Lebreton, I. Abram, R. Braive, I. Sagnes, I. Robert-Philip,* and A. Beveratos

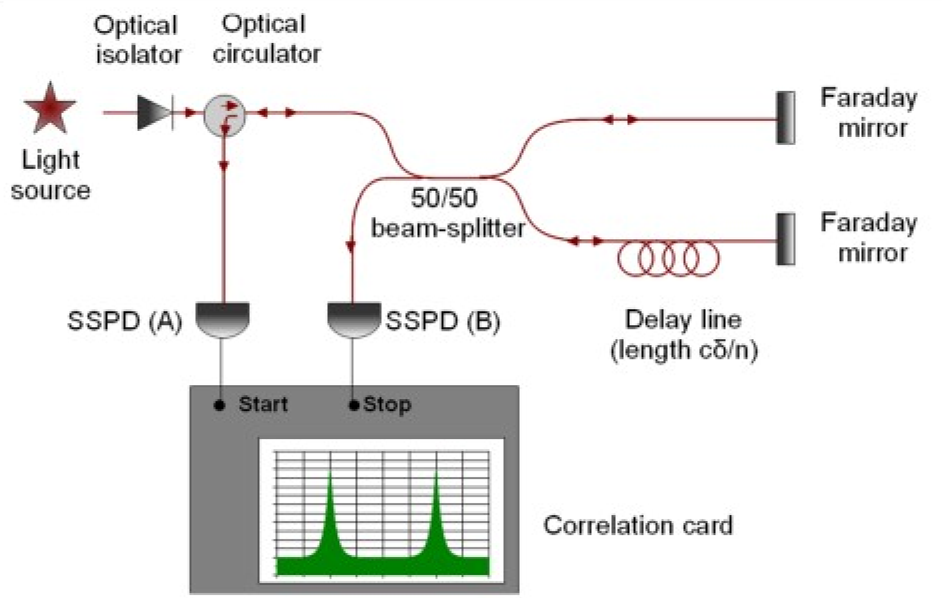



FIG. 1 (color online). Experimental setup. Light is sent into an unbalanced Michelson interferometer made of optical fibers. Two single photon detectors (SSPDs) measure the cross correlations between the two output ports of the interferometer.

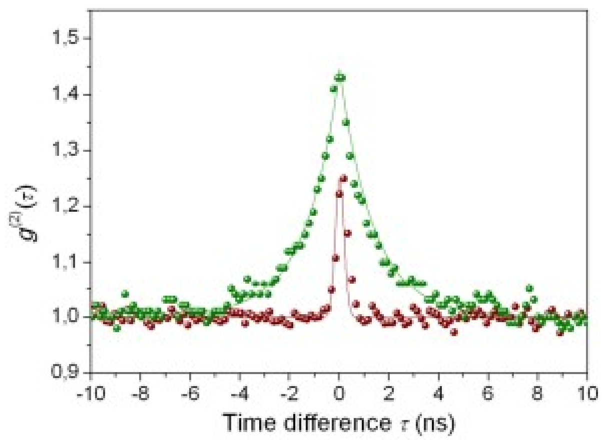
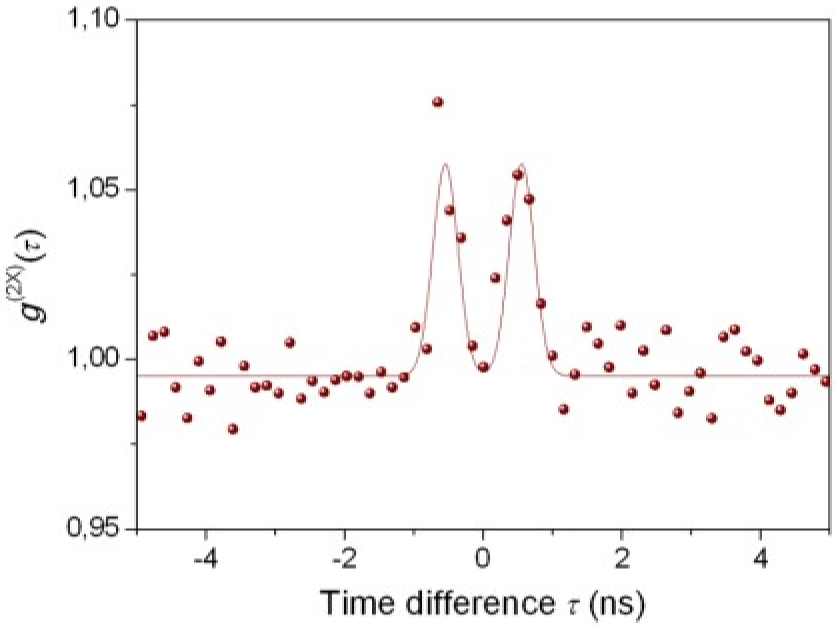



FIG. 2 (color online). Second order autocorrelation function $g^{(2)}(\tau)$ of a nanoscale laser pumped at 1.1 $P_{\mathrm{th}}$ [green (gray) dots and curve] and a filtered chaotic source [red (black) dots and curve]. The points are experimental data and the continuous curves are fits to Eqs. (6) and (9).

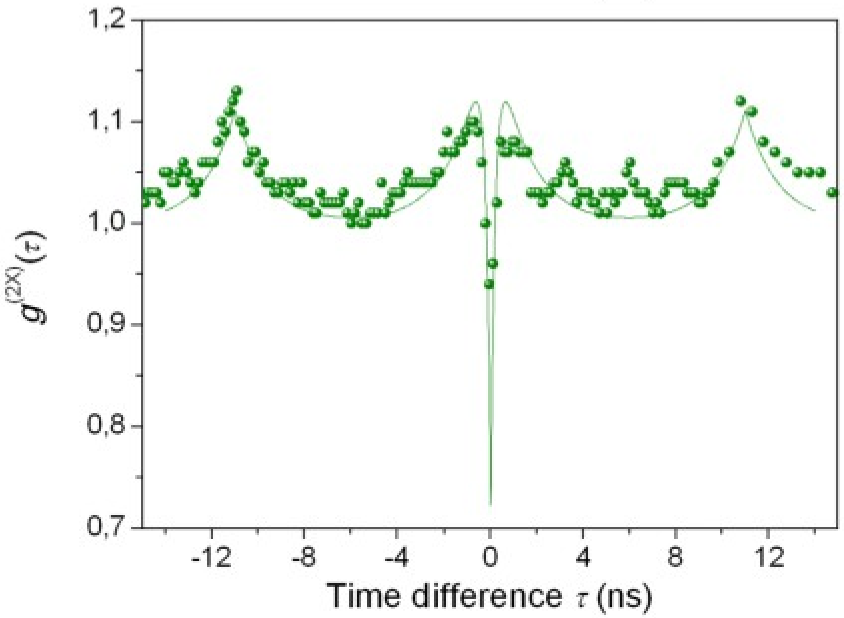
**Photon-correlation Fourier spectroscopy**

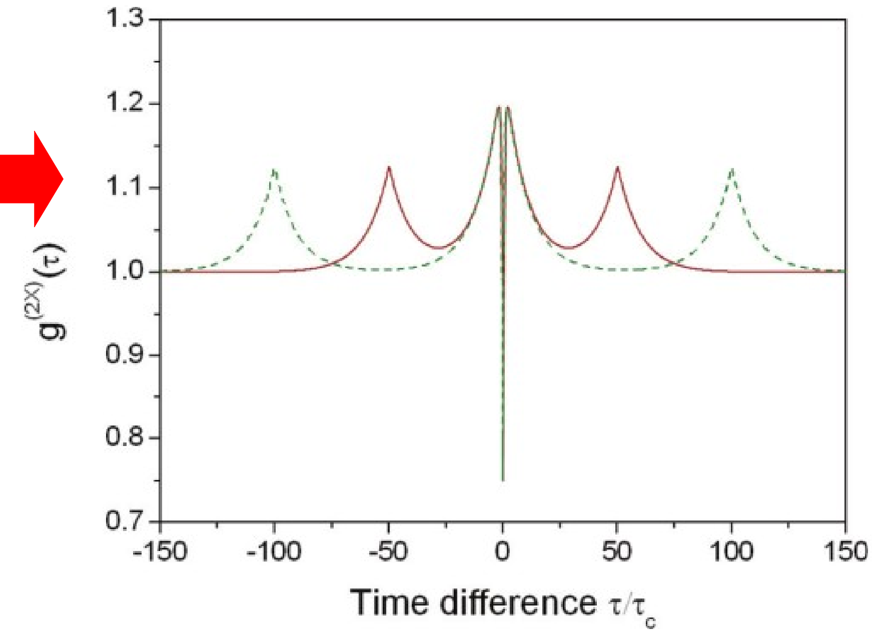



2013) PHYSICAL REVIEW LETTERS week ending 19 APRIL 2013

## Unequivocal Differentiation of Coherent and Chaotic Light through Interferometric Photon Correlation Measurements

A. Lebreton, I. Abram, R. Braive, I. Sagnes, I. Robert-Philip,* and A. Beveratos



# Statistical superposition?



## Summary

***Contradicting information coming from two different experiments***

1. **In the “intermediate threshold region” a statistical superposition of chaotic light (spontaneous emission) and coherent light (laser) is emitted by the device**

2. **The light emitted by the device is coherent, but exhibits (strong) amplitude fluctuations**

**Comparison between the two experiments difficult:**

**Pulsed regime**
**Entirely different devices**
**Reproducibility of samples**

# IV. Oscillations in coherence function

## Experiments and theory in

## Microcavities and nanocavities

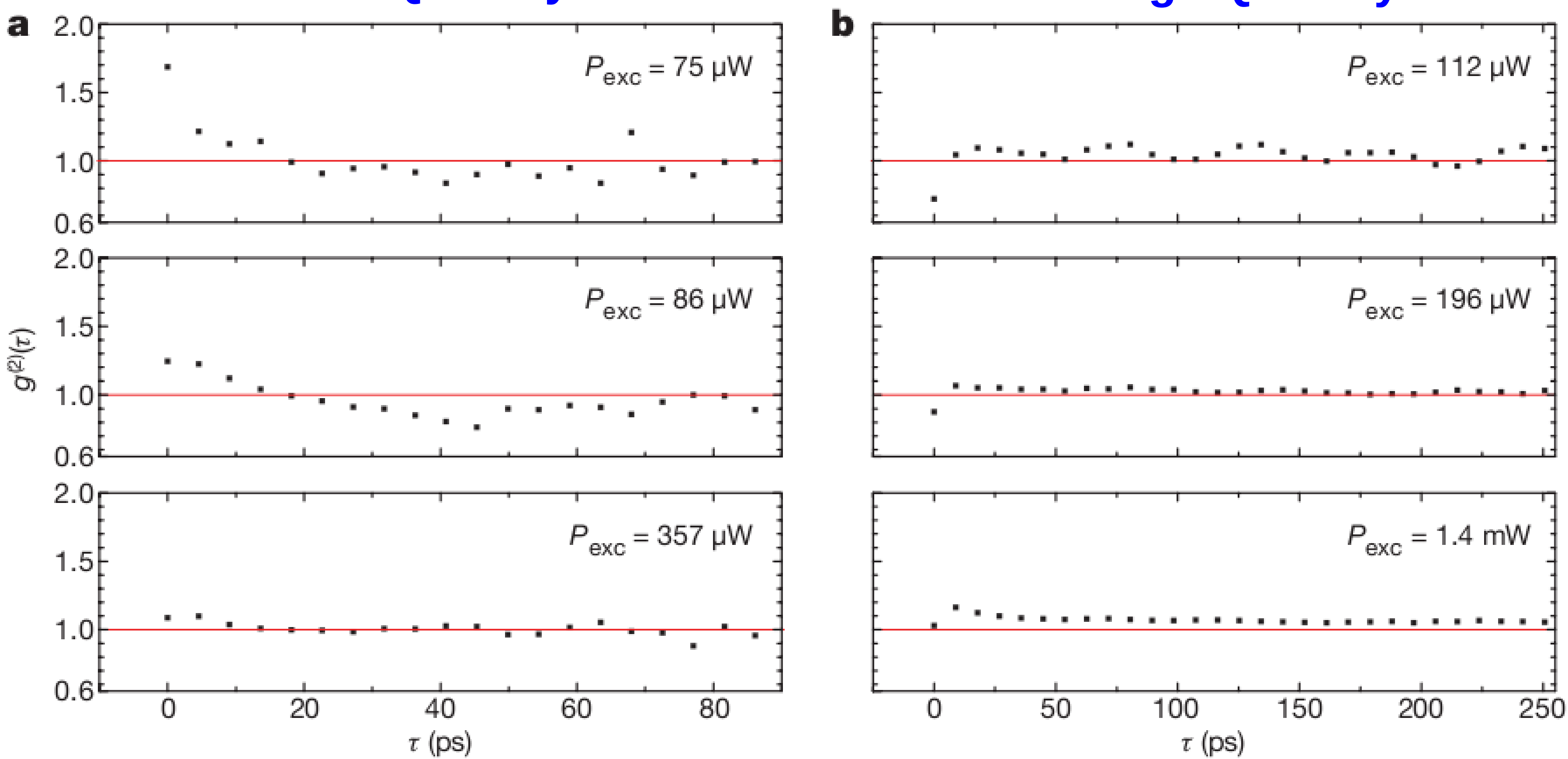
Vol 460 | 9 July 2009 | doi:10.1038/nature08126

# Direct observation of correlations between individual photon emission events of a microcavity laser

***Nanolaser***

J. Wiersig[1]†, C. Gies[1], F. Jahnke[1], M. Aßmann[2], T. Berstermann[2], M. Bayer[2], C. Kistner[3], S. Reitzenstein[3], C. Schneider[3], S. Höfling[3], A. Forchel[3], C. Kruse[1], J. Kalden[1] & D. Hommel[1]

**Low Q cavity** | **High Q cavity**

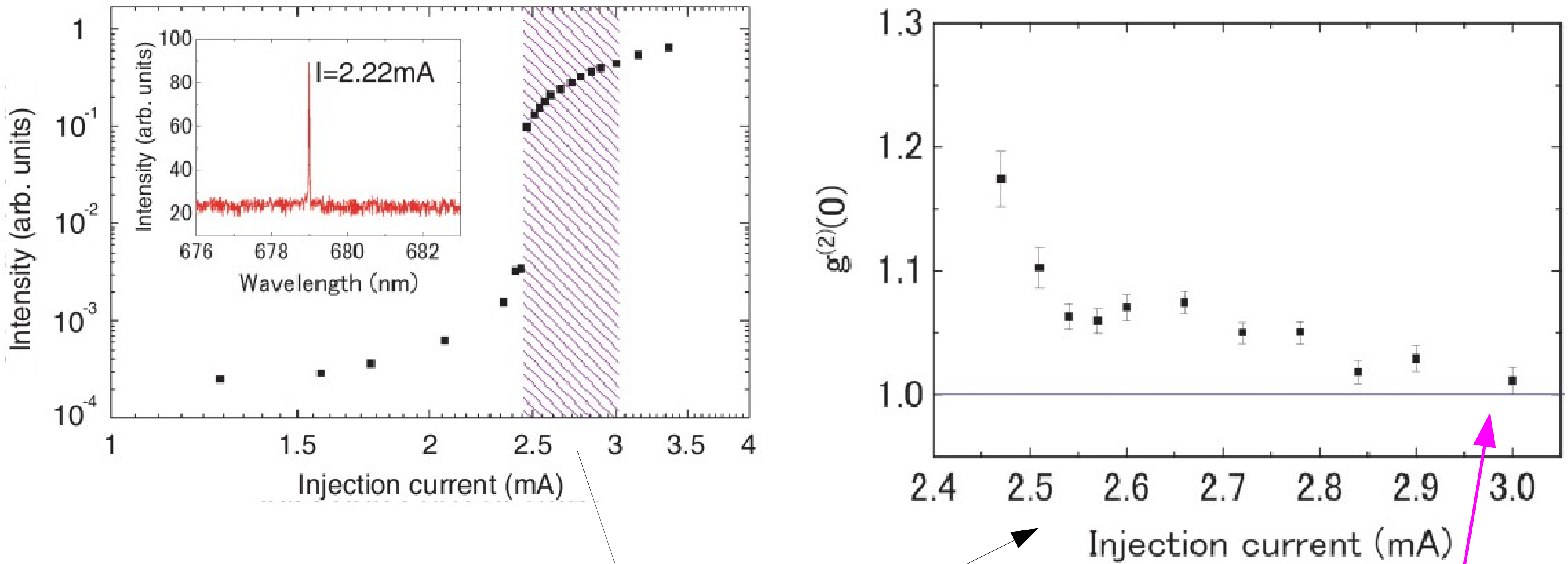


PHYSICAL REVIEW A **85**, 053811 (2012)

# Fast periodic modulations in the photon correlation of single-mode vertical-cavity surface-emitting lasers

Naotomo Takemura,[1] Junko Omachi,[2] and Makoto Kuwata-Gonokami[2,3,*]

**Microlaser**




**coherence**

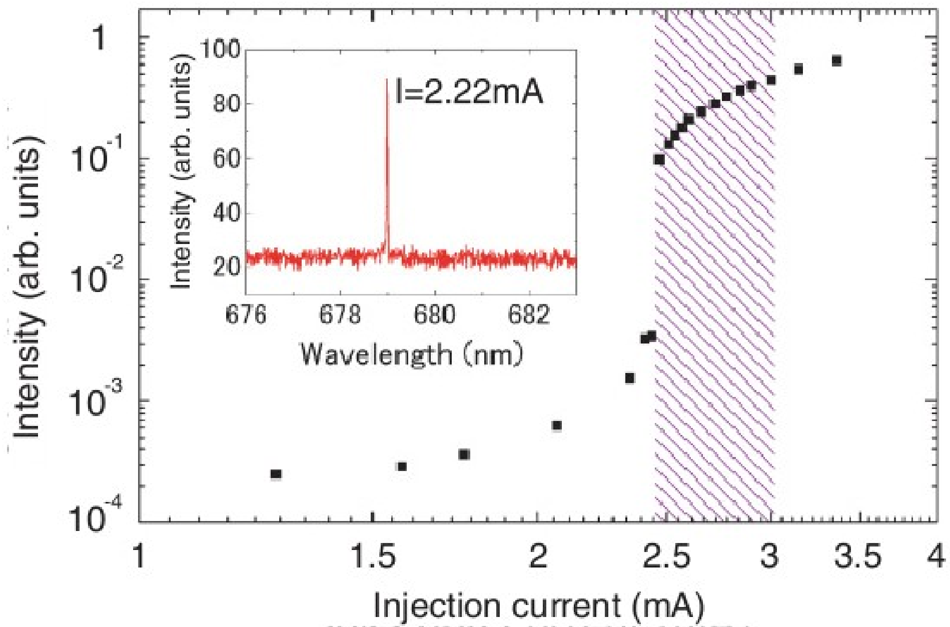
# Coherent oscillations

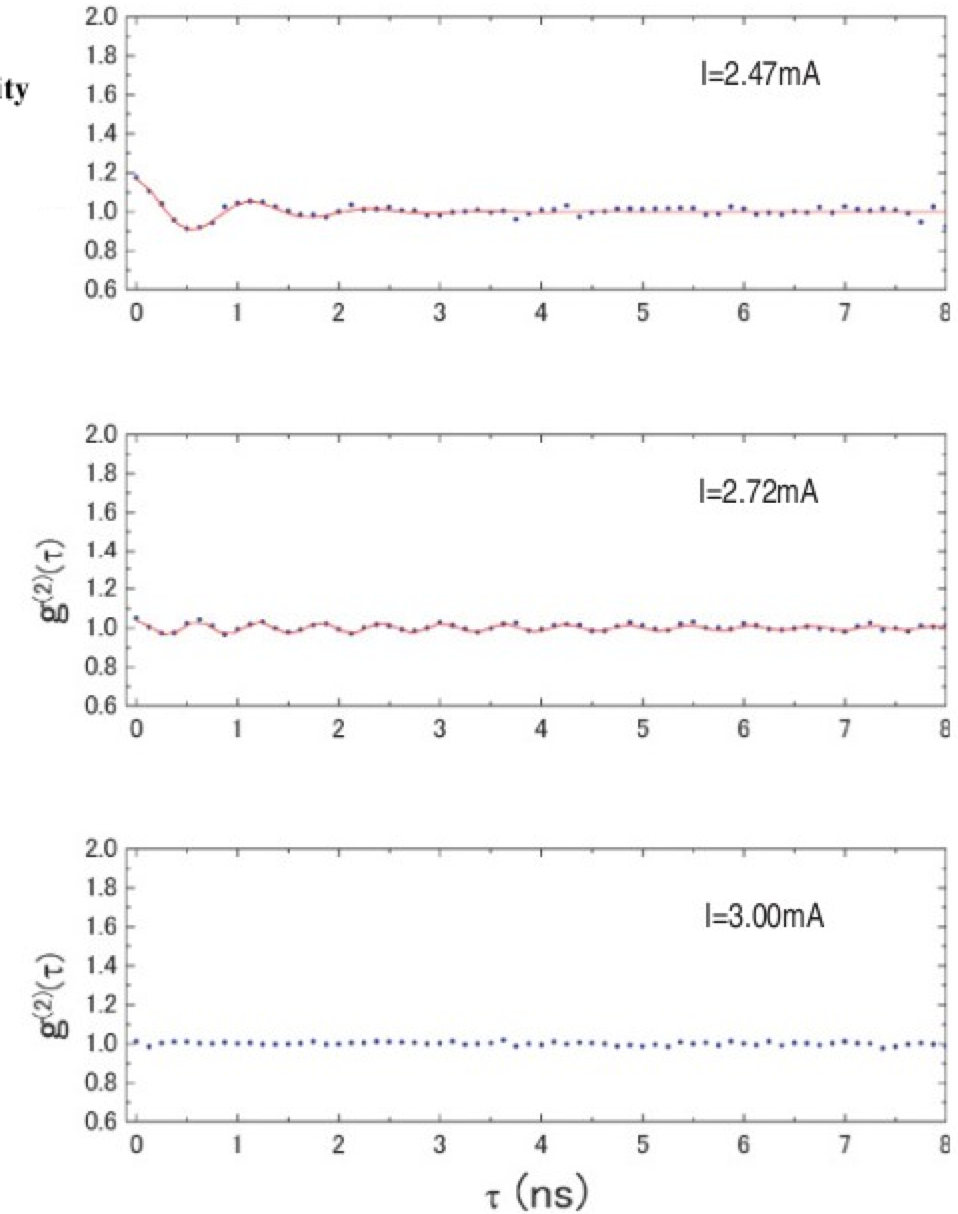
PHYSICAL REVIEW A 85, 053811 (2012)

**Fast periodic modulations in the photon correlation of single-mode vertical-cavity surface-emitting lasers**

Naotomo Takemura,[1] Junko Omachi,[2] and Makoto Kuwata-Gonokami[2,3,*]

***Microlaser***




**Oscillations in coherence**

New Journal of Physics
The open access journal for physics

2013 New J. Phys. 15 033039

**Stochastically sustained population oscillations in high-$\beta$ nanolasers**

A Lebreton[1], I Abram[1], N Takemura[2], M Kuwata-Gonokami[2,3], I Robert-Philip[1,4] and A Beveratos[1]

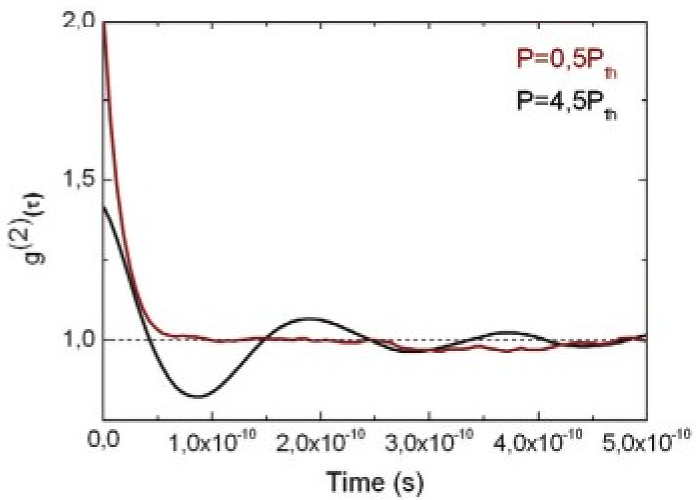



**Figure 3.** Second-order photon correlation function $g^{(2)}(\tau)$ of a nanolaser ($\beta = 0.25$) undergoing photon population cycles, for $P = 0.5P_{\mathrm{th}}$ (red line) and $P = 4.5P_{\mathrm{th}}$ (black line). The dashed horizontal line corresponds to $g^{(2)}(\tau) = 1$, the value in continuous-wave lasers.

$$g^{(2)}(\tau) = 1 + |g^{(1)}(\tau)|^2$$

**Violation of Siegert relation (through population oscillations)**

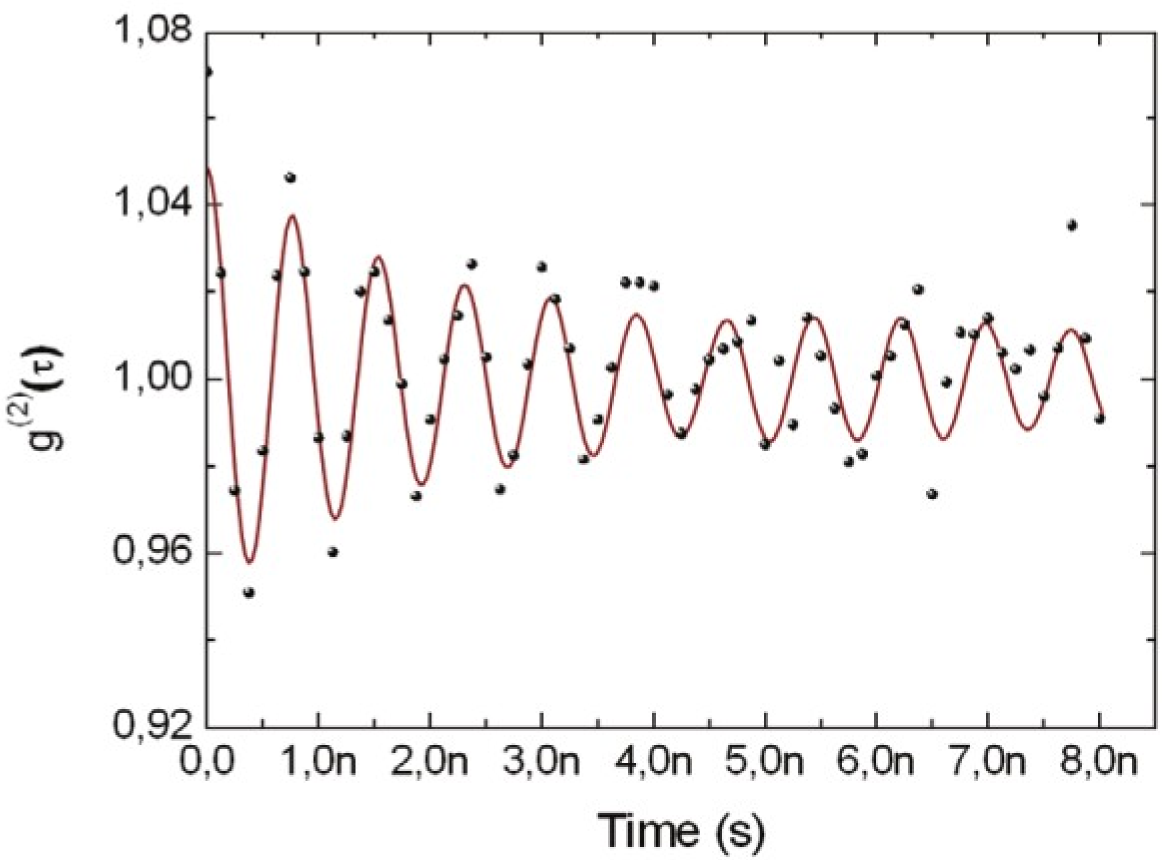
**Numerical: Rate Equations (discrete variables)**

**New Journal of Physics**
The open access journal for physics

2013 New J. Phys. 15 033039

**Stochastically sustained population oscillations in high-$\beta$ nanolasers**

**A Lebreton[1], I Abram[1], N Takemura[2], M Kuwata-Gonokami[2,3],**




**Experimental data from Phys. Rev. A 85, 053811 (2012)**

**Rate equations simulations (discrete variables)**

## Summary

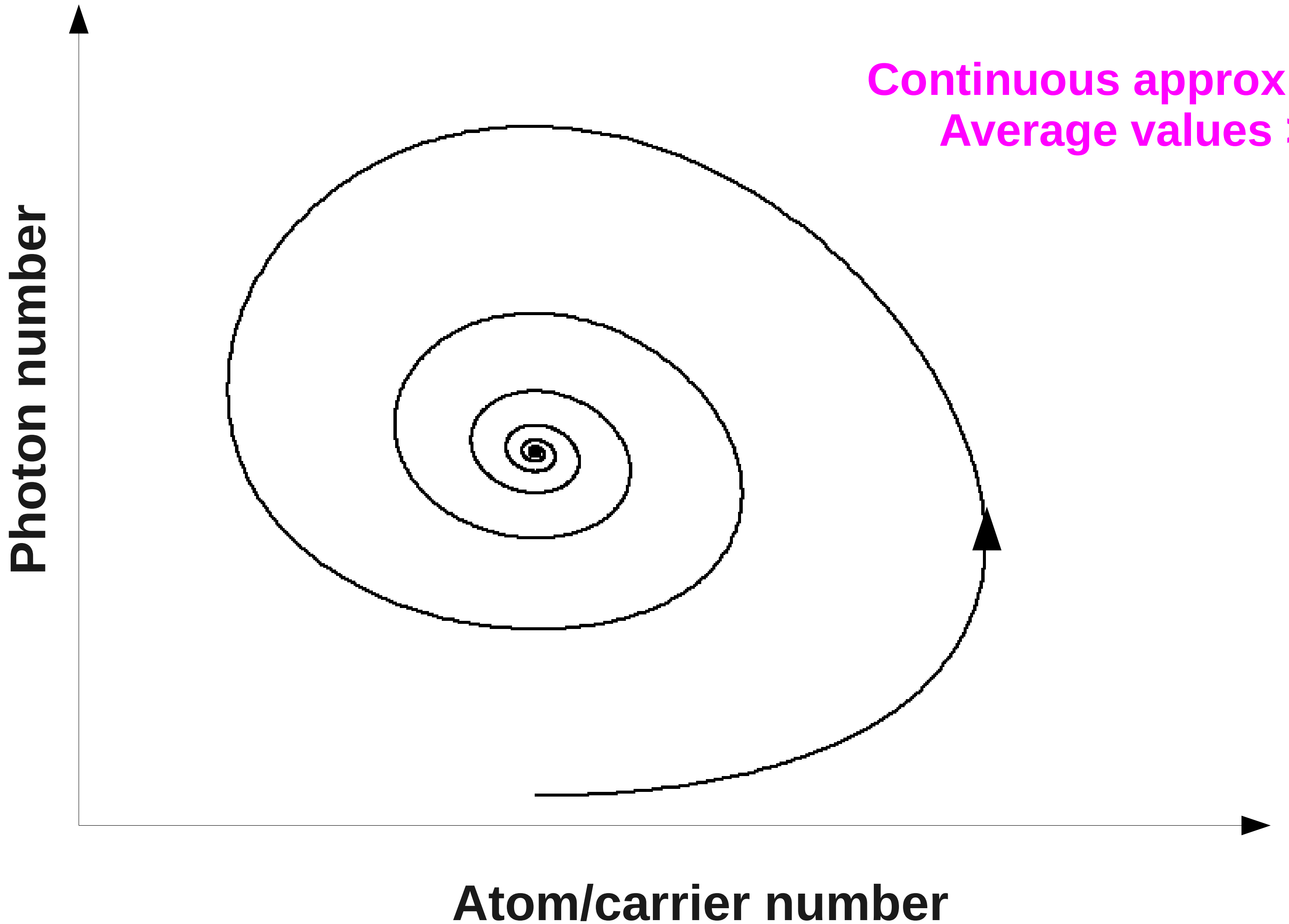
**Oscillations in coherence $g^{(2)}(\tau)$ appear both**
**in (some) nanolasers**
**in microlasers**

**Result from coherent oscillations between population and e.m. field**

**Can give rise to misinterpretation of $g^{(2)}(\tau=0)$ as imperfect coherence**

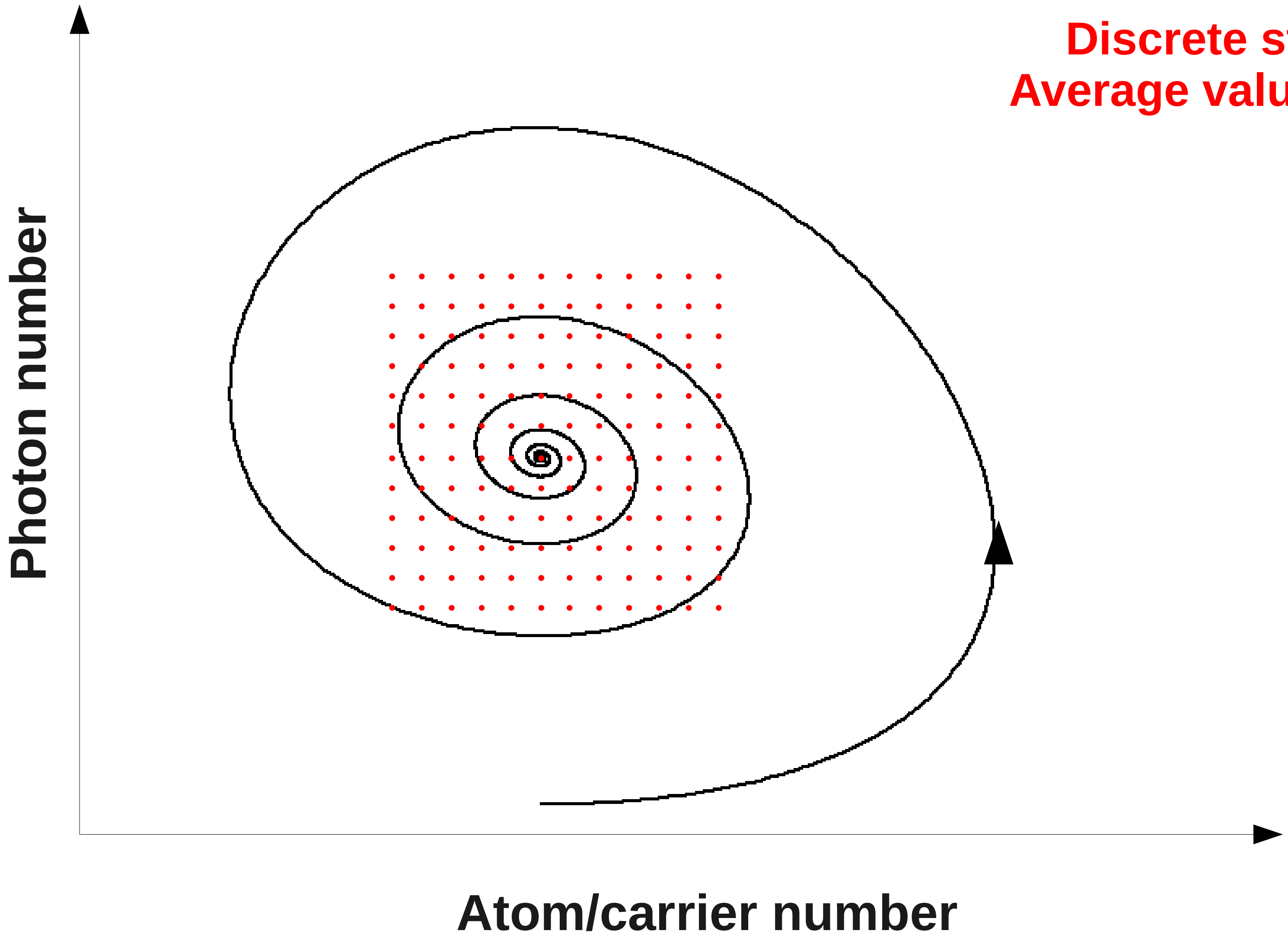
# V. Additional remarks

## Origin of oscillations

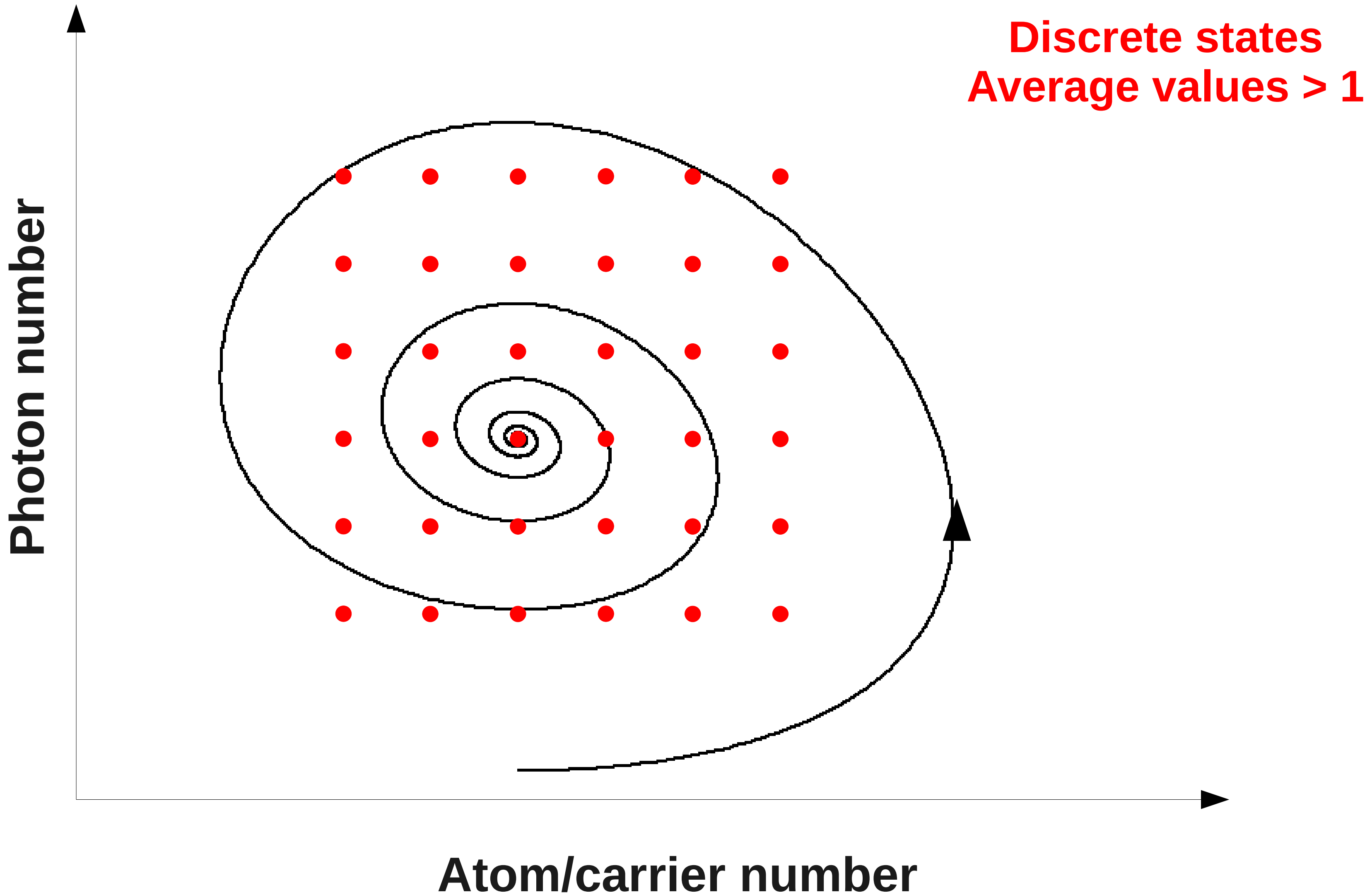



Continuous approximation
Average values >> 1

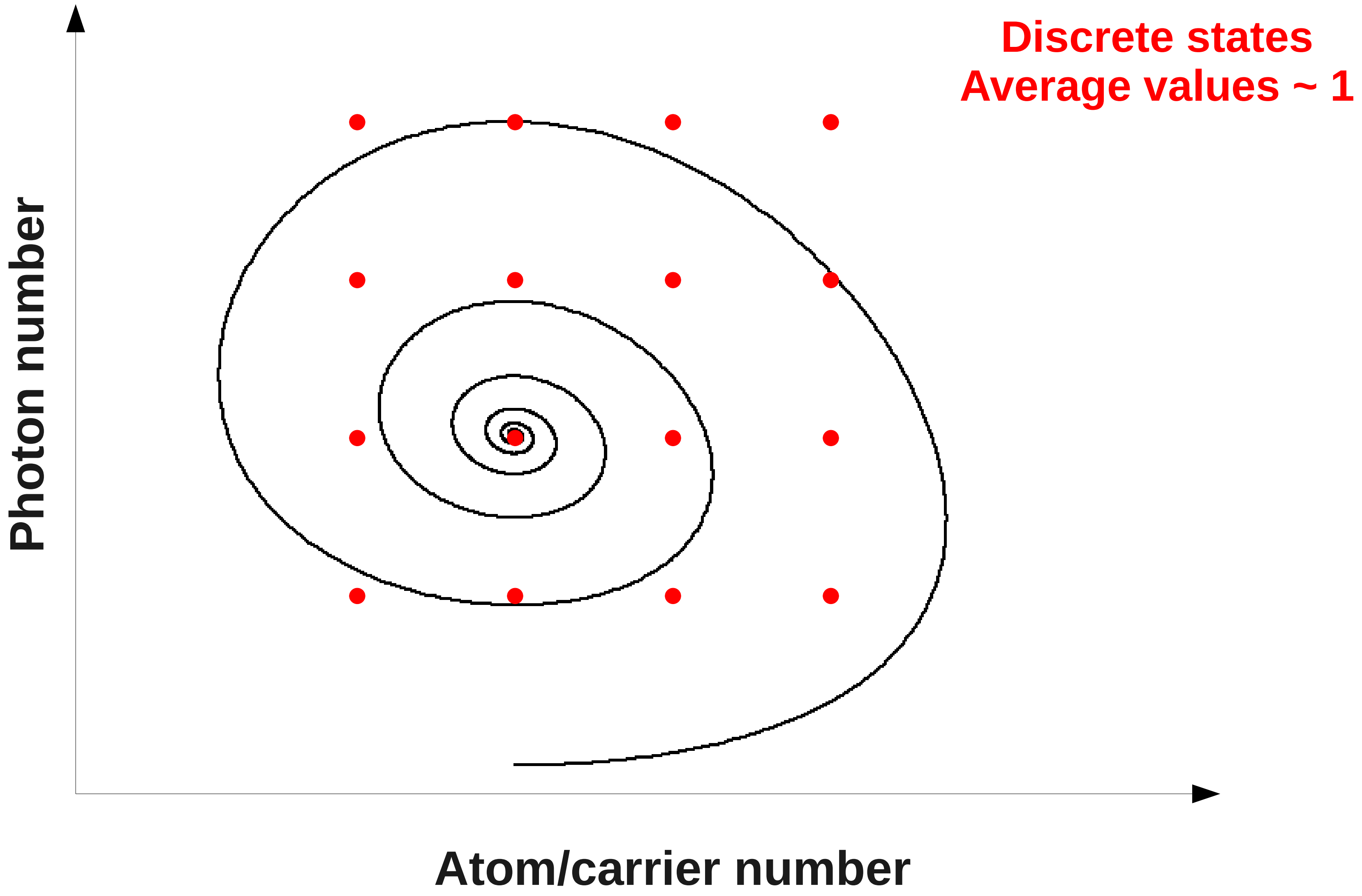
## Origin of oscillations



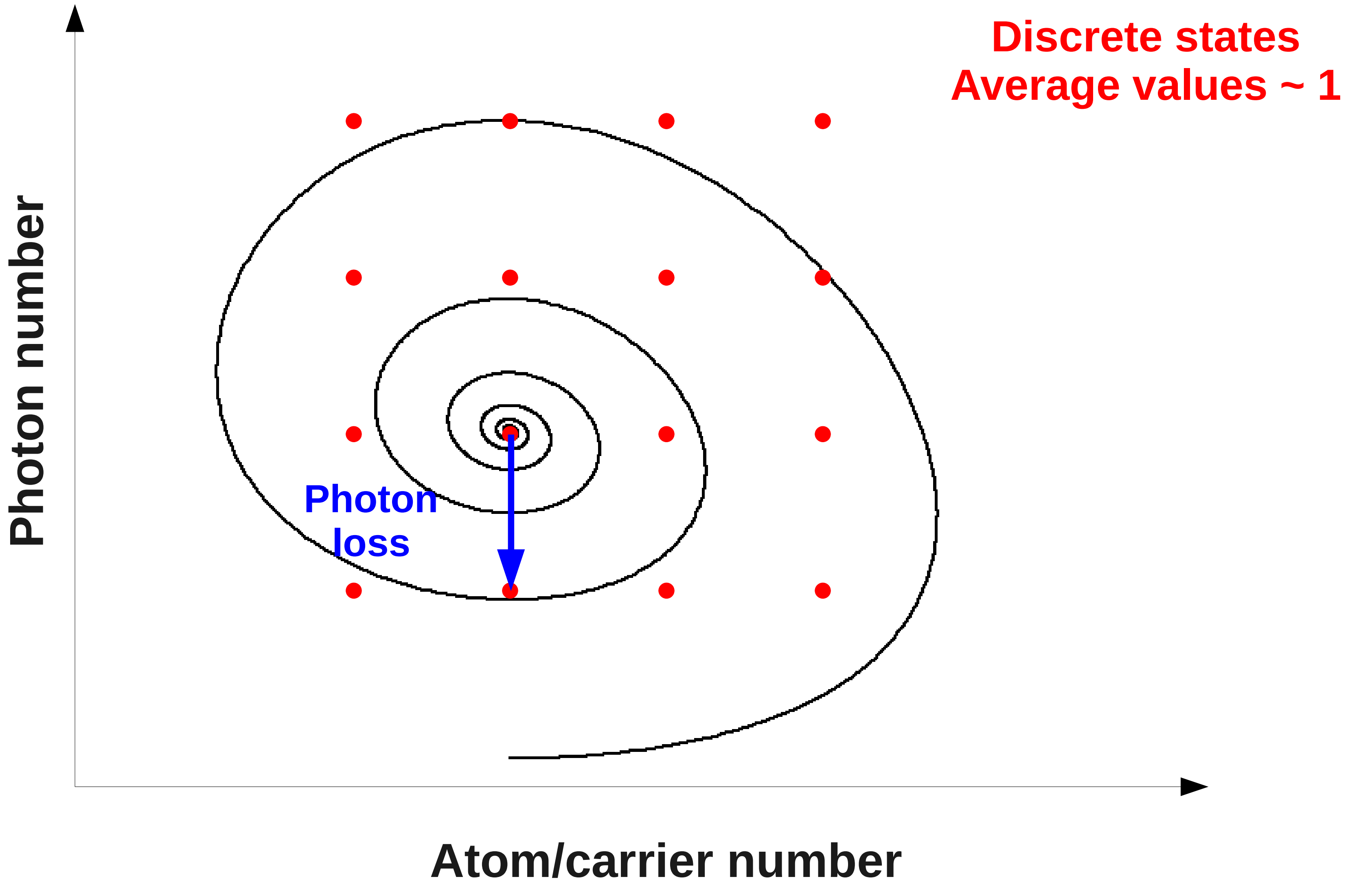
## Origin of oscillations



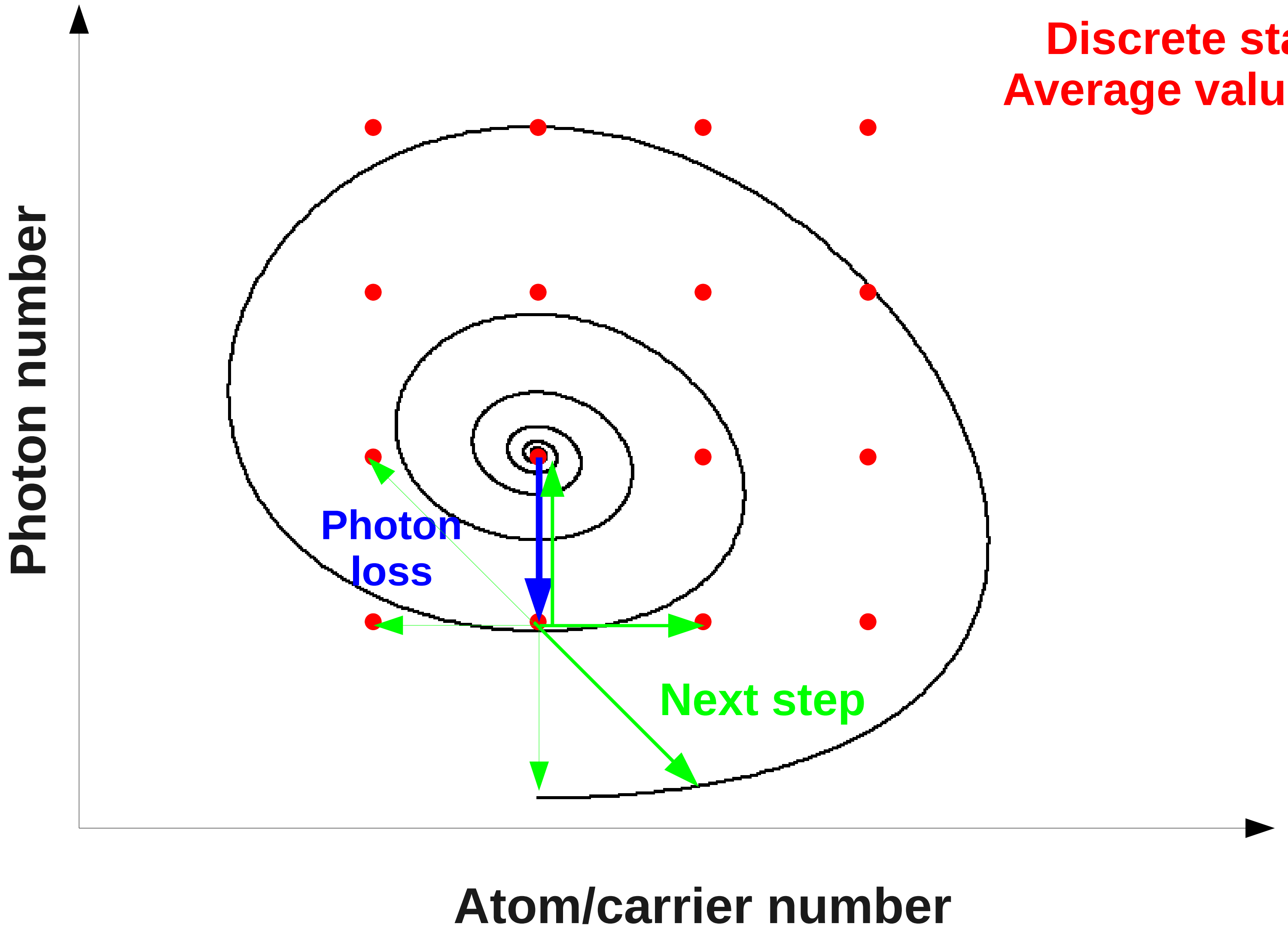
## Origin of oscillations



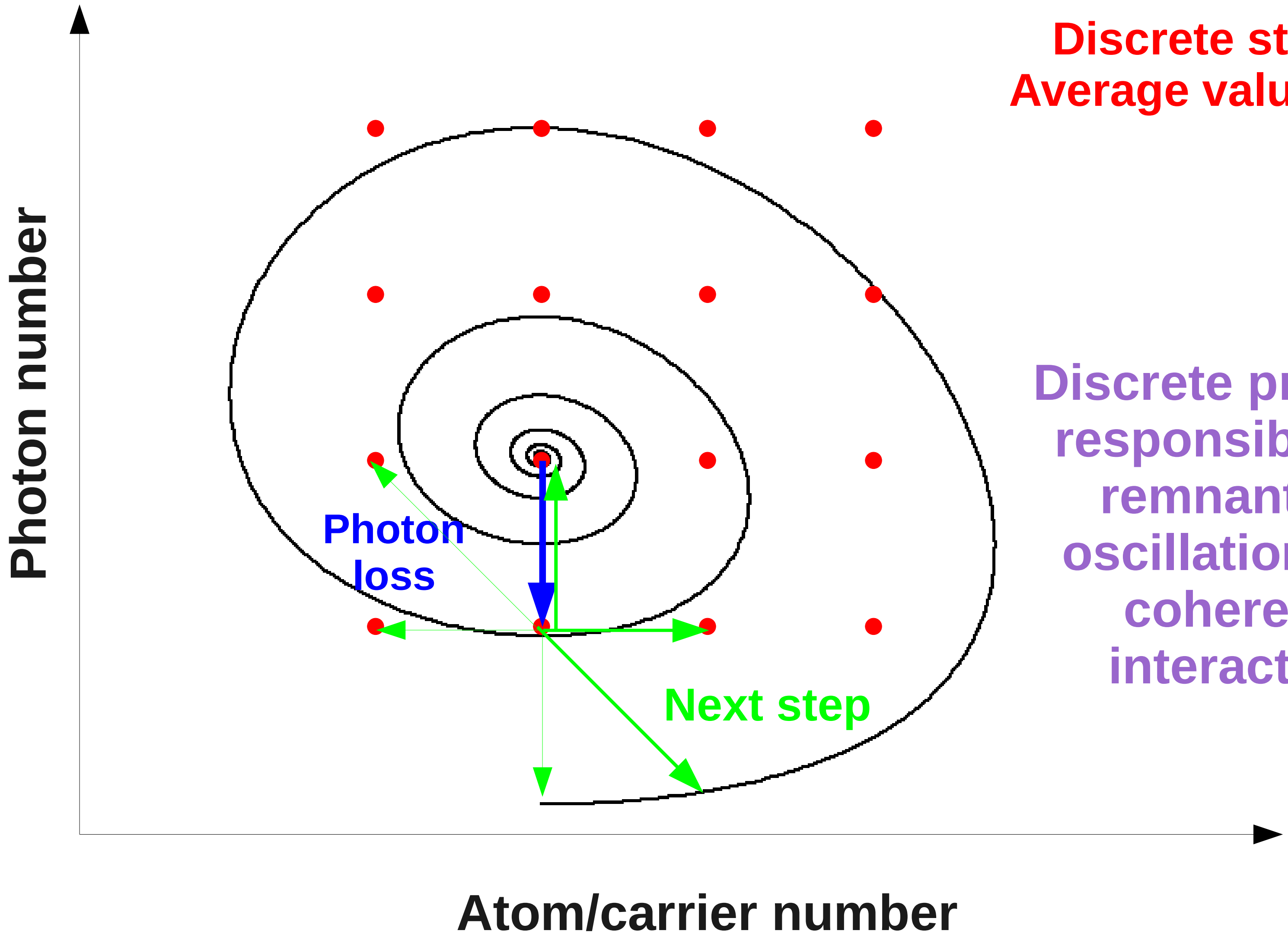
## Origin of oscillations



## Origin of oscillations



## Origin of oscillations




Discrete states
Average values ~ 1

Discrete process responsible for remnant of oscillation in a coherent interaction

# Modeling small lasers

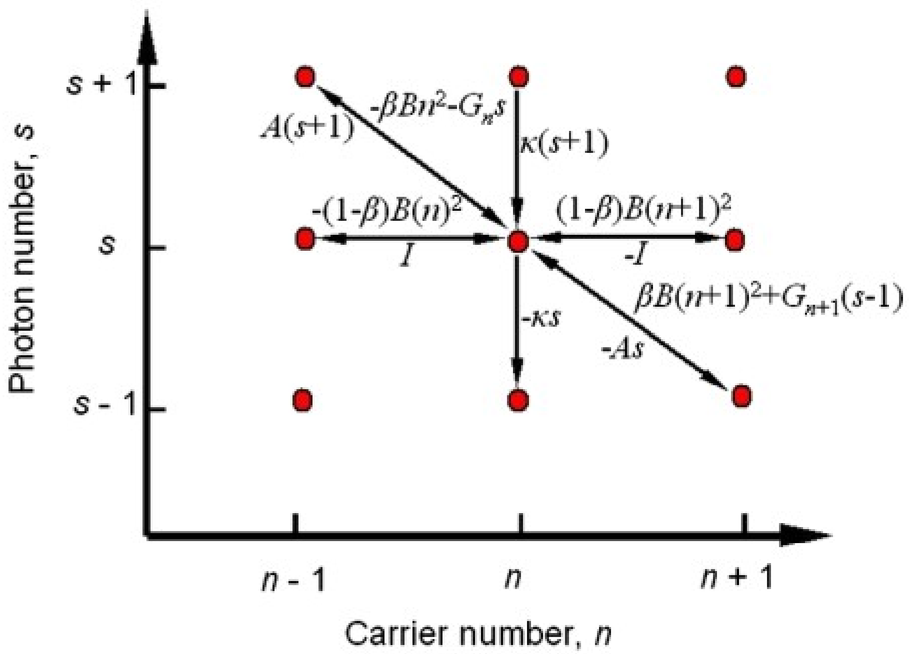
PRL 102, 053902 (2009) PHYSICAL REVIEW LETTERS week ending 6 FEBRUARY 2009

**Quantum Fluctuations in Small Lasers**

Kaushik Roy-Choudhury and Stephan Haas, A. F. J. Levi

## Master equation approach

$N_{eqs} = n\ s$




$$\frac{dP_{n,s}}{dt} = -\kappa(sP_{n,s} - (s+1)P_{n,s+1}) - (sG_nP_{n,s} - (s-1)G_{n+1}P_{n+1,s-1}) - (sAP_{n,s} - (s+1)AP_{n-1,s+1}) - \beta B(n^2P_{n,s} - (n+1)^2P_{n+1,s-1}) - (1-\beta)B(n^2P_{n,s} - (n+1)^2P_{n+1,s}) - \frac{I}{e}(P_{n,s} - P_{n-1,s}) \quad (1)$$

# Modeling small lasers

Phys. Rev. Lett. **102**, 053902 (2009)

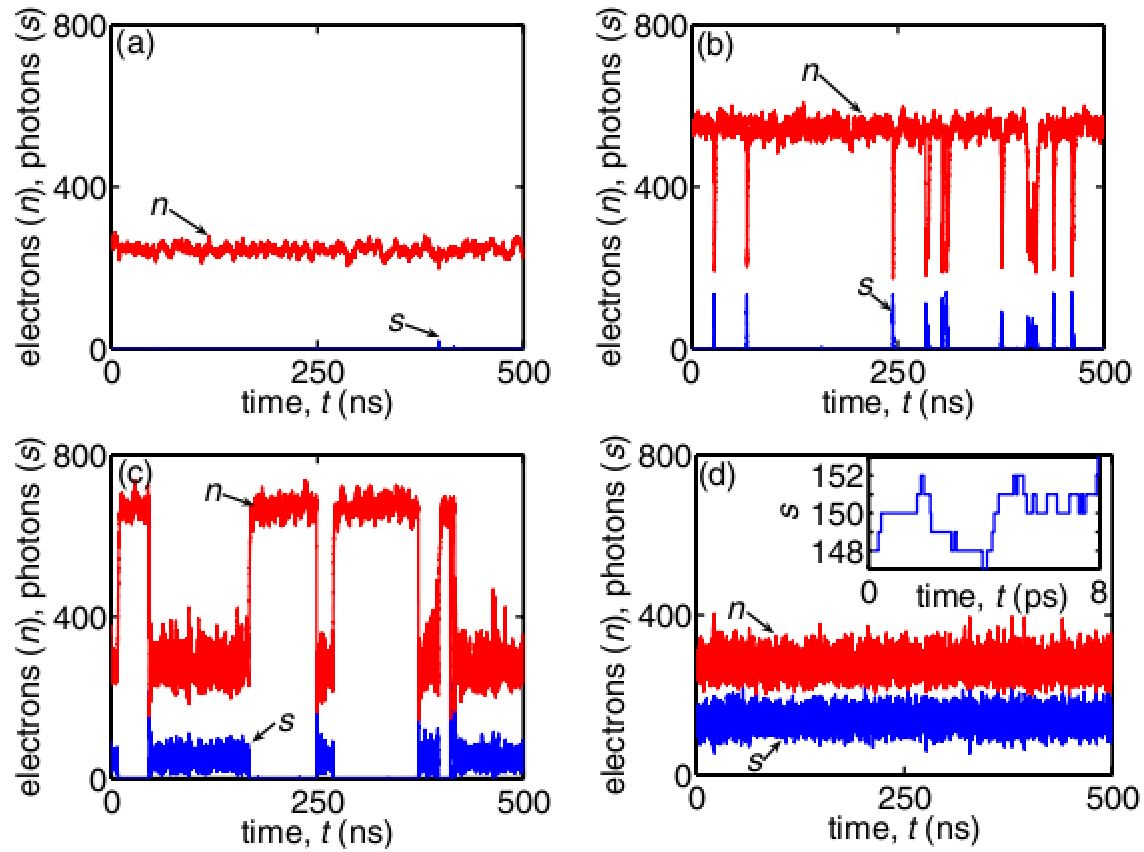
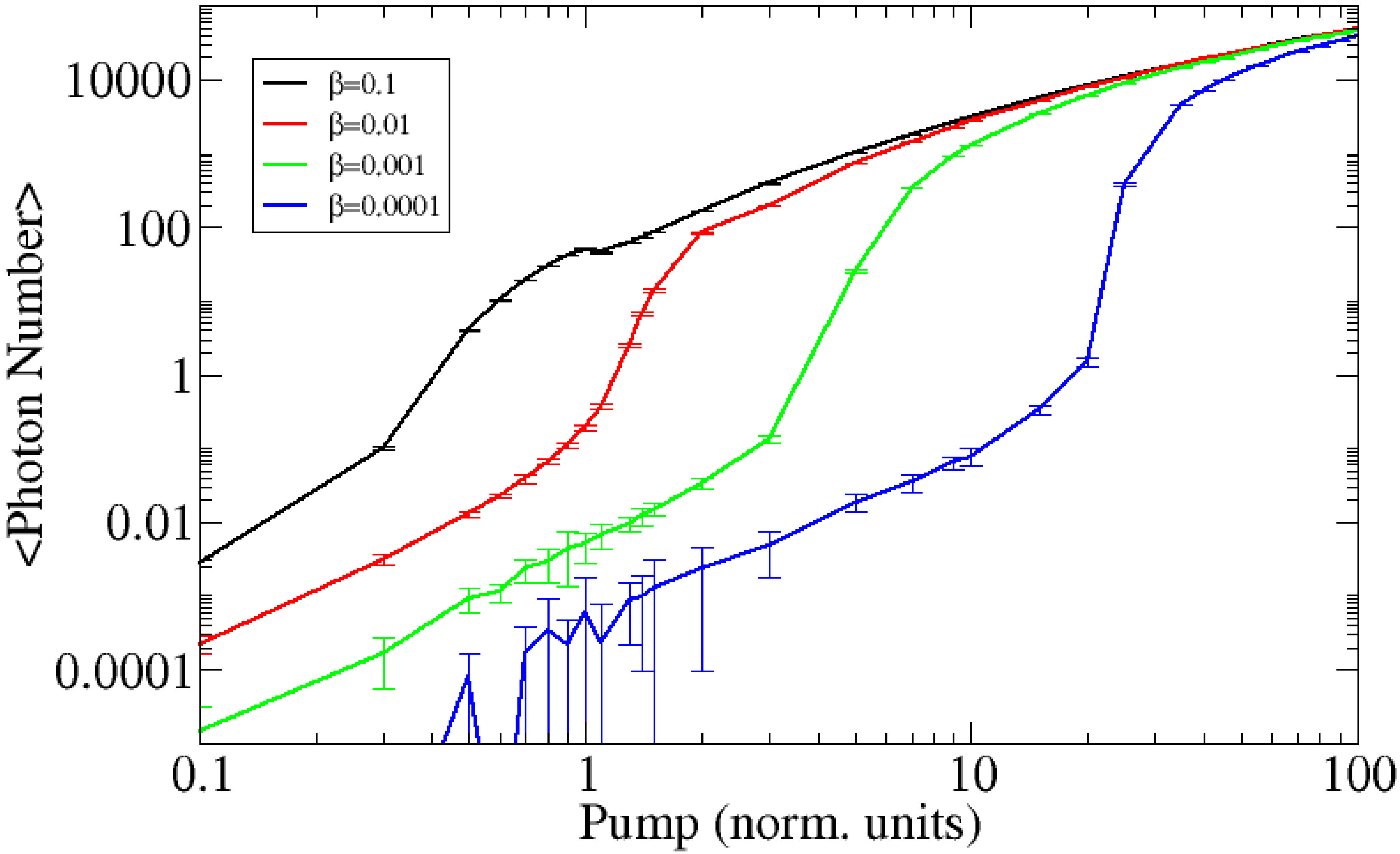



FIG. 4 (color online). Time evolution of electrons and photons calculated by the random walk method. (a) Current, $I = 9.6$ nA. (b) $I = 48$ nA. (c) $I = 72$ nA. (d) $I = 192$ nA. The inset shows discrete step changes in photon number with time. Parameters as in Fig. 2.

**Uniform random walk on the grid defined by the Master Equation**

**Pulsing regime**

## Preliminary results

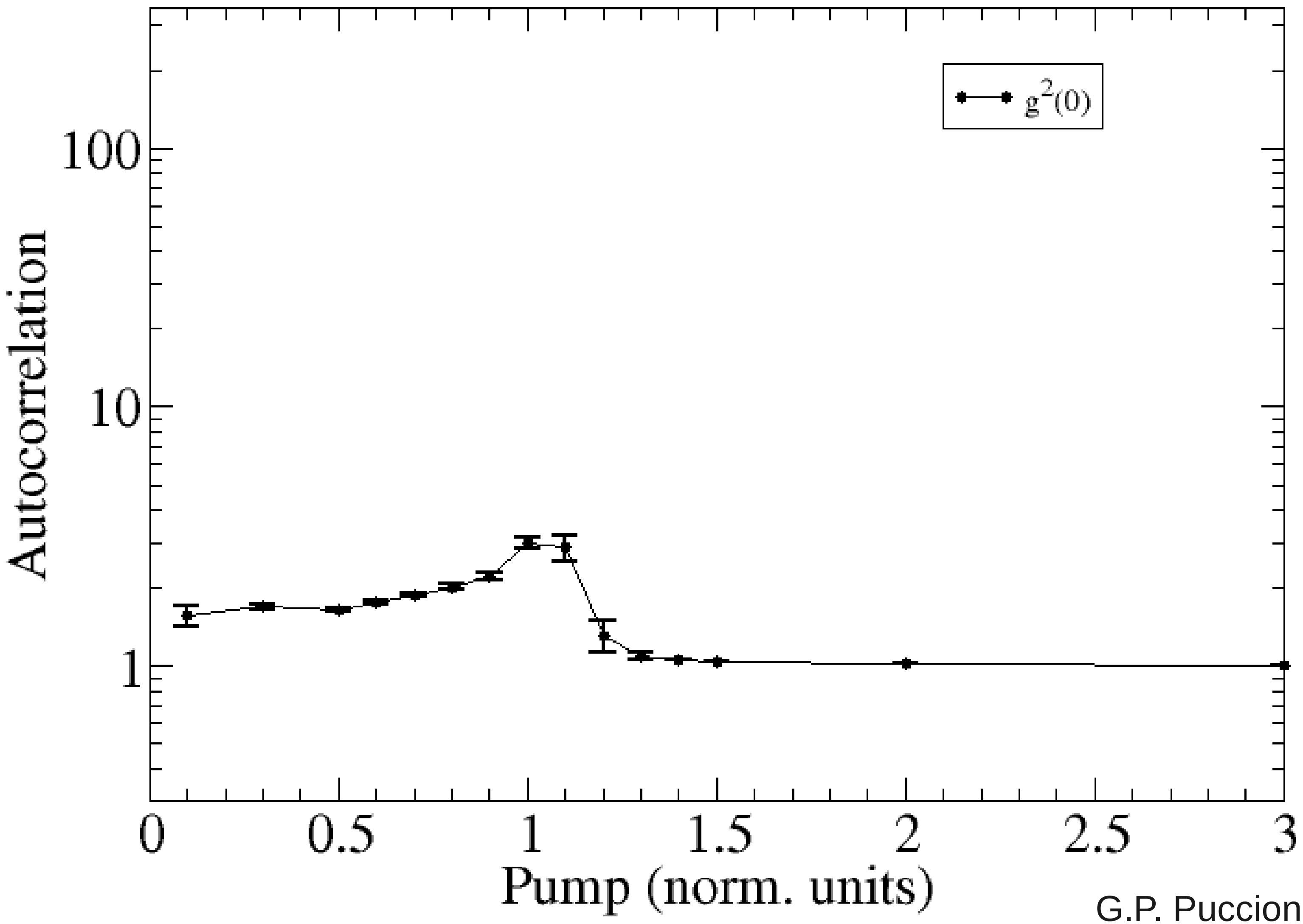



G.P. Puccioni and G.L. Lippi

# Autocorrelations

Preliminary results

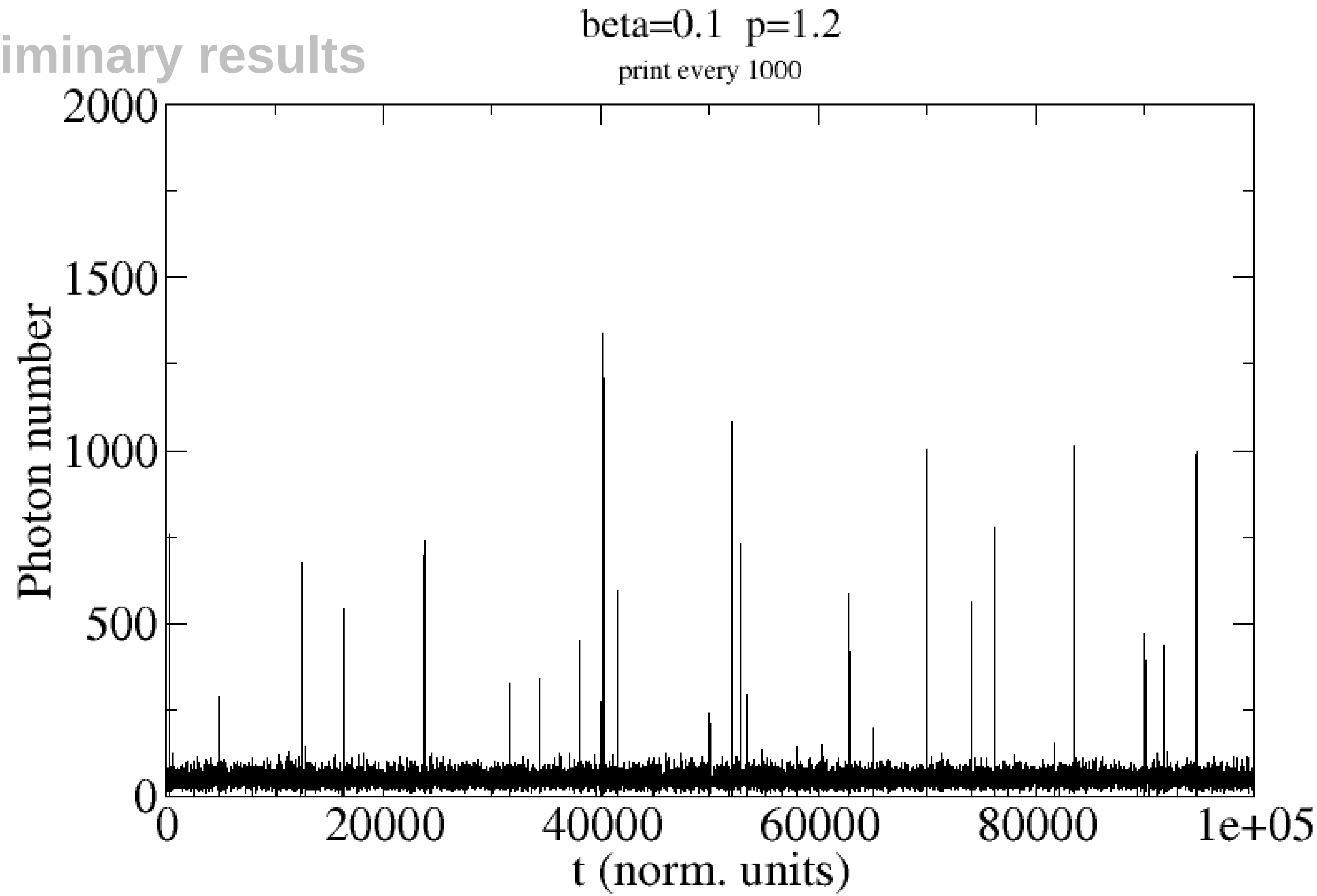
$\beta = 0.1$




G.P. Puccioni and G.L. Lippi

# Spiking output

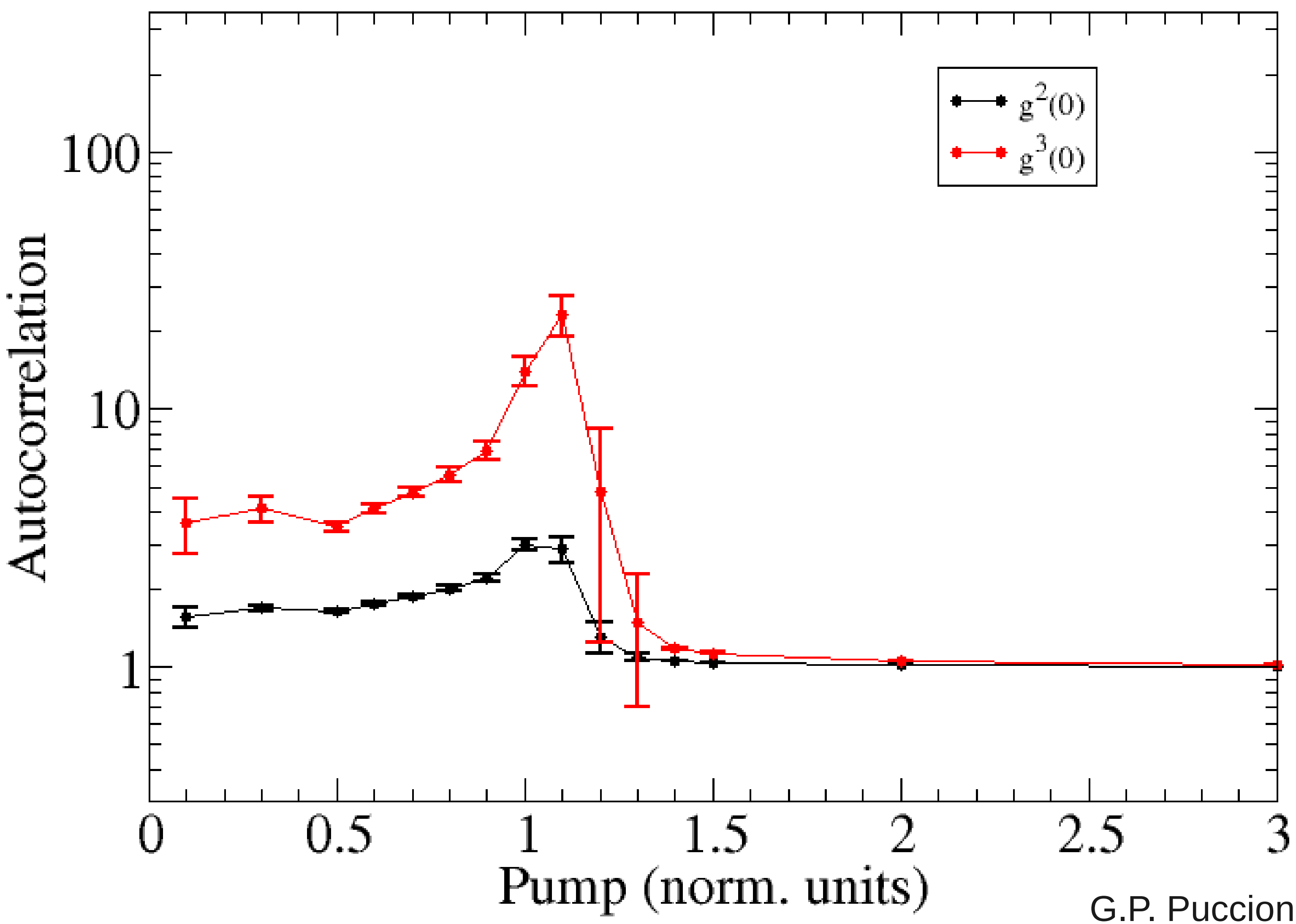
Preliminary results




G.P. Puccioni and G.L. Lippi

## Preliminary results

$\beta = 0.1$

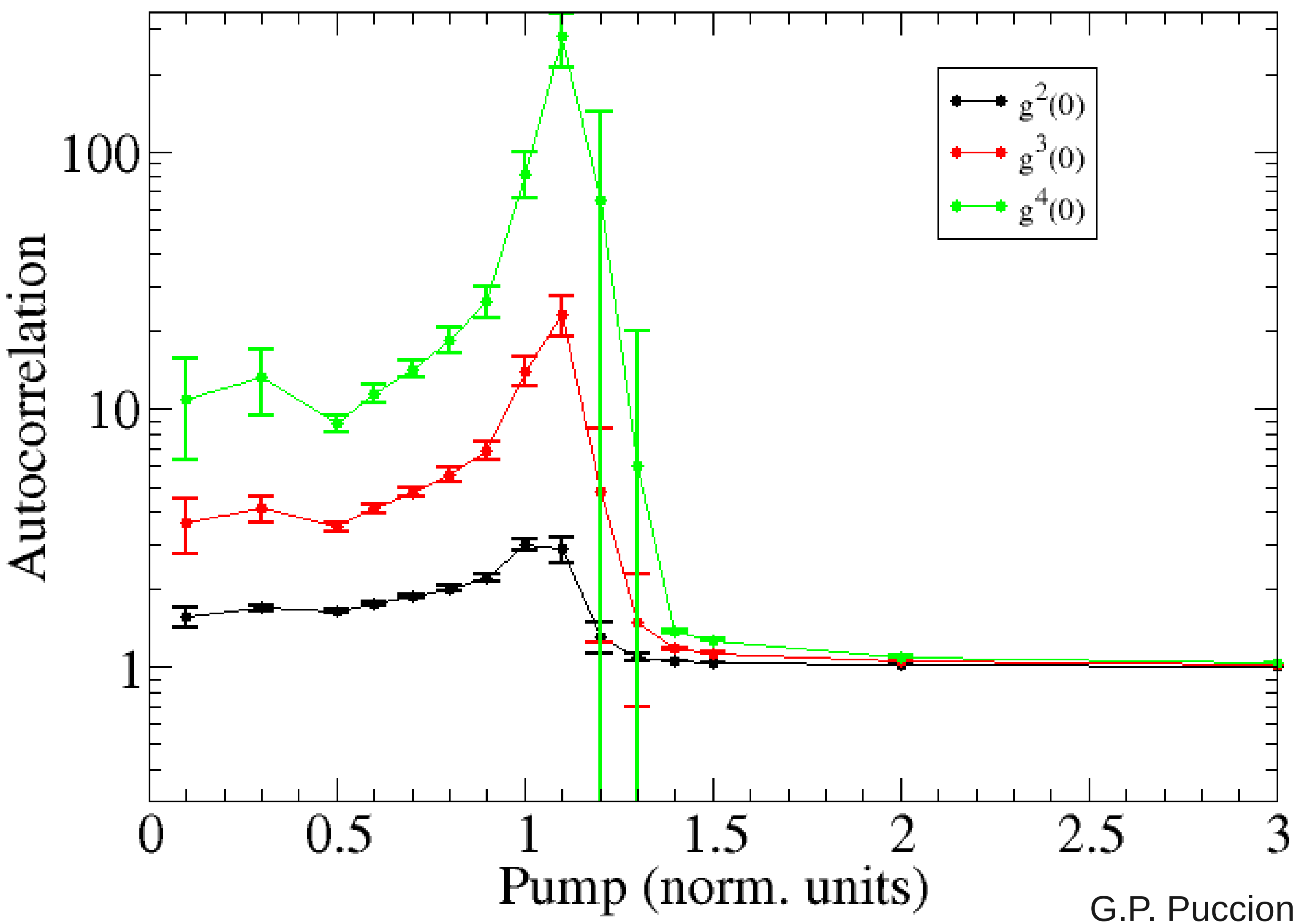



G.P. Puccioni and G.L. Lippi

# Autocorrelations

## Preliminary results

$\beta = 0.1$




G.P. Puccioni and G.L. Lippi

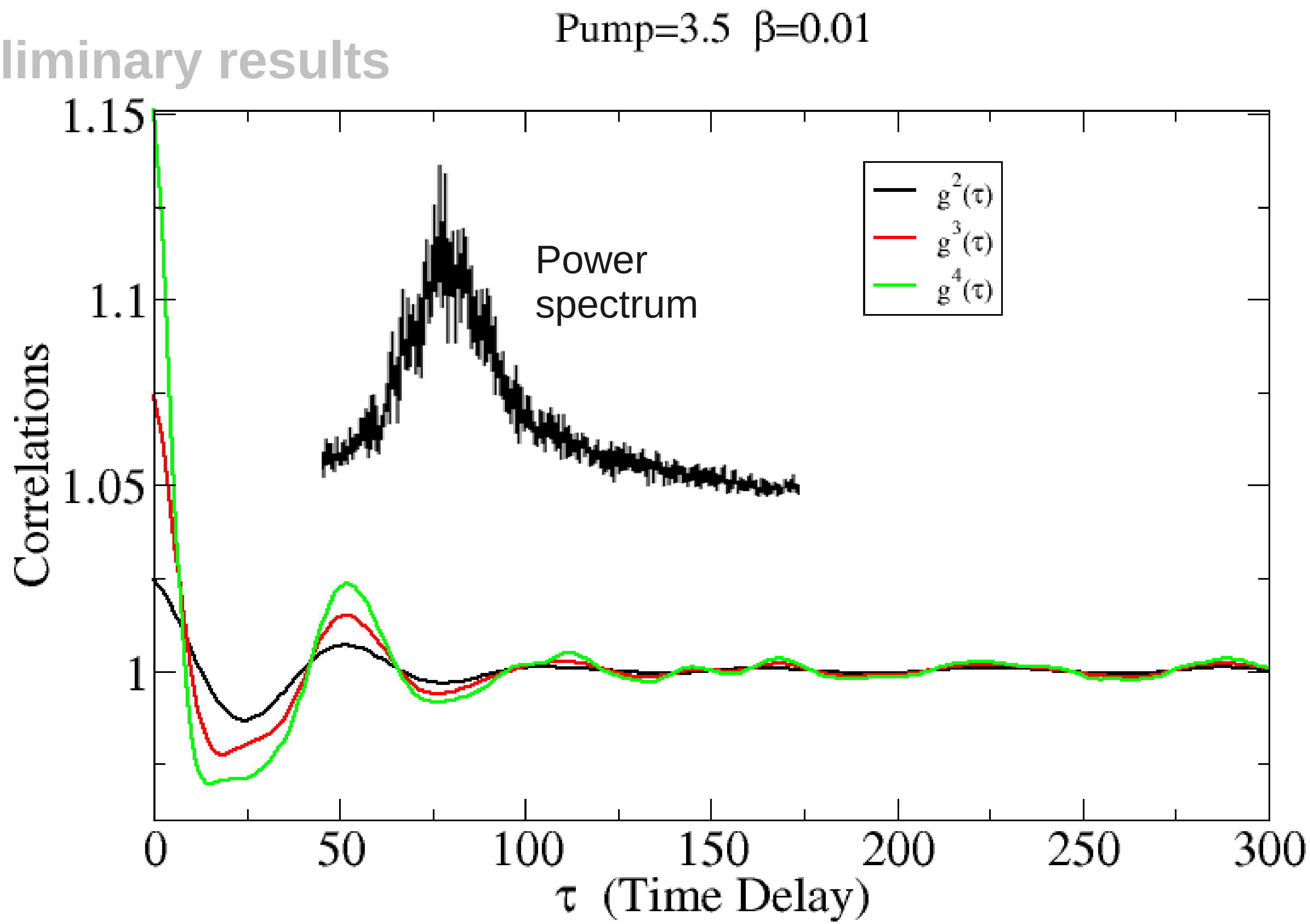
## Summary

**From First Principles, Granular Modeling:**

- **Strong spiking regime**
- **$g^{(2)}(0)$ grows and then decreases**
- **Strong fluctuations in $g^{(2)}(0)$ before reaching coherent value**
- **$g^{(3)}(0)$ and $g^{(4)}(0)$ converge "later"**
- **Increased sensitivity to fluctuations in higher order correlations (especially $g^{(4)}(0)$)**

# Reproducing coherent oscillations

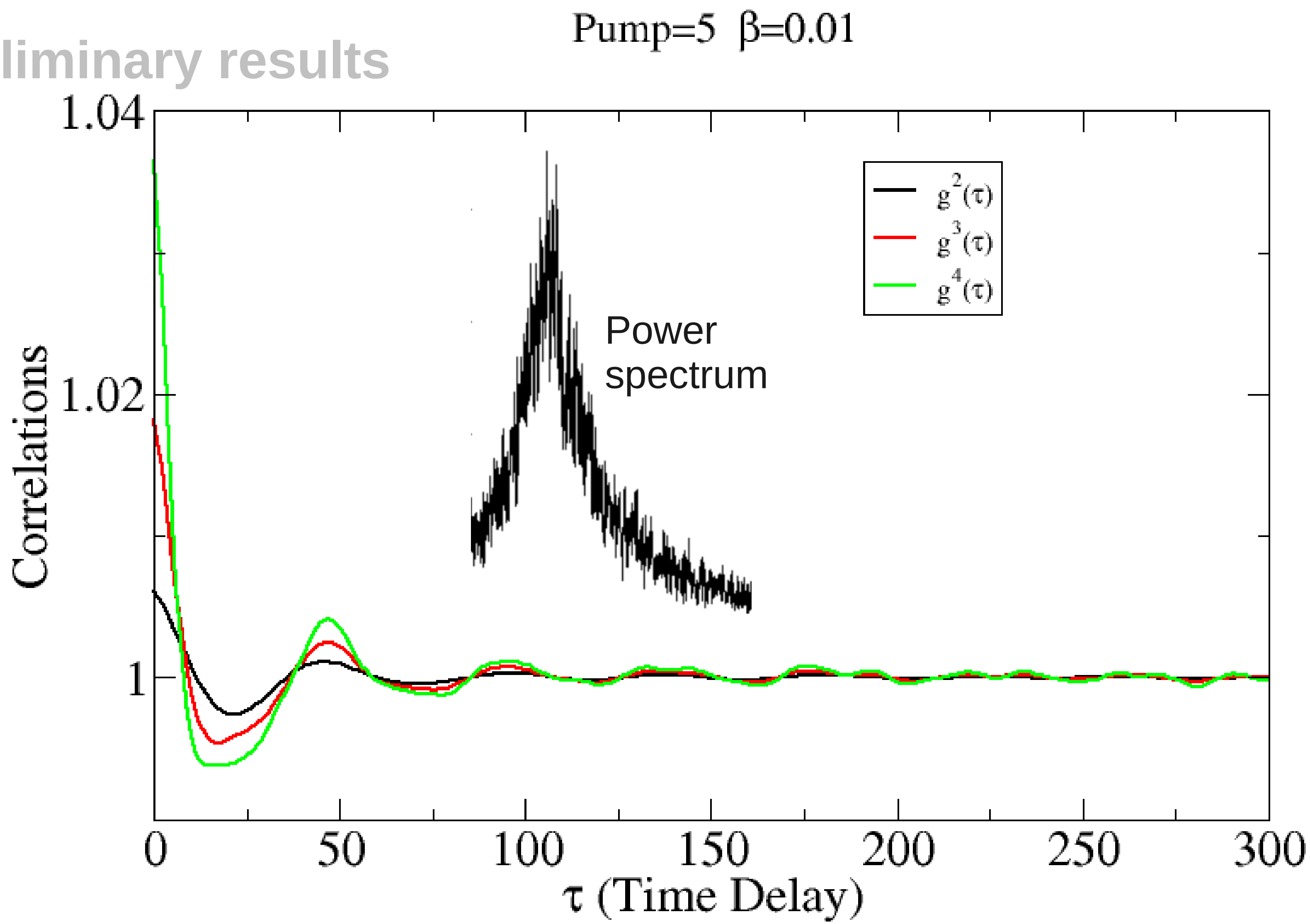
Preliminary results




G.P. Puccioni and G.L. Lippi

# Reproducing coherent oscillations

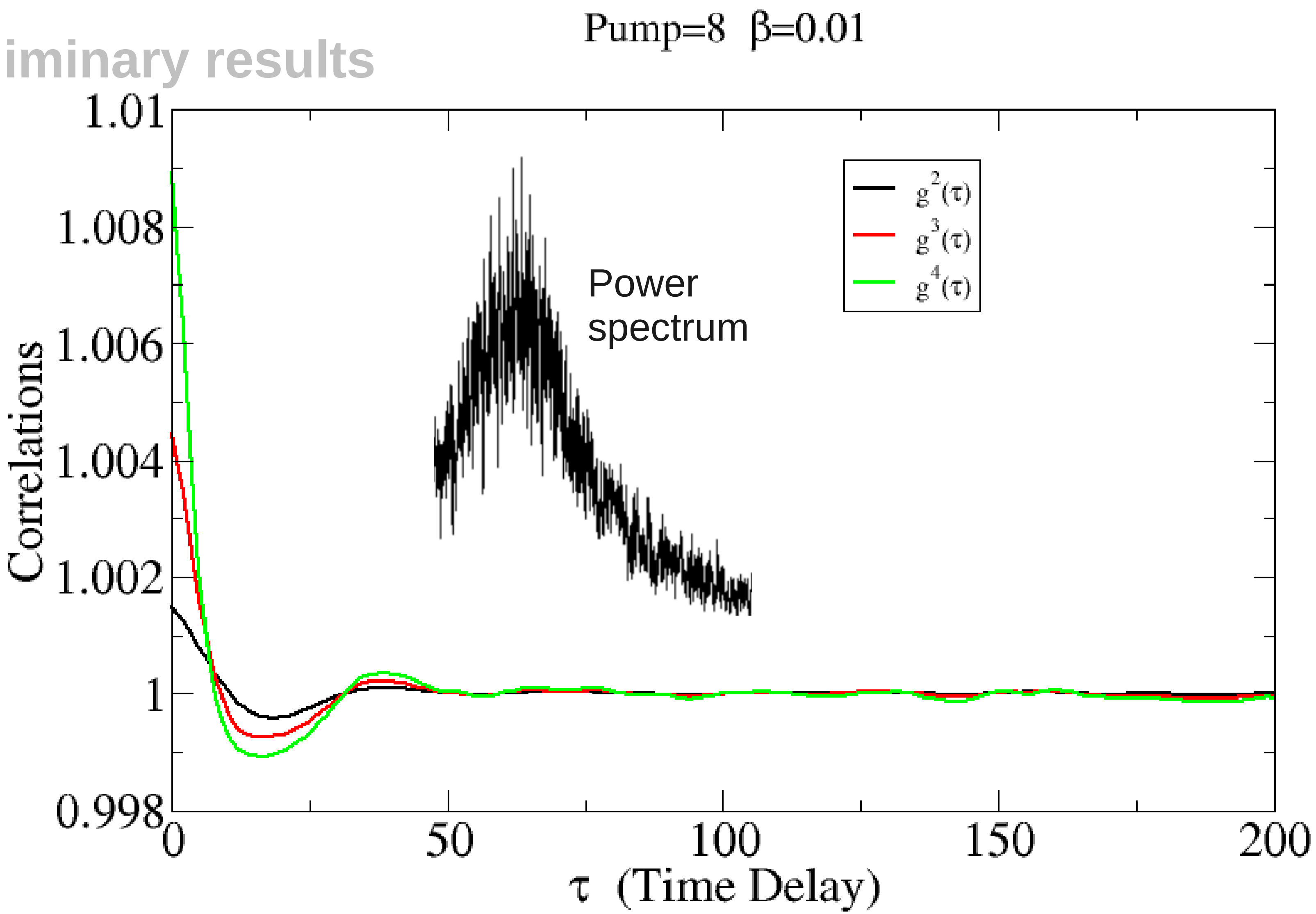
**Preliminary results**




G.P. Puccioni and G.L. Lippi

# Reproducing coherent oscillations

Preliminary results




G.P. Puccioni and G.L. Lippi

# Reproducing coherent oscillations

## Summary

**From First Principles, Granular Modeling:**

- **Oscillations present in signal mimicking the physical process**
- **Power spectrum shows peak features**
- **Autocorrelation > 1 (coherent oscillations)**
- **Oscillations in correlation**
- **Higher order correlations more sensitive (in amplitude and shape)**

# Conclusions

Correlations widely used (and necessary) for characterizing coherence in micro- and nanolasers

Results strongly dependent on experimental system (reproducibility of samples, intrinsic features ...)

Most small lasers are pulsed:  influence on correlations?

Problems with higher correlations

Coherent oscillations, statistical mixture of light ...

Many open questions

**Thank you for your attention!**

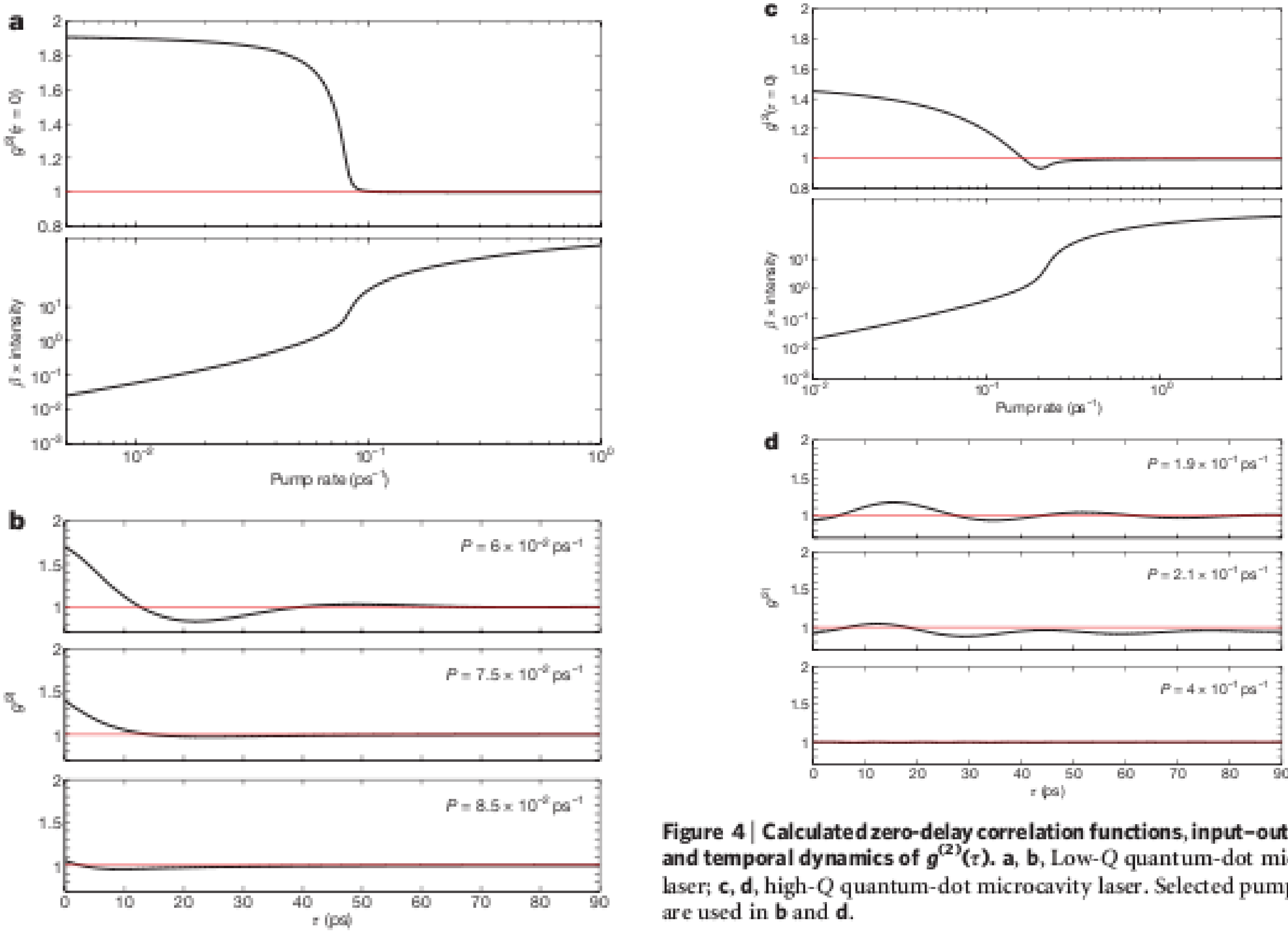


Figure 4 | Calculated zero-delay correlation functions, input–output curves and temporal dynamics of $g^{(2)}(\tau)$. a, b, Low-$Q$ quantum-dot microcavity laser; c, d, high-$Q$ quantum-dot microcavity laser. Selected pump rates, $P$, are used in b and d.

Nature **460**
Wiersig et al.

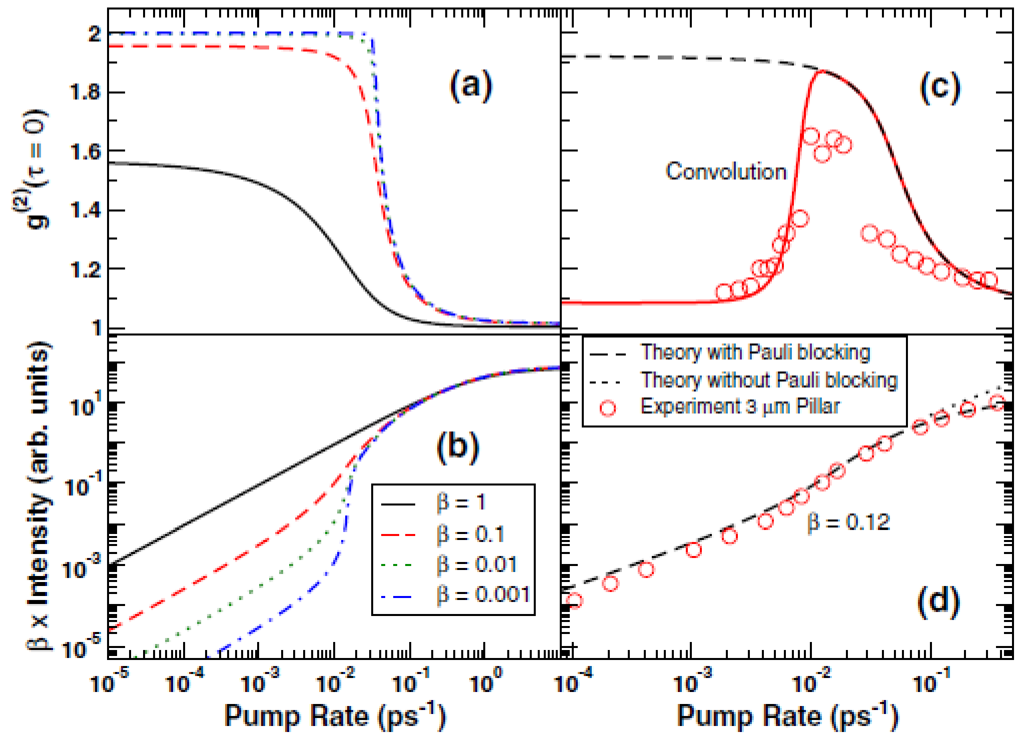



FIG. 5 (color online). (a),(b) Calculated output curves (bottom) and $g^{(2)}(0)$ (top) for various $\beta$. (c),(d) Calculated results vs experimental data (pulsed) from Fig. 3(a) for the 3 $\mu$m pillar. In (c), a convolution (solid line) with the experimental temporal resolution $\tau_c$ is shown. (d) Corresponding I/O curves, explicitly indicating the effects of pump saturation.

Nature **460**
Wiersig et al.

RAPID COMMUNICATIONS

PHYSICAL REVIEW A **84**, 061802(R) (2011)

# Higher-order photon correlations in pulsed photonic crystal nanolasers

D. Elvira,[1] X. Hachair,[1] V. B. Verma,[2] R. Braive,[1] G. Beaudoin,[1] I. Robert-Philip,[1] I. Sagnes,[1] B. Baek,[2] S. W. Nam,[2]
E. A. Dauler,[3] I. Abram,[1] M. J. Stevens,[2] and A. Beveratos[1,*]

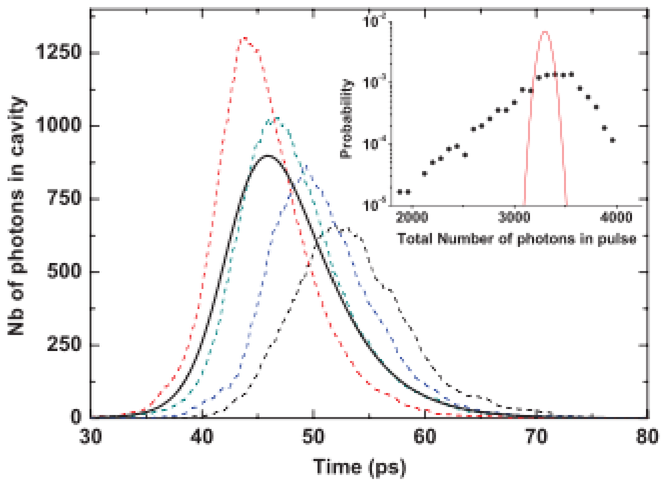
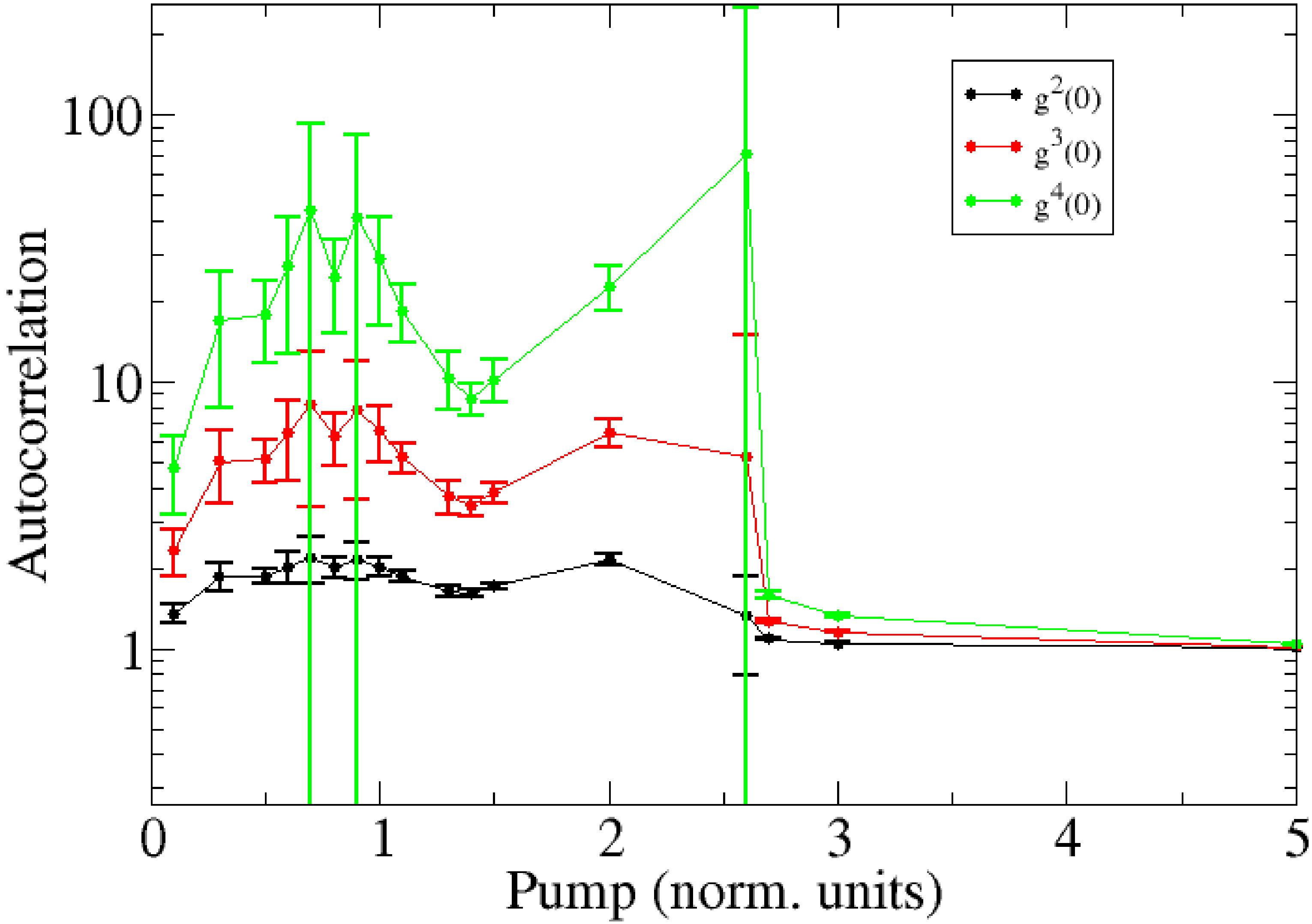
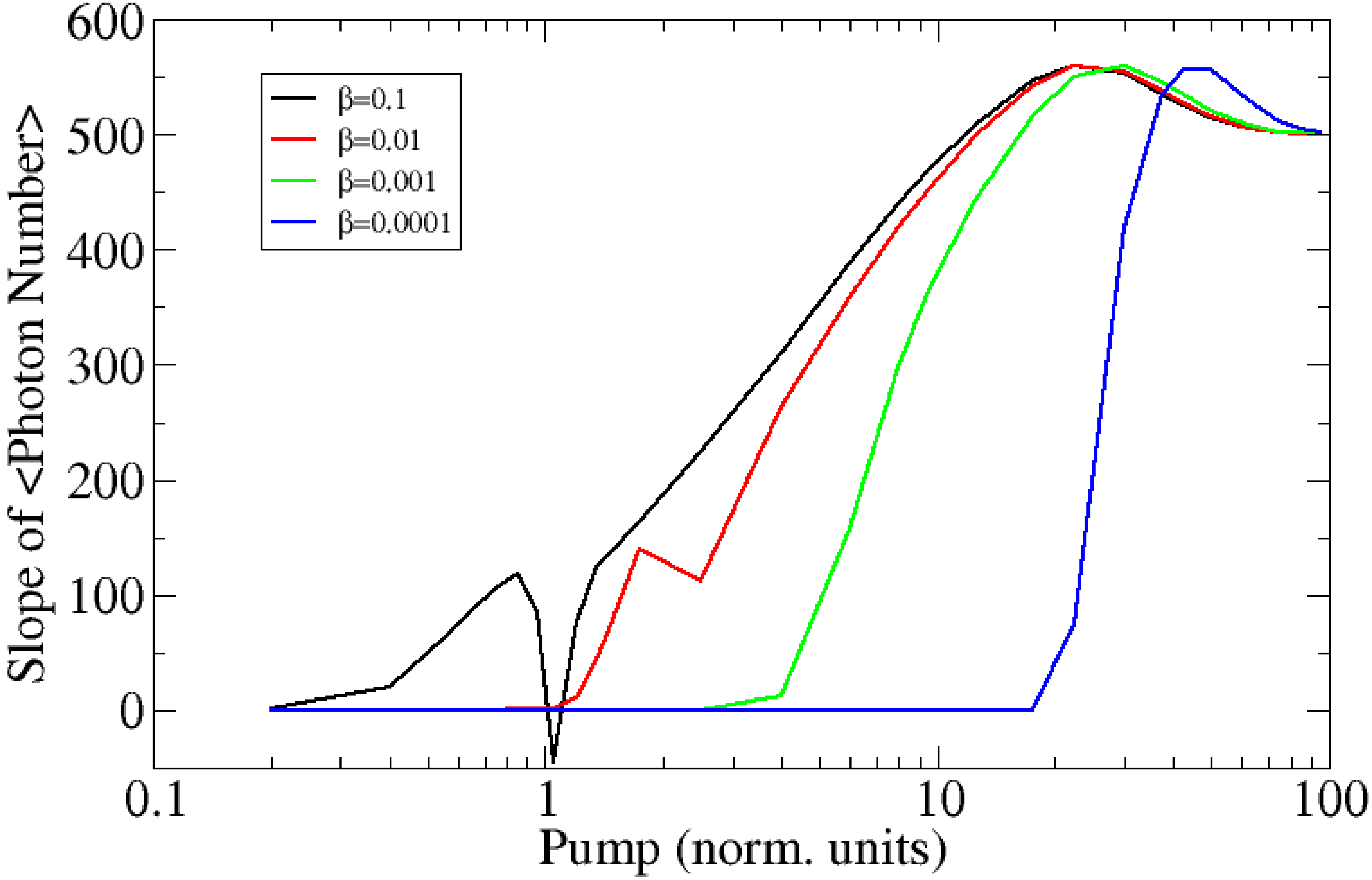



FIG. 4. (Color online) Dashed lines: Four different realizations of the stochastic rate equations at $P = 1.8P_{th}$. Solid line: The mean pulse averaged over 1500 realizations. It can be clearly seen that the longer it takes for the pulse to emerge, the smaller is its amplitude. Inset: The dots show the statistical distribution of the total number of photons per pulse at $P = 1.8P_{th}$, and the line shows the expected distribution for Poisson statistics of the same mean.

$\beta = 0.01$





β=0.1
β=0.01
β=0.001
β=0.0001
Slope of <Photon Number>
Pump (norm. units)
600
500
400
300
200
100
0
0.1
1
10
100